Public Economics and Climate Change Mitigation

The Role of Rent Taxation and Infrastructure Policy

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Abstract

Climate change mitigation under the recent Paris Agreement is based on voluntary, 'nationally determined contributions'. Thus, it is crucial to identify and understand all relevant *domestic* incentives for emission reductions.

This thesis shows that national-level climate policy has important interactions with fiscal instruments, and that careful, integrated policy design is needed to reap their benefits. I first provide an overview of such effects and find that apart from the potential to cut taxes with the help of carbon pricing revenues, several other effects have been underappreciated. I then focus on two classes of interactions for a detailed analysis:

First, climate policy may contribute to the public budget in at least two ways, both involving rent taxation: Carbon pricing acts as a tax on fossil resource rents, and climate policy may increase rents from fixed factors such as land, which can also be taxed. I show that rent taxation in the context of climate policy may entirely finance public investment, may have beneficial macroeconomic impacts on capital accumulation, and has implications for the choice and design of carbon pricing instruments. Specifically, I prove that such taxes on rents (1) can be sufficient to finance the optimal level of productive public capital and (2) increase aggregate private investment and thus efficiency if capital was otherwise underaccumulated. The efficiency gains from rent taxation are inseparable from its redistribution effect, and their size can be increased up to the social optimum by redistributing tax revenues to fundless younger generations. Furthermore, I show that (3) auctioned carbon emission permits are preferable to a carbon tax in this context because they allow for a separate optimization of both climate protection and rent collection.

Second, public spending plays a crucial role for decarbonization. Using the example of different types of transport infrastructure, I demonstrate that public spending should often be used to actively shape private behavior and reduce greenhouse gas emissions. It should not just 'follow' private demand affected by carbon pricing. Specifically, I assume that different public goods complement clean and dirty private goods, respectively. It can then be shown that changes in the composition of public spending should be used to induce demand shifts when the carbon price is too low. Nevertheless, when either the carbon price or the composition of public spending are restricted, the *other* instrument should also be weakened, unless environmental quality is very important for social welfare.

These results imply that climate and fiscal policy at the national level should often be evaluated and designed together, in order to realize beneficial interactions between both fields and to help prevent potentially catastrophic climate change at a global level.

Zusammenfassung

Das vor kurzem geschlossene Pariser Abkommen zur Bekämpfung des Klimawandels basiert auf freiwilligen, von jedem Land selbst festzulegenden Beiträgen. Es ist daher von entscheidender Bedeutung, alle auf *nationaler* Ebene relevanten Motive für Emissionsreduktionen zu ermitteln und zu verstehen.

Diese Arbeit zeigt, dass auf nationaler Ebene wichtige Wechselwirkungen zwischen Klimapolitik und fiskalpolitischen Instrumenten auftreten, und dass ein sorgfältiges, integriertes Politikdesign notwendig ist, um sich diese zu Nutzen zu machen. Zunächst gebe ich einen Überblick und arbeite heraus, dass mehrere Wechselwirkungen bisher zu wenig berücksichtigt wurden – abgesehen von möglichen Steuersenkungen mit Hilfe der Einnahmen durch einen CO_2-Preis. Daher betrachte ich anschließend zwei weitere Arten von Effekten:

Erstens kann Klimapolitik auf mindestens zwei Weisen zu den öffentlichen Finanzen beitragen, die mit der Besteuerung von Renten zusammenhängen: Einerseits wirkt die Bepreisung von Treibhausgasemissionen wie eine Steuer auf die Renteneinnahmen aus fossilen Resourcen. Andererseits kann Klimapolitik die Renteneinnahmen fixer Faktoren wie zum Beispiel Land erhöhen, die ebenfalls besteuert werden können. Ich zeige, dass Rentenbesteuerung im Rahmen von Klimapolitik öffentliche Investitionen finanzieren und wohlfahrtssteigernde Auswirkungen auf die gesamtwirtschaftliche Kapitalakkumulation haben kann, und dass sie wichtige Konsequenzen für die Wahl und Ausgestaltung von Instrumenten zur Emissionsbespreisung hat. Genauer gesagt beweise ich, dass eine derartige Rentenbesteuerung (1) zur vollständigen Finanzierung der sozial optimalen Menge produktiven öffentlichen Kapitals ausreichen kann und (2) die aggregierten privaten Investitionen erhöhen und damit auch effizienzsteigernd wirken kann, wenn andernfalls zuwenig Kapital akkumuliert würde. Die Effizienzsteigerung durch die Rentenbesteuerung ist untrennbar verbunden mit ihrem Verteilungseffekt. Sie kann bis zur Erreichung des sozialen Optimums erhöht werden, indem man die Einnahmen an mittellose jüngere Generationen umverteilt. Weiterhin zeige ich, dass (3) ein System auktionierter Emissionszertifikate einer Steuer auf Emissionen in diesem Zusammenhang überlegen ist, weil es eine separate Optimierung sowohl von Klimaschutz als auch von Rentenbesteuerung erlaubt.

Zweitens spielen öffentliche Ausgaben eine zentrale Rolle für die Dekarbonisierung. Anhand des Beispiels verschiedener Arten von Transportinfrastruktur zeige ich, dass öffentliche Ausgaben oft aktiv benutzt werden sollten, um privates Verhalten zu beeinflussen und Treibhausgasemissionen zu verringern. Sie sollten nicht einfach der privaten Nachfrage 'folgen', die durch Emissionsbepreisung verändert wird. Spezifisch nehme ich an, dass verschiedene

öffentliche Güter jeweils komplementär zu sauberen und schmutzigen privaten Gütern sind. Dann lässt sich zeigen, dass Veränderungen der Zusammensetzung öffentlicher Ausgaben zur Beeinflussung der privaten Nachfrage benutzt werden sollten, wenn der CO_2-Preis zu niedrig ist. Allerdings sollte bei einer Beschränkung des CO_2-Preises oder der Zusammensetzung öffentlicher Ausgaben auch das jeweils andere Instrument abgeschwächt werden – es sei denn, Umweltqualität wäre sehr wichtig für die soziale Wohlfahrt.

Diese Ergebnisse implizieren, dass nationalstaatliche Klima- und Fiskalpolitik oft gemeinsam bewertet und ausgestaltet werden sollte, um positive Wechselwirkungen zwischen beiden Politikfeldern auszunutzen und um einen globalen Klimawandel katastrophalen Ausmaßes vermeiden zu helfen.

An economist is someone who says, when an idea works in practice,
'let's see if it works in theory.'

Walter W. Heller, 1979

Preface

Using only the kind of slight simplifications that are popular with economists, one may say that I wrote this thesis mainly because of two major events in 2009, because I'm originally a physicist, and because I am an optimist.

The first event was the collapse of the global financial system after the bankruptcy of the Lehman Brothers investment bank, and the turmoil of public finances and the real economy in its aftermath. The second was the preparation and ultimate failure of the negotiations for global climate protection in Copenhagen, and the civil society movements and demonstrations accompanying it. Both the financial crisis and anthropogenic climate change have grave social and ecological consequences, which by themselves provide enough motivation to study their respective causes and ways of mitigating them.

Additionally, the two topics are linked politically and economically in many ways. One similarity particularly struck me: the public debate around both issues appeared to be mainly between the same two camps – and the arguments of both camps confused me. In a very stylized description:

For one group, to which many of my fellow demonstrators in Copenhagen belonged, 'the market-economic system' (or plainly 'capitalism') was to be blamed for the financial crisis as well as for the reckless exploitation and destruction of nature. There were different ideas of how this 'system' was upheld only by some kind of conspiracy of a small group of beneficiaries, and how it could be abolished and replaced by something more fair and sustainable. This seemed to mistake outcomes for causes: To my mind, heavily influenced then by the analysis of complex system dynamics in physics, 'the market-economic system' was not a system at all. Instead, I saw it as a relatively stable *state* of an *underlying* social system, in turn shaped by more fundamental forces such as human behavior. I wanted to better understand this latter system, identify those of its features which stabilize its current state, and look for alternative states as well as 'ways of getting there'. Economics seemed to offer suitable tools for this. (Of course, I did not fully reach these formidable goals, but at least that was my vision.)

The opposing group defended economic growth and free markets as if they were primary aims. In their view, the financial crisis had been caused, and its consequences had been made worse, by government intervention in markets. Climate change would be no problem if only entrepreneurship and innovation were given free rein. This position seemed to confuse means and ends and to neglect human well-being, ecological limits and, in its extreme forms, laws of physics (thermodynamics, in particular). During the 'climate summit' in Copenhagen, there was a faint hope among pro-mitigation activists, including myself, that the reality of the financial crisis had politically weakened this camp. Would this provide an opportunity to improve economic and environmental policies, and to switch to a more sustainable way of managing our economies? This hope did not materialize to date, but I refuse to give up as yet, and tried to make a small contribution in the form of the ideas in this thesis.

This thesis would not exist without the steady encouragement and support from my family and friends, the efforts and advice of my collaborators, the inspiring discussions with my colleagues at the MCC, PIK and TU Berlin, or the administrative staff at the MCC. The importance of these great people and their contributions cannot be overstated, and there are too many to list. A big 'thank you' goes to all of them! Nevertheless, I would like to particularly highlight a few:

Ottmar Edenhofer not only provided invaluable ideas and feedback, but also set up and maintained a very motivating environment through his well-balanced leadership, accessibility and humor – and let me be a part of it.

Felix Creutzig patiently helped me in the early stages of my dissertation to disentangle my research ideas.

Linus Mattauch was indispensable as a brilliant, careful collaborator, as a critical and constructive partner in many discussions, and as a reliable friend. Similarly, I thank Anselm Schultes, David Klenert and Max Franks, as well as Christina Roolfs and Gregor Schwerhoff.

The introductory and concluding chapters of this thesis benefited hugely from comments by Blanca Milan-Fernandez, David Klenert, Linus Mattauch and Ulrike Kornek. I would also like to thank again many other colleagues at MCC, PIK and beyond who provided helpful comments on individual chapters in the main part, as acknowledged there.

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Contents

Chapter 1

Introduction

Climate change endangers ecosystems and the livelihoods of billions of people now and in the future. It results from rising average concentrations of greenhouse gases (GHG) in the atmosphere. Thus, climate change is a global externality of local GHG emissions, and limiting it requires global cooperation. This has been known to a wider public for more than two decades (IPCC, 1990). The necessary scale and urgency of GHG emission reductions (IPCC, 2013) as well as its relatively low costs (IPCC, 2014), when optimally implemented, have been repeatedly emphasized.

However, international cooperation on climate change mitigation is difficult, for example because each country can 'free-ride' on mitigation actions of others, and because mitigation potentials and expected climate damages are unevenly distributed, so that countries need to agree on an international burden-sharing mechanism. Consequently, negotiations for a comprehensive international agreement with binding mitigation targets eventually stalled.

This deadlock lead to a paradigm shift in international cooperation, as documented by the recent Paris Agreement (UNFCCC, 2015). The agreement establishes a 'pledge and review' approach based on *national* mitigation targets and actions ('Nationally Determined Contributions', short NDCs), which are centrally recorded and assessed at regular intervals. The voluntary nature of pledges ensured broad support of the new agreement, but successful mitigation also requires *"adequate ambition of the individual contributions"* (Stavins, 2015).

Accordingly, the focus of the economic analysis of costs, benefits and instruments of climate policy also needs to be adjusted: As long as climate policy was mostly framed in terms of direct mitigation costs, burden-sharing and free-riding, most studies considered emission-intensive sectors and the international level (see for example Stern, 2007). Now that NDCs and domestic motives for mitigation are the starting point, the national level comes more into focus. At the national level, climate policy interacts with a broad range of non-climate policy goals and instruments. For example, the determination of optimal domestic mitigation targets and the design of instruments to implement them should consider potential co-benefits in terms of health and local environmental quality (Woodcock et al., 2009; von Stechow et al., 2015). It must also take into account links between climate policy and public finance instruments such as taxes and public spending (Parry et al., 2014; Bowen, 2015).

These fiscal interactions are the subject of this thesis.

My first objective is to provide an overview of climate- and fiscal policy interactions that may enhance incentives for domestic climate change mitigation. It has been pointed out that carbon pricing may raise substantial revenues for the public (Pearce, 1991; Metcalf, 2007), and a large body of literature analyzes if using these revenues to cut distortionary taxes would lead to welfare gains even before accounting for the environmental effects.[1] However, I find that numerous other effects have been underappreciated.

My second objective is thus to address this gap by theoretically analyzing four selected effects. Three effects are related to rent taxation in the context of climate policy. Climate policy affects economic rents[2] from the fixed factor land, for example via deforestation regulation, increasing demand for bioenergy, or urban transport policies. It also affects rents from exhaustible fossil resource stocks, for example by carbon pricing. For a general tax on rents from a fixed factor, it has been shown that it may fully finance the optimal level of local public goods (Arnott and Stiglitz, 1979), but may also cause macroeconomic distortions, for example regarding aggregate investment (Feldstein, 1977). I examine these effects for the case of national climate policy: First, I consider the potential of a tax on rents (from land or fossil resources) to finance the optimal level of national public investment. Second, I analyze how the macroeconomic distortions implied by a tax on *fixed* factors affect social welfare (and thus total mitigation costs), in particular when combined with different revenue redistribution schemes. Third, I investigate if similar macroeconomic distortions also occur for different forms of carbon pricing, acting as a tax on rents from *exhaustible* fossil resource stocks.

The fourth effect concerns the role of public infrastructure provision for climate change mitigation: public infrastructure such as road, rail or electricity networks 'induce' more or less emission-intensive patterns of private demand behavior and production. They require high up-front investments but have very long lifetimes, and exhibit network externalities. Thus, infrastructure provision should be treated as a separate mitigation policy instrument, complementary to carbon pricing (Shalizi and Lecocq, 2009; Guivarch and Hallegatte, 2011; Waisman et al., 2013). However, both policy instruments may not be at their optimal levels: since infrastructure capital stocks are slow-changing, infrastructure provision will be suboptimal for a transition period. Similarly, most practically implemented carbon prices have been suboptimally low. The theoretical literature that considers environmental taxes and public spending together (Bovenberg and van der Ploeg, 1994) has only analyzed restrictions on non-environmental taxation (labor- instead of lump-sum taxation). I will thus analyze second-best scenarios in which either infrastructure provision or the carbon price are constrained.

The remainder of this introductory chapter sets the stage for the detailed analysis of later chapters.[3] Section 1.1 briefly describes the climate change externality and explains why the 'traditional' approach of negotiating a bind-

[1] See Goulder (2013) for a recent overview.

[2] I will use the term 'rents' in the Ricardian sense as payments to a factor in excess of what is needed for the factor to be supplied. Under this definition, all payments to a factor in fixed supply are rents. In an alternative definition due to V. Pareto, rents are payments in excess of what is needed to keep the factor in the same use (Wessel, 1967).

[3] Since Chapter 2 is itself an overview chapter, with a framing section that covers the same subject area, I will keep the overlapping parts brief here.

ing global agreement failed. Section 1.2 describes the 'hybrid' approach taken in Paris, and the need for a broader framing of domestic mitigation motives implied by such an approach. Section 1.3 illustrates the significance of interactions between climate policy and fiscal instruments, using the examples of carbon pricing, land rent taxation and infrastructure provision. Because the main part provides a theoretical treatment of these effects, the examples are mostly empirical here. Section 1.4 derives specific research questions that arise where climate- and fiscal policies overlap, and provides an outlook on the related chapters that follow in the main part.

1.1 Climate change, traditionally framed: damages, technology and international cooperation

This section summarizes the global externality problem of climate change, and failed attempts to solve it by a globally binding, comprehensive agreement that would lead to a cost-effective deployment of mitigation technologies.

The planet has warmed by 0.8 °C during the last century (IPCC, 2013, p.5), and the main driver behind this are anthropogenic emissions of GHG, the concentrations of which *"now substantially exceed the highest concentrations [...] during the past 800,000 years"* (IPCC, 2013, p.11). If emissions continue to grow, global mean surface temperature may rise by more than 4 °C in this century (IPCC, 2013, p.23), implying *inter alia* significant sea level rise, ocean acidification, shifts in precipitation patterns, and more extreme weather events.

To limit the damages to ecosystems and human societies around the globe (as detailed by the IPCC, 2014), GHG emissions must be dramatically reduced. For example, to limit global warming until the year 2100 to 2 °C above pre-industrial times with a probability of at least 66%, cumulative global CO_2 emissions between 2012 and 2100 need to stay below 1000 $GtCO_2$ (IPCC, 2013, p.27). As an illustration, this goal could be achieved if global annual GHG emission were reduced by 40% to 70% until the year 2050, relative to 2010, and if emissions were close to zero or even negative in 2100 (IPCC, 2014).

The gross costs of climate change mitigation may be relatively low if the most cost-effective measures are taken across all countries, sectors and technologies: This can be shown with integrated assessment models (IAMs) that couple models of the climate system and the economy. IAMs typically focus on mitigation technologies in GHG-intensive sectors and abstract from institutional details and constraints, such as national governments and imperfect markets. Accordingly, they yield 'first-best' results on global mitigation costs and pathways (see Weyant et al. (1996); Clarke et al. (2014), and Section 2.1 in Chapter 2).

For example, it can thus be estimated that the 2 °C target may be achieved at a reduction of the annual global consumption growth rate by around 0.06 percentage points in this century, relative to a baseline with annualized consumption growth between 1.6% and 3% (IPCC, 2014, p.15f).[4]

[4]This is a median value across different IAMs and scenarios. It assumes no technological restrictions, in particular on the use of carbon-capture and storage (CCS) technologies,

Such an optimal mitigation pathway could for example be implemented by imposing a globally uniform price on carbon (Pearce, 1991; Stern, 2007).

But optimal mitigation is difficult under realistic institutions. Two main problems relate to the fact that there is no global institution to implement mitigation, but a large number of national governments. Two further points relate to the distribution of costs and (uncertain) benefits over time, and to inefficient national policies.

First, in an international setting, climate change has to be characterized as a global externality of national GHG emissions. Put differently, climate change mitigation is a global public good which is underprovided (in the absence of a global authority) because each individual country cannot internalize all benefits of its own mitigation, but may in turn 'freeride' on the mitigation actions of other countries (Stern, 2007, p.511). Preventing such behavior requires international cooperation, but theories of collective action indicate that it is unlikely to obtain the optimal level of cooperation among all countries (Carraro and Siniscalco, 1993; Barrett, 1994; Finus, 2003, 2008; Harris, 2007).

Second, benefits and costs of optimal mitigation are unevenly distributed between countries: A country's benefits in terms of avoided damages depend on its vulnerability to climate change; its role in globally optimal mitigation depends not only on the size of its emissions, but also on the costs of reducing them (and on potentials to offset emissions, for example by aforestation). As a result, the carbon price that countries may introduce out of self-interest is not only considerably lower than the global optimum (due to the public good problem), it also varies widely between countries or regions.[5] Edenhofer et al. (2015) illustrated this using a game-theoretic model based on Lessmann et al. (2009) (see Fig. 1.1): For example, India and China (and parts of Europe) are vulnerable to climate change and have large mitigation potentials, but at relatively high costs, so that a carbon price of up to 40% and 25% of the globally optimal price would be in their own interest, respectively. In contrast, other large emitters, such as the US, Russia and Japan, expect either small damages or have large low-cost mitigation potentials, so neither of them would individually implement a carbon price beyond 10% of the global optimum. And although many low-income countries in Sub-Saharan Africa are particularly vulnerable (Tol, 2009), they only contribute a relatively small share to GHG emissions (Blanco et al., 2014, p.358) and have low marginal abatement costs. Accordingly, their self-interested carbon price would only be roughly 10-20% of the global optimum (under which they would contribute a more-than-proportional share to optimal mitigation, see Tavoni et al. (2013) and Clarke et al. (2014), p.435). Thus, broad international cooperation and implementing the lowest-cost mitigation options requires some form of burden-sharing between countries, for example by monetary or technology transfers. If all countries were purely self-interested, mitigation would have to be made Pareto-improving (non-negative net benefits for all participating countries). Alternatively, burden-sharing schemes based on different equity principles have been proposed, for example related to historical responsibility, economic capa-

bioenergy, wind, solar and nuclear power in the energy sector. If some of these were restricted, costs would be higher: For example, without large-scale CCS costs would increase by a factor of 2.4.

[5] This analysis is somewhat simplified; for example, international leakage (Jakob et al., 2013) and adaptation options (Fankhauser, 2010) also play a role.

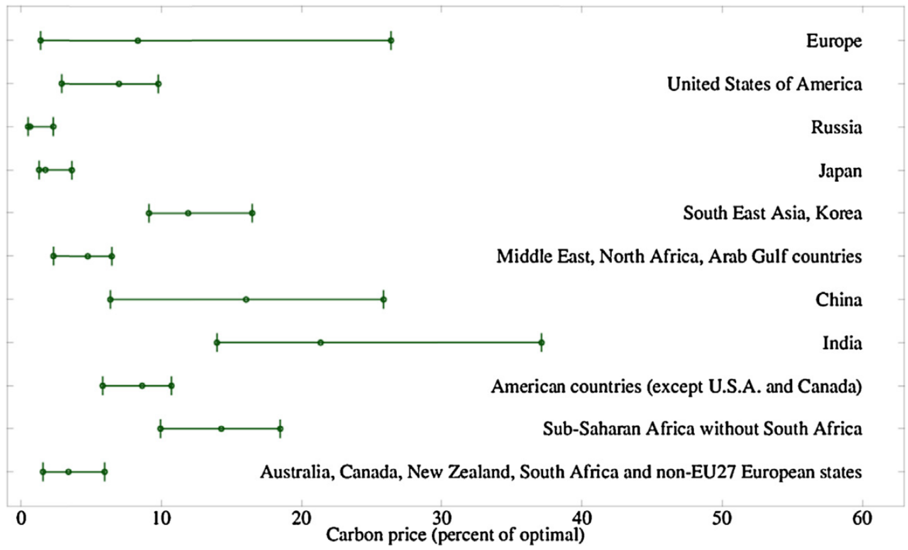

Figure 1.1: Unilateral carbon prices relative to the globally optimal price, based on different damages functions. *(Figure reproduced from Edenhofer et al. (2015), with permission from Elsevier.)*

bility, or equal per-capita emissions (Höhne et al., 2014). These burden-sharing schemes may involve annual transfers of several hundred billion US$ (Clarke et al., 2014, p.461; see also Section 1.3.1).

Third, costs and benefits of mitigation are unevenly distributed over time, and partly uncertain: On the one hand, a large share of the costs of mitigation (including potential needs for international transfers) occurs in the near- to mid-term. In the spirit of the technology-focused IAMs mentioned above, a large number of models has analyzed these costs (Clarke et al., 2014), so they are relatively well understood – at least those accruing directly in emission-relevant sectors, and apart from unavoidable uncertainties regarding innovation. On the other hand, the benefits from avoided climate damages lie in the future, and are both difficult to estimate scientifically and to value economically. This has caused major controversies about intergenerational distribution, discounting and the appropriate handling of uncertainty (Stern, 2007; Nordhaus, 2007; Dasgupta, 2007; Weitzman, 2009; Ackerman et al., 2009; Pindyck, 2013b,a).

Fourth, real costs of national mitigation efforts are higher than in the first-best benchmark derived by IAMs (Staub-Kaminski et al., 2014): One reason is that GHG-intensive sectors, such as electricity generation or transport, suffer from various additional sources of inefficiency, such as markets with imperfect competition, natural monopolies and network externalities, or technology spillovers (Joskow, 1997; Unruh, 2000; Jaffe et al., 2005; Aldy et al., 2010). Another, related reason is that national governments are typically subject to political and information constraints, so they cannot implement the theoretically most efficient set of policy instruments to regulate the GHG emissions and these other inefficiencies.

Given the four problems of freeriding, redistribution, far-off benefits and uncertainty, and second-best policies with higher costs, it is unsurprising that no ambitious, binding and global agreement on climate change mitigation has been achieved yet:[6] The United Nations Framework Convention on Climate Change (UNFCCC) was established in 1992, but since then, international negotiations have failed to establish an efficient 'top-down' agreement, with global abatement targets and a centralized pricing mechanism as well as international institutions to enforce it: The Kyoto Protocol of 1997 only entered into force in 2005; it does not cover major GHG emitters such as China and India; while it contains emission targets for 38 industrialized countries and 'economies in transition' until 2020, these will not (or not fully) be observed by five countries (USA, Canada, Japan, Russia and New Zealand); and its effectiveness is limited further by arguably under-ambitious emission reduction targets and compliance issues (Stavins et al., 2014, p.1041f). In Copenhagen in 2009, the parties to the UNFCCC could not agree on extending the Kyoto Protocol beyond 2020, or on how to replace it.

This failure led to the new 'hybrid' approach to climate change mitigation that was formally accepted in Paris (UNFCCC, 2015).

1.2 Hybrid agreements and a broader framing of domestic benefits and costs

In this section I first summarize the Paris Agreement (UNFCCC, 2015) as the main example of a 'hybrid' approach to international cooperation. It builds on unilateral, voluntary pledges for emission reductions, thus emphasizing domestic mitigation motives. Second, I explain why domestic benefits and costs should be framed more broadly in this context than under the standard 'climate damage and mitigation technology' paradigm presented so far. Non-standard domestic mitigation motives will then be the subject of the rest of this introduction and of the main part of this thesis.

1.2.1 The Paris Agreement

The lack of a near-term perspective for a comprehensive international agreement, which contrasted the willingness demonstrated by some countries to proceed with climate change mitigation nevertheless – for example by the EU (European Council, 2014) and by the US and China (USA, 2014) – has led to a shift of focus towards the national level: Even without a comprehensive global agreement, *some* degree of GHG emission reduction is in many countries' own best interest, and such efforts could be encouraged as a starting point. Accordingly, some recent approaches to international cooperation, sometimes called 'hybrid' or 'pledge and review' approaches (Dubash and Rajamani, 2010), combine 'bottom-up', unilateral pledges for (voluntary) mitigation with centralized 'top-down' elements such as centralized monitoring. The recent Paris Agreement (UNFCCC, 2015) is the main example.

The Kyoto Protocol contained *binding* emission reduction targets only for *some* countries. In contrast, the 'Copenhagen Accord' and the 'Cancún Agree-

[6] In economics, both the difficulty to achieve ambitious global cooperation and the formation of a smaller coalition whose members implement mitigation in line with their self-interest (but below the global optimum) have been explained by collective action theory with the help of game theory (Finus, 2001, 2003; Barrett, 2007; Stavins et al., 2014). See Section 7.2.3 in Chapter 7 for some more details on game-theoretical models of international cooperation and their relation to the methods used in this thesis.

ment' combined overall abatement goals with a request to *all* countries to make *voluntary* mitigation pledges (UNFCCC, 2009, 2010). Building on this, the 'Durban Platform for Enhanced Action' had the explicit mandate to develop an instrument *"applicable to all Parties"* (UNFCCC, 2011, Art.2).[7] This eventually lead to the Paris Agreement which is similarly universal and voluntary in character, but contains some centralized elements (UNFCCC, 2015).

Under the new agreement, all members of the UNFCCC are required to submit 'Nationally Determined Contributions' (NDCs) which detail their national mitigation target. After the conference, 186 out of 195 countries, accounting for 96% of global emissions, had submitted an 'intended' NDC (Stavins, 2015).[8] These show very large variations regarding ambition as well as formulation and precision (different reference points, sectoral coverage, target ranges, etc.), making them difficult to compare.[9] Together, these NDCs are only sufficient to limit global warming to 2.7 °C – and only if they are indeed fully implemented: currently implemented policies indicate that only a 3.6 °C limit can be maintained (Climate Action Tracker, 2015).

Thus, to achieve the overall 2 °C-target – which is re-iterated as a common goal (with a note that a 1.5 °C-target would further reduce risks) – the NDCs will have to become more ambitious over time. To create incentives for this, the agreement contains some 'centralized' elements to review the unilateral pledges and to make more transparent: First, the NDCs are to be renewed every five years, with each new NDC representing a *"progression beyond"* earlier commitments (Art.4). Second, a *"facilitative dialogue among Parties in 2018 [is] to take stock of the collective efforts"* (Decision 20), with a first comprehensive 'global stocktake' in 2023 (Art.14), and every five years thereafter. Third, Stavins (2015) interprets Art.4 of the agreement to the effect that every country will eventually be subject to the same standards of monitoring and reporting.

Despite these provisions, it is not unlikely that a gap will remain between the sum of unilateral pledges and the emission reductions needed for a 2 °C target (Edenhofer et al., 2015). Thus, international cooperation may still be required for providing additional incentives and closing the gap. It is unclear how the new dynamics of domestic mitigation will affect strategic interactions and cooperation at the international level. I will return to this issue in the synthesis (Chapter 7).

For now, however, it seems important to gain a better understanding of domestic mitigation motives.

[7] This has been pointed out by Stavins (2015). See also (Stavins et al., 2014, p.1017) for an overview of alternative forms of international cooperation.

[8] The NDCs are labeled 'Intended Nationally Determined Contributions' (INDCs) until the Paris Agreement enters into force, that is, after it has been ratified by at least 55 countries representing at least 55% of global emissions (UNFCCC, 2011, Art.21).

[9] For example, the EU commits to economy-wide GHG emission reductions of 40% by 2030, relative to 1990 (European Council, 2014). The Climate Action Tracker (2015) *inter alia* reports that China intends to reduce the carbon intensity of GDP by 60-65% in 2030 compared to 2005, Mexico wants to reduce GHG emissions by 25% below baseline emissions in 2030, and the United Arab Emirates do not give specific GHG reduction targets but point to mitigation and adaptation co-benefits from economic diversification.

1.2.2 The need for a broader framing of domestic benefits and costs

It is unclear if and how the unilateral targets under the Paris agreement will be enforced, so it will be crucial for the long-term success of the 'pledge and review'-approach to identify, understand and strengthen all relevant *domestic* incentives for unilateral mitigation:[10]

As discussed in Section 1.1, most studies on climate change mitigation have been conducted either at a sectorally resolved, technologically detailed level, analyzing optimal mitigation and policies for specific GHG-intensive industries, or at the international level, considering the cooperation and feasibility of agreements between nation states. However, not all effects of climate policy on efficiency and distribution can be captured at a sectoral or international level: What has been insufficiently analyzed is the 'intermediate', national level, where climate change mitigation is just one of many objectives, and mitigation policies interact with a broad set of policies (Stewart et al., 2013; Parry et al., 2014; Combet and Hourcade, 2014; Edenhofer et al., 2015; Bowen, 2015).

So far, mitigation has often been perceived as a costly issue that is separate from other domestic policy objectives, apart from *competing* with them for resources: As a consequence of the focus on technology or international distribution, the costs and benefits of mitigation were conventionally framed as near-term costs in regulated sectors, and avoided domestic climate damages, which are uncertain, and for some countries relatively low. In national policy-making, allegedly costly climate change mitigation is then frequently contrasted with other high-priority, urgent objectives that also require resources, such as economic growth, employment, inequality, education and health.

However, this conventional framing is too narrow – there are multiple interactions through which national climate policy packages may actually align with and *contribute* to other objectives:

First, the emphasis on direct costs, and thus on monetary terms, has implied that potential beneficial side-effects from mitigation activities that are harder to monetize have long been neglected. Many of these 'co-benefits' concern local effects on health and environmental quality (von Stechow et al., 2015). For example, in the energy and transport sectors, many technologies with low GHG emissions also cause less local pollution (from nitrogen oxides, sulfur oxides and particulate matter) and thus reduce related respiratory diseases and local environmental damages. In transport, higher public and non-motorized transport shares reduce road congestion.[11] Another example is that replacing motorized local transport by physical activities (cycling and walking) increases health (Woodcock et al., 2009). In the likely case that these non-climate externalities in transport, energy generation and other sectors are *not fully internalized by other policies* (cf. Kolstad et al. (2014), Section 3.6.6), the co-benefits of climate policy can be substantial: when they *are* monetized, they may actually outweigh the benefits of avoided domestic climate damages (West

[10] (Stavins et al., 2014, p.1007) state that *"gaps in knowledge and data [on international cooperation include] understanding the factors that affect national decisions to join and form agreements"*.

[11] Among others, Pearce (1991); Creutzig and He (2009) and Parry et al. (2014) pointed out the effect of climate policies on both local pollution and road congestion.

et al., 2013).[12] Additionally, they occur in the short- to medium-run, so they provide an important incentive for unilateral mitigation in some countries.

Second, even from a fiscal point of view, interactions between climate- and other policies are too complex to be reduced to a competition for public funds. They need to be taken into account in the design of policy packages to achieve efficiency and address distributional concerns (cf. Combet and Hourcade, 2014): On the one hand, governments typically face strong constraints with respect to the choice and design of fiscal instruments such as taxes and public spending. For example, when lump-sum taxes are infeasible the public budget has to be financed by distortionary taxes (on labor and capital income, consumption, etc.). Furthermore, there may be constraints on the level and structure of public spending. On the other hand, climate policy may also raise revenues and involve public spending, and introduces additional (environmental) constraints. In such a setting, the theory of the second best (Lipsey and Lancaster, 1956) implies that both fiscal and climate policy instruments will have to be adjusted to each other for optimal efficiency.

As the next section will show, the significance of interactions between climate policy and public finance becomes evident from the magnitude of the related financial flows and asset values. Nevertheless, the implementation of climate policy under fiscal constraints has only been considered in a few cases – in contrast to many constraints and inefficiencies related to technology and market structures that have been analyzed for GHG-intensive sectors.

1.3 The importance of interactions between climate policies and fiscal policies

This section gives examples of interactions between climate policy and fiscal policies. Two groups of interactions are presented:

On the revenue side of the public budget, I discuss carbon pricing as an alternative source of public revenue in second-best tax systems and its interpretation as a tax on fossil resource rents. I also consider changes in non-urban and urban land rents in response to specific climate policies that suggest land rent taxation as a complementary instrument.

On the spending side, effective climate change mitigation will involve large amounts of public spending, for example on public capital stocks in the transport and energy sectors. It is unclear if *total* public spending will have to increase due to mitigation spending, and if this should have priority over other public spending needs. However, public capital stocks will at least have to be *restructured* at a large scale to support a clean rather than emission-intensive supply of transport services and energy. This may even involve an earlier retirement of existing infrastructure that perpetuates emission-intensive patterns of production and consumption.

Insofar as these examples have not been fully analyzed in the literature, they lead to the specific research questions in the next section. Accordingly, the presentation here is not exhaustive, and focuses on the basic mechanisms and empirical approximations. The main part of this thesis will provide both a

[12] In this case, policies would be primarily designed to improve public health or local environmental quality, and GHG emission reductions would be a co-benefit.

more complete and detailed overview (Chapter 2), and an in-depth theoretical treatment of selected effects (Chapters 3-6).

Furthermore, the exposition here – and in fact the entire thesis – follows the 'traditional paradigm' of public economics, assuming *inter alia* a perfectly informed, benevolent government. Alternative views, and resulting effects, will be discussed in Chapter 7.

1.3.1 Interactions between climate policy and public revenues

This subsection considers interactions on the revenue-side of the public budget, with some distributional implications.

First, climate policy implemented as carbon pricing can raise substantial funds. These can be used to cut taxes or public debt. On the flip side, carbon pricing reduces some rents (mainly from fossil-fuel resources) and can thus be interpreted as a form of rent taxation.

Second, climate policy will affect the rents from agricultural land, and will in many cases increase urban land rents. Thus, it will become more important to consider taxes on such rents when specific mitigation policies are introduced.

Carbon pricing and fossil resource rents

Here I illustrate that carbon pricing has the potential to raise significant public revenues, and briefly summarize the literature on using these revenues for cutting taxes or public debt, as well as studies that have interpreted carbon pricing as a tax on fossil resource rents. I will conclude that the macroeconomic implications of the latter have not been fully appreciated to date.

Regarding the potential revenues of carbon pricing, for a naïve back-of-the-envelope approximation assume that a carbon price of 20 EUR per ton of CO_2-equivalent had been applied to the 4.5 $GtCO_2$(eq) emitted in 2012 by today's 28 EU member states, or Germany's 0.9 $GtCO_2$(eq) (EEA, 2015). This would have generated revenues of 90 or 18 billion Euro in that year alone (compared to total receipts from taxes and social contributions of 5109 or 1043 billion Euro EC, 2014) – ignoring implementation difficulties of such a comprehensive scheme and behavioral responses. More elaborate general-equilibrium models, however, yield comparable results: For a carbon tax between 8 and 40 Euro per tonne of CO_2 in the year 2020, Edenhofer et al. (2015) estimate the annual revenue potential of a carbon tax to be around 40 to 145 billion EUR in Europe.[13] A carbon tax may yield large revenues in other countries and regions as well, see Fig. 1.2.

Since most governments cannot use lump-sum taxes to finance the public budget, they have to resort to distortionary taxes, for example on labor income. Then, carbon pricing revenues can be used to cut these other taxes and lower the (gross) costs of public funds. The resulting potential for a 'double dividend' (together with reducing the environmental externality) has been discussed in depth (see Goulder (2013) and Section 2.2 in Chapter 2 for more details). Alternatively, climate policy revenues could be used to reduce public debt (see Carbone et al. (2013); Rausch (2013) and Section 3.4 in Chapter 2). In

[13]In Edenhofer et al. (2015), 'EUR' represents 27 member states of the European Union, without Croatia. For the year 2020, Fig. 1.2 reports revenues of 50 to 180 billion US$(2005). These values, and the carbon tax, are convertible to EUR(2005) at a rate of 1.24:1.

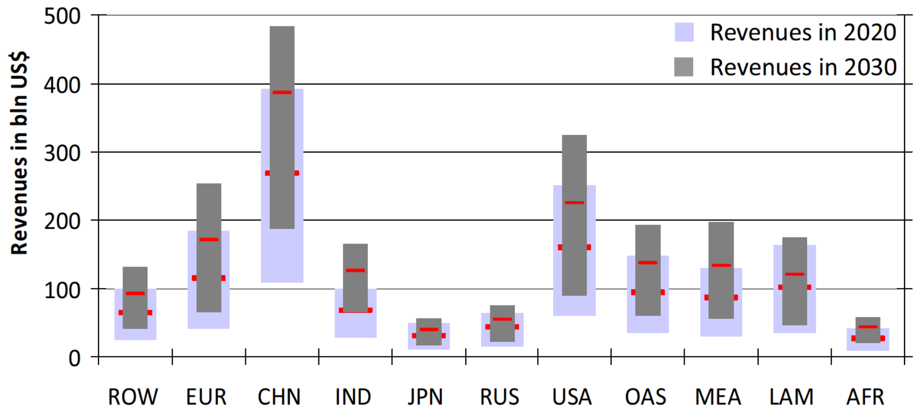

Figure 1.2: Annual revenues in bln US$(2005) of a globally uniform carbon tax for different regions and tax levels in 2020 (light gray) and 2030 (dark gray). Lower and upper bounds of the bars for 2020 represent tax levels of \$10 and \$50 and the red line \$30 per ton of CO_2, respectively (with all mitigation technologies available). Corresponding values for 2030 are obtained by a 5% annual increase. *(Figure and caption adapted from Edenhofer et al. (2015), with permission from Elsevier.)*

the tradition of this literature, carbon pricing is simply a corrective tax, under which all consumers (or producers) internalize the social costs of dirty goods and change their behavior.

In contrast, a few contributions have pointed out that carbon pricing is effectively a tax on fossil resource rents, and considered distributional implications: A carbon tax – or similarly, a system of auctioned emission permits – reduces the earnings of the owners of fossil resource stocks, so the question arises if these 'rentiers' can be compensated to enhance political feasibility of carbon pricing.

Bauer et al. (2013) calculate the net present value (NPV) of global fossil resource rents and a potential global 'carbon permit rent' obtained by the regulator between the years 2010 and 2100, see Fig. 1.3. They report that the NPV of fossil resource rents, which would equal 30 trillion US$(2005) in a business-as-usual (BAU) scenario without mitigation, would be reduced by 9 tril. US$ or 29% by a mitigation policy that establishes an atmospheric GHG concentration equivalent to 550ppm CO_2, and by 12 tril. US$ or 41% for a 450ppm CO_2(eq) target. At the same time, the NPV of the carbon permit scheme would be 21 trillion US$ for the 550ppm and 32 trillion US$ for the 450ppm case, thus exceeding the resource owners' losses. The sum of rents is larger for mitigation scenarios due to the increased scarcity (as a large share of fossil resources will have to remain underground, cf. McGlade and Ekins, 2015) – however, gross GDP will also be lower due to mitigation costs (right side of Fig. 1.3). Furthermore, losses and gains in rents are unevenly distributed over countries and regions (Bauer et al., 2013, supporting online material, Fig. S14). In some cases, for example for Russia, Latin America and Africa, the domestic balance is negative (given an initial permit allocation across countries that matches the market allocation, so that there is no international redistribution). This illustrates the difficulty of implementing

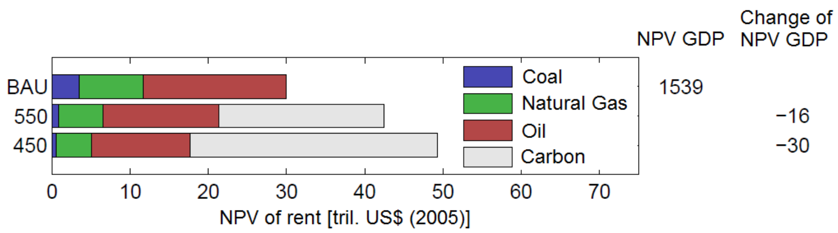

Figure 1.3: Net present value (NPV) of global fossil fuel rents and a global carbon permit rent (2010–2100, discount rate 5%). On the right: NPV of GDP in trillion US$05 and changes from mitigation policies. *(Figure adapted from Bauer et al. (2013), Fig. 7 (default scenario), with permission from Springer.)*

a globally uniform carbon price with or without international transfers (see Section 1.1).

Kalkuhl and Brecha (2013) consider the change in total scarcity rents when a carbon budget is introduced via a GHG emission trading scheme. They find that fossil resource owners may actually be made better off if they receive free emission permits in compensation for their reduced rents.

To summarize, carbon pricing as a source of public revenue has been recognized as a significant interaction between climate policy and public finance. It has been analyzed primarily as an 'ordinary' Pigouvian tax, useful for reducing other taxes or debt; when it has been interpreted as a form of rent extraction, the focus was on compensation for the rentiers. However, the modern interpretation of rent taxation as a means to finance the optimal level of public goods (Arnott and Stiglitz, 1979) or a cause of macroeconomic distortions (Feldstein, 1977) has so far been neglected, as I will point out in Section 1.4.

Climate policy and land rent taxation

In the following, I will point out that climate policy may have considerable effects on land rents: When land use is restricted, for example to conserve forests or to prevent car-oriented, low-density urban development, some land (to which these restrictions apply) will earn lower rents. In turn, the 'remaining' land will become scarcer: For cultivated non-urban land, it is uncertain if this will lead to higher land rents, because rents also depend on changes in yields and demand and potential conflicts between climate change mitigation strategies, other ecological concerns and food production. For the case of urban land, rents can be expected to increase, in particular near city centers.

Non-urban land

Agriculture, forestry and other non-urban land use is doubly important for climate policy: it causes direct GHG emissions, and its produce are required for some mitigation strategies in other sectors. Thus, the effects of different mitigation strategies (and climate change) on non-urban land rents can be expected to be large. In the following, I describe the twofold role of non-urban land in mitigation and some of the complex effects of mitigation policies on land rents. It turns out that the regional distribution of land rent changes and even their respective sign is highly uncertain today.

On the one hand, Smith et al. (2014) report that in 2010, agriculture, forestry and other (non-urban) land use (AFOLU) directly contributed roughly 25% to total global GHG emissions, *"mainly from deforestation and agricultural emissions from livestock, soil and nutrient management"* (*ibid.*, p.816). Reducing these emissions requires land-use measures as well as 'technological' measures: land use for forestry and agriculture will have to be regulated, for example to conserve remaining forests and other sinks and stores of carbon, or for afforestation (in some OECD countries). On the remaining land, other (supply-side) measures affect yields, for example different plant management, fertilizer use or tillage practices (Smith et al., 2014, p.830ff).

On the other hand, mitigation strategies in other sectors may increase demand for some types of agricultural and forestry produce, for example when the share of bioenergy in transport, electricity generation or heating is to be increased. This additional demand may be substantial: Today, total primary energy use is at 492 EJa, of which bioenergy and fossil fuels have a share of 10.2% and 85.1%, respectively (IPCC, 2011, p.10). However, according to (Haberl et al., 2013), bioenergy already accounts for 21.8% of the 230 EJa of biomass used by humans (also called 'human-appropriated net primary production' or HANPP). Thus, raising the primary energy share of bioenergy to 20% by replacing a modest 9.8% of fossil fuels would require 42.8% of HANPP for bioenergy (keeping total energy consumption, HANPP and yields equal; see below for a further discussion of demand and yield changes).

Land-use restrictions will devalue some land, while land still available for agriculture and forestry would serve a demand that may increase due to bioenergy needs, which would *ceteris paribus* increase rents. However, the effect of other technological mitigation measures that affect the yields and production costs is unclear.[14] Furthermore, the feasibility, costs and land-rent effects of land-based mitigation measures also depend on other ecological concerns, competition with food supply, and the evolution of technology and demand:[15]

Rockström et al. (2009) identified biophysical thresholds that should not be crossed to avoid unacceptable environmental change. In addition to climate change, these for example concern biodiversity loss, changes in nitrogen and phosphor cycles mainly through fertilizer use, or freshwater use. Maintaining these thresholds is broadly consistent with (well-designed) measures to reduce direct GHG emissions from AFOLU, but may limit bioenergy-based mitigation strategies, for example the large-scale use of dedicated energy crops rather than residues from agriculture and forestry.

The production of food and fibre, which also provides the livelihoods of rural populations, competes for land (and other natural resources such as freshwater) both with direct measures to reduce GHG emission from AFOLU, and with bioenergy provision. Concerns about global food security, food prices and the livelihoods of rural populations particularly in many low-income countries may thus also restrict land-based mitigation policies.

[14] Foley et al. (2011) argue that large 'yield gaps' could be exploited (and total GHG emissions lowered) by applying state-of-the-art agricultural technology and management practices worldwide. However, the fact that these have not been exploited to date indicates that significant implementation barriers and thus costs exist.

[15] Another source of uncertainty is the effect of climate change, insofar as it is not fully avoided, on agricultural and forest yields.

Two factors crucially affect the competition of conservation, bioenergy and food production for land (and thus the evolution of land rents): technology and demand. First, high yields and a better integration of food and fibre production with biomass production for energy depends on the development and global deployment of new technologies and institutions (Smith et al., 2014, p.835). The global feasibility of high yields is uncertain, for example because it is unclear if the results from field trials can be extrapolated to the global scale (Creutzig, 2014). Second, demand for food and fibre importantly depends on population size, diets, losses in the supply chain and waste in final use (Smith et al., 2014, p.838). Behavioral factors affecting diet changes are particularly uncertain.

Overall, these highly complex interactions between biophysical, technological and socioeconomic dynamics and their respective uncertainties (Creutzig et al., 2015) to date prevent precise predictions of the effect of climate policy on rents from non-urban land (that can still be cultivated). Nevertheless, it is clear that non-urban land rents are due to change as a consequence of climate policy, increasing the importance of land rent taxation as a complementary policy.

Urban land

Urban land use is mainly important for climate change mitigation due to transport emissions:[16] The transport sector accounted for 14% of total GHG emissions in 2010 and 27% of final energy use (IPCC, 2014), of which 40% were related to urban transport (Sims et al., 2014, p.605). Without mitigation, emissions are expected to grow faster than for any other energy end-use sector, mainly in developing and emerging economies. At the same time, these economies have high urban growth rates, offering an opportunity to influence urban form and infrastructure in favor of low-carbon transport (Sims et al., 2014, p.604; Seto et al., 2014, p.928).

Transport emissions can be addressed by a general climate policy that penalizes transport, such as a tax on fossil fuels. Such a tax implies that land rents increase near city centers, where distances to jobs and urban amenities are short, while they decrease at the urban fringe (Bento et al., 2006).

Alternatively, GHG emission reductions can be supported by local policies aimed at making cities more dense and thus more favorable to walking, cycling or public transport, rather than private car transport. For example, low-density development at the urban fringe ('urban sprawl') may be prevented by an 'urban growth boundary' beyond which no land development is permitted; again, this increases land rents within the existing city, at the expense of land owners just outside the city which cannot develop their land anymore (Bento et al., 2006). A similar pattern of changes in land rents may also emerge when urban densification results from (and in turn reinforces) public transport provision (Seto et al., 2014).

Thus, climate policies leading to denser cities should be accompanied by measures to capture the rising urban land rents.

[16] Land use change at the urban fringe, i.e. the development of agricultural land for housing, offices, factories, etc., aggravates the competition for scarce arable land described above (Smith et al., 2014, p.837), but this effect is neglected here.

Overall, this indicates that, although the link between climate policy and land rents is very different for non-urban or urban land, the fiscal instrument of land rent taxation should generally be considered as an important complement to climate policy – both as a source of public revenue, and to address distributional concerns.

Thus, an instrument that is widely neglected at present will have to be revived in the context of climate change mitigation: Although it is theoretically appealing even in the absence of climate policy (see Section 1.4 and for example Oates and Schwab, 2009), a dedicated tax on land is currently only implemented in around 30 countries (often under the label of a 'land value tax', cf. Franzsen, 2009).[17]

1.3.2 Interactions between climate policy and public spending

This subsection turns to interactions between climate policy and public spending: When climate policy changes the structure and costs of public revenues, it may affect general public spending both in optimal settings and under budget constraints. Vice versa, specific types of public spending and public capital stocks play a crucial role for mitigation, for example R&D policies, or spending on transport and energy infrastructures that 'induce' GHG emissions. I will focus on such long-lived public capital stocks and only briefly comment on the other points.

Revenue changes due to climate policy affect general public spending

As discussed above, climate policy may create new public revenue streams (by carbon pricing), or affect other revenues (for example from taxes on land). If the size of the government budget is to be maintained, additional revenues could be used to reduce debt or distortions from other taxes (for example on labor, as analyzed in most of the double-dividend literature. Otherwise, a downward shift of the overall cost function for raising public funds *ceteris paribus* leads to an increase in the optimal government budget.[18] Even if the initial government budget was not optimal and public spending too low (Bom and Ligthart, 2014), for example because taxing powers were politically restricted, additional revenues due to climate policy may be used to sidestep these constraints and still lead to a larger budget (see Section 3.3 in Chapter 2).

The additional spending would optimally finance projects with the highest social benefit, which are *not necessarily* mitigation projects – although in practice, 'earmarking' of revenues for specific spending is common (Anesi, 2006), and some carbon pricing revenues are dedicated to fund GHG abatement activities (Esch, 2013). For example in low-income countries, satisfying basic needs may have a high priority, but universal access to infrastructure for water, sanitation, electricity, transport as well as information and communication technology requires substantial (public) investment (Rothman et al., 2014;

[17] The main difficulties with taxing land rents are assessing the hypothetical value of 'unimproved' land without buildings and other investments (Bell et al., 2009), and political economy issues (Bourassa, 2009). I will return to these implementation issues in the synthesis, Chapter 7.

[18] For a detailed analysis of the optimal public budget in the context of environmental taxation, see Bovenberg and van der Ploeg (1994); Bovenberg and van der Ploeg (1996).

Fuss et al., 2015). Jakob et al. (2016) estimate that if a 450ppm stabilization scenario was implemented by a (globally harmonized, but domestically implemented) carbon price, the revenues between 2015 and 2030 would be more than sufficient to finance universal access to water, sanitation and electricity in all countries.

Nevertheless, the social benefits of *some* public spending related to climate change mitigation will be high enough to attract additional funds, or to replace other spending options, as I will discuss in the following.[19]

The role of public spending for climate change mitigation

This subsection consider two mitigation-related public spending options with relatively high social benefits: One option is to support the development of emission-reducing technologies (Popp and Newell, 2012). The other option (on which I will focus) is the supply of transport and energy infrastructures that support emission-reducing demand patterns and technologies.

First, private funding of R&D for mitigation technologies such as renewable energy sources (Fischer, 2008) or energy efficiency (Gillingham and Palmer, 2014) may be too low because generating knowledge has positive externalities. This can be addressed via patents, by particular environmental policy instruments that may 'induce' innovation – or by fiscal instruments such as subsidies, research grants or tax exemptions for R&D activities (Jaffe et al., 2003). Although often framed primarily as sector-specific technology measures, these are important examples of interactions between fiscal- and climate policies, also because they may contribute to other public sector goals such as employment (Fankhauser et al., 2008) and economic growth (Popp and Newell, 2012).

Second, an adequate infrastructure supply is highly important for mitigation: Public spending on transport infrastructure (airports, harbors and waterways, road and rail networks, cycling and walking infrastructure) drives the choice between transport modes and, as a major determinant of urban form, the demand for short- and medium-distance transport services (the number and distance of trips) (Ewing and Cervero, 2010). In the energy sector, the large-scale integration of location-dependent and intermittent renewable sources of energy (mainly wind and solar energy) and potential energy stores (pumped hydropower) requires major investments into the electricity grid (ENTSO-E, 2014).[20]

While it is unclear if *total* spending on infrastructure will have to increase for any mitigation target, it is uncontroversial that the *composition* of infrastructure spending will have to change. However, most IAMs for optimal mitigation focus on directly emitting capital stocks and do not separately account for infrastructure. As an exception, Waisman et al. (2012, 2013) use a model with mode-specific transport infrastructure investment to compare scenarios with

[19] To the extent that climate change remains unabated, adapting to these new environmental conditions (for example to reduce damages from natural disasters) will also require large public funds. This thesis however focuses on mitigation rather than adaptation policies.

[20] In many countries, the power system has been privatized. However, power grids are a natural monopoly and backup systems provide a public good, so they remain heavily regulated. Thus, investments into these capital stocks may be considered 'quasi-public', although they may not appear in the public budget.

only a carbon price, or with complementary transport policies. These policies include actively shifting infrastructure investments away from airports and roads, and towards water-based, rail-based and non-motorized modes (instead of simply following demand, for example to avoid road congestion). Waisman et al. (2012, 2013) find that these additional transport policies reduce the cost of implementing a given GHG reduction target and lower the required carbon price path. However, total public spending and investment shifts towards low-emission transport modes for mitigation are not determined endogenously, but follow exogenously given scenarios; similarly, the model does not take into account that infrastructure supply may be non-optimal for reasons beyond climate- or transport policy (see Section 1.3.2). I will return to these issues in the next section.

Beyond redirecting new public investment, it may even be necessary to retire part of the existing public capital stock earlier than expected at the respective time of investment, because it would otherwise perpetuate emission-intensive demand patterns for too long. This emerges from a comparison of 'committed emissions' due to existing long-lived capital stocks (LLKS)[21] with or without taking into account the indirect effect of infrastructure:

Davis et al. (2010) use historical lifetimes, GHG emissions data and the vintage structure of only *directly-emitting* LLKS existing worldwide (such as power plants or motor vehicles). They estimate the 'committed' future emissions in different sectors and regions if existing equipment was used as in the past. Overall, they expect cumulative emissions of 496 $GtCO_2$ between 2010 and 2060 (in a 'middle scenario', see gray line in panel (a) of Fig. 1.4). This would exhaust half of the 1000 $GtCO_2$ budget consistent with reaching a 2 °C target (see Section 1.1), and would lead to a rise of global mean temperature of 1.3 °C above pre-industrial times in the year 2060 (see gray line in panel (b) of Fig. 1.4). They thus conclude that *"sources of the most threatening emissions have yet to be built"* (Davis et al., 2010, p.1330).[22]

However, Guivarch and Hallegatte (2011) criticize this assertion as misleading. They point out that the analysis of Davis et al. ignores the effect of existing infrastructures (such as roads and settlements) that perpetuate demand patterns, as well as additional warming from non-carbon GHG. Taking into account the effects of transport-relevant infrastructure and non-carbon GHG and aerosols, Guivarch and Hallegatte (2011) show that relative to the 'middle scenario' of Davis et al. (2010), CO_2 emissions from existing capital stocks are higher by 35% in 2030 and by 134% in 2060 (red line in panel (a) of Fig. 1.4). These 'committed' emissions would lead to a 1.71 °C temperature rise until 2060 (panel (b) of Fig. 1.4). The wedge of remaining emissions between 'committed' emissions and cost-effective emission pathways for a 2 °C target is much smaller (between the solid black line and the red lines in panel

[21] In many high-emission sectors, emission intensities and demand patterns depend on capital goods for which very long lifetimes were observed in the past: Shalizi and Lecocq (2009) distinguish consumer durables, including cars and fridges, with lifetimes of 5-15 years; power plants and factories with 15-40 years; infrastructures such as road, rail and electricity networks, with 40-75+ years; and land use and urban form, determined by buildings, etc., with 100+ years. For a detailed account of the age structure, technologies, etc. of existing European capital stocks, see Odenberger et al. (2009) and Rootzén and Johnsson (2013).

[22] For updated data, see Davis and Socolow (2014) and Pfeiffer et al. (2016). Here, I rely on the original paper by Davis et al. (2010) to contrast it to the analysis of Guivarch and Hallegatte (2011) with infrastructure effects.

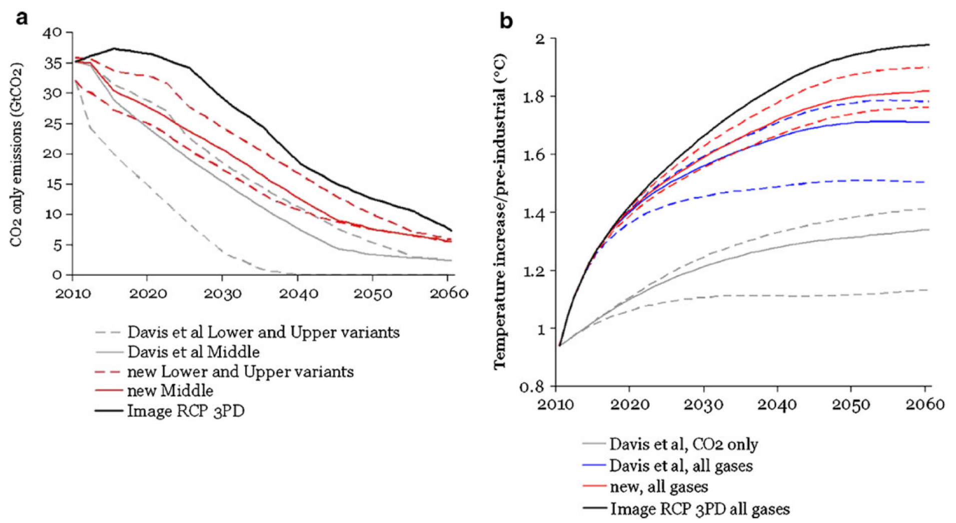

Figure 1.4: Comparison of models with and without indirect infrastructure effects on (a) carbon emissions 'committed' by existing capital stocks and (b) associated global mean temperature increase over pre-industrial level. Gray and blue: only direct emissions (Davis et al., 2010). Red: with infrastructure (Guivarch and Hallegatte, 2011). Black: 2 °C target scenario. Dashed: upper and lower-bound scenarios. *(Figure adapted from Guivarch and Hallegatte, 2011, with permission from Springer).*

(a) of Fig. 1.4). They thus conclude that *"reaching the* 2 °C *target without capital retrofit or early retirement appears extremely difficult"* (Guivarch and Hallegatte, 2011, p.804).

The implications of these studies are twofold.

First, beyond carbon pricing and technology policies, public infrastructure plays a crucial role for climate change mitigation. In particular, cost-effective mitigation requires measures that explicitly address existing long-lived public infrastructure (Shalizi and Lecocq, 2009). This link between climate policy and a traditional realm of public economics has been largely neglected in economic theory.

Second, there is another effect of climate policy on public *revenues* (adding to the examples in Section 1.3.1): Owners of currently existing directly-emitting LLKS will be faced with increasingly stringent mitigation policies well before the end of their assets' historical lifetimes.[23] If such mitigation policies include a carbon price that also covers existing capital stocks, this will generate public revenue and reduce returns from these capital goods. The (increasing) carbon price path determines the utilization and profits of carbon-intensive capital goods until eventually, their operation will become uneconomic (so that they will be retrofitted or retired).

[23]Implementing a 2 °C target in a cost-effective way requires early mitigation – GHG emissions from fossil-fuel combustion and industrial processes will have to peak soon (around 2020, depending on assumptions about future technologies) and then decline rapidly (Clarke et al., 2014, p.432).

1.4 Research questions and outline of this thesis

So far, I first summarized the failure of traditional climate policy, which focused on international agreements and cost-effective mitigation technologies. Second, I described the recent approach based on voluntary unilateral mitigation that depends on domestic motives. At the national-level, climate policy interacts with several other public policy goals and instruments, which have been neglected under the traditional technology focus. Third, I presented several examples which illustrated that interactions between stringent climate policy and fiscal instruments are important both in terms of efficiency and distribution, but have been insufficiently analyzed.

In the present thesis, I address this gap by identifying relevant effects and analyzing some of them theoretically.

This section derives specific research questions and at the same time provides the outline of the thesis, since each question is the subject of one chapter in the main part.[24]

As a starting point, Section 1.3 presented only a subset of interactions between climate policy and other public policies – for example, it neglected the role of carbon pricing as a source of revenues in open economies, and did not systematically discuss distributional issues. A broad overview of relevant effects is needed, so my first objective is to answer the following questions:

1) What are the most important interactions between national climate policy and public finance? In particular, what are the implications of using carbon pricing for public revenue-raising, how do public spending and climate policy affect each other, and what are the distributional effects of this, both within and across generations? Can and should climate policy and public finance be analyzed in a single framework?

Chapter 2 addresses these questions.[25] It first expands on some topics that were described only briefly above, namely standard approaches in integrated assessment modeling, and the debate about a double dividend of environmental tax reforms as a first attempt to bring together environmental and fiscal policies. Then, it describes six further interactions between climate policy and fiscal policy instruments that have been identified so far, grouped under three topics: On the revenue-raising side of the public budget, climate policy may reduce tax competition in an open economy, and induces beneficial shifts in investment behavior. On the spending side, the composition of public spending should complement direct climate policies such as carbon pricing, and revenues from such policies could be recycled for additional productive public investment. Regarding distributional objectives, greater intragenerational equity could be achieved through appropriate revenue recycling, and

[24]While the research leading to this thesis was mainly motivated by concerns about climate change mitigation, some of the results have more general implications. Examples are the importance of rent taxation in the design of tax systems, and the integration of public spending into environmental policies. Consequently, some of the individual chapters are framed in more general terms.

[25]Chapter 2 is in preparation for submission to *CESifo Economic Studies*. An earlier version has been published as a working paper: Siegmeier, J., L. Mattauch, M. Franks, D. Klenert, A. Schultes and O. Edenhofer (2015). A public finance perspective on climate policy: Six interactions that may enhance welfare. *Fondazione Eni Enrico Mattei, Nota di Lavoro* 31.2015.

intertemporal transfers may establish intergenerational Pareto-improvements. Finally, addressing common objections against analyzing climate policy and public finance in a single framework, it is shown that this is indeed legitimate and required for sound policy appraisal. The overview chapter thus illustrates that overcoming the 'compartmentalisation' in climate- and fiscal policy design may improve welfare and change the distribution of mitigation costs within and across generations.

Selecting from the identified effects, the following chapters then provide an in-depth theoretical analysis of two topics: on the revenue-side of the public budget, I will analyze the scope, efficiency and distributional effects of rent taxation in the context of climate policy; and on the spending-side, the role of the composition of public spending for climate policy.

Regarding the role of carbon pricing as a means to raise public revenues, Section 1.3.1 first documented the focus of the existing literature on possibilities to use these revenues to cut other taxes or debt, or to compensate fossil resource owners. Second, it illustrated the importance of considering the taxation of rents from fossil resource stocks and land in the context of climate policy. Although rent taxation is a topic in economics since Ricardo (1821), some of its implications have been underappreciated, at least in climate change economics:

Rent taxation (by definition) leaves the supply of the underlying factor unaffected (Mankiw, 2007). It is thus sometimes presented as an ideal source of revenue (George, 1879) from an efficiency perspective. The studies cited in Section 1.3.1 reported that the revenue potential of carbon pricing may be very large, and taxes on rising land rents may add to these revenues. Accordingly, the following question arises:

2) Is rent taxation theoretically sufficient to fully finance optimal public investment at the national level?

Chapter 3 is devoted to this issue,[26] using models of neoclassical and endogenous growth with a representative, infinitely-lived agent (ILA), land as a fixed factor, and productive public capital. The central result is that a land rent tax can by itself fully finance the socially optimal level of productive public capital, as long as the land rent is at least as high as the public investment requirement. This can be interpreted as a dynamic, national-level version of the Henry George Theorem from urban economics, which states that local land rents equal expenditure on a local public good (provided the population size is optimal). Also, explicit conditions for when the land rent is sufficiently high are derived for a specific production function.

The simple view of rent taxation adopted in Chapter 3 neglects that although the supply of the underlying factor remains unchanged, it may still distort other economic variables[27] – for example if the 'rentiers' pursue economic activities besides earning rents: Feldstein (1977) demonstrated that if investors have a choice between assets, a tax on rents shifts investment away

[26]Chapter 3 is in preparation for submission to *Finanzarchiv / Public Finance Analysis*. An earlier version has been published as a working paper: Mattauch, L., J. Siegmeier, F. Creutzig and O. Edenhofer (2013). Financing public capital through land rent taxation: A macroeconomic Henry George Theorem. *CESifo Working Paper* No. 4280.

[27]For this reason, the estimations of fossil resource rents cited in Section 1.3.1 should be considered as a first approximation of potential carbon pricing revenues.

from a rent-generating fixed factor towards producible capital. Land owners lose, but aggregate capital accumulation increases. The tax is partly shifted to capital, which receives lower interest. This shows that rent taxation has both distributional and efficiency effects, which are inseparable. However, Feldstein did not evaluate the welfare consequences entailed by this shift, and by recycling the tax revenues.

The welfare consequences of rent taxation are important for climate policy in two ways: first, mitigation policies may increase land rents (Section 1.3.1). If taxing these rents (and some pattern of redistributing the revenues) leads to an increase in welfare, this lowers overall policy costs. Second, assume that the effect is beneficial. Then, if it holds not only for taxes on fixed factor rents, but also for a carbon price that extracts exhaustible resource rents, this would further reduce the overall costs of climate policy.

This gives rise to the following questions:

3) What are the welfare implications of taxing the rents from a fixed factor? Specifically, is the aggregate investment effect beneficial, and how much can additionally be achieved by redistributive recycling of the rent tax revenues?

4) Does the aggregate investment effect similarly occur for carbon pricing, which acts as a tax on the rents from exhaustible resources? Is there a difference between carbon pricing instruments, such as a permit scheme and a carbon tax?

Chapter 4 treats the welfare effects of distortionary rent taxation.[28] It employs a continuous overlapping-generations (OLG) model with agents differentiated by age and corresponding wealth, which consists of land (a fixed factor) and capital (which is underaccumulated due to a lack of intergenerational altruism). It is shown that land rent taxation induces a higher capital stock and is thus beneficial, but cannot implement the social optimum, which defined as the dynamically optimal consumption allocation. This additionally requires a redistributive recycling of the rent taxation revenues towards the young.

Chapter 5 analyzes the applicability of the results in Chapter 4 to different forms of carbon pricing.[29] A similar OLG model is used, but now with an exhaustible fossil resource instead of the fixed factor. It is proved that all different forms of carbon pricing induce an aggregate investment effect, which is beneficial if capital is underaccumulated. Nevertheless, GHG emission permit schemes are preferable to carbon taxation in this context: because the total number and auctioned share of permits can be chosen separately, a simultaneous maximization of the benefits from rent taxation and climate change mitigation is possible. In contrast, a time-varying carbon tax rate that induces mitigation cannot collect a high share of the resource rent at all times. Also, an innovative permit scheme based on ownership of parts of the stock of the atmosphere is suggested. Under this scheme, the beneficial aggregate investment effect even occurs when trade in fossil resource stocks is restricted.

[28] Chapter 4 has been published according to journal format requirements as: Edenhofer, O., L. Mattauch and J. Siegmeier (2015). Hypergeorgism: When rent taxation is socially optimal. *Finanzarchiv / Public Finance Analysis*, 71(4): 474-505.

[29] Chapter 5 is to be resubmitted with revisions to the *Journal of Environmental Economics and Management*. An earlier version has been published as a working paper: Siegmeier, J., L. Mattauch and O. Edenhofer (2015). Climate policy enhances efficiency: a macroeconomic portfolio effect. *CESifo Working Paper* No. 5161.

Regarding public spending, Section 1.3.2 pointed out, first, that the composition of public infrastructure plays a crucial role for climate change mitigation, for example due to its effect on private choices between clean and dirty transport modes, and because infrastructure is particularly long-lived. Second, this has been mostly overlooked by economic theory. In fact, the few studies that have considered public goods in the context of environmental policy, such as Bovenberg and van der Ploeg (1994), have only analyzed *optimal* levels of public good provision and environmental taxation.

In practice, however, second-best settings are much more relevant – because of high inertia in infrastructure provision, and due to the additional fact that environmental taxes (such as a carbon price) are often also (politically) constrained. Then, an important question is if one policy instrument can compensate for limitations of the other: For example, assume that the fuel price cannot be increased enough to fully internalize environmental damages. Should this be compensated by building less roads, and more bicycle paths? And vice versa, if it takes long to adapt the infrastructure, should the fuel price be increased more in the meantime? This motivates my final research question:

5) When the provision of different types of infrastructure affects private choices, what is the effect of its non-optimal provision on optimal environmental taxation? Vice versa, how does non-optimal environmental taxation affect optimal infrastructure provision?

This is analyzed in Chapter 6,[30] based on a standard model of optimal environmental policy with two public goods complementing a clean and dirty private good in utility, respectively. It is demonstrated that marginal changes in consumer behavior can be induced by changes in the environmental tax or the composition of public goods alike. General conditions are derived for optimal environmental taxation and public good provision when the other policy instrument is constrained, respectively: compared to the first-best conditions, the second-best tax rule is unchanged, but the rule for second-best infrastructure provision contains an additional term that reflects its role in addressing environmental damages. For a specific utility function, it is shown that both policy instruments have lower values in their respective second-best than in the first-best (if the dirty good is 'important' in utility).

After the main part, Chapter 7 provides a synthesis: I summarize and link the results, discuss the methods and provide an outlook for future research, and conclude with policy implications.

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[30] Chapter 6 is to be resubmitted with revisions to *Environmental and Resource Economics*. It has also been published as a working paper: Siegmeier, J. (2016). Keeping Pigou on tracks: second-best carbon pricing and infrastructure provision. *MPRA Paper* No. 69046.

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Chapter 2

The fiscal benefits of climate policy: an overview[1]

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The fiscal benefits of climate policy: an overview

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Abstract

Climate change economics mostly neglects sizeable interactions of carbon pricing with other fiscal policy instruments. Conversely, public finance typically overlooks the effects of future decarbonization efforts when devising instruments for the major goals of fiscal policy. We argue that such a compartmentalisation is undesirable: policy design taking into account interdependencies may enhance welfare and change the distribution of mitigation costs within and across generations. To support this thesis, we systematically discuss the hitherto identified interactions between climate change mitigation and public finance. These concern, first, public revenue-raising, as climate policy may reduce tax competition and induce macroeconomic portfolio effects. Second, they concern public spending, which needs to be restructured in line with climate policy, while carbon pricing revenues may be recycled for productive public investment. Finally, distributional effects matter, since intragenerational equity depends on appropriate revenue recycling and intergenerational Pareto-improvements are possible through intertemporal transfers. We thus show that jointly considering carbon pricing and fiscal policy is legitimate and mandatory for sound policy appraisal.

JEL classification: B41, H21, H23, H54, H60, Q54

Keywords: carbon pricing, taxation, public spending, redistribution, policy interactions

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1 Introduction

Climate economics usually considers only inefficiencies directly related to climate change mitigation. It typically ignores interactions with other fiscal policy instruments, such as taxes, subsidies or public investment that are motivated by non-climate aims such as job creation, debt reduction, provision of infrastructure, health services, education or distributive justice. Vice versa, public finance typically ignores constraints and opportunities of future decarbonization when designing instruments for such major goals of fiscal policy.

However, some instruments of climate policy would generate large revenue streams. Assume for a crude approximation that a carbon price of US$15 per ton of CO_2 was applied to 6 billion tons of CO_2 emitted by the United States in 2005: This amounts to annual revenues of US$90 billion, ignoring behavioral responses (Metcalf, 2007).[1] Given revenues of this magnitude and their distributional significance, interactions between climate policy and other fiscal policy instruments are non-negligible. These interactions also depend on the way these revenues are spent, and the distortions and scarcity rents created or affected by climate policy. Ignoring such interactions in climate economics may lead to inaccurate policy appraisal in two ways: first, the situation prior to a policy reform is inaccurately described because some important distortions are neglected; second, taking into account these distortions will attribute greater welfare gains to policy reform. Along similar lines, for public finance, taking the challenge of climate change mitigation into account may offer new solutions to well-known problems.

This article argues that standard welfare analysis of both climate change mitigation policy as well as fiscal policy neglect important interactions between the two that (1) lead to efficiency gains and (2) impact intra- and intergenerational distribution. To support this thesis, we discuss and structure the hitherto identified interactions between climate change mitigation and public finance, which can be grouped under the topics of public revenue-raising, public spending and distribution. Each effect is attributable to a coincidence of the climate externality with a second major externality or goal of public finance. Whenever such effects occur, taking them into account by an integrated design of fiscal- and climate policies may lead to welfare gains that would be forgone by separate treatment of the public finance topics and climate mitigation.

In contrast to well-known 'double-dividend' arguments of environmental taxation, all arguments but one are independent of the assumption of pre-existing inefficient taxes and most of the effects analyzed are unambiguously welfare-enhancing. We both summarize mechanisms that have already been described in the existing (if sparse) literature on public finance topics in climate policy (but were largely omitted in previous overviews on the fiscal dimension of climate policy, such as Jones et al., 2012; de Mooij et al., 2012), and discuss some previously unexamined effects. We conclude by discussing why it is methodologically legitimate to integrate climate change mitigation policies into public finance and outline potential implications for policy assessment.

We briefly review the standard approach of climate economics as well as the argument that an environmental tax swap may offer a double dividend (Section 2). In the main part (Section 3), we first consider other effects related to the

[1] For more elaborate estimations, see Bauer et al. (2013), or Carbone et al. (2013).

raising of public revenues via climate policy instruments. There are two effects, one in an open economy, the other in a closed economy, and both related to capital accumulation:

1. There are sizable welfare losses from international capital tax competition. These can be shown to be mitigated when climate policy revenues replace capital taxation in an open economy where capital is mobile (Section 3.1).

2. Climate policy inevitably creates new rents. If private capital is insufficiently accumulated, rent collection causes distortions that are beneficial (besides correcting the climate externality and collecting the rents for distributional motives). These distortions increase aggregate efficiency by redirecting investment towards producible capital (Section 3.2).

We then consider the structure and the total level of public expenditures:

3. The provision of different combinations of public investment (at a given total level) affects both the direct costs of climate change mitigation and the strength of its general equilibrium effects. The degree to which direct climate policy is matched by a restructuring of public goods provision thus affects future productivity and macroeconomic efficiency (Section 3.3).

4. When government funding from other sources is lower than optimal, it can be beneficial that some climate policy instruments raise additional funds. We consider spending options with a positive aggregate effect, such as investment in underfinanced public capital stocks or public debt reduction (Section 3.4).

Finally, we consider issues of intra- and intergenerational (re)distribution due to climate policy:

5. If inequality (at a point in time) impairs economic performance, or if equality as such is considered to be a component of social welfare, there are welfare losses from high inequality. While the direct effect of climate policy on heterogeneous households is likely to be regressive, revenues from climate policy instruments can be used to more than offset this regressivity. This may be achieved by tax rebates for low-income households or public spending on education and local public goods (Section 3.5).

6. There are large intergenerational gains from using public finance instruments to redistribute the costs and benefits of climate change mitigation over time: If climate policy were combined with intergenerational redistribution so that future generations contribute to mitigation efforts, the net mitigation costs could be negative at each point in time, implying a Pareto-improvement across generations (relative to the no-policy case). Options for organizing such a transfer include changes to debt policy and to pension schemes (Section 3.6).

These arguments are based on the premise that climate policy and additional non-climate effects should not be studied separately, but within a comprehensive public finance framework. The reason is that separate estimates cannot be directly added up due to the non-negligible general equilibrium effects that effective mitigation policies would cause. Our discussion addresses this as well as potential consequences for the evaluation of climate change mitigation policies, both in climate economics and public economics (Section 4).

2 Current assessments of climate change mitigation policies

This section summarizes two strands of literature on which our study builds: First, mitigation strategies have commonly been evaluated by so-called integrated assessment models. Our brief description of the main methods in Section 2.1 underlines the contrast between highly detailed modeling of climate change, its damages and technological mitigation strategies, and the simplified treatment of the policy space, which is confined to climate policy. Second, Section 2.2 covers the double-dividend debate as the most prominent attempt to include interaction effects of carbon taxes with fiscal policy.

2.1 Integrated assessment modeling of optimal mitigation and second-best policies

Optimal climate change mitigation targets, pathways to implement them and the associated gross and net mitigation costs (without and with avoided damages from climate change) are commonly estimated with integrated assessment models (IAMs). These are numerical simulations that combine a model of the climate system with an economic model (typically a multi-sector neoclassical growth model). Two optimization approaches[2] can be distinguished by their treatment of mitigation targets and damages due to climate change: cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA).

CBA in the context of climate change focuses on the optimal choice of a mitigation target, which is determined by weighing the opportunity costs of consumption foregone by investing into mitigation against the benefits of avoided damages from climate change, expressed as social costs of carbon, which are the economic damages resulting from a marginal increase in carbon emissions (the difference between costs and benefits gives the net costs, which are negative for the optimal mitigation path). In principle, this requires a detailed representation of a multitude of channels by which climate change may affect human welfare, such as a rising sea level, extreme weather events (for example storms, heat waves, droughts), water availability, the spread of diseases or agricultural yields (Reilly et al., 2013). Instead, stylized damage functions are standardly used to capture some of these effects (e.g. Hope, 2006; Nordhaus, 2007).[3] Thus, findings of different IAMs used for CBA depend on their respective modeling of market- and non-market damages, as well as the choice of the social discount rate, treatment of uncertainty and extreme outcomes, or

[2]Alternatively to optimization with policy variables as controls, the effects of a given policy proposal can be simulated with IAMs to evaluate its costs. This is called the evaluation approach (Weyant et al., 1996).

[3]A rare exception is Reilly et al. (2013), who explicitly model the health effect of higher ozone concentrations due to climate change.

substitution possibilities between physical capital and environmental services (Stern, 2007; Ackerman et al., 2009; Weitzman, 2009; Pindyck, 2013).

CEA focuses on optimal strategies to achieve an exogenously given mitigation target (damage level). Only mitigation measures and gross policy costs, for instance, expressed as discounted consumption losses, are determined endogenously. Thus, the complexity of modeling climate damages is avoided; instead, high-emission sectors and mitigation technologies are represented in more detail. This also allows for a comparison of different assumptions about the availability of technologies to inform policy choices: for example, the 'option value' of developing carbon-capture-and-storage or nuclear power for decarbonisation can be estimated (see for example Luderer et al. (2012), or Clarke et al. (2014) for an overview).

Thus, the representation of the climate system and emission-relevant economic sectors is often highly detailed in IAMs of either type – but other welfare-relevant aspects of the socio-economic system that have strong interactions with climate change and mitigation strategies, such as health or the distribution of income and wealth, are often only modeled in a crude and incomplete fashion, or not at all: For example, health is only considered in terms of negative effects of climate change, and mostly only as part of the motivation for very stylized aggregate damage functions. The distributions of income and wealth within countries are generally not considered.[4]

A more detailed representation of these non-climate aspects of welfare and related inefficiencies is important for both the identification of optimal mitigation strategies, and for the analysis of specific policies:

First, the optimal mitigation paths and the related costs and welfare effects obtained from IAMs may change, since (1) there may be trade-offs (in a CBA) between investing in the low-carbon transition or for example poverty reduction (Dasgupta, 2007), and (2) some non-climate objectives, such as health or distribution, are strongly affected not only by climate change itself, but also by the choice of mitigation measures (examples: local air pollution from electricity generation and transport, health effects of non-motorized transport, food prices affected by biofuel demand). Ignoring non-climate inefficiencies may lead to a too optimistic description of the situation without climate change mitigation, and ignoring the interactions with mitigation measures leaves out important welfare gains that can be attributed to it. For this study, this means that the welfare gains described occur relative to a baseline that contains more inefficiencies than standardly considered by IAMs.

Second, it is even more important to take into account non-climate issues when practical GHG mitigation policies are considered in decentralized models, because limitations of climate- and non-climate policy instruments imply even more scope for interactions. It is common practice to analyze climate policy instruments (such as different forms of carbon pricing, emission standards or R&D support schemes for low-carbon technology) in second-best settings with another non-climate inefficiency, but the latter is usually directly related to emission-relevant sectors (such as imperfect coverage of carbon pricing schemes, or market failures in the energy sector related to innovation or

[4]This refers to models for determining globally optimal GHG mitigation pathways. For related literature that does include distributional and health effects see, for example, Rausch et al. (2010) who analyze specific climate policy instruments for the USA with respect to their distributional effects; Thompson et al. (2014) additionally include health effects.

imperfect competition). In such settings, it is generally preferable to use more than one policy instrument to address all sources of market failure, and to adjust these instruments to each other (e.g. Sorrell and Sijm (2003), Fischer and Newell (2008), Gillingham et al. (2009), Fischer and Preonas (2010), Kalkuhl et al. (2011), Kalkuhl et al. (2013), Mattauch et al. (2015); Aldy et al. (2010) provide a good overview).

We argue that second-best analysis of climate policy should be systematically extended to include inefficiencies (and policies to correct them) that are neither related to climate change nor specific to emission-relevant sectors, but nevertheless have interactions with mitigation policies. Integrating them is important for the choice, design and evaluation of policy reform packages that involve both climate- and non-climate policies (see also Section 4).

2.2 Lower cost of public funds: The 'double dividend' of environmental tax swaps

There is one interaction of environmental and fiscal policies that has been discussed very prominently: the use of pollution tax revenues for cutting distortionary taxes elsewhere and thus potentially reaping a double dividend (Tullock (1967); see Pearce (1991) for an early application to climate policy). We summarize the argument because it is structurally similar to those brought up in the next section, and because this similarity makes clear how policy-relevant these new effects are, given the considerable political impact of the 'classical' double-dividend argument.

Assume some unspecified public spending requirement in a second-best setting where no lump-sum taxes but only distortionary taxes are available (this is the additional non-environmental inefficiency here), so the costs of raising public funds are non-zero. Then, if an environmental policy is introduced that not only corrects an externality (the first dividend), but also generates revenues, this could lower the cost of public funds (the second dividend) and thus the gross costs of environmental policy, because distortionary taxes could be reduced ('revenue recycling effect'). The claim that this constitutes an improvement over lump-sum recycling of the revenues to households is called the 'weak' double dividend hypothesis, which is widely confirmed to hold (Goulder, 1995b; Bovenberg, 1999).[5]

More controversial is a stronger version of the hypothesis: an environmental tax swap does not only have lower, but even zero or negative gross costs. However, via general equilibrium effects, environmental taxes can also exacerbate the distortions from pre-existing taxes in factor markets that they are meant to reduce: Higher product prices reduce real factor returns, thus substituting an implicit for an explicit tax and causing a negative third effect on welfare, the so-called 'tax interaction effect' (Bovenberg and De Mooij, 1994; Bovenberg and van der Ploeg, 1994; Parry, 1995). Due to the narrower tax base, this may more than offset the revenue recycling effect, thus increasing the gross costs and rendering a strong double dividend unlikely (the net costs including benefits from higher environmental quality are likely to remain negative).

[5] Another case of a potential double dividend is the so-called employment dividend, where an environmental tax reduces involuntary employment (Carraro et al., 1996; Bovenberg, 1999).

For the case of a carbon tax, early numerical simulations supported these findings (Goulder, 1995a,b; Bosello et al., 2001).

However, some crucial assumptions of the original analysis have been challenged. We summarize three arguments that make the existence of a second, fiscal dividend of climate policy more likely:

First, the strong double-dividend hypothesis is more likely to hold if the initial tax system is inefficient, and if the environmental tax swap moves it closer to its non-environmental optimum. As summarized by Bovenberg (1999) and Goulder (2013), this includes situations when clean goods are better substitutes for leisure than dirty goods, but consumption is uniformly taxed; when taxation imposes different marginal excess burdens on different factors; when polluting activities are initially subsidized; when the environmental tax (partially) falls on Ricardian rents from a fixed factor used in the production of polluting goods (Bento and Jacobsen, 2007); or when labor markets are imperfect (Koskela et al., 1998; Koskela and Schöb, 2002; Schöb, 2005). A related effect is the potential reduction of the informal sector (and broadening of the labor tax base) that may result from an environmental tax swap (Markandya et al., 2013).

Second, the studies above rejecting the strong double-dividend hypothesis mostly rest on the assumption that environmental quality enters the utility function only, where it is (weakly) separable from consumption and leisure. This separability assumption has been challenged, either because environmental damages may shift consumption towards 'defensive expenditures' (Schöb, 1995; FitzRoy, 1996), or because improved environmental quality implies better health and thus potentially higher labor supply.[6] Each works in favor of a strong double dividend. A counter-effect is that improved environmental quality may also act as a complement to leisure, thus reducing labor supply (Bovenberg and van der Ploeg, 1994).

Third, and maybe most importantly, it is unclear if environmental quality interpreted as the long-run climate is adequately modeled as a direct impact on utility only. If it is assumed on the contrary that environmental quality also serves as a public input to production, as is common in much of climate change economics (for examples, see Nordhaus, 1993; Tol and Fankhauser, 1998), a strong double dividend also becomes more likely (Bovenberg and de Mooij, 1997).[7] Barrage (2014) finds that neglecting climate change impacts on production and only focusing on direct utility losses leads to a carbon tax that is around 10% lower than optimal.

Overall, this underlines the importance of designing and analyzing climate policy in conjunction with the tax system due to fiscal interactions (Goulder, 2013). But despite being in the focus of previous literature on interactions between environmental and other public economics, a distortionary tax system is by far not the only additional non-climate source of inefficiency, and its revenue-neutral restructuring not the only policy option that needs to be

[6]This argument by Schwartz and Repetto (2000) is backed empirically for example by Thompson et al. (2014), who report substantial positive health co-benefits of climate policy due to local air quality improvements.

[7]Goulder (1995b, p.169) notes that when environmental quality is an input to production, the notion of 'gross costs' of tax reform as welfare costs without direct environmental benefits becomes ambiguous: "*In my view, [the result of Bovenberg and De Mooij (1994)], strictly speaking, does not provide support for the strong double-dividend notion because it involves benefit-side issues; this is not a case of negative gross costs.*"

considered in a full assessment of the costs of climate policy. We now turn to additional effects that have been underappreciated so far.

3 Why climate change mitigation enhances welfare

In this section we give an overview of specific arguments for the thesis that interactions of climate change mitigation with other public policy objectives enhance welfare beyond the environmental improvement.

We first consider the advantages of a tax on carbon emissions for raising public revenues, both in an open economy subject to tax competition under capital mobility (Section 3.1) and in a closed economy when it affects investment behavior (Section 3.2).

Two further arguments concern public expenditures: the effect of restructured public spending on private abatement costs or general equilibrium effects (Section 3.3), and options to spend additional revenue from climate policy on productive public capital or for debt reduction (Section 3.4).

The final two arguments concern the intra- and intergenerational distribution of the costs of climate change: At any point in time, a carbon tax is likely to be regressive. However, its revenues may be so high that not only compensating measures could be financed, but even inequality reductions beyond that (Section 3.5). Over time, it might be possible to reallocate some of the future benefits of avoided climate damages to reduce current mitigation costs. When combined with such a transfer the correction of the climate externality should not lead to net costs to any generation (Section 3.6). These distributive consequences of climate policy matter normatively, but also crucially affect political feasibility, which is a topic we only elaborate on briefly in this review.

Of course, this list is not exhaustive; the focus of this article is to point out in a structured manner when welfare impacts of climate policy have been underexplored, not to exhaustively review the field. Other non-climate inefficiencies which may interact with climate policy include informational asymmetries between the government and the private sector, horizontal and vertical externalities of public policies in countries with a federal structure (Keen, 1998), labor market rigidities (Guivarch et al., 2011), tax-base effects related to the informal economy (Markandya et al., 2013), or weak institutions leading to tax evasion (Liu, 2013). Cyclical climate policy or 'Green Keynesianism' is another related field not considered here (Fischer and Heutel, 2013; Harris, 2013). Furthermore, not every effect will be relevant in every situation. To facilitate the selection of the most important effects for a specific policy package and economic environment, we emphasize the conditions under which each effect occurs.

3.1 Reduced international tax competition: Substituting rent taxation for capital taxation

The double-dividend literature discusses a restructuring of the tax system in a closed economy. We now turn to another possibility for tax reform which is peculiar to the case of an open economy. If we assume that capital is internationally mobile,[8] social welfare could be increased if the following effect is taken into account:

When governments use climate policy revenues to finance their budgets and in turn cut taxes on private capital, this improves the efficiency of the national tax system by reducing the interregional externality of tax competition, which is due to capital mobility.

This effect may arise when three premises regarding international capital flows hold. In the field of public economics, in particular the literature on horizontal fiscal federalism, a consensus has emerged that all these premises in fact hold true. The first is that capital is mobile internationally to a sufficiently high degree (Zodrow, 2010). Second, this capital mobility restricts fiscal policy choices and causes a race-to-the-bottom in capital tax rates. Finally, this in turn leads to an inefficient underprovision of local public goods. The mechanism has been shown analytically by Wilson (1986) and Zodrow and Mieszkowski (1986). Empirically, the underprovision of local public goods is reflected e.g. in the observed underprovision of public infrastructure (Bom and Ligthart (2014); see also Section 3.3). Next to the more empirical survey by Zodrow (2010), other good overviews of the tax competition literature can be found in Wilson (1999) or Keen and Konrad (2013).

Thus, as long as capital markets are characterized by deep international integration, capital must be considered an inefficient tax base. In this international setting, taxation of fossil resources is preferable to capital taxation for three related reasons (Franks et al., 2015):

First, the supply of fossil resources is less elastic than the supply of capital, because the total stock of fossils is fixed, income from selling fossils is a rent and the resource owner will sell even at low prices, depending on buyers' behavior. Taking into account strategic behavior, it indeed turns out to be optimal to levy taxes on the use of fossil fuels and thus capture part of the resource rent.

Second, reductions of the rate of return on capital by a carbon taxes are smaller than for a capital tax. Since mobile capital chases the highest rate of return, a unilateral increase of the capital tax leads to capital flight. When instead a carbon tax is increased, then less fossil resources are used in the country. Fossil resources and capital are complementary to a certain degree, thus the return to capital also decreases. However, this indirect effect on the rate of return is weaker than the direct effect caused by capital taxation. Thus, there is relatively little relocation of capital to other countries when carbon taxes are increased unilaterally. More capital relocates under a comparable unilateral increase of capital tax rates.

Third, if revenues from fossil resource taxation finance a budget that contains productivity-enhancing public spending, e.g. on public infrastructure, this has a positive impact on rates of return to capital.

The efficiency result, that is, that carbon taxes are preferable to capital taxes, holds quite generally. Franks et al. (2015) exemplify this in a model of a global economy in which several regions compete for mobile capital and have to import fossil resources from an exporting region. They discuss two

[8] In the context of the analysis of open economies and climate policy the field of carbon leakage has received great attention. In the present study we do not discuss carbon leakage, because the overlaps between climate change economics and public finance seem less important for this topic.

assumptions about the strategic behavior of the governments of the importing and exporting countries explicitly. First, the efficiency result holds irrespective of whether the resource importing countries cooperate among each other or not. Further, it does not matter whether the resource exporting countries can coordinate their actions to influence the resource price or not.

Concerning the first assumption, a buyers' cartel may exercise a kind of monopsony power to extract the resource rent (see e.g. Tahvonen, 1995; Karp, 1984). We shall refer to this as the monopsony effect. It also occurs in the model of Franks et al. (2015). Moreover, they show how in the absence of cooperation among buyers, unilateral climate policy in the form of carbon pricing allows governments to appropriate part of the rent. Governmental expenditures enhance productivity, as shown e.g. by Bom and Ligthart (2014). Thus, as long as the effect of diminishing returns to scale does not dominate, it is optimal both from a global welfare perspective as well as from an individual country's perspective to unilaterally increase taxes. The productivity-enhancing properties of public spending align the incentives of competing resource-importing countries in a similar way as cooperation would do, such that a weak form of the monopsony effect may take place.

Second, when the governments of resource-exporting countries are assumed to interact strategically on the resource market, they will react to buyers' carbon taxation by increasing their taxes on resource exports with the effect of raising the consumer price of fossil resources. In that case, the rent that buyers may capture using the carbon tax is decreased. Nevertheless, the governments of importing countries may still capture a sufficiently large amount of the rent such that the carbon tax is superior to the capital tax.

Considering the environmental effects, Franks et al. (2015) find that an increase in both the buyers' and the sellers' taxes increases the consumer price and thus decreases the amount of resources sold. A green paradox, as brought up by Sinn (2008), does not occur. Resource sellers increase neither their rate of extraction nor the cumulative amount of extraction. Thus, substituting carbon taxes for capital taxes has beneficial environmental implications under all assumptions about strategic behavior mentioned above.

In sum, it is likely that for a wide range of assumptions about the strategic behavior of resource-buying and selling countries the unilateral substitution of carbon taxation for capital taxation increases social welfare. Through the above outlined mechanisms, such a substitution is not only attractive for countries with a strong preference for environmental protection; more importantly, it is highly relevant for countries which are exposed to the negative impacts of capital mobility and which are thus constrained by tight budgets (see also Section 3.4).

The study by Franks et al. (2015) implies that environmental and fiscal externalities such as tax competition should be studied within one integrated framework. Omitting the beneficial effects of a carbon tax on the problem of local public goods provision overstates the costs of climate change mitigation. If there is a pre-existing inefficiency, which is caused by capital tax competition, then unilaterally implementing a carbon tax enables governments to reap a double dividend by addressing climate change and alleviating tax competition.

3.2 Alleviated underinvestment: Inducing a 'macroeconomic portfolio effect' by rent taxation

The arguments above considered cuts of non-environmental taxes in return for imposing a carbon price. This section considers an effect related to investment behavior under a carbon price, independent of the rest of the tax system.

We argue here that the welfare effect of climate policy may exceed its environmental benefits if a carbon price on a flow of GHG emissions (or fossil fuel inputs) reduces the rent of an underlying stock that is part of a larger asset portfolio, and if the resulting rebalancing of this portfolio cures a non-climate inefficiency. Our example for such an inefficiency is the underaccumulation of producible capital due to imperfect intergenerational altruism.

The common argument in favor of a tax on rents that it is non-distortionary does not hold if there are alternative assets Feldstein (1977), since saving behavior and thus portfolio composition change. However, it has been shown that this may actually constitute an efficiency and welfare improvement, e.g. for a tax on a fixed factor, 'land', when some type of producible capital is underaccumulated (Petrucci, 2006; Koethenbuerger and Poutvaara, 2009; Edenhofer et al., 2015b). A similar effect occurs for the case of carbon pricing acting as a tax on rents from fossil fuel stocks (Siegmeier et al., 2015):

Assume that there is a finite stock of fossil resources which is fully owned, and that the extraction cost path is fixed, abstracting from new discoveries and uncertain technology improvements.

Then, without climate policy, the productive sector borrows physical capital and buys fossil fuel as input factors, while GHG emissions are free (but deplete the atmospheric reservoir). Capital yields interest payments and resource ownership yields the value of the extracted part of the stock, at a price reflecting extraction costs, the opportunity costs of extracting and selling the fuel later, and a scarcity rent (depending on demand elasticity, total supply and market structure). Households will divide their savings between capital and (ownership claims to) resources, balancing their portfolio according to a no-arbitrage condition on expected returns.

Now introduce climate policy in the form of a quantity instrument, specifically a permit scheme that directly controls the path of GHG emissions. For simplicity, assume that the government implements an upstream policy by perpetually issuing resource extraction permits, the total amount of which is exogenously given (e.g. reflecting an optimal mitigation pathway derived from an IAM, see Section 2.1). The fraction of the total resource stock that a household owns will also be the fraction of total extraction permits that this household obtains in each period.[9] Thus, households do not choose resource ownership and resource extraction independently, but the former implies the latter. Now, if the government decides to auction some or all of the permits instead of allocating them for free (or equivalently, to tax the revenues from permitted resource extraction), the resource stock owners' rent is transferred to the government. The expected returns and thus the value of the resource stock decrease, and households will direct more of their savings towards capital as the alternative asset until the no-arbitrage condition is restored due to the falling interest rate. If capital was initially underaccumulated, efficiency

[9] For simplicity, we assume that the structure of the portfolio of resource stocks (which may differ for example in terms of extraction costs) is identical across homogenous households.

increases, and the welfare losses of climate change mitigation are reduced. (Siegmeier et al., 2015) provide a formal proof for this 'macroeconomic portfolio effect' in an overlapping-generations model with an exhaustible resource and publicly financed technological progress.

The argument also applies to implementations of climate policy via a carbon tax. However, a complicating factor in this case is that mitigation can only be enforced via a tax rate that decreases over time to provide an incentive for conservation (Sinclair, 1992). Thus, the objectives of climate change mitigation and rent extraction for the public have to be weighed against each other. In contrast, a permit scheme has two policy parameters to optimally achieve both objectives: the quantity of permits and the share that is auctioned.

In practice, the most important limitations will be that the permit scheme does not cover all global resource stocks, and that ownership claims to these stocks may not be freely tradable (as required for optimal portfolio adjustment). The latter concern may be addressed by implementing climate policy as a scheme of individual ownership claims to the stock of the atmosphere, which might change the political economy of climate policy (Siegmeier et al., 2015).

So far, we have neglected uncertainty, which is of central importance in the resource sector: The costs of exploration and extraction and research efforts to lower them, total supply of fossil fuels, and the costs of substitute technologies are generally highly uncertain. While the portfolio effect described above will still occur under uncertainty, additional effects are possible – among them a 'second-order' portfolio effect may arise between equally risky investment opportunities: If climate policy extracts rents from the fossil resource sector, the attractiveness of investment into resource exploration endeavors or R&D in extraction technologies deteriorates vis-à-vis R&D in resource productivity or substitutes for fossil fuels, for example renewable sources of energy.[10] Lower investment in risky fossil resource projects is likely to increase extraction costs and decrease resource supply in the future, thus providing an additional incentive for improving resource productivity and reducing the costs of renewables.

Relaxing other simplifying assumptions such as ideal policy implementation and market structures may also affect the importance of the macroeconomic portfolio effect for the relative efficiency of specific carbon pricing schemes but not its general occurrence whenever fossil resource stocks are one of several investment options.

3.3 Lower private abatement costs: Restructuring public spending

We now turn to public spending: This subsection discusses the implications of climate policy for the optimal composition of public spending; the next subsection considers its optimal level.

Our argument here is that the structure of public spending is insufficiently adjusted to policies that directly target GHG emissions, and vice versa. Effi-

[10]Although the funds withdrawn from such fossil resource projects could also be directed towards less risky assets altogether, it is plausible that some investors ('venture capitalists') will switch to risky alternatives, including R&D in renewable energy technologies which at the same time become more attractive under a credible political commitment to climate protection.

cient and effective climate policy consists of two parts: Direct measures (such as a carbon price) to induce private substitution of clean for dirty technologies, and indirect, complementary adjustments of public spending (in particular on physical infrastructure) so that private abatement is less costly, because the utility and/or productivity of clean substitutes are enhanced. These two parts are typically not optimized together, although doing so would significantly lower total costs of climate policy and increase social welfare.

We highlight the importance of public spending for climate change mitigation, point out how this fact is neglected in mainstream analysis and practical implementations of climate policy, and summarize first insights and future challenges regarding the integration of direct and indirect climate policy.

The feasibility and costs of climate change mitigation depend on how fast different parts of the capital stock can be adapted to the use of low-carbon technologies, since almost 80% of today's emissions are directly related to producible capital, as they stem from burning fossil fuels and industrial processes (IPCC, 2014). Emissions are reduced by clean substitution of directly GHG-emitting devices such as power plants or vehicles, but the speed and costs at which this can be done also strongly depend on the (non-emitting) physical systems that complement them,[11] such as the wider electricity system and transport infrastructure. These parts of the capital stock are often publicly financed or subsidized, and differ strongly between high- and low-emission scenarios, so the structure of public spending plays a key role for the low-carbon transition.

This can be illustrated by contrasting two studies: Davis et al. (2010) calculate emissions 'committed' by already existing directly CO_2-emitting capital stocks, and find that using these devices to the end of their technical lifetimes (up to 40 years) could lead to a global warming of 1.3 °C by 2060. They acknowledge the role of non-emitting parts of the existing capital stock for the inertia of the system, but do not model them. Guivarch and Hallegatte (2011) partly close this gap by additionally modeling transport infrastructure and asset location, which cause inertia in transport demand. They show that this implies committed emissions that are 35% higher in 2030 than those projected by Davis et al. (2010). Furthermore, they find that if this additional inertia as well as non-carbon GHG are accounted for, a 2 °C warming target cannot be achieved by only regulating new investments (as could be erroneously concluded from Davis et al., 2010). Instead, even existing capital stocks need to be adjusted by retrofitting or premature retirement, including "*the drivers of energy services demand, and in particular modal shift and mobility needs linked to infrastructure and assets locations*" (Guivarch and Hallegatte, 2011, p.804). Similar results could be expected from extensions for other high-emission sectors, in particular energy, where non-emitting capital stocks such as networks for electricity and gas transport or sea ports for coal and liquefied natural gas play a large role, for supply as well as demand.[12]

[11] The carbon lock-in literature discusses a wide range of sources of inertia in GHG-emitting activities, which may be interdependent in a techno-institutional complex (Unruh, 2000). We focus here on technological dependencies only.

[12] While infrastructure in the transport sector is still largely publicly owned, privatization in the energy sector has often included infrastructure such as electricity and gas networks, backup generation capacity, or gas storage. But since the energy sector for technological reasons suffers from a host of market failures, it remains heavily regulated: Prices and important physical infrastructure parameters (e.g. location, type and size of installations)

Despite its central role for decarbonisation, infrastructure spending has been neglected in the analysis, design and implementations of optimal mitigation pathways and climate policy to date. Most formal analytical or numerical models focus on directly GHG-emitting capital stocks and direct measures such as carbon pricing, without separate representations of infrastructure and other indirectly emission-relevant capital stocks. This implies the assumption that a social planner or an idealized government optimally adjusts the composition of publicly provided goods (that are complementary to GHG-emitting private goods) so that the costs of (private) direct abatement are minimal. However, Shalizi and Lecocq (2010) argue that carbon pricing does not provide a sufficient signal for efficient investment into (public or private) long-lived capital stocks more generally, and that dedicated mitigation programs targeting these stocks are required.

However, this is not what we observe – instead, direct policies and infrastructure policies are often inconsistent: For example, many European countries that ratified the Kyoto protocol (and participate in the European Emissions Trading System) have not directed public infrastructure spending away from roads and airports and towards rail (ITF, 2014); commuter tax benefits persist in countries such as Germany, despite the importance of dense settlement patterns for transport emission reduction; while there is direct support for EV by price instruments in many European countries (Kley et al., 2010), public provision or support of electric vehicle charging infrastructure is rare, although the lack of charging infrastructure has been identified as a major obstacle to higher electric vehicle deployment (Sims et al., 2014). Efforts certainly fall far short of the adaptation of existing dirty capital stocks, or active policies to promote asset relocation, that Guivarch and Hallegatte (2011) consider necessary for reaching a 2 °C target.

Two recent studies do consider integrated environmental policy and point out the potential benefits. Waisman et al. (2012) use a second-best CGE where households and firms have imperfect foresight, and exogenously impose a specific set of adjustments of transport infrastructure and the related spatial asset distribution. They show numerically that this leads to significantly lower climate change mitigation costs, in particular in the long run: Beyond the mid-2030's, estimated costs of mitigation are lowered by 50% and more (and the carbon price is also drastically lowered). However, since the complementary measures are ad-hoc and exogenous, their (second-best) optimal level cannot be elucidated. Siegmeier (2016) analyzes a static model with two policy instruments: an environmental tax, and the ratio of spending on two publicly provided goods which are complementary to clean and dirty private consumption goods, respectively. He finds that when either the environmental tax rate or the public spending ratio is constrained below its first-best level, the second-best level of the other policy variable is also *lower* than its respective first-best (unless environmental quality is very important in utility). A tighter constraint means an even lower second-best level of the other policy variable.

are still generally controlled by government agencies, and subsidies are significant. Thus, even though changing the energy infrastructure may not be a pure public spending issue, it is still a subject of public policy due to the public good characteristics of many crucial system elements, so the main arguments of this section still apply.

To reap the benefits of an integrated climate policy, a better understanding is needed of why governments have not optimally adjusted the structure of public capital stocks so far. Potential explanations include technological aspects (cf. Shalizi and Lecocq, 2010): (1) uncertainty of technological development, which weighs particularly heavily for long-lived public capital, (2) economies of scale for incumbent technologies and network effects, combined with the longevity of existing capital stocks, (3) long lead times for investment into infrastructure. Furthermore, institutional aspects may play a role, such as (4) conflicting competences (vertical externalities) between several levels of government, or (5) competition (horizontal externalities) between neighboring localities.

In sum, it seems likely that better integration of instruments directly targeting GHG emissions and complementary adjustments of public spending could yield significant welfare improvements. More research is required to determine the optimal balance between these two elements of climate policy, in particular in various scenarios with deficits of market- and government institutions.

3.4 Optimal public spending level: Alleviating budget constraints

In this section, we consider policy reforms that are not revenue-neutral and discuss when and how additional revenues from climate policy may improve welfare by increasing the total level of public spending, or by debt reduction. We first argue that revenue- and spending side effects of climate policy may lead to a larger optimal public budget. We then introduce the additional inefficiency that the public spending level is sub-optimally low. We argue that additional revenues raised by climate policy may offer an opportunity to increase the public budget (closer) to its optimal size. Specifically, we review some empirical evidence that public capital is underprovided, potential explanations for this observation, and why revenue from climate policy may offer a remedy. Finally, the related topic of using climate policy revenues for public debt reduction is discussed.

The impact of climate policy when the public budget was previously (second-best) optimal

An optimal reaction in terms of public spending to the introduction of a consistent, stringent climate policy would be to adjust to a new (probably higher) spending level, for two reasons:

First, a given level of public funds may be raised at a lower cost when climate policy raises revenue via carbon pricing (see revenue-side arguments in Sections 2.2, 3.1 and 3.2).[13] Graphically, the curve of marginal costs of public funds is lower.

Second, the benefit that can be achieved at any level of public spending is likely to be higher under comprehensive climate policy: In some of the most emission-intensive sectors that require a transition to low-carbon technologies,

[13] Goulder (2013) points out that 'green taxes' should not only be part of an optimal tax portfolio, but that even if the starting point is a sub-optimal distortionary tax system, additional revenue should come from a higher green tax rather than an 'ordinary' tax, as long as the green tax is not 'too large'.

public spending plays a particularly large role and will be more beneficial when it is adapted, e.g. infrastructure in energy and transportation (see Section 3.3). Public spending will also play a large role in adaptation to climate changes, and potentially in offsetting distributional effects of climate change (Section 3.5). Graphically, the curve of marginal benefits of public spending is higher.

Together, this implies a larger public budget: the marginal cost- and benefit curves intersect at a higher spending level.[14] The increase in public spending in this new optimum may of course also include spending options that are unrelated to climate change, depending on the marginal benefit of each option.

Underprovision of public investment: why climate policy may help

Of course, the public budget is not always optimally sized in practice. There is evidence that public investment may be too low in many countries: Aschauer (1989) was the first to estimate a production function that includes public capital and found that public capital is undersupplied in the United States. Gramlich (1994) reviewed literature following up on Aschauer's study for the US and finds evidence for an undersupply at least for some types of public capital (e.g. urban transport infrastructure). More recently, Bom and Ligthart (2014) conducted a meta-regression analysis over 68 empirical studies for OECD countries. Their estimate for the output elasticity of public capital ranges from 0.08 (short-run effect of public capital broadly defined, at the national level) to 0.19 (long-run effect if only transport infrastructure and utilities at the regional level are included). Taking an approximate ratio of public capital to GDP of 0.5, this implies a marginal rate of return on public capital of 0.16 to 0.38. Comparing this to a depreciation rate of 0.1 and interest rate of 0.04, they conclude that public capital is indeed undersupplied.

We now consider four potential explanations for the non-optimal public budget, and why these problems may not apply or be weaker if additional revenues from climate policy are available:

First, public revenues may be too low due to weak institutions (this explanation will be more relevant for non-OECD countries). More specifically, institutions may be ineffective at implementing or enforcing conventional taxes, e.g. on income or consumption. Enforcing a carbon price may be less demanding, in particular when it is done upstream (fossil fuels consumption is relatively easy to measure). Political feasibility remains an issue though, since many implementations of a carbon price are visible to consumers (gasoline prices), and carbon pricing may affect rents from fossil fuels and/or existing energy- and carbon-intensive capital stocks.

Second, the existing allocation of other public funds may be inefficient in the sense that spending does not maximize net benefits. For example, when conventional taxes were introduced or increased in the past, political feasibility might have required the earmarking of revenues from specific taxes for specific spending (Wagner, 1991). But even if the allocation of revenues

[14] When public investment is financed by taxing the rents on fixed factors (along the lines of a Henry George Theorem, see Arnott and Stiglitz, 1979), it may even be possible to establish the socially optimal allocation, see Mattauch et al. (2013). However, given a situation in which there are two externalities, related to the climate and to productive infrastructure which is publicly funded, it is unclear if the social optimum can be reproduced by using the revenues from correcting the climate externality to finance the public investment.

from other taxes cannot be changed, the new revenues from climate policy can be allocated freely to different spending options, at least initially.[15]

Third, imperfect altruism towards future generations, or myopic politicians, may lead to high discounting of future benefits and thus to too little investment into projects with long-term benefits, which make up a substantial part of the public budget. If this were true, choosing stringent climate policy would be inconsistent, absent some mechanism that lets current generations benefit from future avoided damages (e.g. increasing asset prices, see Section 3.6). If climate policy was chosen nevertheless, it would under these circumstances more likely be designed in a revenue-neutral way, i.e. combined with cutting other distortionary taxes rather than an increase in the public budget - or at least a budget increase would probably not be in favor of projects with long-term benefits. Among the latter, mitigation policy still may stand the highest chances of realization, if the political momentum for climate policy is strong enough to lead to an 'earmarking' of climate policy revenues for mitigation spending, as discussed above.

Fourth, even if investments with long-term benefits were supported for the sake of future generations, there may be a lack of fiscal tools for financing their high up-front costs, e.g. political limits on public debt such as a maximum ratio of total or new debt to GDP (if the limit is set by financial markets due to doubts about a country's creditworthiness, this can often be traced back to weak institutions or inefficient political processes, which we already discussed above as the first two potential explanations of public underfunding). Then, additional revenues from climate policy may indeed offer more flexibility to invest in long-term projects. A related option that is discussed more prominently is using climate policy revenues for the reduction of public debt, which is covered next.

Public debt reduction

High levels of public debt have increasingly come into focus of policy makers, especially after their dramatic increase in developed countries as a result of the financial crisis. This is linked to the issue of climate change, as both are long-term challenges concerning many future generations.

Whether the existence of public debt in itself has a deteriorating effect on the economy is discussed controversially in the empirical literature (Kumar and Woo, 2010; Herndon et al., 2013), and to our knowledge not clearly supported by theory. In our view, the literature on public debt and climate policy (Carbone et al., 2012; Ramseur et al., 2012; Rausch, 2013) does also not give a genuinely new argument of why debt would by inefficient. Instead, the additional inefficiency that comes with the inclusion of public debt is represented through a government that fails to pay off the debt in an optimal way. This combines two effects that we treat in other sections:

[15]Of course, for the same political economy reasons that led to an earmarking of non-carbon pricing revenues, a climate policy package may also contain restrictions on how to use carbon pricing revenues, e.g. for spending on climate change mitigation measures. As long as public spending on mitigation is marginally productive - which is probably currently the case, given the weakness of climate policy - it still constitutes a welfare improvement, even though there may be better uses for at least some part of the funds. See Burtraw and Sekar (2014) for data on the use of revenues from currently existing carbon pricing schemes, or Brett and Keen (2000) for an attempt to explain earmarking of environmental taxes.

First, debt reduction using revenue generated by climate policy can be less costly than financing it by other taxes – this is the classical double-dividend argument, as discussed in Section 2.2.

Second, revenue from climate policy can also help governments to optimize the intertemporal distribution of debt repayment. This argument affects intergenerational distribution, as worked out in more detail in Section 3.6.

For example, both effects are captured by Rausch (2013): Using a numerical model, he finds that a revenue-neutral inclusion of a carbon tax in the tax portfolio would entail a gross welfare loss. But since the availability of the carbon tax also opens the possibility to raise additional revenue (at lower marginal costs of public funds) which can then be used to reduce the public debt, future interest payments can be avoided and welfare improved (even before taking avoided climate damages into account). This obviously has strong implications for the inter-generational distribution of welfare, as both the benefits from avoided environmental damages and those from lower interest payments on public debt would accrue to future generations, leaving today's generations at a loss. It has been argued elsewhere that the opposite approach, leaving future generations with more public debt, but an improved environment may be a way to finance mitigation measures today (see Section 3.6).

3.5 Using carbon revenues for reducing inequality: the role of public investment

So far, we have considered interactions of climate policy and public finance at the aggregate level, both concerning the levying of revenue from limiting emissions as well as alternatives for spending these revenues, and tacitly made the assumption that households are homogeneous. Distributive effects both on the revenue-raising and spending side become important in two cases: First, if inequality of income or wealth is taken to be undesirable as such (reflected by a specific concept of social welfare); second, if some types of inequality lead to aggregate inefficiency (which is our focus here).

Climate policy is likely to be regressive (Bento, 2013) and may thus increase inequality, which in turn could harm overall economic performance (Berg and Ostry, 2011; Berg et al., 2012; Kumhof et al., 2015). Recent publications treating household heterogeneity and climate policy demonstrate that it is possible to reduce or even eliminate the regressivity of climate policies by a carefully chosen recycling of the revenues. There are several mechanisms for this: Most of the literature focuses on household transfers and cuts in distorting taxes and finds that regressivity can be reduced, or even eliminated (Bureau, 2011; Metcalf, 1999; Chiroleu-Assouline and Fodha, 2009; Rausch et al., 2010). In contrast, how the financing of public investment with climate policy revenues affects the regressivity of these policies and thereby the overall efficiency remains unexplored. We suggest that if inequality is indeed harmful to overall economic performance, then such a policy could be another reason for lower welfare losses from climate change mitigation. Alternatively, if inequality reduction is valued as such, whether or not it impacts aggregate efficiency, social welfare is increased by combining climate policy with appropriate revenue recycling options that may alleviate, not increase inequality.

We subsequently first explain why climate policy is often considered regressive and which remedies have been proposed for this. We find broad agreement in the literature that recycling the revenues through household transfers and tax cuts drastically reduces the overall regressivity. Second, we explore whether inequality reduces economic efficiency and we find that in particular inequality of opportunities is detrimental to overall economic performance. Third, we argue that this strengthens the case for public investment as another remedy for inequality of opportunity, notably investment in education (OECD, 2012). Finally, we integrate the first and the third argument by raising the question to which degree the regressivity of climate policy could be offset by using its revenues specifically for public investment.

Environmental taxation: regressivity and remedies

Research on the equity impacts of climate policy has focused on factors that may make policy instruments regressive while neglecting the question of how revenue-recycling may achieve distributional goals (Bento, 2013). Following Fullerton (2011), there are several reasons why environmental policies can be regressive: The two most important effects are that, first, low income households spend a larger portion of their income on products which require fossil inputs. Environmental policy would increase the price of these goods and thus be regressive. Second, unskilled workers might lose their jobs in the polluting industry, while jobs in the renewable sector preferably go to high-skilled workers.[16]

Bento (2013) reviews recent empirical literature and finds that environmental policies are likely to have a regressive effect. Furthermore there is wide agreement that the revenues from environmental policies can be used to mitigate these regressive effects (Metcalf, 1999; Chiroleu-Assouline and Fodha, 2009; Bento et al., 2009; Bureau, 2011; Parry and Williams III, 2010). There may even exist ways to implement Pareto-improving environmental policies in a heterogeneous household setting.

Theoretical work that accounts for revenue recycling mainly focuses on transfers to households and cutting distorting taxes with climate policy revenues to mitigate regressivity: Chiroleu-Assouline and Fodha (2014) use an overlapping generations approach in which agents differ in their skill level and their time preference rate. They analyze budget-neutral carbon tax reforms and show that for any degree of regressivity of a carbon tax, the tax revenue can be used for a progressive reform of the income tax system that renders the tax reform Pareto-improving. In their framework, pollution is a by-product of using capital for production and climate policy hence acts like a capital tax. The existence of a subsistence level of carbon-intensive consumption as

[16]Other distributional effects of environmental policies are: First, for capital-intensive abatement technologies, environmental policies would drive up the demand for capital. This would depress wages which would have a regressive effect since low-income households receive most of their income from wages. Second, when pollution permits are grandfathered to firms, scarcity rents are created, which again go to the high-income firm owners (Parry, 2004). Third, low-income households may attach a lower value to environmental quality and care more for goods like food and shelter. Thus high-income households would benefit more from avoided damages. Fourth, avoided damages to capital increase the present value of capital, for example of an oceanfront house. Since capital owners are already better off, this policy would also have a regressive effect.

an important driver of the regressivity of climate policy is mentioned, but not modeled explicitly.

Klenert and Mattauch (2016) and Klenert et al. (2016b) also confirm that redistribution of the carbon tax revenue can make an (otherwise regressive) carbon tax reform Pareto-improving. In contrast to previous work, they explicitly take into account that poorer households spend a larger fraction of their income on carbon-intensive subsistence goods, thus addressing the first concern about inequality regarding environmental policies raised above.

Rausch et al. (2010) look at a broader range of revenue redistribution mechanisms, such as transfers and tax cuts, in a more detailed general equilibrium model which is calibrated to the US economy. They find that the tax itself can have a slightly progressive effect, due to the dependence of poor households from transfer payments, which are unaffected by climate policies. Accounting for revenue recycling renders the tax reform even more progressive.

Does inequality reduce economic efficiency?

The conventional view of economic theory is that inequality reduction as a policy goal reduces the overall efficiency of an economy due to losses in the redistribution process (Okun, 1975). In particular, Kaldor (1955), based on the observation that rich households save more than poor households, comes to the conclusion that redistributive policies would thus lead to less capital accumulation. In the context of environmental taxation, Metcalf (1999) and Parry and Williams III (2010) point out that there is a trade-off between efficiency and the degree of reduced regressivity: more efficient environmental policies tend to be more regressive.[17]

However, the conventional view neglects that there are two fundamentally different types of inequality: inequality of opportunity is caused by factors which are beyond an individual's personal responsibility, like the economic situation of the parents (Roemer, 1993). In contrast, inequality of returns to efforts gives incentives to households to work harder. The conventional view is correct with respect to inequality of returns to efforts as it increases an economy's growth rate; however inequality of opportunities decreases it (Marrero and Rodríguez, 2013). High levels of inequality of opportunity are usually coupled to low social mobility, a fact which is also known as the 'Great Gatsby Curve' (Corak, 2013).

Berg and Ostry (2011) and Berg et al. (2012) look at growth in the long term and find that a trade-off between equity and efficiency might not exist. It rather seems that in countries with low economic inequality, the length of periods of strong economic growth, so-called 'growth spells', is increased. Moreover, Kumhof et al. (2015) claim that increased inequality and debt-to-income ratios can trigger economic crises, based on an analysis of the economic

[17] Burtraw and Sekar (2014) highlight that treating efficiency and equity as two objectives between which a government needs to strike a balance reflects a view where the atmosphere is owned by the state. In contrast, "if one views the property right to atmosphere resources as inherently assigned to individuals and held in common, the issue of how to use the economic value created from introducing a price on carbon might be viewed as illegitimate, at least from the perspective of the resource owner" (Burtraw and Sekar, 2014, p.4f).

crises in the U.S., 1929 and 2007, which both were foreshadowed by a strong increase in wealth and welfare inequality.[18]

Additionally, inequality has been found to increase the risk of civil conflicts (Ostby, 2008; Ostby and Strand, 2013; Cederman et al., 2011), which in turn reduce growth.

Reducing inequality while promoting efficiency via public spending

High inequality of opportunity makes health care, education and other factors unaffordable for some parts of the population. This situation can partially be alleviated by public spending (OECD, 2012). A short-term impact of education on inequality of opportunity can in particular be expected from measures such as further training of unemployed or continued education for more senior workers in order to include or keep them in the labor market as well as language courses for immigrants.

Additionally, public investment in physical infrastructure is known to promote efficiency and growth (Romp and De Haan, 2007; Agénor, 2013), but the empirical literature regarding its effect on inequality is inconclusive: while some studies find that investment in infrastructure, which is financed by distorting taxes, reduces inequality (Calderón and Chong, 2004; Calderón and Servén, 2004; Lustig et al., 2011; Jacoby, 2000), there is also evidence for increased inequality through public spending (Artadi and Sala-I-Martin, 2003).

The theoretical literature is similarly ambiguous: In a growth model with heterogeneous dynastic agents, Chatterjee and Turnovsky (2012) show that government spending increases inequality in welfare and wealth in the long run. Glomm and Ravikumar (1994) find that income tax-financed public spending is neutral on the income distribution. Mattauch et al. (2016) and Klenert et al. (2016a) show in a heterogeneous-agent model that Pareto-improving public spending can have a distribution-neutral effect when it is financed by a tax on consumption, and even an inequality-reducing effect when financed by a tax on capital. In their model, agents are distinguished by their saving motive, their time preference and their source of income. These assumptions are well founded in the empirical literature[19] and are necessary to reproduce a realistic wealth distribution (De Nardi, 2004; De Nardi and Yang, 2014).

Financing public investment by carbon pricing

Combining the aspects discussed above raises two additional points: First, instead of directly redistributing revenues from carbon taxes (to mitigate their regressivity) or cutting distortionary taxes (which could also enhance inequality, see Klenert et al., 2016b), governments could also invest in infrastructure to enhance growth. The resulting higher living standards of most households may alleviate inequality of opportunity directly. Second, climate policy revenues could be used for public investments that specifically reduce intragenerational

[18] Additionally, it is debated whether inequality harms aggregate welfare by increasing health and social problems independently of its impact on economic growth (Wilkinson and Pickett, 2009). A part of the debate is summarized in Noble (2009) and Liebig (2012).

[19] Attanasio (1994), Dynan et al. (2004) and Browning and Lusardi (1996) demonstrate that the savings motive varies across income classes. Quadrini and Ríos-Rull (1997), Diaz-Gimenez et al. (2011) and Wolff (1998) highlight the role of different income sources and Lawrance (1991) show that households' time preference rate decreases the more wealth they own.

inequality. What is unclear in both cases is the size of the inequality-reducing effect that climate policy revenues alone could finance. Future work on this would need to model household heterogeneity to reflect both the regressivity of environmental taxation as well as differential benefits from public investment. If the result was that for inequality reduction, public investment is preferable to direct financial benefits to poor households, then discussions of mitigating the regressive nature of environmental policies should focus on this option.

3.6 Intergenerational distribution: fiscal strategies for Pareto-improving climate policy

Climate change is fundamentally an intertemporal problem: If climate policy is to avert dangerous anthropogenic interference with the climate system, then substantial mitigation costs arise today, but much higher benefits through avoided damages occur in the future.

So the net costs of climate change could be lower at each point in time if climate policy were combined with intergenerational redistribution: Future generations as the main beneficiaries of mitigation measures could be made to bear some of today's mitigation costs by a transfer to present generations. The resources for financing low-carbon infrastructures and emission reductions could thus be mobilized from future generations who have higher benefits from climate protection than the current population.

Such a transfer may be welfare-enhancing because it could achieve a Pareto-improvement, that is, negative net costs of climate policy in this context. Combining climate policy with intergenerational transfers that make it Pareto-improving could be a politically feasible solution to the climate problem: Given the standstill in international negotiations, Pareto-improving climate policy would separate the solution of the climate problem from the more general (and politically even more difficult) considerations of intergenerational justice (Broome, 2012). It differs from socially optimal climate policy by violating the optimal intergenerational distribution of welfare, but could potentially imply negative net costs of climate policy at each point in time.

But is Pareto-improving climate policy possible? Could intergenerational transfers from people yet unborn to those alive be implemented by fiscal policy? Recently different possibilities for such transfers have been explored. The remainder of this section first clarifies the above argument about Pareto-improving climate policy and then discusses suggestions for organizing an intergenerational transfer from the future to the present.

There is universal agreement about the basic economics of the climate problem: Climate change is a market failure as the emission of greenhouse gases are an externality. Economic theory holds that the correction of this externality comes at no cost. Some theorists have thus claimed that there really are no costs of climate change if those who will benefit from mitigation pay for it (Foley, 2008; Broome, 2010, 2012). However, climate change is an externality spread out over time so that rather than saying that there are no (net) costs of climate change, it seems more apt to conclude that there are net costs of climate change mitigation today, while higher benefits occur in the future. Thus only by arranging for an intergenerational transfer from the future beneficiaries of climate policy to the present generation that has to bear the costs of low-carbon investments, a Pareto-improving solution to the climate problem could be reached: no generation would need to pay more for climate change mitigation than the benefits it will receive. But only when climate mitigation policy is thus complemented by carefully designed transfer measures should there not be net costs to the present generation.

Recent research has considered two options for organizing intergenerational transfers: Diminution of capital stocks, and higher returns for current holders of assets such as fixed factors of production. An earlier strand of research has investigated a third option: public debt. Most of these options cannot be examined in representative-agent models, so that modeling is usually carried out using overlapping-generations models.

First, an obvious possibility for a transfer from future to current generations would be that current generations leave future generations less (private or public) capital in return for a cooler world (Foley, 2008; Broome, 2012). Rezai et al. (2012) use a variant of the DICE model (Nordhaus, 1993) to examine the possibility of financing mitigation with resources diverted from other investments. They find that implementing the social optimum compared to a true business-as-usual scenario[20] leads to higher consumption for all future people except those living in the first decade. Moreover, a more equity-conscious social planner, mimicking an intergenerational transfer, would want to allocate more consumption to the first decade, leading to a Pareto-improvement for all generations. However a mechanism to achieve this based on tax policy instruments is not described.

On the contrary, von Below et al. (2013) propose a mechanism based on pay-as-you-go (PAYG) pensions between generations, using an overlapping-generations model. Therein, the old generations are compensated for their mitigation efforts by the respective young generation alive at the same time through a PAYG transfer payment. With this transfer scheme extending far into the future, a mitigation policy that is Pareto-improving for all generations can be achieved.

This result may be very sensitive to the way of modeling the PAYG transfers. Governments usually must rely on distortive taxation, typically on wage income, to finance the transfers which results in additional welfare losses. von Below et al. (2013) collect the PAYG pensions in a lump-sum fashion, which makes the proposed mechanism less useful for real-world fiscal policy.

Second, another possibility to organize an intergenerational transfer builds on the idea that climate change mitigation will change the value of current assets: their future returns will differ from a business-as-usual scenario due to fewer damages to production in the future. Karp and Rezai (2014b) demonstrate in a stylized overlapping-generations model that if agents live for two periods, capital is a fixed production factor and agents only own assets when they are old, a Pareto-improving transfer is possible in the following sense: If the mitigation of an externality requires investments today, all generations' welfare is improved except that of the current young. Their welfare can also be improved if the current old compensate them with a share of their increased asset value. Karp and Rezai (2014a) confirm this result for a non-fixed capital stock with adjustment costs between investment and consumption as well as standard dynamics of the atmospheric stock.

[20]In which agents are deprived of mitigation instruments and do not see themselves capable of influencing the level of emissions.

However, one may doubt whether such a model captures the relevant features of asset-holders behavior. The premise that future generations would pay today's proprietors higher prices for assets if future rents were higher due to mitigation measures today seems credible. But then rational proprietors today would welcome or execute investment in climate-friendly infrastructure, which largely does not conform to the current economic reality. Possible reasons for this mismatch include free-riding behavior, commitment problems, lack of information and imperfect foresight or time inconsistency.

Another possible explanation for this mismatch is brought forward by Schultes et al. (2015). In a setting similar to that of Karp and Rezai (2014a), today's generations have a stake in future avoided damages through the only durable asset, land in their case. While this also leads to non-altruistic generations enacting some climate policy, they find that the level of mitigation depends on the type of damages: For damages biased towards land, the incentive to mitigate is diminished, as mitigation would decrease the price of land. In effect then, today's generations may decide to mitigate very little because they wish not to diminish future scarcity rents accruing to the durable assets they own.

Third, an earlier line of inquiry has focused on constructing an intergenerational transfer by debt policy. When the Ricardian equivalence does not hold, it is possible to compensate current generations for their welfare losses from mitigation by transfer payments that are financed by increasing public debt. For instance Bovenberg and Heijdra (1998, 2002) find that environmental tax policy can be Pareto-improving when combined with public debt in a continuous overlapping-generations model. However their results hinge on a number of assumptions of which it is unclear whether they are a credible representation of the climate problem. Environmental degradation depends on the size of the capital stock, and harms utility, not production. Mitigation is only possible through either taxation (and thus reduction) of capital Bovenberg and Heijdra (1998) or public abatement spending Bovenberg and Heijdra (2002). These modeling assumption make it difficult to compare these earlier results to contemporary findings.

In sum, climate change mitigation in principle does not require sacrifices from the current generation in order to benefit future generations if these could be made to bear some of the costs of decarbonization. The net costs of climate change mitigation for the near future could thus be lower or even non-existing if an appropriate Pareto-improving intergenerational transfer can be realized. On a theoretical level, recent research has identified several options open to fiscal policy to organize such a transfer, although the robustness of the proposed mechanisms is unclear. On a practical level, political feasibility of committing long into the future to elaborate intergenerational transfers may well be doubted and is a topic for further research.

4 Discussion: Integrating climate policy and public finance in one framework

The thesis defended in this article - that taking into account the interactions between public finance and policies leads to welfare gains relative to treating the two fields in isolation - is dependent on two premises. The first premise concerns the framework of economic policy evaluation: Climate policy happens in a world with multiple market failures and pre-existing distortions (for instance due to taxes) which are in turn influenced by climate policy. We assume that models designed to evaluate climate policy should take these into account. Otherwise effects that might substantially change the outcome of the evaluation will be missed. The second premise concerns the benchmark of evaluation: Compared to evaluations under standard discounted utilitarianism, if (intragenerational) equality is valuable as such (see Section 3.5) one may find that welfare gains are larger. Seeking intergenerational Pareto-improvements instead of intertemporal optimality (see Section 3.6) reinforces this conclusion. The following discussion focuses on the first premise and justifies why it is appropriate to consider the welfare effects of climate change in a framework that also includes other fiscal policy objectives.[21]

From a practitioner's perspective, there is a straightforward answer to this question: Whenever substantial interactions between two distinct fields exist, one should include these interactions into policy appraisal. This is particularly true if such interactions become tangible in terms of large financial flows, as is the case for interactions between climate change mitigation and public finance: If mitigation efforts yield revenues that can form a substantial part of national budgets (see Section 1), policy-makers will de facto be concerned with the interactions of climate policy with fiscal policy.

To the theorist, such an answer may seem naïve. We discuss and rebut two major objections to the practitioner's perspective. The first objection concerns the legitimacy of treating certain economic phenomena together and not in isolation. The second is the doubt that through the advent of a 'new' problem to be addressed by policy, addressing existing imperfections becomes any more feasible or actually yields a genuine benefit.

Regarding the first objection, the question to which degree abstraction, simplification and isolation is warranted in economic theory is arguably the most important methodological problem for economics (Hausman, 2013). Hence whether merging two previously unrelated subfields is considered an improvement over previous research may fundamentally depend on one's basic methodological commitments. Examining these for the case of merging climate policy with major topics of public finance is beyond the scope of this article. However, the thesis that embedding analysis of climate policy in a public finance framework results in non-negligible effects for both fields is a theoretically very modest claim. We do not know of any metaphysical, methodological or normative controversy (see Mäki, 1992, Section 10) that would provide arguments for or against merging the two fields; on the contrary doing so is likely to yield sounder policy advice. Current greater interest (or earlier lack thereof) in linking the fields of public finance and climate change mitigation may thus need to be discussed differently: first, evidence for the fact that linking the two fields would yield truly non-negligible effects is provided by relatively recent studies (Metcalf, 2007; Bauer et al., 2013; Carbone et al., 2013) that show that ambitious climate protection will yield substantial revenues for gov-

[21] For extensive discussions about the appropriateness of discounted standard utilitarianism for evaluating climate change and alternative welfare criteria concerning intra- and intergenerational equity, see e.g. Dasgupta (2001); Roemer (2011); Broome (2012). As there is a very prominent debate within climate change economics about the benchmark for evaluating policies, our discussion is limited to a justification of the first premise.

ernment budgets. Second, economic research is typically conducted with a narrow focus on the essentials of a problem, sometimes at risk of missing some of its broader implications. Already Tullock (1967, p.643), who may have been the first to note a potential double dividend of environmental taxation, remarks that "*economists, like everyone else, sometimes keep ideas in watertight compartments. Fiscal policy has normally been dealt with quite separately from the problem of externalities*". Goulder (1995a, footnote 3) reinforces this claim when writing that "*the neglect of these interactions reflects a tradition in the field of public finance, where theoretical analysis of pollution taxes [...] has generally been kept separate from the analysis of ordinary distortionary taxes*". Combet (2013) and Combet and Hourcade (2014) defend a view similar to that of this article for the case of interactions of climate policy with the social security system. The reply to the first theoretical objection thus bolsters the intuition implicit in the practitioner's perspective.

Regarding the second objection, the theorist will wonder why the advent of stricter climate policy will impact the success of policy to address other externalities. Why would the introduction of climate policy imply that other unrelated real-world imperfections should suddenly be addressed in combination with the climate policy instrument? If public spending is non-optimally composed, inequality imperfectly addressed, public debt at non-optimal levels, etc., there should be reasons independent of climate policy why this is so and a reason why this may be changed even if climate policy is not enacted. One answer to this objection comes from economic theory; another answer from political economy.

The theory of second-best allocations stresses that in a situation in which one externality is not corrected, the optimal allocation on all other markets differs from the firstbest allocation (Lipsey and Lancaster, 1956). Thus if one moves from a situation in which the climate externality is unaddressed to one in which it is addressed, in general some other regulated market equilibria should be changed as well to achieve the first-best outcome. Some of the effects considered in Sections 2 and 3 indeed confirm that adjusting policy measures supposed to address distortions independent of climate policy does have beneficial effects when stricter climate policy is introduced.

A different answer to this objection complements the practitioner's perspective by infusing it with political economy. Politically, it is typically more feasible to design tax reforms that combine various public finance measures tailored to win the support of special interest groups (Grossman and Helpman, 2001) and voters (Castanheira et al., 2012). In particular, the government may be constrained by not being able to raise non-environmental, distortionary taxes on political grounds, even if levying these taxes to increase government spending would increase total productivity. Poterba (1993, p.55) stresses this point: "*On reflection the [double-dividend argument] may make more sense. If there is a causal link between enacting a carbon tax and cutting particular other taxes, perhaps because of political constraints on raising existing taxes, and if there are no other ways to enact changes in these other taxes, then it is appropriate to consider how the funds are used in evaluating the net benefit from a carbon tax*".

Recent work in climate economics has been impacted by similar, but even broader considerations: Opinions differ on whether to include beneficial side-effects of climate change mitigation that are not of fiscal nature, often labeled 'co-benefits' (Haines et al., 2009; West et al., 2013; Ürge-Vorsatz et al., 2014) such as improved health through reduction of local air pollution and increased model share of non-motorized transport, or energy security into cost assessments of climate policy (Nemet et al., 2010; Kolstad et al., 2014; Edenhofer et al., 2015a).[22] Arguments in favor of the inclusion of co-benefits in policy appraisal based on welfare theory are similar to those already given for fiscal interactions of climate policy (greater realism of effects of climate policy; sounder policy advice). We conclude the discussion of a joint analysis of fiscal and climate policy by indicating why the two principal objections prominent in the co-benefit debate do not apply to fiscal side-effects of climate change mitigation.

A first principal objection against accounting for non-fiscal co-benefits is that studies of their magnitude do not happen in a framework suitable for welfare analysis. This may be the case for studies mostly analyzing a specific sector in one location, although some studies do assess the welfare effects of policy options (IPCC, 2014). This is an objection less acute for fiscal co-benefits of climate change mitigation such as those scrutinized in Section 3 as research on interactions of mitigation policy with other fiscal policy has typically been analyzed in general equilibrium contexts.

A different objection against the inclusion of co-benefits in cost assessments of climate policy is that the uncertainty around some side effects of climate policy is too great to include them into policy appraisal. Even if many co-benefits are said to be less uncertain than future mitigation benefits, estimates of the uncertainties might still be incommensurable (Nemet et al., 2010; West et al., 2013). A further worry is that these effects are difficult to monetize (Ürge-Vorsatz et al., 2014). Whether or not this critique is legitimate (Edenhofer et al., 2013, 2014; von Stechow et al., 2015), it does not apply to public finance co-benefits: Estimates of the revenue from carbon taxation and of the size of other fiscal interactions are both relatively robust and such estimates are already expressed in monetary terms.

5 Conclusion: Implications for Policy Assessment

This article highlighted the close links between climate change mitigation and other, allegedly conflicting objectives of economic policy such as financing public investment or reducing tax competition and inequality. These links include, but go far beyond the idea of a potential double dividend of substituting environmental for distortionary taxes. It has been shown that the welfare effects of climate policy should be assessed in a comprehensive public finance framework, and that this reveals efficiency gains. There may also be more flexibility in terms of the intra- and intergenerational distribution of costs, helping to avoid potential conflict over carbon tax reforms.

We conclude by highlighting some consequences for the assessment of climate policy and public finance research:

[22] The effects studied in Section 3 can be seen as 'co-benefits' of climate change mitigation if the term is to include all beneficial side effects of climate policy. However as some of the effects mentioned in this article are non-incremental and /or have intertemporal ramifications, it is at present unclear how to incorporate them into the framework on co-benefits recently proposed by the IPCC (Kolstad et al., 2014).

Concerning the assessment of climate policy, IAMs have generally been designed to include as many effects relevant climate change mitigation as possible.[23] Some of the arguments given above to support the thesis of this article have been endorsed by the integrated assessment community to justify the inclusion of as many technological options as possible for the assessment of climate policy (Schneider, 1997). If such assessments have a direct policy impact this may even be mandatory to prevent 'cherry picking' by lobby groups, that is the willful exclusion of relevant, but unwelcome effects. However, climate policy assessments have predominantly focused on technological options (Millner, 2013; Staub-Kaminski et al., 2014), neglecting interactions with public finance (Howarth, 2006). The contribution of this article thus underlines that integrating the above interactions of climate policy with topics in public finance could change results of climate policy assessments significantly.

Furthermore, IAMs have also been accused of insufficiently analyzing climate policy under welfare conceptions different from standard discounted utilitarianism (Howarth, 2000; Llavador et al., 2011; Millner, 2013). Regarding the significance of the two alternative welfare criteria employed in this article, intragenerational inequality reduction as an end in itself and intergenerational Pareto-improvements, it may thus be enlightening to conduct an assessment of climate policy with IAMs from these different viewpoints. There is preliminary evidence that applying these alternative welfare criteria indeed leads to markedly different evaluations of climate policy (see Rausch et al. (2011) for inequality reduction; Rezai et al. (2012) for Pareto-improvements).

Public finance vice versa typically neglects issues of climate policy, presumably because the field is unaware of the high fiscal revenues to be expected from ambitious climate policy. Exceptions are the classical double-dividend discussion (Goulder, 1995b, 2013) and a few applications to the problem of tax competition (Eichner and Runkel, 2012; Habla, 2014; Franks et al., 2015). But in an economy that will be significantly constrained by (mitigated or unmitigated) climate change (IPCC, 2014) the field should take ramifications of climate policy into account more, as the analysis of the major effects above has shown. The contribution of this article could thus also be seen as a first attempt to structure the mitigation effects to be included into a public economics of a climate-constrained world.

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[23] For instance, they have even been defined to *"(2) constructively force multiple dimensions of the climate change problem into the same framework, and (3) quantify the relative importance of climate change in the context of other environmental and non-environmental problems facing mankind."* (Kelly and Kolstad, 1999, p.3, summarizing Weyant et al., 1996).

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Chapter 3

Financing public capital through land rent taxation: A macroeconomic Henry George Theorem[1]

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Financing public capital through land rent taxation: A macroeconomic Henry George Theorem

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Abstract

Financing productive public capital through distortionary taxes typically creates a trade-off between efficiency-enhancing public investment and perturbing market efficiency. In contrast, such a trade-off may be avoided if public capital is financed by taxing the rent of a fixed production factor, such as land. We prove that the socially optimal level of the public capital stock can be financed by a land rent tax, provided that the income share of land exceeds the public investment requirement. This result can be considered a macroeconomic version of the Henry George Theorem from urban economics. It holds for both neoclassical and endogenous growth.

JEL classification: H21, H54, Q24

Keywords: land rent tax, public investment, infrastructure, Henry George Theorem, social optimum

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1 Introduction

Public capital is a key determinant of aggregate productivity (Romp and De Haan, 2007; Bom and Ligthart, 2013): productivity increases may stem from investments into physical infrastructure, but also into the health and the education system or into the stock of publicly available knowledge. However, collecting revenue for public investment through taxation usually creates inefficient allocations (Barro, 1990; Barro and Sala-I-Martin, 1992). Typically, a trade-off between productivity growth from public investment and efficiency loss from distortionary taxation is identified, which determines the best possible level of public investment. It is lower than the socially optimal level, which thus cannot be reached when lump-sum taxation is infeasible.

In this article, we examine a case in which such a trade-off does not exist: public investment is financed by taxing rents from fixed factors of production such as land. We prove that if the land rent is higher than the socially optimal level of public investment, taxing the rent and investing the revenue in public capital is a socially optimal policy. This result can be considered a dynamic and macroeconomic analogue to the "Henry George Theorem" or the "golden rule" of local public finance. While the original theorem requires a 100 % tax on land rents, our macroeconomic result merely requires that the income share accruing to land is sufficiently high: the socially optimal tax thus need not be at a rate of 100 %. The result of this paper may thus be seen as a new starting point for addressing underfunding of public infrastructure on a national scale, while the original Henry George Theorem has been applied in urban public economics only.

Our argument is based on two premises. First, we assume that public investment is productivity-enhancing[1], be it in the form of infrastructure (Barro, 1990; Gramlich, 1994), research and development (Romer, 1990) or investment into human capital via education or the health system (Glomm and Ravikumar, 1992; Bloom et al., 2004). The nature of the investment may differ according to the state of a country's economy: In developing countries, *building* new infrastructures and public capital stocks would enhance productivity (Agénor, 2013). In developed countries, *maintaining* the existing, but deteriorating infrastructures requires public investment. Moreover, *transforming* infrastructures is required for overcoming the lock-in into carbon-intensive production processes to mitigate global warming and its economic damages (Unruh, 2000; Davis et al., 2010; Lehmann et al., 2012; Mattauch et al., 2012).

Second, we assume that fixed factors are relevant for the production process: In fact the rents on non-reproducible factors such as land are a highly significant share of total economic output (Caselli and Feyrer, 2007). Furthermore, while our model assumes that taxing land rents is non-distortionary, our results translate to settings in which it *is* distortionary, but beneficial (as in Feldstein (1977) or Edenhofer et al. (2013); see Section 5.2).

The main result of this article is related to the Henry George Theorem, which states that local land rents equal expenditure on a local public good

[1] For a review of the theoretical literature of the link between government spending and growth, see Irmen and Kuehnel (2009). Empirical reviews of this premise are provided by Romp and De Haan (2007), Bom and Ligthart (2013), Zagler and Dürnecker (2003) and Creel and Poilon (2008).

provided the population size is optimal (Arnott and Stiglitz, 1979; Arnott, 2004). A major consequence of the Henry George Theorem is that a single 100 % land rent tax is sufficient to finance a local public good. It is based on a static relationship and has chiefly been applied in the context of urban economics. In contrast, our result concerns the dynamics of relevant capital stocks and should be seen as a dynamic and macroeconomic analogue: If land is an important production factor, the land rent is sufficient to finance the socially optimal public capital level *provided that the accumulation of private capital is optimal*. Compared to the static version, the optimal public capital provision requires the assumption that the income share of land exceeds the required public investment, but then does not necessitate a 100 % land rent tax. If instead of land rents, firms' profits arising from public investment are considered, those profits are always sufficient to finance the optimal level of public investment under optimal capital accumulation in the long-run.

To establish our results we extend the neoclassical model of economic growth to include public capital and land as factors of production. We also examine the validity of our results in the endogenous growth variant of the AK-model with public capital (Barro, 1990; Turnovsky, 1997). We proceed as follows: In Section 2, we determine the socially optimal allocation and the corresponding decentralized equilibrium. In Section 3, we prove that financing public investment by a tax on land rent reproduces the social optimum, provided the land rent is sufficiently high. For a Cobb-Douglas production function, a formula for the socially optimal public investment in terms of the land rent is derived, both for the neoclassical growth- and the AK-regime. In Section 4, we consider a variant of the neoclassical growth version of the model: If firms make profits, a direct analogue to the Henry George Theorem can be obtained. In Section 5, we discuss several possible extensions and modifications as well as the empirical relevance of our result: we verify that the land rent may in fact be higher than the socially optimal public investment in many economies.

Our contribution is related to two strands of literature: First, while the question of financing public capital on a national scale has been studied extensively, the role of land as a source of government revenue has been hitherto ignored. Barro (1990); Futagami et al. (1993) and Turnovsky (1996, 1997, 2000) have all studied the financing of public capital in endogenous growth models which inherit the dynamics of the AK-model, clarifying the welfare effects of different options. For instance, Turnovsky (1997) and Chatterjee and Ghosh (2011) reproduce the social optimum with tax-financed public investment; however they employ (politically infeasible) lump-sum taxes to balance the government budget. Turnovsky (1996) does not use a lump-sum tax to reproduce the social optimum, but uses a constant consumption tax that is assumed to be non-distortionary. To this it has been objected that consumption taxation typically distorts the labour-leisure choice. In sum, none of these authors obtains a result on reproducing the social optimum *without recourse to lump-sum(-like) taxes to balance the governments budget*. An exception is Turnovsky (2000), addressing the shortcoming of a non-distortionary consumption tax by introducing an endogenous labour-leisure choice: In this setting the social optimum *can* be reproduced by a distortionary consumption tax for empirically plausible parameter values, provided the tax revenue is not only used to finance the socially optimal public investment, but also to subsidize wages. The present article provides an alternative to this well-explored approach to fiscal policy. We introduce a very different option that also reproduces the socially optimal allocation without lump-sum taxation under a condition on parameters: the taxation of land.

Second, in the context of urban economics, land has been considered as an income source for the financing of public capital: a dynamic Henry George Theorem has been introduced by Fu (2005) and Kawano (2012) for studying transition phenomena of cities. These authors extend the Henry George Theorem by considering the present-value of future public investments and land rents under the usual condition of optimal population size. Our extension of the theorem is different as it considers its translation to optimal capital accumulation instead of optimal population size and thus to a macroeconomic setting. In a macroeconomic context, the relationship between the land price, the land rent and the interest rate has been captured as a (no-)arbitrage condition in growth models by Feldstein (1977), Calvo et al. (1979), Burgstaller (1994) and Foley and Michl (1999). Our study adopts their treatment of the production factor land in a growth model.

2 Model

We first describe the structure of the economy and determine the socially optimal allocation. We then develop a decentralized version of the model.

2.1 Socially optimal allocation

We begin by detailing the economy's production possibilities. We then solve the social planner problem, which serves as a benchmark for evaluating policy instruments.

Output Y depends on a private capital stock K, a public capital stock G, labor L and land $\bar{S}$:

$$Y_t = F(K_t, G_t, L, \bar{S}). \tag{1}$$

The production function has the conventional properties that $F_K, F_G, F_L\ F_S > 0$, but $F_{KK}, F_{GG}, F_{LL}, F_{SS} < 0$, where $F_S := \mathrm{d}F/\mathrm{d}S(K_t, G_t, L, \bar{S})$ etc. In Section 3, we distinguish two cases: the production function has (i) decreasing returns to scale in the accumulable factors private and public capital and (ii) constant returns in these factors. The two cases lead to steady-state convergence and long-run endogenous growth, respectively. Labour supply is constant. Total land $\bar{S}$ is also constant over time, so the social planner seeks the optimal distribution of private capital K and public capital G. Unless noted otherwise, it is additionally assumed that the production function is linearly homogenous in private capital, labour and land. Output is divided between consumption C_t and investment into the two capital stocks, which have depreciation rates δ_k and δ_g respectively.

The social planner chooses consumption C_t and investment into public capital I_{gt} to maximize the welfare of an infinitely-lived representative household with instantaneous utility given by $U(C) = (C^{(1-\eta)} - 1)/(1-\eta)$. The maximization problem of the social planner is thus

$$\max_{C_t, I_{gt}} \int_{t=0}^{\infty} U(C_t) e^{-\rho t} dt$$

$$\text{s.t.} \quad \dot{K}_t = F(K_t, G_t, L, \bar{S}) - C_t - I_{gt} - \delta_k K_t \quad \text{and} \tag{2}$$

$$\dot{G}_t = I_{gt} - \delta_g G_t. \tag{3}$$

The maximization problem is completed by initial conditions ($K(0) = K_0$, $G(0) = G_0$).[2] Solving the maximization problem by standard optimal control theory yields a Keynes-Ramsey rule for K and G :

$$\frac{\dot{C}_t}{C_t} = \frac{1}{\eta}[F_K(K_t, G_t) - \rho - \delta_k] \tag{4}$$

and similarly

$$\frac{\dot{C}}{C} = \frac{1}{\eta}[F_G(K_t, G_t) - \rho - \delta_g],$$

which implies

$$F_K(K_t, G_t) - \delta_k = F_G(K_t, G_t) - \delta_g. \tag{5}$$

2.2 Decentralized equilibrium

In this subsection the decentralized equilibrium corresponding to the social planner solution is introduced. The decentralized version of the economy consists of two stock markets for capital and land and one flow market for the final consumption good. We detail the role of the households, the firms and the government in turn.

2.2.1 Households

The economy is populated by a continuum of homogenous households, whose behavior can be described by a representative household. It seeks to maximize its intertemporal utility $V = \int_0^\infty U(C_t)e^{-\rho t}\mathrm{d}t$, with $U(C) = (C^{1-\eta}-1)/(1-\eta)$, subject to its budget constraint:

$$\dot{K}_t + p_t\dot{\bar{S}} + C_t = r_t K_t + w_t L + (1 - \tau_t) l_t \bar{S}. \tag{6}$$

Here p_t denotes the land sales price, l_t the land rental price, w_t the wage and r_t the interest rate. Initial conditions $K_0 = K(0)$ and $G_0 = G(0)$ and a transversality condition[3] are observed. Income from renting out capital and land as well as labour can be spent on consumption, invested in capital or used to (potentially) increase the amount of land assets. Although total land is fixed and homogenous households do not actually trade land among them,

[2] Land is not a state variable of the optimization: It is assumed that all – available, fertile – land can always be used in production and that its use has no opportunity costs.

[3] The appropriate transversality condition is:

$$\lim_{t\to\infty} [k(t) + p(t)\bar{S}]e^{-\xi(t)} = 0$$

$$\text{with} \quad \xi(t) \equiv \int_0^t r(\tilde{t})\mathrm{d}\tilde{t}.$$

it makes sense to introduce a land market in this way in order to yield a price for the asset, reflecting households' wealth (see also Section 5.2).

Solving the intertemporal control problem, the behaviour of the household is captured by two first-order conditions: A (no-)arbitrage condition

$$r_t = (1-\tau_t)\frac{l_t}{p_t} + \frac{\dot{p}_t}{p_t} \tag{7}$$

linking the evolution of land price, land rental price and the interest rate and the Keynes-Ramsey Equation:

$$\frac{\dot{C}_t}{C} = \frac{1}{\eta}(r_t - \rho). \tag{8}$$

Solving the arbitrage condition (7) for p_t shows that the land price is equal to the net present value of all future land rent income.

2.2.2 Firms

The production sector consists of a representative firm, whose profit maximization

$$\max_{K,S} \quad F(K_t, L, \bar{S}; G_t) - \tilde{r}_t K_t - l_t \bar{S}$$

with $\tilde{r}_t = r_t - \delta_k$ implies the standard first-order conditions

$$\tilde{r}_t = F_K(K_t, L, \bar{S}; G_t) \tag{9}$$

$$w_t = F_L(K_t, \bar{S}; G_t) \tag{10}$$

and

$$l_t = F_S(K_t, \bar{S}; G_t). \tag{11}$$

Using the assumption of constant returns to scale in K, L and S, it follows that $F(K_t, \bar{S}; G_t) = F_K K + F_L L + F_S \bar{S}$ and thus the firm's profit is zero.

2.2.3 Government

The government finances the provision of the public capital stock G with the tax revenue T_t :

$$\dot{G}_t = T_t - \delta_g G_t. \tag{12}$$

The tax revenue stems entirely from the land rent tax: $T_t = \tau_t l_t \bar{S}$. Below we also consider the option of a land *value* tax and discuss why other revenue-raising options are less preferred in this framework.

3 Main results

In the decentralized equilibrium the socially optimal level of welfare may not be reached for two reasons: First, the government may not be able to mobilize funds for providing the desired steady-state level of public capital G. Second, it may be able to mobilize the resources only in a distortionary way, that is, although the steady-state level of G is socially optimal, the distribution of capital and consumption may not be optimal. We prove that if the first point is not an issue because the land rent is sufficiently high to finance the socially optimal level of public capital, generating public revenue by taxing the land rent is socially optimal. This holds for both transition phases and the long-run equilibrium. We then determine conditions for both the case of steady-state convergence and endogenous growth that indicate when the land rent actually is sufficiently high.

3.1 Land rent taxation reproduces the social optimum

In this subsection, the consequences of levying different taxes for financing public capital are examined: the main contribution of this article is that a tax on land rent permits to reproduce the social optimum if the land rent is sufficiently high (Theorem 1). Moreover, a land value tax is equivalent to a land rent tax (Corollary 2). We then briefly compare land rent taxation to other financing options: capital or output taxes are distortionary and hence cannot reproduce the social optimum. Lump-sum taxation is excluded from the spectrum of possibilities as it is politically infeasible. A consumption tax may or may not reproduce the social optimum, but a different framework would be needed to assess this (Turnovsky, 2000).

In the following the superscript ^{M} stands for the value of the respective variable from the decentralized model.

Theorem 1 (Land rent taxation reproduces the social optimum)**.** *A land rent tax allows reproducing the social optimum if the land rent is sufficient to finance the socially optimal public investment at all times.*

We explore in the next sections special cases in which it can be verified whether the assumption of the theorem holds, that is we derive conditions stating when the land rent tax is higher than the socially optimal investment and check available data whether such formulae plausibly hold for most economies.

In practice, it may be more feasible to tax land value rather than land rent. We provide a corollary to show the equivalence of the two options:

Corollary 2 (Land value taxation)**.** *A tax on land value allows to reproduce the social optimum if the land value is sufficiently high to finance the socially optimal public investment at all times.*

Proof of Theorem 1. The idea of proof is to show that the dynamical systems of the socially optimal allocation (Equations 2-5) and the decentralized equilibrium (Equations 6-12) are identical. Then, if the social planner and the decentralized equilibrium have the same initial level of both K_0 and G_0, the latter will reproduce the paths of the former.

Assume that the land rent is sufficient to fully finance the public good: the government can set the tax $\tau_t \in [0, 1)$ such that

$$T_t = \tau_t l_t \bar{S} = I_{gt}. \tag{13}$$

If the previous equation holds, then the path for the public capital stock G_t will be identical in both dynamical systems, as

$$\dot{G}_t = I_{gt} - \delta_g G_t \tag{14}$$

and

$$\dot{G_t^M} = \tau_t l_t \bar{S} - \delta_g G_t^M = I_{gt} - \delta_g G_t^M. \tag{15}$$

Since there is just one representative agent and total land is fixed, $\dot{\bar{S}} = 0$ in Equation (6). Substituting the first-order conditions of the firm (9-11) and employing the assumption that the production function has constant returns to scale in the privately available production factors then implies that Equations (6) and (8) are equivalent to:

$$\dot{K}_t^M = F(K_t^M, G_t, L, \bar{S}) - \delta_k K_t^M - I_g t - C_t^M \tag{16}$$

$$\frac{\dot{C}_t^M}{C_t^M} = \frac{1}{\eta}(F_K(K_t^M, G_t, L, \bar{S}) - \rho - \delta_k). \tag{17}$$

This implies that the respective social planner and decentralized versions of the equations for consumption and capital accumulation are identical, which completes the proof.

□

Proof of Corollary 2. For a property tax τ_t, the tax revenue amounts to $T = \tau p_t \bar{S}$ and the budget constraint of the household (6) becomes

$$\dot{K}_t + p_t \dot{\bar{S}}_t + C_t = r_t K_t + w_t L + l_t S_t - \tau_t p_t \bar{S}_t. \tag{18}$$

Similarly to the previous proof, it can be shown that the aggregate variables are at the socially optimal level.[4] □

If the land rent is lower than public investments, it may still be beneficial that the government obtains more funds for public investment through levying another tax. However, if no other non-distortionary possibilities for taxation exist, the usual trade-off between productivity-enhancing investment in the public capital stock and distortionary taxation exists again for that part of the investment need that exceeds the land rent. For other financing possibilities in the context of this model, the usual results about taxation in a neoclassical growth or AK model apply: Capital and thus output taxation cannot reproduce the social optimum as they are distortionary (Groth, 2011, ch.11; Acemoglu, 2008, ch.8; Barro, 1990).

In the model presented in this article a labour income tax and a constant consumption tax would also be non-distortionary. However, addressing the effects of a labour income or consumption tax properly would require to consider a labour-leisure choice (Turnovsky, 2000; Chatterjee and Turnovsky, 2012; Klenert et al., 2014). If agents have the possibility to adjust their labour supply in response to a consumption or labour income tax, these will also be distortionary. A potential remedy for this is – at least theoretically – to tax consumption *as well as* to subsidize wages (as an application of the Ramsey principle of optimal taxation). This opens up another possibility of reaching the social optimum if some condition on parameters holds (Turnovsky, 2000).

[4] However, the arbitrage condition is modified for this case:

$$r = \frac{l}{p} + \frac{\dot{p}}{p} - \tau. \tag{19}$$

3.2 A macroeconomic Henry George Formula

Having established the main result that land rent taxation can reproduce the socially allocation when a government needs to finance productive public investment, we investigate the premise of this result: The land rent has to be sufficient, namely higher than the socially optimal public investment. For the specific case of a Cobb-Douglas function, we derive a formula for this both for the case of neoclassical growth in the steady-state and the balanced growth path when there is endogenous growth. Such a "Simple Macroeconomic Henry George Formula" is derived for the socially optimal allocation, by the equivalence of Theorem 1 this also gives the socially optimal tax to be levied on the market for land rental.

3.2.1 The case of the neoclassical growth model

We first derive a "Macroeconomic Henry George Formula" for the case of steady-state convergence, which occurs if the production function has decreasing returns to scale in accumulable factors. The case of endogenous growth is similar and will be briefly treated subsequently.

For any initial capital stocks (K_0, G_0) the economy converges to a (non-trivial and saddle-point stable) steady state (K^*, G^*, C^*, I_g^*) as there are decreasing returns to scale in accumulable production factors. In the steady-state, time-derivatives in Equations (2), (3) and (4) are zero, whence the steady-state is characterized by:

$$F_K^* = F_K(K^*, G^*, L, \bar{S}) = \rho + \delta_k \tag{20}$$
$$F_G^* = F_G(K^*, G^*, L, \bar{S}) = \rho + \delta_g \tag{21}$$
$$F(K^*, G^*, L, \bar{S}) = C^* + I_g^* + \delta_k K^* \tag{22}$$
$$I_g^* = \delta_g G^*. \tag{23}$$

To obtain a relation between the optimal public investment I_g^* and the land rent $R = F_S \cdot \bar{S}$ in the steady state, assume that the production function has Cobb-Douglas form:

$$F(K, G, L, \bar{S}) = G^\gamma K^\alpha L^\beta \bar{S}^{1-\alpha-\beta} \tag{24}$$

(with $0 < \alpha, \beta, \gamma < 1$ and $\alpha + \gamma < 1$), which implies

$$F_G = \gamma \frac{Y}{G}. \tag{25}$$

The land rent R is thus given by

$$R = F_S(K_t, G_t, L, \bar{S}) \cdot \bar{S} = (1 - \alpha - \beta)Y. \tag{26}$$

When is the land rent greater than the socially optimal amount of public investment?

Proposition 3 (Simple Macroeconomic Henry George Formula)**.** *Suppose production can be described by the Cobb-Douglas function given by Equation (24). Then, in the steady state of the socially optimal allocation, the investment in public capital is related to the land rent as follows:*

$$I_g^* = \frac{\delta_g}{\rho + \delta_g} \frac{\gamma}{1 - \alpha - \beta} R. \tag{27}$$

The result has the intuitive interpretation that if the national income share of land is greater than that of the public capital stock, the socially optimal investment in public capital is lower than the land rent (assuming that the first factor is approximately equal to one). So Theorem 1 applies to the steady state of the neoclassical growth case if $\frac{\delta_g}{\rho+\delta_g}\frac{\gamma}{1-\alpha-\beta} < 1$ and the socially optimal land rent tax rate to be implemented by the government needs to be $\tau = \frac{\delta_g}{\rho+\delta_g}\frac{\gamma}{1-\alpha-\beta}$.

Proof. We exploit the steady state relationships. By Equations (23) and (25),

$$I_g^* = \delta_g \gamma \frac{Y^*}{F_G^*}. \tag{28}$$

To eliminate F_G^*, Equation (21) is used:

$$I_g^* = \frac{\delta_g}{\delta_g + \rho}\gamma Y^*. \tag{29}$$

Inserting Equation (26) yields the claimed formula. □

3.2.2 The case of endogenous growth

A similar formula can be derived for the balanced growth path in the case of endogenous growth. Assume, contrary to the previous subsection, that the production function has *constant* returns to scale in the accumulable factors K and G. Thus in the specification of the production function as Cobb-Douglas in Equation (24) assume $\alpha + \gamma = 1$. For simplicity, we only consider the case $\delta := \delta_k = \delta_g$. The socially optimal allocation converges to a balanced growth path, on which aggregate variables grow at the same rate:

$$\frac{\dot{C}_t}{C_t} = \frac{\dot{K}_t}{K_t} = \frac{\dot{G}_t}{G_t} = g. \tag{30}$$

To obtain a formula for the common growth rate g^* use that, from Equations (5) and (24),

$$G_t = \frac{\gamma}{1-\gamma}K_t \tag{31}$$

so that

$$F_K(G_t, K_t, L, \bar{S}) = F_G(G_t, K_t, L, \bar{S}) = \frac{\gamma^\gamma}{(1-\gamma)^{\gamma-1}} L^\beta \bar{S}^{1-\alpha-\beta}. \tag{32}$$

Inserting this in Equation (4) yields

$$g^* = \frac{1}{\eta}\left(\frac{\gamma^\gamma}{(1-\gamma)^{\gamma-1}} L^\beta \bar{S}^{1-\alpha-\beta} - \rho - \delta\right). \tag{33}$$

The analogue of Proposition 3 for the balanced path of the case of endogenous growth is as follows:

Proposition 4 (Macroeconomic Henry George Formula for the endogenous growth case)**.** *Suppose production can be described by the Cobb-Douglas function given by Equation (24) with $\alpha+\gamma = 1$. Then, on the balanced growth path* *of the socially optimal allocation, the investment in public capital is related to the land rent as follows:*

$$I_{gt} = \frac{(\delta + g)}{F_G} \frac{\gamma}{1 - \alpha - \beta} R_t \tag{34}$$

where F_G is constant with the value given in Equation (32).

As in the case of neoclassical growth, the socially optimal allocation can be reached if the two fractions are smaller than 1. In particular, this is true if the national income share of land is greater than that of the public capital stock and

$$\frac{(\delta + g)}{F_G} < 1. \tag{35}$$

By inserting Equation (33), it can be verified that this inequality is true for all $\eta \geq 1 - \frac{\rho}{F_G - \delta}$, so in particular for all $\eta \geq 1$.

Proof. The proof is similar to that of the previous proposition. From Equation (3), it follows that for the case of endogenous growth, $I_{gt} = (g^* + \delta)G_t$. The formula is then obtained by combining the equations for the factor shares for G_t and the land rent R_t and inserting Equation (32). □

4 Dynamising the Henry George Theorem: Taxing firms' profits instead of the land rent

In this section we elaborate on the kinship of the main result of the present article and the Henry George Theorem of local public finance. The theorem states that "with identical individuals, in a city of optimal population size, differential land rents (the aggregate over the city of urban land rent less the opportunity cost of land in non-urban use) equal expenditure on pure local public goods" (Arnott, 2004, p.1057). This means that confiscating the entire land rent – a Georgist "single tax" – is sufficient to finance any level of the public good, whether socially optimal or not. The theorem is a very general relationship that has been discovered in different forms independently by several scholars. We are here concerned with its simplest version, proved by Stiglitz (1977), that considers profits instead of land rents: it is socially optimal to use the total profit in a static urban economy to finance a local public good provided the population size is optimal (see also: Atkinson and Stiglitz, 1980, p.522-525; Arnott and Stiglitz, 1979).

So far the analogy to our result has been that a single (land) rent tax is necessary and (sometimes) sufficient to finance the optimal public investment, under the modification that the macroeconomic setting requires optimal capital accumulation instead of optimal population size. In this section we demonstrate that the analogy can be even closer: If not land, but firms' profits are considered, the original Henry George Theorem uses that the benefit of the public good is fully captured in firms' profits. This partially carries over to a growth model in which the public and the private capital stocks are optimal – although the benefit of the public capital stock is then not fully captured by profits, these are sufficient to finance the optimal investment in the steady state. Because of the dynamic context, the pure rate of time preference causes the profit to be higher than the required optimal public investment in the steady state (as Proposition 5 will show).

To demonstrate the analogy, we consider a slightly modified model. Assume for this section that the production function is linearly homogenous in all four arguments: public capital, private capital, labor and land. Thus we are here only concerned with the case of convergence to a steady state, not with endogenous growth. The provision of public capital by the government results in a positive externality that allows firms to make profit Π_t under this functional form:[5]

$$\Pi_t = F(K_t, \bar{S}; G_t) - \tilde{r}_t K_t - w_t L - l_t \bar{S} = F_G(K_t, \bar{S}; G_t) G_t. \tag{36}$$

These profits can be taxed to finance public expenditure. While this policy is socially optimal if profits are higher than the socially optimal public investment both in the steady state and the transitional dynamics of the model, one can show more for the steady state:

Proposition 5 (Macroeconomic Analogue of Stiglitz' Henry George Theorem)**.** *The social optimum can be implemented by taxing firms' profits, if these are higher than the socially optimal investment. In the steady state, taxing profits is always sufficient: The optimal tax rate on profits is* $\tau = \frac{\delta_g}{\delta_g + \rho}$.

In Stiglitz' result $\tau = 1$. In our dynamic setting a non-zero rate of pure time preference ρ causes $\tau < 1$. This reflects that in neoclassical growth models the optimal capital stock does not maximize instantaneous consumption. If the steady-state marginal productivity of public capital (21) was independent of ρ, then the analogy would be complete.[6]

Proof. With a tax on profits, tax revenue is $T = \tau \Pi_t$ and the budget constraint of the household (6) becomes

$$\dot{K}_t + p_t \dot{\bar{S}}_t + C_t = r_t K_t + l_t \bar{S}_t + (1 - \tau) \Pi_t. \tag{37}$$

Assuming that the tax revenue from taxing profits is sufficient to finance the socially optimal level of G_t,

$$T = \tau_t \Pi_t = I_{gt}. \tag{38}$$

It can then be verified with arguments similar to those in the proof of Theorem 1 that all aggregate variables of the decentralized equilibrium have their socially optimal steady state values by comparing the corresponding systems of differential equations.

In particular, for the steady state $F_G(K, G; \bar{S}) = \delta_g + \rho$ by Equation (21). Thus

$$\Pi_t = F_G(K^*, G^*, L, \bar{S}) G^* = (\delta_g + \rho) G^*. \tag{39}$$

Combining Equations (23), (38) and (39) yields

$$\tau(\delta_g + \rho) G^* = \delta_g G^*.$$

[5]This is a credible assumption for some public investments, such as technology parks. However the focus of this section is on highlighting the close kinship of our results with the Henry George Theorem, not on exploring which assumptions concerning the impact of public investments on the economy are most realistic.

[6]Stiglitz' Henry George Theorem is valid even if the local public good is not of optimal size (that is, if the corresponding Samuelson condition is violated). In the model under discussion, it is not the case that for arbitrary production functions and any level of G, a profit tax would fully finance it in a modified steady-state because the stock of private capital may be too small so that $F_G(K, G; \bar{S}) > \delta_g$, thus violating Equation (40).

Hence

$$\tau = \frac{\delta_g}{\delta_g + \rho} < 1. \tag{40}$$

□

5 Discussion

We discuss modifications, limitations and the empirical relevance of our results. First, as many alternative formulations of government investment are considered in the literature, we outline why our results do not essentially change when some other formulations are chosen. Second, we briefly discuss that a crucial limitation of a neoclassical growth model with several stock markets is that due to household homogeneity, there is no trade on these markets. Third, we delineate the role of labour- and land-augmenting technological progress when growth is not endogenous. Finally, we compare data on public investment needs and non-producible factor income and find that the latter plausibly exceeds the former.

5.1 Alternative models of government spending

Alternative formulations of government expenditure besides investing into a productive public capital stock have been extensively considered in public economics, for instance productive government flow expenditure or investment into utility-enhancing public or private goods, which each may or may not be congestible (Barro and Sala-I-Martin, 1992; Turnovsky, 1997; Irmen and Kuehnel, 2009). We limit our discussion to two close variants of the above model that seem most interesting in the specific context of land rent taxation financing public investment: first, the public capital stock may enter the utility function instead of the production function; second, the difference between investment in a public capital stock and productive government flow expenditure is examined.

Concerning the first variant, assume that government expenditure provides private goods entering the individuals' utility function. Then, no simple proportionality between optimal government expenditure and land rent as in Proposition 3 or 4 can be derived even with the simplest functional forms, since there is no direct link between the public good and land via the production function anymore. However, in the decentralized model, the households' and firms' optimization problem remains virtually unchanged since G only appears in the utility function and disappears from the production function, but does not become a control variable. Thus, it can be shown that Theorem 1 still holds.[7]

For the second case, it can be shown that the findings of this study are all valid regardless of whether the productive public good is formulated as a stock (to which the government expenditure continuously adds) or flow (equal to government expenditure). However, the stock formulation seems preferable as we are chiefly concerned with *productivity-enhancing* public expenditure such as infrastructure provision. Considering a public capital stock is also more convenient for further empirical analyses because of symmetry: for instance, depreciation parameters for public and private capital may be different.

[7]Proposition 5 is pointless if G generates no profits.

Moreover, it is plausible that in developed economies land rents are sufficient to finance what is generally defined as public investment up to the socially optimal level (see Section 5.4) – but it is doubtful that they can additionally cover the much broader category of government flow spending.

5.2 Stock markets and household heterogeneity

Analysing the dynamics of stock markets for fixed factors of production, such as land, with the neoclassical growth model has severe limitations. (This may have been first noted by Feldstein (1977); see Burgstaller (1994) for a comprehensive overview.) Although a price for land – the present value of all future land rent income – is formed, land will not be traded: the continuum of homogenous agents of this model own an equal share of land, but have neither an incentive nor a trade partner to buy or sell any of it. A neoclassical growth model with land, as introduced above, thus exhibits "partial equilibrium" properties concerning the factor land: for instance, land rent taxation is non-distortionary and the tax falls entirely on the owners of land, although this is not the case in more general circumstances (Feldstein, 1977). There is in particular no rebalancing of households' savings portfolios: households have no incentive to invest more in capital when a land rent tax is introduced. Edenhofer et al. (2013) explore, by means of a continuous overlapping generations model, the social optimality of land rent taxation when heterogeneous households acquire more land as they get older. In such a model, which exhibits suboptimal capital accumulation, when land is taxed, households invest into other assets, notably private capital. Thus land rent taxation is distortionary, but beneficial. The results of the present study can be reproduced in such a framework with some minor modifications due to the demographic structure.

More generally, as long as the unregulated equilibrium exhibits underaccumulation in private capital the conclusions of the present study hold in frameworks in which such a "macroeconomic portfolio effect" exists. Only if overaccumulation prevails in an economy, this effect may create again a tradeoff between the welfare loss caused by the land tax and the benefits from public investment.

5.3 Labour- and land-augmenting technological progress

Our results are valid for both the case of a steady state and endogenous growth. For the steady state, they have been cast in a simple neoclassical growth model without technological progress in order to isolate the specific fiscal policy this article is concerned with. Here we explore the impact of adding (exogenous) technological progress to our model for the case of steady state convergence.

The main results of this paper hold as long as the economy is on a balanced growth path. Such a path can exist if and only if productivity growth in land equals productivity growth in labor (including population growth). If the economy is not on the balanced growth path, factor shares may be different, depending on the production function. The feasibility of the social optimum depends on the factor shares according to Proposition 3: outside the balanced growth path an increasing factor share accruing to land makes reaching the social optimum more likely. For example, for the case of a CES production function with substitution elasticity σ, the factor share accruing from land

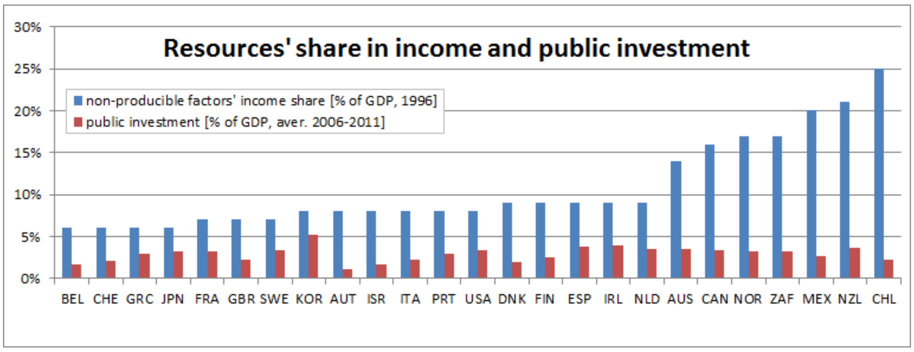

Figure 1: Income shares of non-producible factors (Caselli and Feyrer, 2007) and public investment (OECD, 2013), ISO3 country codes.

grows faster than the factor share accruing from labour if and only if either $\sigma > 1$ and productivity growth in land is greater than that in labour or $\sigma < 1$ and labour productivity growth is greater than that in land.

Henry George claimed that the factor share accruing to land grows faster than that accruing to labour.[8] While this is not possible in the steady state or under a Cobb-Douglas production function in general, outside a balanced growth path Henry George's claim about the role of the land rent may be true. In particular the condition that $\sigma < 1$ and productivity growth in labour was greater than in land seems to have some plausibility for economic development in the 19^{th} century. It is less plausible for current developed economies, for which it may be supposed that $\sigma > 1$, but still that labour productivity grows faster than land productivity.

5.4 Empirical relevance

In practice, fixed factor rents often exceed funding needs for public capital stocks considered here, and are thus highly relevant for financing government expenditure in general. Figure 1 illustrates this by reproducing actual public investment shares and non-producible factor income shares for 25 (mostly OECD) countries. We summarize some empirical findings, first on public investment needs and then on rents.

Regarding the investment needs of industrialized countries, maintaining the infrastructure and adapting it to the challenges of climate change (Davis et al., 2010) translates into significant shares of government spending: The OECD reports public investment shares averaged over 2006 to 2011 for 34 countries that range between 1.1% (Austria) and 5.22% (South Korea) of GDP. The investment needs in poorer countries are highlighted by data from the World Bank (2009) showing that access to basic utility services such as water, sanitation and electricity in low-income countries was 65%, 36% and 23%, respectively, and still only 92%, 72% and 97% for upper-middle income countries. Estache and Fay (2007) estimated overall infrastructure investment and maintenance expenditure needs between 2005 and 2015 for low, lower-middle

[8] "In identifying rent as the receiver of the increased production which material progress gives, but which labor fails to obtain; [...] we have reached a conclusion that has most important practical bearings." (Bk. 4, ch.1 §1) "[...] and wages are forced down while productive power grows, because land, which is the source of all wealth and the field of all labor, is monopolized." (Bk. 6, ch.2, §2) (George, 1920)

and upper-middle income countries to be 7.5, 6.3 and 3.1 percent of GDP, respectively, just to meet increasing demand due to projected growth. While these actual or projected spending figures may not be *optimal* by some welfare criteria, they show the order of magnitude and the larger public investment needs in poorer countries lacking the most basic infrastructure.

Regarding the fixed factor rents, Caselli and Feyrer (2007) estimate income shares of non-producible factors such as land and natural resources for the year 1996 for 51 countries and find values ranging from 6% in Belgium to 47% in Ecuador, with a median of 14%. Also, non-producible factors tend to be more important for poorer countries. We do not have data that permit to isolate the income share of land across different countries. However, Caselli and Feyrer (2007) use "Proportions of different types of wealth in total wealth" (p.547) to show that land wealth is relatively more important in most cases: Although subsoil resources matter for some countries and the mean wealth share is 10.5% (with a standard deviation of 16.4), the mean share of land-related wealth is at 34.8%. The median wealth share of subsoil resources is only 1.5%; compared to a 23.5% median share of land-related wealth. Moreover, the data set of that study excludes countries in which fossil fuel extraction is a main income source, such as countries on the Arabic Peninsula.

These figures may change slowly over time (note that the diagram plots data from 2006-2011 and 1996). However, the significant gap between fixed-factor income shares and public investment persists across structurally very different economies: Even the lowest fixed-factor income, 6% for Belgium is higher than the highest public investments, 5.22% for Korea. Overall, this indicates that fixed factor rents can be assumed to be of a magnitude that is at least comparable to that of infrastructure spending needs.

6 Conclusion

This study set out to determine how public investment can be financed by a tax on the rent of fixed factors such as land. It was proved that if the land rent is sufficiently high, the social optimum can be implemented by using the tax revenue for investment into a productive public capital stock. This result is a macroeconomic analogue of the Henry George Theorem from urban public finance: the socially optimal public investment can be financed by taxing rents, whereas the usual condition of optimal population size in a static model is replaced by optimal capital accumulation in the dynamic context. The main theoretical result of this study is robust under a variety of different assumptions: (i) neoclassical growth (both short- and long-run) or an endogenous growth regime, (ii) profit-making firms instead of land rents earned by households, (iii) utility-enhancing public capital or government flow spending, (iv) underaccumulation in public capital due to for instance overlapping generations, (v) technological progress in land and labour compatible with balanced growth. It was verified that for OECD countries, land rents are significantly higher than current public investment, so that our result suggests an empirically plausible mechanism for ensuring sufficient public investment.

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Chapter 4

Hypergeorgism: When rent taxation is socially optimal[1]

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Hypergeorgism: when rent taxation is socially optimal*

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20 July 2015

Abstract

Imperfect altruism between generations may lead to insufficient capital accumulation. We study the welfare consequences of taxing the rent on a fixed production factor, such as land, in combination with age-dependent redistributions as a remedy. Taxing rent enhances welfare by increasing capital investment. This holds for any tax rate and recycling of the tax revenues except for combinations of high taxes and strongly redistributive recycling. We prove that specific forms of recycling the land rent tax - a transfer directed at fundless newborns or a capital subsidy - allow reproducing the social optimum under parameter restrictions valid for most economies.

JEL classification: E22, E62, H21, H22, H23, Q24

Keywords: land rent tax, overlapping generations, revenue recycling, social optimum

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1 Introduction

Rent taxation may become a more important source of revenue in the future due to potentially low growth rates and increased inequality in wealth in many developed economies (Piketty and Zucman, 2014; Demailly et al., 2013), concerns about international tax competition (Wilson, 1986; Zodrow and Mieszkowski, 1986; Zodrow, 2010), and growing demand for natural resources (IEA, 2013). It may alleviate spending constraints for reducing high public debt (Bach et al., 2014) and public investment (Mattauch et al., 2013). In particular, fixed factors of production, such as land, matter considerably for the size of economic output (see Caselli and Feyrer (2007) for an analysis of the role of land and natural resources). Land scarcity is ubiquitous in explaining economic outcomes, from the real estate (Knoll et al., 2014; Stiglitz, 2015) to the agricultural sector (Smith et al., 2014).

On a theoretical level, it is well-known that the taxation of rents from fixed factors such as land is non-neutral and may lead to higher output if there is capital underaccumulation (Feldstein, 1977; Fane, 1984; Petrucci, 2006). One reason for underaccumulation is imperfect altruism between generations, which is standardly assumed in models. However, imperfect intergenerational altruism also leads to an unequal, age-dependent distribution of assets across households. Indeed, great disparities in rent income are observed in most developed economies, but the role of distributional spending of rent tax proceeds has so far been ignored in the literature.

The present article fills this gap by providing a distributional argument for the desirability of taxation of rents that goes beyond the traditional case for rent taxation based on the inelastic supply of the respective production factor. We show that, given capital underaccumulation, reaching the socially optimal allocation[1] *requires both* rent taxation and spending the revenue by redistributive transfers. A uniform transfer increases capital accumulation and welfare, but can never be socially optimal. Giving instead a disproportionately high share of the tax revenue to the poor, younger generations does allow to reproduce the social optimum by making the productivity loss vanish (but can lead to overaccumulation if the land rent tax is very high). The mechanism underlying these results is composed of two effects: first, the tax shifts investment towards capital, alleviating its undersupply and leading to higher output and aggregate consumption. Second, redistributing the tax revenue to those generations in the economy who benefit most from transfers additionally increases welfare. The results are at odds with the common view that redistribution creates losses in total output.

A central tenet of Georgism (Heavey, 2003), going back to Henry George's proposal to abolish all taxes in favour of a single tax on land (George, 1920), is that taxing rents from fixed production factors is a non-distortionary way of raising fiscal income. From a historical perspective, our result is closer to Henry George's original thinking than to Georgism or to the neoclassical Henry George Theorems (Stiglitz, 1977): George was chiefly concerned with poverty eradication (George, 1920). We show that taxing rent income and

[1] We follow Calvo and Obstfeld (1988) in assuming that in a setting with imperfect altruism between generations, social welfare consists in the preference satisfaction of all heterogeneous individuals weighted by a utilitarian social welfare function. Implications of this are discussed in detail in Section 2.2.

giving it to the poor young generations actually enhances output and welfare by reducing inequality. We hence label this result *Hypergeorgism*.

Our work builds on studies of the incidence of a tax on pure rent (Feldstein, 1977; Calvo et al., 1979; Fane, 1984; Chamley and Wright, 1987). Feldstein (1977) argued that rent taxation *is distortionary* if it has income effects (owners of land also provide other factors such as labor), if there is a choice to invest in land or capital, or if these assets have different risks. But the *welfare effects* of rent taxation have not been systematically analysed in this context: while we confirm that taxing fixed factors can increase aggregate capital and consumption, our contribution is that a tax on such rents, combined with age-dependent redistributive transfers, can even be socially optimal.

In the continuous overlapping generations (OLG) model of Blanchard (1985), Buiter (1989) introduced land as a fixed production factor and proved that Ricardian equivalence holds despite the arrival of newborn generations. Engel and Kletzer (1990) studied the impact of age-dependent redistributions in an open economy model with tariffs, but did not provide a normative analysis. Calvo and Obstfeld (1988) determined the socially optimal allocation in a continuous OLG model.

Even closer to the present contribution, Petrucci (2006) studied the incidence of a land rent tax under endogenous labour-leisure choice in a model similar to ours. Koethenbuerger and Poutvaara (2009) analysed the impact on transition generations of shifting taxation from labour to land rent. Both papers state that a land rent tax leads to higher capital and consumption for Feldstein's original case, but then model a small open economy with a fixed interest rate, without considering welfare effects or possibilities to redistribute land tax revenues. Hashimoto and Sakuragawa (1998) found that in a discrete OLG model with endogenous technological change, redirecting land tax revenue to the young increases the growth rate, but a Pareto improvement cannot be reached in their model, and social optimality was not analysed.

We proceed as follows: Section 2 introduces an OLG model to study the relationship between household heterogeneity in age and the trade-off between investing in land or producible capital. Households are differentiated only by age: there are no bequests, so individuals are born fundless and accumulate wealth (with a constant birth- and death rate). This implies, first, that the inter- and intragenerational distribution are symmetric in the model. Second, capital accumulation is suboptimally low compared to the case of perfect altruism between generations: the old and wealthy consume more than the young. So the turnover of generations implies that aggregate consumption grows more slowly than individual consumption, negatively impacting capital accumulation in equilibrium. This standard feature of the continuous OLG model makes the setting second-best, and aggregate consumption growth depends on the redistribution of tax revenues. As the benchmark for tax policy evaluation, we take social welfare to be the preference satisfaction of all heterogeneous individuals (Calvo and Obstfeld, 1988).

Section 3 evaluates different redistribution schemes for the land rent tax revenue: first, a fiscally realistic uniform (age- and wealth-independent) redistribution cannot implement the social optimum, but is still preferable to compensating land owners for reduced rents (Section 3.1). Second, redistributing the revenue exclusively to the newborn generation can establish the social optimum if the originally missing capital share of the newborns is smaller than the land rent, which is the main result. We find empirically that this condition plausibly holds for a large and diverse set of countries (Section 3.2). Third, we show that *any* feasible age-dependent redistribution that is stable in the long run and not too egalitarian stimulates capital accumulation, thus increasing total consumption and welfare – but overaccumulation is possible if the tax rate is high (Section 3.3). Fourth, the alternative use of the revenue as a capital subsidy may also establish the dynamically socially optimal allocation under a condition which is empirically weaker than that for transfers, but cannot achieve the social optimum by redistribution (Section 3.4).

Section 4 outlines extensions of the model. Section 5 concludes.

2 Model

We extend an OLG model (Yaari, 1965; Blanchard, 1985) to include a fixed factor of production, which we label land (Buiter, 1989). The model describes an economy with one final good of unit price and three other flow markets for labour, capital and land rental as production inputs as well as two stock markets for capital and land ownership.[2] We first detail the decentralised model (the optimization of households and firms for given government policies), while the second subsection provides the social planner solution, which will serve as a benchmark for evaluating policies. The third subsection then discusses essential properties of the steady-states of both the decentralised and the social planner version of the model. This sets the stage for the inspection of various policies in Section 3.

2.1 Decentralised model

We first describe individual behaviour and the instruments of the government and then proceed to the aggregation of demand-side quantities before specifying the model's simple production structure.

Assume a constant birth rate ϕ, equal to each individual's instantaneous probability of death and thus to the death rate in a large population. Therefore population size is constant – henceforth normalised to 1 – and individuals' lifetimes are exponentially distributed. The size at time t of a cohort born at time ν is thus $\phi e^{-\phi(t-\nu)}$. For the total population, the aggregate X of any individual variable x is

$$X(t) = \int_{-\infty}^{t} x(\nu, t)\phi e^{-\phi(t-\nu)}\mathrm{d}\nu. \tag{1}$$

For an individual born at time ν with a rate of pure time preference ρ, consumption path $c(\nu, \tau)$ and instantaneous utility $\ln c(\nu, t)$, expected lifetime utility $u(\nu, t)$ at time $t \geq \nu$ is given by

$$u(\nu, t) = \int_{t}^{\infty} \ln c(\nu, \tau)e^{-(\phi+\rho)(\tau-t)}\mathrm{d}\tau. \tag{2}$$

Individuals own capital k and a share s of total land S, which can be bought and sold at a price p. Each individual supplies one unit of labour and

[2] Our model is hence a closed-economy version of the one employed by Petrucci (2006), but with inelastic labour supply and age-dependent transfer schemes.

receives an age-independent wage w, rents out capital and land to firms at market rates r and l, respectively, with a tax T on land rents, and obtains potentially age-dependent transfers z from the government. Thus, individuals have the following budget identity for all $\tau \in [t, \infty)$:

$$\dot{k}(\nu,\tau) + p(\tau)\dot{s}(\nu,\tau) = w(\tau) + [r(\tau)+\phi]k(\nu,\tau) + \\ + [(1-T)l(\tau) + p(\tau)\phi]s(\nu,\tau) + z(\nu,\tau) - c(\nu,\tau) \quad (3)$$

where $\dot{k}(\nu,\tau) = \mathrm{d}k(\nu,\tau)/\mathrm{d}\tau$, etc.[3] There are no bequest motives, so newborns' wealth is $k(\nu,\nu) = s(\nu,\nu) = 0$. Instead, to close the model, a competitive, no-cost life insurance sector pays an annuity ϕk in return for obtaining the individual's financial assets in case of death (thus, all financial wealth of those who died is redistributed to the living in proportion to their capital). Similarly, the insurance sector distributes land to individuals in proportion to their land ownership (ϕs), in return for receiving their land in case of death. Thus, while total land is constant and all land is owned by somebody,

$$\int_{-\infty}^{t} s(\nu,t)\phi e^{-\phi(t-\nu)}\mathrm{d}\nu = S(t) = S, \quad (4)$$

the *changes* in land ownership of all *living* generations do not sum to zero:

$$\int_{-\infty}^{t} \dot{s}(\nu,t)\phi e^{-\phi(t-\nu)}\mathrm{d}\nu = \phi S. \quad (5)$$

The individual also respects a solvency condition which prevents her from playing a Ponzi game against the life-insurance companies (see Heijdra (2009), Ch. 16.2-3):[4]

$$\lim_{\tau\to\infty}[k(\nu,\tau) + p(\tau)s(\nu,\tau)]e^{-R(t,\tau)} = 0 \quad (6)$$

$$\text{with} \quad R(t,\tau) \equiv \int_{t}^{\tau}(r(\tilde{t}) + \phi)\mathrm{d}\tilde{t}.$$

The government collects a tax T on land rents and instantaneously redistributes the entire revenues by choosing a redistribution scheme that consists of transfers z to individuals, who take T and z as given. Specific redistribution schemes are the subject of our main analysis in Section 3. However, we generally require any redistribution scheme $z(\nu,t)$ to be *permissible*, which we define as being non-negative for all ν and t and satisfying the government budget equation at all times:

$$\int_{-\infty}^{t} z(\nu,t)\phi e^{-\phi(t-\nu)}\mathrm{d}\nu = Tl(t)S \quad \text{for all } t. \quad (7)$$

This implies that the government budget is always balanced (see Section 4 for an extension with government debt).

[3]Frequently, a different notation in terms of non-human assets $a \equiv k + ps$ is used in the literature: we deviate from it to make more transparent the relation of the no-arbitrage condition (9) below to the individual optimisation problem and the role of the land price, which are crucial for our results. To obtain the more conventional form of the budget identity, use (9) in (3) to obtain $\dot{a} = (r+\phi)a + w + z - c$.

[4]Although the individual can take up debt ($k < 0$), the limit of the present value of her total financial and land wealth at infinity has to be zero. Note that there can be no debt in terms of land, so land appears as collateral for capital debt in the transversality condition.

Individuals maximise utility (2) by choosing paths for c, k and s, subject to budget identity (3) and transversality condition (6). From the first-order conditions of this optimisation problem, one obtains the usual Keynes-Ramsey rule for the dynamics of individual consumption

$$\frac{\dot{c}(\nu,t)}{c(\nu,t)} = r(t) - \rho \tag{8}$$

and a no-arbitrage condition (Burgstaller, 1994; Foley and Michl, 1999) between land and capital (see Appendix A.1):

$$\frac{(1-T)l(t)}{p(t)} + \frac{\dot{p}(t)}{p(t)} = r(t). \tag{9}$$

The arbitrage condition is crucial for the main result below since it links the stock and flow markets for land by relating the unit value of land as an investment p to its after-tax rent, $(1-T)l$.

Using the instantaneous budget identity (3), transversality condition (6) and arbitrage condition (9), the lifetime budget constraint can be derived:[5]

$$\int_t^\infty c(\nu,\tau)e^{-R(t,\tau)}\mathrm{d}\tau = k(\nu,t) + p(t)s(\nu,t) + \bar{w}(t) + \bar{z}(\nu,t) \tag{10}$$

$$\text{where} \quad \bar{w}(t) \equiv \int_t^\infty w(\tau)e^{-R(t,\tau)}\mathrm{d}\tau$$

$$\text{and} \quad \bar{z}(\nu,t) \equiv \int_t^\infty z(\nu,\tau)e^{-R(t,\tau)}\mathrm{d}\tau.$$

This means that the present value of the consumption plan at time t of individuals born at ν equals their total wealth consisting of capital, land and the present values of lifetime labour income $\bar{w}$ and transfers $\bar{z}$.

Solving the Keynes-Ramsey rule (8) for c and using the result in Equation (10) shows that all individuals consume the same fixed fraction of their total wealth consisting of capital, land and the present value of lifetime labour income and transfers (see Appendix A.2):

$$c(\nu,t) = (\rho+\phi)[k(\nu,t) + p(t)s(\nu,t) + \bar{w}(t) + \bar{z}(\nu,t)]. \tag{11}$$

We proceed with the aggregate demand-side quantities (see Equation 1): Using Equation (4) for total land, aggregation of Equation (11) yields:

$$C(t) = (\rho+\phi)[K(t) + p(t)S + \bar{W}(t) + \bar{Z}(t)], \tag{12}$$

$$\text{with} \quad \bar{W}(t) \equiv \int_{-\infty}^t \bar{w}(t)\phi e^{-\phi(t-\nu)}\mathrm{d}\nu = \bar{w}(t)$$

$$\text{and} \quad \bar{Z}(t) \equiv \int_{-\infty}^t \bar{z}(\nu,t)\phi e^{-\phi(t-\nu)}\mathrm{d}\nu,$$

where C and K denote total consumption and capital, and $\bar{W}$ and $\bar{Z}$ the total present values of labour income and transfers from the government to

[5] See Appendix A.2. Conventionally, human wealth is defined to include wage and government transfers, $h(\nu,t) \equiv \bar{w}(t) + \bar{z}(\nu,t)$. We separate these terms here since our analysis focusses on z.

individuals. Therefore, aggregate consumption is the same constant fraction of total wealth as for each individual.

For the dynamics of the total capital stock, apply the definition of K, Leibniz' rule and the individual budget constraint (3) to get (Appendix A.3):

$$\dot{K}(t) = r(t)K(t) + l(t)S + w(t) - C(t). \tag{13}$$

Taxes and transfers do not appear in this expression, as the aggregate tax payments and transfers from the individuals' budget constraint are equated via the government's budget constraint.

Finally, derivation of the dynamics of aggregate consumption uses the definition of C, Leibniz' rule and Equations (8) and (11):[6]

$$\frac{\dot{C}(t)}{C(t)} = r(t) - \rho - \phi(\rho + \phi)\frac{K(t) + p(t)S + \bar{Z}(t) - \bar{z}(t,t)}{C(t)}. \tag{14}$$

The last term reflects the 'generation replacement effect': a fraction ϕ of the total population, owning aggregate capital K and land wealth pS as well as expecting lifetime transfers of $\bar{Z}$, dies and is replaced by newborns, whose only 'non-human wealth' are expected lifetime transfers $\bar{z}(t,t)$. Since individuals consume a fixed fraction $(\rho + \phi)$ of their wealth, this continuous turnover affects aggregate consumption growth. Growth is diminished by the newborns' missing capital and land but also impacted (positively or negatively) by future transfer payments, depending on how these redistribute wealth between generations. We will come back to this mechanism in Section 3.

On the supply side, assume a single final good is produced from inputs K, S and aggregate labour L ($L = 1$ as individuals constantly supply one unit of labour). The production function features constant returns to scale, diminishing marginal productivity in individual inputs and satisfies the Inada conditions in all arguments. The representative firm's problem is

$$\max_{K(t),L(t),S(t)} F(K(t), L(t), S(t)) - [r(t) + \delta]K(t) - w(t)L(t) - l(t)S(t) \tag{15}$$

yielding the standard first-order conditions

$$r(t) + \delta = F_K(K(t), L(t), S(t)), \tag{16}$$
$$w(t) = F_L(K(t), L(t), S(t)), \tag{17}$$
$$l(t) = F_S(K(t), L(t), S(t)). \tag{18}$$

where δ is the depreciation rate of private capital.

---

[6] See Appendix A.3. Alternatively, directly differentiate Equation (12) and use that, by Leibniz' rule, $d\bar{W}/dt = (r + \phi)\bar{W} - w$ and $d\bar{Z}/dt = (r + \phi)\bar{Z} - Z - \phi(\bar{Z} - \bar{z}^N)$, where $\bar{z}^N = \bar{z}(t,t)$. This implies that the general result for the dynamics of human wealth in conventional notation is $\dot{H} = (r + \phi)H - w - Z - \phi(\bar{Z} - \bar{z}^N)$. The last term disappears *if and only if* transfers are age-independent ('lump sum', see Section 3.1), so $\bar{Z} = \bar{z}^N$. Thus, the expression $\dot{H} = (r+\phi)H - w - Z$, often considered a standard result in the literature, is in fact a special case (see also the proof of Proposition 1 for an intuition). In particular, in work related to this paper and unnoticed by the respective authors, Equation (4c) in Petrucci (2006) and Equation (11) in Marini and van der Ploeg (1988) require the assumption of uniform transfers.

2.2 Social planner

The social planner solution is chosen as a normative benchmark to evaluate the tax policies examined below. We assume that social welfare consists of the preference satisfaction of all heterogeneous individuals weighted by a utilitarian social welfare function. For simplicity, we assume that the socially optimal rate of pure time preference equals the private rate of pure time preference.[7]

Social welfare V at time t is defined as follows:

$$\begin{aligned} V(t) = & \int_{-\infty}^{t} \left\{ \int_{t}^{\infty} \ln c(\nu,\tau) e^{-\rho\tau} \phi e^{-\phi(\tau-\nu)} \mathrm{d}\tau \right\} \mathrm{d}\nu \\ & + \int_{t}^{\infty} \left\{ \int_{\nu}^{\infty} \ln c(\nu,\tau) e^{-\rho\tau} \phi e^{-\phi(\tau-\nu)} \mathrm{d}\tau \right\} \mathrm{d}\nu. \end{aligned}$$

This is equivalent to the social welfare function considered by Calvo and Obstfeld (1988) when the private and social rates of pure time preference are equal.

We now use the two-step procedure of Calvo and Obstfeld (1988) for evaluating social welfare in economies with overlapping generations to determine the socially optimal level of aggregate capital and consumption: (i) the optimal static distribution at any point in time is chosen, (ii) the intertemporally optimal solution is chosen independently.

(i) Define $U(C(t))$ as the optimal solution to the *static maximisation problem*:

$$\begin{aligned} U(C(t)) = & \max_{\{c(\nu,t)\}_{\nu=-\infty}^{t}} \int_{-\infty}^{t} \ln c(\nu,t) \phi e^{-\phi(t-\nu)} \mathrm{d}\nu \\ \text{subject to:} \quad C(t) = & \int_{-\infty}^{t} c(\nu,t) \phi e^{-\phi(t-\nu)} \mathrm{d}\nu. \end{aligned}$$

Solving the static optimal control problem with an integral constraint (see Appendix A.4), it can be found that

$$U(C(t)) = \ln(C(t)).$$

This result can be obtained because all agents have the same utility function. Distributing the fixed amount $C(t)$ among all living agents at time t thus makes giving an equal share to each of them optimal. As population is normalised to one, the share given to the individual equals the total amount of consumption, $C(t)$, so that total utility is $\ln(C(t))$. (For a proof see Appendix A.4.)

[7] It is sometimes considered normatively more justified to assume that the social discount rate is lower than the private rate of pure time preference. Adopting this viewpoint would introduce a further cause of underaccumulation in the present model. The effect of policy instruments introduced below would not change, while the social optimum would be harder to achieve than for the case considered in this paper.

(ii) The *intertemporal maximisation problem* of the social planner is hence the following optimal growth problem:

$$\max_{C(t)} \int_{t=0}^{\infty} U(C(t))e^{-\rho t}dt \tag{19}$$

$$\begin{aligned} \text{with} \quad & U(C) = \ln(C) \\ \text{s.t.} \quad & \dot{K}(t) = F(K(t), L(t), S(t)) - C(t) - \delta K(t). \end{aligned}$$

The corresponding rule for socially optimal aggregate consumption growth is thus the Keynes-Ramsey rule

$$\frac{\dot{C}(t)}{C(t)} = F_K(K(t), L(t), S(t)) - \delta - \rho. \tag{20}$$

We can therefore take the Keynes-Ramsey level of consumption and capital, the dynamically optimal allocation, as the reference point for social optimality in the following. The reason is that we are in this article chiefly concerned with policy measures that raise total consumption. For this purpose can ignore the question of its static distribution: when social welfare is increased, it is acceptable that some individuals lose if others gain more. This means that our suggested redistribution schemes are not Pareto-improving even when comparing steady-states only: older generations – 'rentiers' – will be worse off in some cases. However, the fact that aggregate welfare is higher in all suggested redistribution schemes implies that our policies satisfy the Kaldor-Hicks criterion (Kaldor, 1939; Hicks, 1940), that is, they constitute a potential Pareto-improvement.

Whenever in the following we refer to 'social optimality', this denotes the dynamically optimal allocation, unless we explicitly say otherwise.

2.3 Steady states

Since L and S are fixed, we drop them as arguments from the production function in the following. The social planner's system is in a steady state if the capital stock and consumption level satisfy

$$\begin{aligned} \dot{K} = 0 \rightarrow \quad & C^{kr} = F(K^{kr}) - \delta K^{kr} \\ \dot{C} = 0 \rightarrow \quad & 0 = F_K(K^{kr}) - \delta - \rho. \end{aligned} \tag{21}$$

This characterises the optimal Keynes-Ramsey levels, denoted by superscripts ^{kr}, to which we compare the decentralised outcome: coupled differential equations for the aggregate capital stock (13), aggregate consumption (14) and the land price (9) govern the dynamics of the decentralised system.[8] Inserting the conditions on prices (16–18), we obtain the steady-state conditions:

$$\dot{K} = 0 \rightarrow \quad C_P(K) = F(K) - \delta K \tag{22}$$

$$\dot{C} = 0 \rightarrow \quad C_H(K) = \phi(\rho + \phi)\frac{K + p(K)S + \bar{Z}(K) - \bar{z}^N(K)}{r(K) - \rho} \tag{23}$$

$$\dot{p} = 0 \rightarrow \quad p(K) = \frac{(1-T)l(K)}{r(K)}. \tag{24}$$

[8] Any specific redistribution $z(\nu, t)$ is expressed in terms of K,C and p and their time derivatives, so Z and z are not independent dynamic variables themselves.

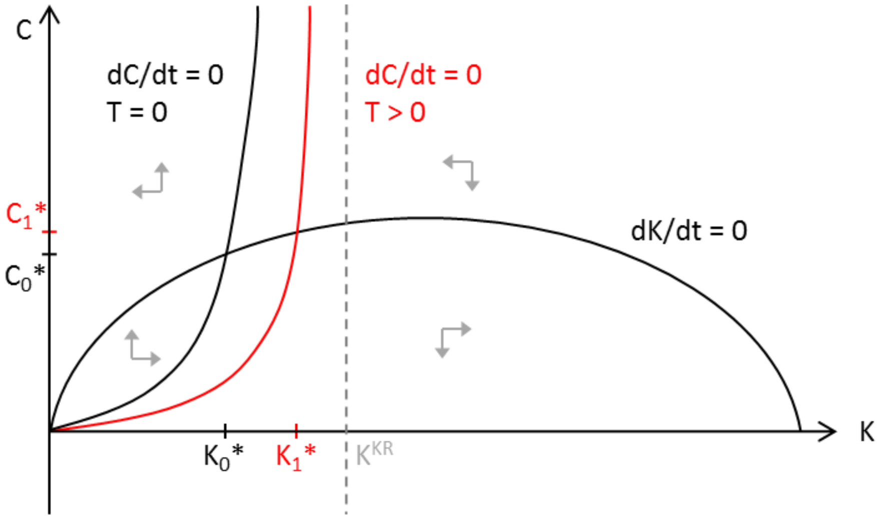

Figure 1: Phase diagram for redistributions with $\bar{Z}^{\dagger}(K) - \bar{z}^{N\dagger}(K) \geq 0$ for all $K \in [0, K^{kr}]$ and all $T \in [0;1]$

The subscripts $_P$ and $_H$ highlight that the first equation defines a curve in the C-K-plane shaped like a parabola and the second a hyperbola (compare Heijdra, 2009, p.572f and Figure 1; exceptions are discussed below). The present value of current and future transfers to the newborns is denoted by $\bar{z}^N(K) = \bar{z}(t,t)$.

A unique (non-trivial) steady state solution exists and the steady state is saddle-point stable. In the following the system is reduced to two dimensions by setting $\dot{p} = 0$. This projection captures all relevant dynamics.[9] We denote variables at the steady state (where all three of Equations (22–24) hold) by an asterisk *. In particular,

$$
\begin{aligned}
p^* &= p(K^*) = \frac{(1-T)l(K^*)}{r(K^*)} \qquad (25)\\
r^* &= r(K^*) = F_K(K^*) - \delta \\
l^* &= l(K^*) = F_S(K^*).
\end{aligned}
$$

Note that not every redistribution scheme yields a steady state: intuitively, the scheme must not introduce any asymmetry between individuals of the same age, but born at different times. An example for a redistribution that is permissible according to Equation (7), but not consistent with a steady state, is a scheme in which only generations born before a certain fixed date receive transfers. Formally, the aggregated present values of transfers $\bar{Z}^*$ (depending also directly on T, see Equation 7) must fulfil the following condition:

Proposition 1. *In a steady state, permissible redistribution schemes satisfy*

$$\phi \bar{z}^{N*} + r^* \bar{Z}^* = Tl^* S. \qquad (26)$$

[9]This can be shown in the three-dimensional system: linearising around the steady state shows that it is a saddle point with one stable arm. Since C is a jump variable which instantaneously adjusts such that the optimality and transversality conditions are observed, the system is on the stable path (see Appendices of Petrucci (2006)).

Moreover, the aggregate of individual present values of future transfers in the steady state *for a permissible redistribution scheme satisfies*

$$\bar{Z}^* < \frac{Tl^* S}{r^*}. \tag{27}$$

Proof. We require $d\bar{Z}^*(t)/dt = 0$ in the steady state.[10] Applying Leibniz' rule yields:

$$\frac{d\bar{Z}(t)}{dt} = \phi \bar{z}^N(t) + r^* \bar{Z}(t) - Z(t).$$

This equation means that the change in the aggregate present-value of all future transfers is the sum of three components: future transfers to newly born generations and interest on existing aggregate future transfers minus presently paid out aggregate transfers. These three terms cancel for a uniform ('lump-sum') redistribution scheme, but not for other redistributions. Setting to 0 and inserting the government budget equation (7) leads to the first result. Furthermore, for a permissible redistribution scheme, we have $\bar{z}^{N*} > 0$. The second result then follows directly from Equation (26). □

Finally, in the steady state, the growth factor $R(t, \tau)$ simplifies to

$$R(t,\tau) = \int_t^\tau (r(\tilde{t}) + \phi)\mathrm{d}\tilde{t} = (r^* + \phi)(\tau - t).$$

This simplification will be used for the rest of the article wherever steady-state properties are discussed.

2.4 Underaccumulation and redistributive effects

We now first show that there is underaccumulation of capital due to the generation replacement effect. Then, we give an intuition why this can be mitigated by land rent taxation, which directs investment towards capital, and by redistribution favouring the fundless newborns. We also sketch why achieving the social optimum requires giving a high share of tax revenue to the newborn generations (this is formally derived in the next section).

Equation (23) is essential for analysing the welfare effects of policies. Solving for the steady state interest rate yields

$$r^* = \rho + \phi(\rho + \phi)\frac{K^* + p(K^*, T)S + \bar{Z}^* - \bar{z}^{N*}}{C^*}. \tag{28}$$

Without taxes and transfers ($T = z = 0$), there is suboptimal underaccumulation due to the generation replacement effect, as is standard in continuous OLG models: since newborns have a lower level of consumption than the average household, aggregate consumption growth is lower than individual consumption growth. Through general equilibrium effects, this leads to a suboptimally low level of aggregate capital. More precisely, using Equation (25), the numerator of the second term simplifies to $K^* + l^* S/r^*$ which is always positive. Thus, the interest rate of the decentralised case is higher than the implied price of capital in the social planner's steady state (compare Equation 21). It then follows from $F_{KK} < 0$ and Equation (16) that capital accumulation is lower, $K^* < K^{kr}$. As K^{kr} is to the left of the maximum of the

[10] We are indebted to Dankrad Feist for suggesting this derivation.

parabola described by Equation (22), a lower capital stock implies suboptimal consumption, $C(K^*) < C(K^{kr})$ (see also Figure 1).

Further, consider the case with taxes and transfers. There is an inefficiency in the equilibrium because of the distribution obtained for the unregulated case: newborns come into existence without any funds as there are no bequests. However, the inefficiency can be cured by targeted transfers to age-groups. This is the point of introducing (positive) taxes and transfers, with which two competing effects enter Equation (28): the land price effect given by $p(K^*, T)S$, and the overall redistribution effect given by $\bar{Z}^* - \bar{z}^{N*}$.

First, the price effect always reduces underaccumulation compared to the no-policy case, since the tax lowers pS, so *ceteris paribus* the second term in Equation (28) is smaller. Intuitively, this is because a land rent tax makes investment in land less attractive relative to investment in capital, as reflected in the no-arbitrage condition (9). Also, a lower land price implies that land wealth contributes less to the generation replacement effect. (These effects cannot, of course, be treated in isolation as the model describes a general equilibrium. Hence a formal derivation that accounts for all effects is needed and provided in Section 3.3.)

Second, for the redistribution effect, the sign and relative size depends on the specific transfer scheme. There are two classes of redistributions, those that cannot and those that can reproduce the social optimum:

As long as the newborns do not receive higher transfers than the average (Figure 1), the redistribution effect is positive or zero in Equation (28), but the contribution of the price effect dominates (according to Proposition 1, $\bar{Z}^* < Tl^*S/r^*$), so welfare is still increased. Since the price effect is on land wealth only, the generation replacement effect does not fully disappear and the social optimum cannot be achieved. This class of redistribution schemes includes important cases such as a uniform transfer to every individual, independent of age, and a regime where land owners are compensated for the flow of tax payments (see Section 3.1 below).

If the distribution is tilted towards the young (Figure 2), the redistribution effect is also negative in Equation (28). It shifts the aggregate steady state capital stock and consumption to higher values, and even to the social optimum, the main result of our article. However, if the tax is high at the same time, both effects together may result in overaccumulation (Figure 3). From this second class, we analyse schemes where only the newborn receive transfers, or where transfers decline exponentially with age (see Section 3.2 below).

All particular redistribution schemes discussed are steady-state compatible because of their symmetry.

3 Formal results: The welfare effects of rent tax redistribution schemes

We show formally which redistribution schemes can achieve the social optimum and which cannot. We first prove that the social optimum is infeasible when tax proceeds are redistributed uniformly (age-independent) to households (Section 3.1). We then obtain a feasibility condition for the social optimum given transfers to newborns only (Section 3.2). Then a proposition on the beneficial welfare effects of land rent taxation for arbitrary steady-state compatible redistributions is formulated and proved. This last result serves as a characterization of all possible welfare consequences of arbitrary age-dependent redistributions. It shows that welfare improvements are possible by a very diverse set of possible *specific* redistributions (Section 3.3). Finally, we consider a capital subsidy as an alternative way of reaching the dynamic social optimum without redistribution (Section 3.4).

3.1 Non-optimal redistributions: uniform and compensatory

For a uniform age-independent transfer scheme, *per capita* transfers are

$$z_u(t) = Tl(t)S. \tag{29}$$

Thus, the present value of transfers to individuals and its aggregation over all cohorts have the same value:

$$\bar{z}_u(t) = \int_t^\infty Tl(\tau)Se^{-R(t,\tau)(\tau-t)}\mathrm{d}\tau, \tag{30}$$

$$\bar{Z}_u(t) = \int_{-\infty}^t \bar{z}_u(t)\phi e^{\phi(\nu-t)}\mathrm{d}\nu = \bar{z}_u(t). \tag{31}$$

In the steady-state the integrals have an explicit solution:

$$\bar{z}_u(t)^* = \bar{Z}_u(t)^* = \frac{Tl^*S}{r^*+\phi}. \tag{32}$$

One can derive

Proposition 2. *Reaching the social optimum is infeasible with the uniform redistribution of tax revenues.*

Proof. Using Equations (30) and (31) in (14) gives

$$\frac{\dot{C}(t)}{C(t)} = r(t) - \rho - \phi(\rho+\phi)\frac{K(t)+p(t)S}{C(t)}. \tag{33}$$

The capital stock dynamics $\dot{K}$ remain unchanged.

While the two distribution-related terms have cancelled in Equation (33), the effect of a land rent tax $T > 0$ on land price p via Equation (9) remains and leads to a welfare improvement compared to the case $T = 0$. But even if p falls to zero for the maximum tax rate $T = 1$, the last term does not vanish: aggregate growth is still lower than optimal due to the newborns' lack of capital. □

From this result it also follows that a 'compensatory' redistribution cannot be socially optimal.[11] A simple compensation would be to continuously remunerate land owners for taxes they paid, as considered for example by Calvo

[11] A sketch proof of its non-optimality is as follows: starting from a uniform redistribution, some of the transfers from selected young generations are shifted to selected older generations, which have more land and thus a higher tax burden. At time $\tilde{t}$, the shift of *contemporaneous* transfers does not affect C since any cohort consumes the same fraction of their wealth (Equation 11). However, the expectation of similar *future* transfers does have an effect, since the expected increased transfers towards today's youngest generations will be at the cost of unborn generations ($\nu > \tilde{t}$), whose future loss finances today's consumption. Technically,

et al. (1979). This is important to analyse because isolating the effect of the tax as a shift in relative prices requires compensating the tax payers.

Fane (1984) points out that this does not constitute a *full* compensation as used in tax incidence analysis. Instead it would be required that the initial wealth loss due to the drop in land price also be compensated: the government issues bonds (when the tax is announced) to finance a lump-sum payment to land owners, and using tax revenues for interest payments subsequently. In terms of the normative analysis of the present paper, Fane's case constitutes the worst possibility. No welfare gain is realised because the tax is completely unshifted and all agents are fully compensated.

3.2 Optimal redistributions: 'newborns only' and exponential

The main result of this article is that land rent taxation combined with age-dependent redistribution tilted towards the young is necessary and sufficient to reach the social optimum. Here we formally demonstrate this result, focusing first on the case of redistributing all revenue to the newborn generation only. Such a distribution is formally defined in terms of age-dependent transfers as

$$z_n(\nu, t) = \frac{Tl(t)S}{\phi}\delta(\nu - t). \tag{34}$$

Here $\delta(\cdot)$ is a Dirac distribution defined such that

$$\int_I \delta(x) f(x) \mathrm{d}x = \begin{cases} f(0) & \text{if } 0 \in I \\ 0 & \text{otherwise} \end{cases} \tag{35}$$

for any continuous function $f : \mathbb{R} \to \mathbb{R}$ and compact interval I.[12]

The present value of transfers to individuals and its aggregation over all cohorts are[13]

$\bar{Z}(\tilde{t})$ is higher than without the shift. By itself, this effect increases C at any given K – the hyperbola of Equation (23) with shifted transfers is above the original hyperbola for all K. (Additionally, $\bar{z}^N$ is lower when transfers are shifted, since increased transfers in the far future are discounted more than losses in the nearer future. This strengthens the overall effect of the shift of transfers, $(\bar{Z}^* - \bar{z}^{N*})$ in Equation (23).) However, since higher C implies foregone investment and thus a lower K^*, the overall effect on C^* is negative.

[12] This definition provides the necessary properties of the Dirac distribution for the computations below. It can be loosely thought of a function that is zero everywhere except at zero, where it is 'infinity'. The Dirac distribution is a certain ('weak') limit of a sequence of continuous functions with an ever taller and narrower spike at zero. A more detailed and rigorous description can be found in Milne (1980), Ch. 5 or Yosia (1980), Ch. I.8.

[13] It is instructive to consider two ways of obtaining the latter result, $\bar{Z} = 0$. The first is to directly use $\bar{z}_n$ in the definition of $\bar{Z}$,

$$\bar{Z}_n(t) = \int_{-\infty}^{t} \int_{t}^{\infty} \frac{Tl(\tau)S}{\phi}\delta(\nu - t)e^{-R(t,\tau)}\mathrm{d}\tau\phi e^{\phi(\nu - t)}\mathrm{d}\nu.$$

The inner integral is TlS/ϕ for $\nu = t$ and zero for $\nu < t$. Unlike the Dirac distribution itself, the value at $\nu = t$ is finite – thus, the outer integral is zero.
The second approach is to approximate the Dirac distribution by an exponential function (in the sense of a weak limit),

$$z(\nu, t) = Gue^{-u(t-\nu)} \overset{u\to\infty}{\to} z_n(\nu, t) \quad \text{where} \quad G = TlS/\phi,$$

which yields

$$\bar{Z}_n(t) = \frac{G\phi u}{(r + \phi + u)(\phi + u)} \overset{u\to\infty}{\to} 0.$$

$$\bar{z}_n(t,t) = \frac{Tl(t)S}{\phi}, \tag{36}$$

$$\bar{z}_n(\nu,t) = 0 \quad \text{for } \nu > t \quad \text{and} \tag{37}$$

$$\bar{Z}_n(t) = 0. \tag{38}$$

In this case, aggregate consumption (12) and consumption growth (14) become

$$C(t) = (\rho+\phi)[K(t) + p(t)S + \bar{W}(t)] \tag{39}$$

$$\frac{\dot{C}(t)}{C(t)} = r(t) - \rho - (\rho+\phi)\frac{\phi[K(t)+p(t)S] - Tl(t)S}{C(t)}. \tag{40}$$

Again, $\dot{K}$ remains unchanged.

If there exists a tax $T \leq 1$ such that the last term in Equation (40) is zero, the social optimum can be reproduced (see Equation 20). That is, the optimal tax in the steady state is

$$T^{opt} = \frac{\phi(K^* + p^*S)}{l^*S} = \frac{\phi(r^*K^* + l^*S)}{(\phi + r^*)l^*S}. \tag{41}$$

Intuitively, the optimal tax revenue compensates a newborn for her missing share of wealth $K^* + p^*S$. If $T^{opt} \leq 1$, the social optimum is feasible. Thus we have proved:

Proposition 3 (Feasibility of the social optimum)**.** *The socially optimal outcome can be implemented with a land rent tax and a redistribution of the tax revenue to only the newborns if*

$$\phi K^{kr} \leq l^{kr} S. \tag{42}$$

This is an intuitive result, stating that a tax and targeted redistribution achieves the social optimum if the (originally) missing capital of the newborns is smaller than the transfers that they may receive – which is at most the entire land rent. So the negative effect on aggregate consumption of the former can be compensated by the latter.

The redistribution to newborns further has the advantage of achieving the dynamic social optimum by also providing the statically optimal allocation. The reason is that the optimal tax rate yields a redistribution that equalizes wealth across individuals in the optimal way (see Subsection 2.2).

Further, the proposition also gives an absolute bound for reaching the social optimum in our model: in continuous OLG models, underaccumulation is the result of a lack of wealth of the newborns; thus redistributing to that generation the full revenue is the most efficient way of curing the underaccumulation. (If the revenue is so high that it leads to overaccumulation, the tax rate can be lowered, see below.) To justify the claim that Condition (42) gives an absolute bound and as a robustness check, we next consider a redistribution based on an exponential function in age that approximates the Dirac distribution.[14] Such a redistribution scheme can be thought of as child subsidies which decline with age or more generally as state benefits to the poor part of the population that decrease with higher income. A broader interpretation of

[14] We are indebted to Dankrad Feist for suggesting this redistribution.

such a redistribution scheme is the creation of a national fund which endows the young with an inheritance which they can use for investments in human or physical capital.

This redistribution has two parameters: a_0 denotes the value of the redistribution at birth and a_s denotes the speed of the exponential change with age. The exponential redistribution scheme depending on a_0 and a_s is then defined by

$$z_e(\nu, \tau) = a_0 e^{-a_s(\tau-\nu)}. \tag{43}$$

For this redistribution to be permissible in the sense of Equation (7), a restriction on the choice of a_0 and a_s is required:

$$Tl^*S = \frac{a_0\phi}{(a_s+\phi)} \quad \text{with } (a_s+\phi) > 0. \tag{44}$$

The restriction is obtained by solving the integral in Equation (7) for z_e. It implies that a_0 is positive and that $a_s > -\phi$.

When can this redistribution be socially optimal? For $-\phi < a_s < 0$, the redistribution is permissible, but exponentially increasing with age. It can be shown that for this parameter range it cannot be socially optimal. For $a_s > 0$, on the contrary, a condition for social optimality can be calculated. Evaluating the integrals in the respective definitions yields

$$\bar{z}_e^* = \frac{a_0}{r^*+\phi+a_s} \quad \text{and} \tag{45}$$

$$\bar{Z}_e^* = \frac{\phi a_0}{(r^*+\phi+a_s)(\phi+a_s)}. \tag{46}$$

To determine when the social optimum can be reached by this redistribution, Equations (44), (45) and (53) below need to be combined to calculate a_0 and a_s explicitly. It can be shown that

$$a_0 = \frac{Tl^*Sr^*(r^*K^*+l^*S)}{Tl^*S(r^*+\phi) - \phi(r^*K^*+l^*S)}. \tag{47}$$

Note that a_0 is positive if the denominator is. Setting $T = 1$, and determining when the denominator in Equation (47) is positive, it is proved that

Proposition 4. *A redistribution scheme in which land rents are given back to individuals according to an exponential function decreasing in age can reach the social optimum if*

$$\phi K^{kr} < l^{kr}S. \tag{48}$$

This result reflects that the exponential redistribution approximates the distribution to the newborns only in terms of their welfare properties. Moreover, if social optimality is feasible, the optimal tax is

$$T^{opt} = \frac{(r^*+\phi)a_0 - r^*(r^*K+l^*S)}{a_0\phi(r^*K+l^*S)} \tag{49}$$

for arbitrary $a_0 > 0$, $a_s > 0$ that satisfy Equation (44).

Empirical relevance Empirical data shows that Condition (42) for implementing the social optimum by redistributing all land tax revenues to the newborns is often met in practice (and thus also Condition (48) for exponential redistribution, which cannot be distinguished empirically): Assume a Cobb-Douglas production function (as in Caselli and Feyrer, 2007)

$$Y = F(L, K, S) = F_0 L^{(1-\alpha-\beta)} K^{\alpha} S^{\beta}, \tag{50}$$

so that $l^* S = \beta Y^*$. Denoting the steady-state ratio of the total capital stock to total output by $\kappa = K^*/Y^*$, the feasibility condition (42) becomes

$$\phi\kappa \leq \beta. \tag{51}$$

We use estimation results from Caselli and Feyrer (2007) for κ and to approximate β.[15] Their study covers a wide variety of countries, ranging from Côte d'Ivoire and Peru to Switzerland and the USA.

We find that the feasibility condition is satisfied with realistic values of ϕ for all 53 countries quoted, often by a wide margin.[16]

For the Cobb-Douglas case, the optimal steady state tax is

$$T_{CD}^{opt} = \frac{\phi\kappa\alpha + \phi\kappa\beta}{\alpha\beta + \phi\kappa\beta}. \tag{52}$$

This implies that the lower κ and the higher β, the lower the share of the land rent that has to be redistributed to the newborns.

3.3 Hypergeorgism: general result

Beyond specific redistributions, general conditions on age-dependent redistribution schemes that ensure that land rent taxation is welfare-enhancing can be provided. In fact, one can completely characterize the welfare consequences of any permissible redistribution scheme. The following result achieves this by distinguishing which redistributions cannot produce overaccumulation because newborns do not get more than the average. It also contains a condition for those redistributions in which they do, limiting the funds the government mobilizes. In the statement and proof of the proposition, quantities will be discussed for values of K outside the steady state as if these capital levels were steady states, thus assuming that $r(K)$ is constant. We write $\bar{Z}^{\dagger}(K)$ and $\bar{z}^{N\dagger}(K)$ to highlight this.

[15] Caselli and Feyrer (2007) do not report β directly, but estimates of "one minus the labor share" (p.541) in income and the share of reproducible capital in income. The difference – our approximation for β – is the income share of land and other natural resources, some of which are not fixed factors. However, the authors report "Proportions of different types of wealth in total wealth" (p.547) which demonstrate that while subsoil resources are important for some countries, land wealth dominates in most cases. Since the dataset does not include any countries that mainly rely on fossil fuel extraction and given the wide margin by which the sufficiency condition is fulfilled for most countries, we consider this rough approximation as sufficient for our purposes.

[16] For example, Switzerland has the highest $\kappa = 3.59$ and lowest $\beta = 0.06$ in the dataset (Caselli and Feyrer, 2007), so we need $\phi \leq 0.017$. The real birth rate is 0.010 (Eurostat, 2012), so there is even scope to accommodate modest population growth (the death rate is 0.008 (Eurostat, 2012)). Also, ϕ is lower than the real birth rate because in reality there are *some* bequests. For comparison, the U. S. have $\kappa = 2.19$ and $\beta = 0.08$ (Caselli and Feyrer, 2007), implying $\phi \leq 0.037$. Values for most other developed countries in the dataset range between those for Switzerland and the USA, while most industrializing and developing countries have lower capital-to-output ratios and higher shares of land in output than the U. S. allowing sufficient transfers to newborns even for a high population growth rate.

Proposition 5. *The government can increase social welfare by choosing both a land rent tax T and a permissible redistribution scheme z yielding a steady state in a way that*

- *new generations do not receive more than the average: $\bar{Z}^{\dagger}(K) \geq \bar{z}^{N\dagger}(K)$ for all $K \in [0, K^{kr}]$, or*
- *new generations do receive more than the average, but the tax rate T is not too high: $\bar{Z}^{\dagger}(K) < \bar{z}^{N\dagger}(K)$ for some K and $T \leq \phi/(\phi+\rho)$. For higher T, suboptimal overaccumulation of capital is possible, depending on the particular redistribution.*

The proposition is proved in Appendix A.5. An intuition why the result is true has already been developed in the introduction to Section 3. The idea of proof is to trace the price effect and the redistribution effect of taxing land in the general equilibrium setting. The second half of the statement follows by showing that the two effects cannot lead to overaccumulation given the upper bound on the tax rate.

The proposition is very general regarding the redistribution scheme, but the generality implies two disadvantages: First, only a comparison between the unregulated market outcome and a policy case is possible. One may also want to know whether a higher tax implies higher welfare in general. Given the uniform redistribution, a higher tax rate does in fact imply higher welfare, but this is not necessarily true for all other redistributions. Second, the proposition considers a welfare improvement only and is not informative about the achievability of the social optimum. But a general optimality condition for arbitrary tax rates and redistribution schemes can be obtained from Equation (28) if we use Equation (26) to replace $\bar{Z}^*$:

$$\bar{z}^{N*} = \frac{r(K^*)K^* + l(K^*)S}{r(K^*) + \phi}. \tag{53}$$

To assess the feasibility of a socially optimal fiscal policy[17], this general condition needs to be evaluated for specific redistribution schemes $z(\nu, \tau)$, as done above.

3.4 Capital subsidy

An alternative to redistributing tax revenues directly to individuals is to subsidise capital in the form of a markup on the market interest rate. This does not change the results in Section 2 except that r is replaced by $\tilde{r} \equiv r + \epsilon$, with ϵ being the markup financed by land rent tax revenues. Specifically, aggregate consumption growth becomes

$$\dot{C}(t) = C(t)\left[r(t) + \epsilon - \rho\right] - \phi(\rho+\phi)\left[K(t) + p(t)S\right] \tag{54}$$

so restoring the Keynes-Ramsey case requires

$$\epsilon C = \phi(\rho+\phi)(K(t) + p(t)S). \tag{55}$$

[17] Although the condition for social optimality defines a steady-state – for any C, $r^* = \rho$ is a solution to Equation (23) –, we do not claim stability for this steady-state as it is unknown whether it holds for all redistributions considered above. However, as the redistributions which reach the social optimum also approximate this steady-state arbitrarily closely by the (stable) 'hyperbolic' steady-state solution of Equation (23), the previous sections legitimately evaluate the redistribution schemes.

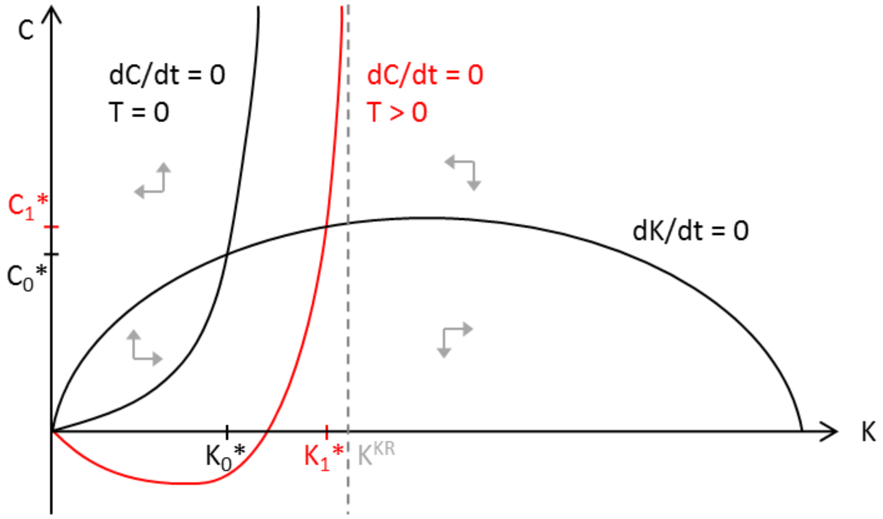

Figure 2: Phase diagram for redistributions with $\bar{Z}^{\dagger}(K) - \bar{z}^{N\dagger}(K) < 0$ for some $K \in [0, K^{kr}]$ and $T < T^{opt}$

Using $\epsilon K^* = Tl(K^*)S$ and $p^* = (1-T)l(K^*)/r^*$, a steady state condition for the optimal tax is obtained:

$$\left[\frac{l^*S}{K^*} + \phi(\rho+\phi)\frac{l^*S}{r^*C^*}\right] T^{opt} = \phi(\rho+\phi)\left[\frac{K^*}{C^*} + \frac{l^*S}{r^*C^*}\right]. \tag{56}$$

Hence a proposition on the feasibility of the social optimum for the capital subsidy can be deduced by inserting $T \leq 1$:

Proposition 6. *Reaching the socially optimal level of aggregate consumption with a tax on land rents to finance a capital subsidy is feasible if*

$$\phi K^* \leq \frac{1}{(\rho+\phi)}\frac{C^*}{K^*}l^*S. \tag{57}$$

Of course, subsidizing capital does not achieve the socially optimal level of aggregate consumption by *redistribution,* so that if one is concerned with reaching also the static socially optimal allocation of consumption, further redistribution would be required (see Subsection 2.2).

Empirical relevance We can test Condition (57) empirically as in Section 3.2. Again, assume the Cobb-Douglas production function given by Equation (50). From Equation (13), we have $\dot{K} = Y^* - \delta K^* - C^* = 0$ in the steady state, thus by eliminating C^* the feasibility condition (57) becomes

$$\phi\kappa \leq \frac{1}{(\rho+\phi)}(\frac{1}{\kappa} - \delta)\beta. \tag{58}$$

Even if we assume high values for the additional parameters in this equation, for instance $\rho = 0.05$ and $\delta = 0.15$, we find that this feasibility condition is weaker than Condition (51) for the case of transfers to newborns by a factor of two or more for the 53 countries quoted (Caselli and Feyrer, 2007). It is weaker by a factor of ten and more if we assume $\rho = 0.01$ and a more realistic depreciation rate of $\delta = 0.05$.

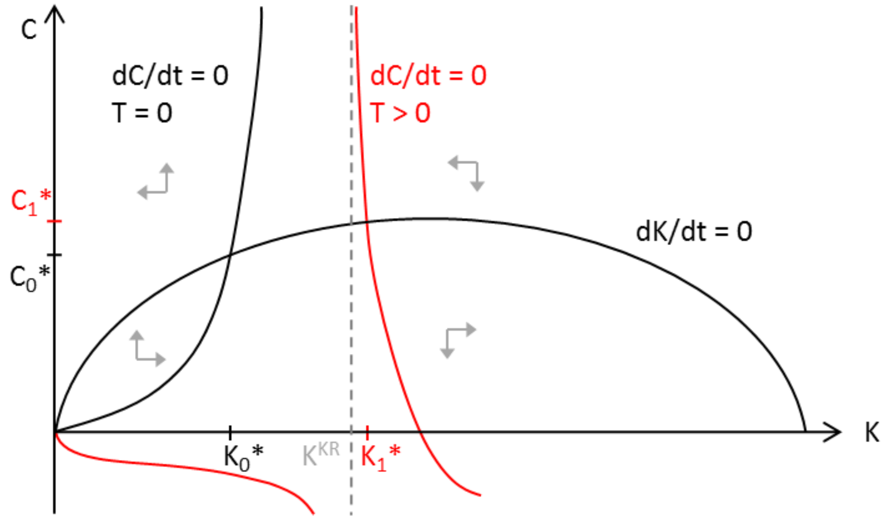

Figure 3: Phase diagram for redistributions with $\bar{Z}^{\dagger}(K) - \bar{z}^{N\dagger}(K) < 0$ for some $K \in [0, K^{kr}]$ and $T > T^{opt}$

4 Extensions

Here we consider four extensions to our model: We provide additional results on adding debt or the need to finance productive public capital to the government's problem. We then present conjectures on transitional dynamics and on the impact of other causes of underaccumulation.

First, consider adding the possibility of debt-financing to the model, noting that Ricardian Equivalence holds for land rent taxation, but not for targeted lump-sum transfers (see Buiter (1988, 1989)). It can be shown that, when considering steady-state welfare only, zero government debt opens up the greatest possibility for reaching the social optimum. Let B^* denote the steady-state debt level. Modifying the model to include the standard treatment of government debt in continuous OLG models (see Heijdra (2009), Ch. 16.3), it can be shown that a modified version of Proposition 4 holds, according to which the social optimum is feasible if

$$\phi(K^{kr} + B^{kr}) + r^{kr} B^{kr} \leq l^{kr} S. \tag{59}$$

So with zero debt, the social optimum is easiest to reach. The reason is that positive debt makes the economy less efficient, as the wealth gap between newborns and older generations widens (see also Blanchard (1985), p. 243).

Second, land rent taxation may be also desirable because the revenue could be used for reducing other inefficiencies than suboptimal capital accumulation, notably investments in productive public capital. For the case of a single dynastic household, Mattauch et al. (2013) provides results that can be extended to the setting of overlapping generations (see also Heijdra and Meijdram, 2002). While using the tax revenue for investment in public capital will constitute a welfare improvement, this will not generally be socially optimal if no further revenue is left for redistributive transfers to the newborns. Only if the land rent exceeds the sum of the socially optimal investment in public capital and the minimum amount ϕK required for curing the inefficient capital accumulation can the social optimum be reproduced. The content of the neoclassical Henry George Theorems is that in some circumstances confiscating (land) rents is sufficient for financing the optimal level of a public good (Stiglitz, 1977). The suggested analysis would be an extension of this result to the context of intertemporal infrastructure financing with an additional redistributive element. A further extension is to translate the results of this study to a setting with a portfolio of capital assets and natural resources other than land (see Siegmeier et al., 2015a, Section 3.3 and Siegmeier et al., 2015b, Sections 3.2 and 3.3).

Third, welfare effects during the transition to a new steady-state differ from those of the above analysis. Recall that above we compare an existing steady-state without policy to a new steady-state with policies in place. This means that our policies are no Pareto-improvements as some generations might be worse off during the transition from a steady-state without policies to one with a policy in place.

Here we consider the case that the introduction of a land rent tax together with one of the redistribution schemes is unanticipated by households. For this, one can conjecture that (i) generations born after the tax reform will always be better off (at least under the additional assumption that $F_{KL} > 0$). (ii) For existing generations, there is a threshold in age determining whether the tax reform will make them better off. If agents are older than this threshold they will lose. The threshold depends on the redistribution scheme and the tax rate.

A brief justification for this conjecture is as follows: agents born after the tax reform have no non-human wealth and their human wealth increases by the tax reform, because they now receive transfers. Moreover, their wage rate increases. The reason for this is that aggregate capital increases during the transition, although aggregate consumption first declines before it increases to a new, higher level. Agents born before the tax reform loose in proportion to the wealth they own, while all face the same probability of dying before the new steady-state level has been reached. The transitional welfare effects thus leave scope for a welfare improvement through a bond path that uses some of the efficiency gains when close to the new steady-state to partially compensate the losers at the time of enactment of the tax. One might prove these conjectures by applying methods similar to those used in Heijdra and Meijdram (2002) if these can be adapted to the closed-economy setting.

Fourth, it should be analysed whether Hypergeorgism is also a valid theory for other causes of underaccumulation of capital than that implicit in the continuous OLG model, imperfect altruism between generations. Further potential causes of underaccumulation that need to be considered are: inefficient capital investment by firms (Scharfstein and Stein, 2000), uninternalised spillovers raising the social value of investment above the private value (Romer, 1986), inefficient capital markets (Fama, 1970, 1991), and time-inconsistent preferences by households that have self-control problems about saving (Laibson, 1997; Thaler and Benartzi, 2004). Additionally, a bubble on the real estate market may lead to underinvestment in productive capital (Buiter, 2010) and conversely, high land prices may be a sign of underaccumulation.

5 Conclusion

This paper studied the welfare effect of land rent taxation and how the revenues should be redistributed to a population of heterogeneous households with imperfect intergenerational altruism. It was shown that, as taxing land rents leads to an increase in aggregate welfare, by redistributing the tax revenue to the newborns the government can achieve the social optimum. This is true as long as the land rent tax rate is not chosen too high. Achieving the social optimum by such a policy is possible as long as the total land rent is greater than the stock of productive capital multiplied by the birth rate, a condition which could be confirmed for a diverse set of countries. By contrast, the government cannot implement the social optimum with a compensatory or a uniform redistribution, which nevertheless increase welfare. Subsidizing productive capital is also a potentially socially optimal policy.

In summary, our findings support the view that under imperfections in the accumulation of productive assets, taxing and redistributing rents on fixed production factors is a policy measure that leads to a welfare gain – a view we label *Hypergeorgism*.

A Appendix

A.1 Derivation of the Keynes-Ramsey rule and the arbitrage condition

The budget constraint (3) can be split into a constraint on monetary terms and a constraint on land size by defining $d(\nu,t) = \phi s(\nu,t) - \dot{s}(\nu,t)$. Dropping the time arguments, we obtain:

$$\dot{k} = w + [r+\phi]k + (1-T)ls + pd + z - c \tag{60}$$

$$\dot{s} = \phi s - d. \tag{61}$$

Individuals maximise utility given by Equation (2) by choosing $c(\nu,\tau)$ and $d(\nu,\tau)$, subject to Equations (60), (61) and the transversality condition (6). Writing λ and μ for the multipliers of (60) and (61) in the current value Hamiltonian H_c, we obtain the following first order conditions:

$$\frac{\partial H_c}{\partial c} = \frac{1}{c} - \lambda = 0 \tag{62}$$

$$\frac{\partial H_c}{\partial d} = \lambda p - \mu = 0 \tag{63}$$

$$\frac{\partial H_c}{\partial k} = (\rho+\phi)\lambda - \dot{\lambda} \quad \Rightarrow \quad \lambda(r+\phi) = (\rho+\phi)\lambda - \dot{\lambda} \tag{64}$$

$$\frac{\partial H_c}{\partial s} = (\rho+\phi)\mu - \dot{\mu} \quad \Rightarrow \quad \lambda(1-T)l + \mu\phi = (\rho+\phi)\mu - \dot{\mu}. \tag{65}$$

Inserting the time derivative of (62) into Equation (64) yields the Keynes-Ramsey rule (8). Using Equation (63) and its time derivative to replace μ and $\dot{\mu}$ in Equation (65) and applying Equation (64) gives the arbitrage condition for investing in land or capital (9).

A.2 Individual lifetime budget constraint and consumption level

First, the lifetime budget constraint (10) is derived, from which the individual consumption level can then be obtained. Dropping the time arguments ν and τ where no confusion is possible, regrouping terms in (3) and adding $\dot{p}s - (r+\phi)ps$ on both sides, it follows that:

$$\begin{aligned}\dot{k} + p\dot{s} + \dot{p}s - (r+\phi)(k+ps) &= w + (1-T)ls + z + \dot{p}s - rps - c = \\ &= w + z - c.\end{aligned}$$

The last equality follows from (9). This leads to

$$\begin{aligned}\frac{d}{d\tau}\left[(k+ps)e^{-R}\right] &= (w+z-c)e^{-R} \\ \Rightarrow \int_t^\infty \frac{d}{d\tau}\left[(k+ps)e^{-R}\right]\mathrm{d}\tau &= \int_t^\infty (w+z-c)\,e^{-R}\mathrm{d}\tau.\end{aligned}$$

For the integral on the left-hand side, note that $\exp(-R(t,t)) = 1$ and use (6) to obtain

$$\begin{aligned}&\int_t^\infty \frac{d}{d\tau}\left[(k+ps)e^{-R}\right]\mathrm{d}\tau = \\ &= \lim_{\tau\to\infty}([k(\nu,\tau) + p(\tau)s(\nu,\tau)]e^{-R(t,\tau)}) - k(\nu,t) - p(t)s(\nu,t) = \\ &= -\,k(\nu,t) - p(t)s(\nu,t).\end{aligned} \tag{66}$$

Using the definition of $\bar{w}(t)$ and $\bar{z}(\nu,t)$ from the main text, the right-hand side can be written as

$$\int_t^\infty (w+z-c)\,e^{-R}\mathrm{d}\tau = \bar{w}(t) + \bar{z}(\nu,t) - \int_t^\infty c(\nu,\tau)e^{-R}\mathrm{d}\tau. \tag{67}$$

Combine Equations (66) and (67) to obtain the lifetime budget constraint (10).

Then, the individual consumption level follows in two steps. First, solve the Keynes-Ramsey rule for c,

$$\begin{aligned}(8) \Rightarrow \int_{c(\nu,t_0)}^{c(\nu,\bar{t})} \frac{1}{c(\nu,\tau)}\mathrm{d}c &= \int_{t_0}^{\bar{t}} (r(\tau)-\rho)\mathrm{d}\tau \\ \Rightarrow c(\nu,\bar{t}) = c(\nu,t_0)\exp&\left(\int_{t_0}^{\bar{t}} (r(\tau)-\rho)\mathrm{d}\tau\right).\end{aligned}$$

Second, setting $t_0 = t$ and $\bar{t} = \tau$ in the last expression and replacing c in the lifetime budget equation,

$$\begin{aligned}k(\nu,t) + p(t)s(\nu,t) + \bar{w}(t) + \bar{z}(\nu,t) &= \int_t^\infty c(\nu,t)e^{\int_t^\tau [r(\tilde{t})-\rho]\mathrm{d}\tilde{t}}e^{-R(t,\tau)}\mathrm{d}\tau = \\ &= c(\nu,t)\int_t^\infty e^{-\int_t^\tau (\rho+\phi)\mathrm{d}\tilde{t}}\mathrm{d}\tau = \\ &= c(\nu,t)/(\rho+\phi).\end{aligned}$$

Thus, the level of individual consumption is a fixed fraction of wealth independent of time or the individual's age.

A.3 Aggregate solution

We derive the aggregate quantity for general age-dependent transfers $z(\nu, t)$ as given in Section 2.

The aggregate consumption level $C(t)$ for general transfers is obtained directly from aggregation of Equation (11), as given by Equation (12) in the main text.

The dynamics of the total capital stock (13) are obtained by applying Leibniz' rule to

$$K(t) = \int_{-\infty}^{t} k(\nu, t)\phi e^{\phi(\nu - t)} \mathrm{d}\nu,$$

replacing $\dot{k}$ by its expression from the individual budget constraint (3), and using Equation (5) for aggregate changes in land ownership:

$$\begin{aligned}
\dot{K}(t) &= \underbrace{k(t,t)}_{=0} \phi e^{\phi(t-t)} - 0 + \int_{-\infty}^{t} \frac{\mathrm{d}}{\mathrm{d}t} \left[k(\nu, t)\phi e^{\phi(\nu - t)} \right] \mathrm{d}\nu = \\
&= -\phi K(t) + \int_{-\infty}^{t} \dot{k}(\nu, t)\phi e^{\phi(\nu - t)} \mathrm{d}\nu = \\
&= w(t) + r(t)K(t) + [1 - T(t)]l(t)S + \\
&+ p(t) \underbrace{\left[\phi S - \int_{-\infty}^{t} \dot{s}(\nu, t)\phi e^{\phi(\nu - t)} \mathrm{d}\nu \right]}_{=0} - C(t) + \underbrace{\int_{-\infty}^{t} z(\nu, t)\phi e^{\phi(\nu - t)} \mathrm{d}\nu}_{=T(t)l(t)S} = \\
&= w(t) + r(t)K(t) + l(t)S - C(t).
\end{aligned}$$

The government budget constraint (7) was used in the last step, so taxes and transfers always cancel out in the last step and the result does not directly depend on the redistribution $z(\nu, t)$. However, it may have an indirect effect via prices, stock levels and consumption.

Similarly, we derive the dynamics of aggregate consumption given by Equation (14):

$$\begin{aligned}
\dot{C}(t) &= c(t,t)\phi e^{\phi(t-t)} - 0 + \int_{-\infty}^{t} \frac{\mathrm{d}}{\mathrm{d}t} \left[c(\nu, t)\phi e^{\phi(\nu - t)} \right] \mathrm{d}\nu = \\
&= \phi(\rho + \phi)[\bar{w}(t) + \bar{z}(t,t)] - \phi C(t) + \underbrace{\int_{-\infty}^{t} \dot{c}(\nu, t)\phi e^{\phi(\nu - t)} \mathrm{d}\nu}_{=(r(t)-\rho)C(t)} = \\
&= [r(t) - \rho]\, C(t) - \phi(\rho + \phi)[K(t) + p(t)S + \bar{Z}(t) - \bar{z}(t,t)].
\end{aligned}$$

The first equality follows from Leibniz' rule. For the second, $c(t,t) = (\rho + \phi)[k(t,t) + p(t)s(t,t) + \bar{w}(t) + \bar{z}(t,t)] = (\rho + \phi)[\bar{w}(t) + \bar{z}(t,t)]$ is used. In the third step, $\phi C(t)$ is replaced using Equation (12).

A.4 Solution of the static optimisation problem of the social planner

We justify that the solution to the static part of the social planner problem

$$U(C(t)) = \max_{\{c(\nu,t)\}_{\nu=-\infty}^{t}} \int_{-\infty}^{t} \ln c(\nu,t)\phi e^{-\phi(t-\nu)} \mathrm{d}\nu \tag{68}$$

$$\text{subject to:} \quad C(t) = \int_{-\infty}^{t} c(\nu,t)\phi e^{-\phi(t-\nu)} \mathrm{d}\nu \tag{69}$$

is

$$U(C(t)) = \ln(C(t)).$$

The result is intuitive as all agents have the same utility function. To prove it, one can solve the maximisation problem with integral constraint: writing λ as multiplier to the integral constraint, one obtains the current-value Hamiltonian

$$H_c = \phi \ln c(\nu,t) + \lambda\phi c(\nu,t)$$

and thus finds the first-order conditions:

$$\frac{\partial H_c}{\partial c} = \frac{\phi}{c(\nu,t)} + \lambda\phi = 0 \tag{70}$$

$$(t-\nu)\lambda = (t-\nu)\lambda - \dot{\lambda}. \tag{71}$$

The last equation implies that λ is constant, so that from Equation (70) it follows that the optimal $c(\nu,t)$ is constant for all ν, too. Setting $c(\nu,t) = c'(t)$ in Equation (69) implies

$$C(t) = c'(t).$$

Inserting this in Equation (68) finally implies that $U(C(t)) = \ln(C(t))$.

A.5 Proof of Proposition 5

Proof of Proposition 5. We prove the first half of the proposition and then show how the second half follows under the additional assumption on the tax rate.

For the first part, the idea of the proof is to compare the steady state of the system with no policy to that of the policy case: it will be shown that although for a *fixed* capital stock, consumption is lower with the policy, both consumption and capital stock are higher in the steady state of the policy case. This is illustrated in Figure 1.

Consider two cases, one without taxes and the other with a land rent tax rate $T > 0$. Denote the steady states defined by Equations (22) and (23) for the two cases by (K^{0*}, C^{0*}) and (K^{1*}, C^{1*}) and let the superscripts 0 and 1 also indicate the no-policy and policy case for the parabola and the hyperbola. From the social welfare function chosen in Section 2.2, it follows that for an increase in social welfare it is sufficient to prove that

$$C^{0*} < C^{1*}.$$

The parabola defined by $\dot{K} = 0$ is unaffected by taxes and transfers, but the hyperbola, defined by $\dot{C} = 0$, changes: Equation (23) can be rewritten as

$$C^1_H(K) = \phi\frac{\rho+\phi}{r(K)-\rho}\left\{K + \frac{l(K)S}{r(K)} - \frac{Tl(K)S}{r(K)} + \bar{Z}^\dagger(K) - \bar{z}^{N\dagger}(K)\right\}, \quad (72)$$

where we treat any value of K as if it was the steady state value (hence the †-notation). The second part of Proposition 1 can then be written as $\bar{Z}^\dagger(K) < Tl(K)S/r(K)$. This implies that the last three (the directly policy-dependent) terms in the curly bracket together are negative, and thus that $C^1_H(K) < C^0_H(K)$ for all $K \in [0, K^{kr}]$. In Figure 1, the hyperbola for $T > 0$ is below the no-policy case.

For any $K < K^{0*}$, we also have $C^0_H(K) < C^0_P(K)$ and $C^0_P(K) = C^1_P(K)$ since the parabola is policy-independent, so $C^1_H(K) < C^1_P(K)$ for $K < K^{0*}$. By the assumption that $\bar{Z}^\dagger(K) \geq \bar{z}^{N\dagger}(K)$ and as $T \leq 1$, C^1_H is positive for all $K \leq K^{kr}$, and thus tends to $+\infty$ as K approaches K^{kr}. Hence the (non-trivial) intersection of parabola and hyperbola for T_1 must occur at a capital stock K^{1*} with $K^{0*} \leq K^{1*} < K^{kr}$. In this interval, $C_P(K)$ is increasing in K, thus $K^{0*} < K^{1*}$ and also $C^{0*} < C^{1*}$, as required for the first part of the proposition.

For the case $\bar{Z}^\dagger(K) < \bar{z}^{N\dagger}(K)$ in the second part of the proposition, over-accumulation is possible. It occurs if $K^{1*} \geq K^{kr}$, which is only possible if the hyperbola C^1_H tends to $+\infty$ when approaching its singularity from the right. We show that this is impossible if $T \leq \phi/(\phi+\rho)$.[18] Given this bound on T, we prove in the following that it holds that

$$N(K) := K + (1-T)\frac{l(K)}{r(K)}S + \bar{Z}^\dagger(K) - \bar{z}^{N\dagger}(K) \geq 0$$

for all $K \geq K^{kr}$. This is sufficient because the intersection of parabola and hyperbola then occurs for $K^{1*} \leq K^{kr}$ by continuity of $N(K)$ (see Figures 2 and 3). The argument of the first part of the proof is then valid because then there exists some K' such that $C^1_H(K)$ is positive for $K' \leq K \leq K^{kr}$.[19] Again, we treat any value of K as if it was the steady state value.

From Proposition 1 it follows that in the steady state $\bar{z}^{N\dagger}(K) \leq Tl(K)S/\phi$ and thus

$$\bar{Z}^\dagger(K) - \bar{z}^{N\dagger}(K) \geq -\frac{Tl(K)S}{\phi},$$

as $\bar{Z}^\dagger(K) \geq 0$. It hence remains to prove that

$$K + \frac{(1-T)l(K)S}{r(K)} - \frac{Tl(K)S}{\phi} \geq 0 \quad \text{for all } K \geq K^{kr}.$$

To this end, it is sufficient to show

$$\frac{(1-T)}{r(K)} \geq \frac{T}{\phi} \quad \Leftrightarrow \quad r(K) \leq \frac{\phi(1-T)}{T} \quad \text{for all } K \geq K^{kr}.$$

[18] Under some regularity conditions on higher derivatives of the production function, which are for example satisfied by a Cobb-Douglas function, it follows that even $T \leq \phi(\rho K^{kr} + l(K^{kr})S)/(\rho l(K^{kr})S)$ is sufficient for the second statement of the proposition, but this is not true for the general production function considered in this paper.

[19] The case that $N(K^{kr}) = 0$ is special, the argument of the proof collapses as Equation (72) cannot be derived, but the result is true because $K^{1*} = K^{kr}$.

For such K, $r \leq \rho$, so that it remains to verify

$$\rho \leq \frac{\phi}{T} - \phi.$$

The last equation holds if and only if $T \leq \phi/(\phi + \rho)$, as required. $\square$

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Chapter 5

Capital beats coal: how collecting the climate rent increases aggregate investment[1].

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Capital beats coal: how collecting the climate rent increases aggregate investment

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Abstract

Carbon pricing regulates emission flows, but also collects rents from underlying fossil resource stocks. Assuming that these stocks are tradable, carbon pricing shifts aggregate investment towards alternative assets. If capital is underaccumulated, this implies lower costs of climate policy and a welfare improvement. We prove that three climate policy instruments induce a beneficial investment shift from fossil fuel stocks towards capital: for an emission trading scheme implementing an arbitrary mitigation path, the higher the share of auctioned permits (and thus rent collection), the larger the beneficial aggregate investment effect. The same holds for a 'stock instrument', under which the right to recurrently receive emission permits is a tradable asset; when this asset replaces fossil stocks in investors' portfolios, the effect is more robust to trade restrictions on fossil stocks. Finally, a carbon tax that is constantly high to maximize the aggregate investment effect cannot achieve any desired mitigation path.

JEL classification: E22, H21, H23, Q30, Q54

Keywords: carbon pricing, resource rent taxation, overlapping generations, capital underaccumulation

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1 Introduction

To keep global warming below 2 °C above pre-industrial times, cumulative global carbon emissions have to be limited to less than 1000 $GtCO_2$ in this century.[1] Enforcing such a carbon budget creates scarcity rents. If this is done by carbon pricing, some of the rents will be collected by the state: for example, auctioning a fixed amount of emission permits, or implementing a carbon tax, extracts rents from fossil resource stocks. This is frequently recognized as a distributional issue: the political feasibility of climate policy depends on the possibility to compensate fossil resource owners.[2] However, the focus on rent *distribution* has meant that the original motivation for rent taxation – that it may be non-distortionary and thus *efficient* – has not been re-assessed for the case of climate policy. Under carbon pricing, fossil resource stocks are becoming less attractive as an asset for investment, but their supply remains unchanged. This frees funds for alternative investments, leading to a larger overall supply of productive factors.

This paper specifically shows, first, that pricing the flow of carbon emissions induces a macroeconomic distortion: it reduces the rents from fossil resource stocks and thus directs investment towards producible capital as the alternative asset. If capital was previously underaccumulated, this 'macroeconomic portfolio effect' constitutes a welfare improvement and lowers the gross costs of climate policy. Second, while the basic effect applies to all forms of carbon pricing, there is no full symmetry between instruments: for emission permit schemes, the total amount of permits and the auctioned share separately determine mitigation and rent extraction. In contrast, a carbon tax cannot implement simultaneously any desired combination of climate protection (requiring a varying tax rate) and rent extraction (which is largest under a constantly high tax rate).

These results have three major policy implications: First, and most importantly, there is generally an *efficiency* reason for the appropriation of climate rents for the public, rather than only a distributional motive. It may be *necessary* to collect the rents to implement the socially optimal allocation. This contradicts the common perception of a trade-off between climate policy and capital accumulation (or growth) and may thus facilitate the introduction of a substantial price on carbon. Second, dynamic effects on stocks matter for the efficiency of flow-oriented climate policy instruments, and for the choice between them. Third, specifically for climate policy implemented as a permit scheme, the previous points imply an additional reason why permits should not be allocated for free.

Furthermore, the prominent role of rents from non-producible stocks in our analysis suggests an alternative climate policy instrument based on private property rights to the 'stock of the atmosphere': tradable rights to perpetually obtain a certain fraction of annual emission allowances. It has the same aggregate effects as conventional carbon pricing mechanisms, but two potential

[1] This gives at least a 66% probability of staying below 2 °C, according to the IPCC (2013), p.27.

[2] See for example Asheim (2012); Kalkuhl and Brecha (2013); Bauer et al. (2013). Other options for spending the significant revenues have also been discussed, such as the reduction of public deficits, or of distortionary (labor) taxes (Rausch, 2013; Carbone et al., 2012; Goulder, 2013; Siegmeier et al., 2015).

advantages in realistic settings: the macroeconomic portfolio effect requires unrestricted investment opportunities in both asset classes. Newly created atmospheric property rights may be more freely tradable than fossil resource stocks. Additionally, atmospheric property rights could make environmental limitations (and revenues from climate policy) more visible to individuals, thus enhancing environmental awareness.

We use a specific formal model and policy instrument, namely a two-asset overlapping-generations (OLG) model and three forms of carbon pricing, to prove the main result of this article and prove its robustness. However, this specific model should be interpreted as an illustration of the more general idea of a beneficial macro-economic portfolio effect due to rent collection via climate- and resource policy. This general idea is based on three major assumptions:

First, we assume that capital is suboptimally underaccumulated. This seems generally plausible if capital is broadly defined to include physical as well as human capital.

Second, the investment choice between capital and fossil resource stocks requires that both are available as privately owned, tradable assets in the economy under consideration. This may be the case either for a national economy that has both substantial fossil resources and capital goods, or for the world economy (interpreting rent collection as a global carbon pricing scheme). The liquidity of markets for emission-related assets also depends on the climate policy instrument chosen; for example, if the right to perpetually obtain a certain share of annual (national or global) emission rights was a tradable asset, the distribution of property rights to fossil resources would be less important for the portfolio effect to occur (see Section 3.2).

Third, we consider a situation where long-term climate policy has already been imposed (the government has credibly committed to paths for the total and auctioned amounts of permits, or for the carbon tax rate), and the economy has already adapted to each of these measures. We thus neglect the anticipation and transitional effects of the tax reform and only compare economic aggregates on balanced paths with limited emissions, but with or without rent collection.[3]

We relate our main result to three fields of research:

First, Bento and Jacobsen (2007) model a fixed factor used in dirty-good production, and assume that the resulting rents are (partially) untaxed. Then, levying an environmental tax that implicitly acts as a tax on these rents and *using the revenues* to cut distortionary labor taxes is not only preferable to *lump-sum redistribution*; it may even imply negative gross costs of the policy package because it improves an initially inefficient tax system. See Bovenberg (1999) for an overview of previous results on such 'double dividends', and Goulder (2013) for climate policy implications. While the effect presented in the present paper also stems from the collection of rents from a fixed factor, it is independent of a pre-existing distortionary and inefficient tax system. Instead, welfare is increased if a dynamic inefficiency in savings behavior is addressed:

[3] This is relevant for cases such as the European Emissions Trading System (EU ETS), where permits were initially allocated for free, and auctioning was introduced (and the total permit supply tightened) gradually and without full prior anticipation. This option improves the political feasibility of introducing such a scheme, which may be an advantage over a carbon tax. See Section 3.1.4 for a discussion.

Given that GHG emissions will be reduced, *using a policy instrument that collects the rents* from the emissions-related fixed factor (here, fossil resource stocks) to finance a given public revenue requirement *is preferable to lump-sum taxation* because it stimulates alternative, productive investment (capital accumulation). The effect is unambiguously welfare-enhancing if capital is otherwise underaccumulated. Moreover, it is independent of the recycling of the policy's revenues.[4]

Second, our contribution is related to results on non-environmental optimal rent taxation. The basic insight that a tax on rents from a fixed factor such as land generally is distortionary, since it directs investment away from land and towards capital, goes back to Feldstein (1977). Petrucci (2006) and Koethenbuerger and Poutvaara (2009) noted that this distortion is beneficial if capital was previously underaccumulated, for example due to imperfect intergenerational altruism. Edenhofer et al. (2015) provided a formal proof and found that some forms of revenue recycling can establish the social optimum. Although Feldstein already suggested that his findings would apply to resource rent taxation, we are not aware of any work on this in the pertinent literature, nor related to environmental policy. Although rents in the context of climate policy did recently receive some attention (Fullerton and Metcalf, 2001; Bauer et al., 2013; Carbone et al., 2012), previous studies focused on the size of and spending options for revenues of climate policy, while the macroeconomic effects of raising such revenues have been neglected. A potential reason for this is that collecting rents is still often presented as a non-distortionary source of public revenue (Segal, 2011; Mankiw, 2008, Chapter 8), despite Feldstein's findings.

Third, the present paper complements results on asset price changes due to avoided climate damages, and on resource taxation in an endogenous growth setting. Regarding the former, Karp and Rezai (2014b) use a discrete OLG model to demonstrate that climate policy can have aggregate beneficial effects due to a change in asset values. When capital is a fixed production factor, a Pareto-improving transfer is possible: If mitigation necessitates some investments today, all generations' welfare is increased except that of the current young. However, their effect is due to reducing overuse of a productive renewable resource and not to wealth effects due to the mitigation policy. Karp and Rezai (2014a) generalize the insight to the case of accumulable capital with adjustment costs for transforming consumption into investment goods and a climate damage function. Here we abstract from climate damages and focus on the wealth effects of the instruments that correct the externality. By contrast, Groth and Schou (2007) also consider taxation in general equilibrium with capital and non-renewable resources as alternative assets, but focus on its effects on long-run endogenous growth in a dynamically efficient setting with infinitely-lived agents. They show that taxation of a non-renewable resource that enters the 'growth engine' of an economy affects long-run growth, while capital taxation does not.

The remainder of this article is structured as follows. Section 2 lays out the basic model, in which households own both capital and fossil resource

[4]However, we formally show that the social optimum as defined by Calvo and Obstfeld (1988) can be reached if rent taxation is sufficient to finance both technical progress offsetting resource depletion and a redistribution scheme that addresses imperfect altruism between generations, the root cause of underaccumulation in our model.

stocks and are confronted with carbon pricing. Section 3 presents the result that carbon pricing induces a macro-economic portfolio effect: the higher the share of rents that is collected, the more investment is shifted away from fossil resource stocks and towards undersupplied capital, and the higher is social welfare. This is proved for two permit schemes, a conventional as well as a 'stock instrument' related to personal carbon trading schemes. Reaching the social optimum by revenue distribution is discussed. Section 4 shows that a carbon tax also induces the portfolio effect, but in contrast to permit schemes, the degree of rent extraction and the ambition of climate change mitigation cannot be chosen separately. Section 5 concludes.

2 Basic model

In this section, we set up a continuous overlapping generations (OLG) model (Yaari, 1965; Blanchard, 1985) to study whether climate policy induces a beneficial portfolio effect. There are two assets, capital and an exhaustible resource, no bequests (which leads to capital underaccumulation), and we assume technological progress in resource efficiency which is publicly financed. This will be analytically convenient when we analyze different forms of carbon pricing in the following sections: the resource extraction path (which is not our focus) can be neutralized by a matching resource efficiency path, to keep effective resource supply constant and thus obtain a balanced path. Then, the dependence of the balanced path on the share of rents that is collected by carbon pricing can be analyzed to obtain the main results. We keep brief our description of standard elements that have been developed in more detail elsewhere (Edenhofer et al., 2015).

On the supply side, assume a single final good produced from aggregate capital $K(t)$, labor $L(t)$ and fossil resource extractions $E(t)$ augmented by publicly provided technology $A(t)$.[5] The production function has constant returns to scale, diminishing marginal productivity in individual inputs and satisfies the Inada conditions in all arguments. The representative firm's problem is

$$\max_{K(t),L(t),E(t)} F(K(t), L(t), A(t)E(t)) - [r(t)+\delta]K(t) - w(t)L(t) - b(t)E(t) \quad (1)$$

yielding the standard first-order conditions

$$r(t)+\delta = F_K(\cdot), \quad w(t) = F_L(\cdot), \quad b(t) = F_E(\cdot), \quad (2)$$

with r and δ denoting the interest rate and depreciation rate of private capital, w the wage rate and b the price of an extracted unit of the resource.

Assume for simplicity that the change in technological progress is linear in public investment I_A into resource productivity improvements,

$$\dot{A}(t) = \theta I_A(t)A(t), \quad (3)$$

with R&D investment efficiency θ.

On the demand side, let ϕ be the birth rate, equal to each individual's instantaneous probability of death. Thus ϕ is also the death rate in the entire

[5]Private investment in R&D for resource efficiency may be insufficient due to the public good properties of knowledge, cf. Popp et al. (2010).

population (population size is constant and normalized to one) and individuals' lifetimes are exponentially distributed. If, for individuals born at time ν, some age-dependent variable at time t has a value $x(\nu, t)$, its aggregate (population) value is denoted by the capital letter, and

$$X(t) = \int_{-\infty}^{t} x(\nu, t)\phi e^{-\phi(t-\nu)} \mathrm{d}\nu. \tag{4}$$

At time t, an individual born at $\nu \leq t$ has expected lifetime utility

$$u(\nu, t) = \int_{t}^{\infty} \ln c(\nu, \tau) e^{-(\phi+\rho)(\tau-t)} \mathrm{d}\tau \tag{5}$$

with consumption $c(\nu, t)$ and rate of pure time preference ρ. Individuals' budget identity is

$$\begin{aligned} \dot{k}(\nu, t) + p(t)\dot{s}(\nu, t) + c(\nu, t) = r(t)k(\nu, t) + [(1 - T(t))b(t) - p(t)]e(\nu, t) + \\ + w(t) - z(t) + \phi[k(\nu, t) + p(t)s(\nu, t)] \end{aligned} \tag{6}$$

with $\dot{k}(\nu, t) = \mathrm{d}k(\nu, t)/\mathrm{d}t$, etc.[6] Individuals own capital k, on which they earn interest at rate r, and a share s of the total (exhaustible) fossil resource stock S, which they can sell or buy at a price p. Alternatively, they can extract an amount e at zero cost and sell it at price b, but have to surrender a share T of the revenue to the regulator. We assume that the resource stock is homogeneous and that all resource deposits are known (and fully owned), thus abstracting from new discoveries and (uncertain) technological change. Each individual receives the same wage w and potentially pays a lump-sum tax z (in Section 3.3, we discuss the consequences of age-dependent transfers $z(\nu, t) < 0$ for social welfare). There are no bequest motives, but a competitive, no-cost life insurance sector to close the model, which pays an annuity $\phi(k + ps)$ in return for obtaining the individuals' assets in case of death. Thus, the changes in resource ownership of all *living* generations after accounting for extractions do not sum to zero:

$$\int_{-\infty}^{t} \dot{s}(\nu, t)\phi e^{-\phi(t-\nu)} \mathrm{d}\nu + E(t) = \phi S(t). \tag{7}$$

The total resource stock S evolves according to

$$\dot{S}(t) = -E(t). \tag{8}$$

Finally, the individual also respects a solvency condition:

$$\lim_{\tau \to \infty} [k(\nu, \tau) + p(\tau)s(\nu, \tau)]e^{-R(t,\tau)} = 0 \tag{9}$$

$$\text{with} \quad R(t, \tau) \equiv \int_{t}^{\tau} (r(\tilde{t}) + \phi)\mathrm{d}\tilde{t}.$$

The government always collects a share T of the (resource) rent and instantaneously invests it, together with potential revenues from lump-sum taxes z,

[6] See Edenhofer et al. (2015) on the equivalence to a notation in terms of nonhuman assets $a = k + ps$. We separate the two assets here to make the portfolio effect more transparent.

into technological progress offsetting the decreasing supply of fossil fuels. The government's budget identity thus is

$$T(t)b(t)E(t) + Z(t) = I_A(t). \tag{10}$$

We subsequently consider different carbon pricing instruments that collect the rents and enhance mitigation to prove the main result and illustrate its robustness.

3 The beneficial portfolio effect of carbon pricing: emission permit schemes

In this section, we prove that carbon pricing may induce a beneficial macroeconomic portfolio effect. The idea of the proof is to compare two ways of financing a given public revenue requirement (here, for R&D directed at resource efficiency improvements), either by a lump-sum tax or by carbon pricing as a means to collect rents. Lump-sum taxation does not affect capital underaccumulation (which is a feature of the OLG model), while collecting scarcity rents from resource stocks makes investing in capital relatively more attractive, which enhances efficiency and welfare.

The *basic mechanism* occurs for all forms of carbon pricing. Specifically for carbon pricing implemented as a permit scheme with auctions, the *strength* of the portfolio effect is also independent of the degree of climate change mitigation: its strength increases with the share of permits that is auctioned, independently of the total number of permits.[7] Thus, both the benefits of rent collection and of mitigation can be fully exploited (according to some additional optimality criterion, which we do not model here). This is not the case for a carbon tax, which has one policy parameter less: in the choice of the (path of the) tax rate, there is a fundamental trade-off between climate change mitigation and the beneficial portfolio effect, as we will show in Section 4. Here, we analyze the welfare effect of auctioning permits under two different permit schemes, and the possibility to reach the social optimum.

In Section 3.1 we prove that for a conventional emission trading scheme which controls the flow of emissions over time, auctioning a (larger) share of the permits induces a (stronger) beneficial portfolio effect.

In Section 3.2 we discuss a hitherto unexamined instrument that limits availability of the atmospheric *stock* directly rather than the flow of emissions: households hold tradable ownership certificates to the stock of the atmosphere, they temporarily 'rent out' their part of the atmosphere to polluters and pay taxes on the revenues. We show that this instrument is equivalent to a conventional permit scheme under the assumptions employed here. However it may be more effective in realistic settings in which fossil resources are not perfectly tradable and households are motivated to protect the environment.

[7]However, the total number of permits relative to the demand for emissions determines the scarcity and thus the total price of the permits; their total number relative to the size of the remaining fossil resource stocks determines the losses faced by the owners of those stocks when the permit scheme is first introduced. Kalkuhl and Brecha (2013) and Bauer et al. (2013) analyze the potential for compensating the owners of fossil resource stocks from carbon pricing revenues. In contrast, our analyzes takes as a starting point the situation after climate policy has been introduced.

In Section 3.3 we consider the social optimum as defined in Calvo and Obstfeld (1988), which implies that the Keynes-Ramsey levels of capital and consumption are socially optimal given the assumptions of our model (see Appendix A.6). It cannot be achieved, unless permit auctioning yields sufficient revenues in excess of technology investment which are distributed disproportionately to fundless individuals rather than lump-sum.

3.1 A conventional (flow-based) emission permit scheme

We start by assuming that climate policy is implemented as a relatively short-term, upstream emission trading scheme. That is, the regulator repeatedly issues a certain amount of permits, for free or in auctions; permit lifetimes are short relative to the total time horizon over which GHG emissions have to be limited by the permit scheme; and, because we assume that there is a direct correspondence between GHG emissions and resource extraction, these permits effectively regulate fossil resource extraction. This simplifies the exposition because we do not need to model two stocks (of permits and fossil resources) and the path of resource extraction and thus GHG emissions is exogenous. Section 4 extends this result to a carbon tax that keeps the emission path endogenous.

First, we detail the policy and solve the model introduced in Section 2. Second, we characterize balanced paths on which capital and consumption stay constant while regulated resource depletion and R&D offset each other. Third, we compare pure lump-sum R&D funding to an auctioning of permits (or a tax on extraction revenues) on balanced paths. In the former case, there is underaccumulation, which is mitigated in the latter case, leading to higher aggregate consumption. Fourth, we discuss some assumptions underlying our modeling of a permit scheme.

3.1.1 Goverment policy, individual optimization and aggregate dynamics

The government implements an upstream climate policy that limits GHG emissions by limiting fossil resource extraction, and uses the revenues to finance resource efficiency improvements (as already described above). These policies do not result from endogenous maximization of a welfare criterion, but are exogenously given. More precisely, the government continuously limits aggregate resource extraction by issuing an exponentially decreasing amount of extraction permits[8] $\bar{E}(t)$, so that

$$E(t) \leq \bar{E}(t) = E_0 e^{-\sigma t}. \tag{11}$$

We assume that this constraint is binding at all times, i.e. that unregulated extraction rates would exceed the maximum permissible extraction rate σ. Thus, replacing the total resource stock dynamics (8), we have

$$\dot{S}(t) = -\bar{E}(t). \tag{8'}$$

[8]Extraction permits are equivalent to issuing permits for the amount of CO_2 emissions that the use of the extracted resource will cause, but simplifies exposition here. Moreover, note that non-exponential mitigation paths can also be accommodated: the crucial assumption for reaching an analytical solution is that technological progress can keep effective resource supply constant. See Section 3.1.4 for a discussion.

Using Equation (11) and setting $\lim_{t\to\infty} S(t) = 0$ for simplicity (implying full extraction of the initial quantity S_0), we thus obtain $\bar{E}(t) = \sigma S(t)$ and $E_0 = \sigma S_0$. A similar relationship holds for individuals, who do not choose s and e separately: even if there are several different resource stocks, their combination in individuals' portfolios is identical across homogeneous households. Thus individual resource owners will extract an amount $\bar{e}(\nu, t)$ in the same proportion to the aggregate admissible extraction as their individual resource share in the total resource stock, so $\bar{e} = \bar{E}s/S = \sigma s$. Suppressing time dependencies, we can then rewrite the budget constraint (6) as

$$\dot{k} + p\dot{s} + c = w + rk + [(1-T)b - p]\sigma s - z + \phi(k + ps). \tag{6'}$$

The share T of rents from resource extraction can be interpreted as an ongoing auctioning of a share T of permits and free allocation of the remaining permits, or equivalently, as initial free allocation of all permits followed by a tax on revenues from resource extraction.

Individuals maximize utility (5) by choosing paths for c and s, subject to budget identity (6′) and solvency condition (9). From the first-order conditions of this optimization problem, one obtains the usual Keynes-Ramsey rule for the dynamics of individual consumption

$$\frac{\dot{c}(\nu, t)}{c(\nu, t)} = r(t) - \rho \tag{12}$$

and a no-arbitrage condition between the resource stock and capital (Appendix A.1):

$$\frac{\dot{p}(t)}{p(t)} = r(t) + \frac{p(t) - [1 - T(t)]b(t)}{p(t)}\sigma. \tag{13}$$

The last term reflects the effect of exogenously imposing the resource extraction path on the resource stock price dynamics.

From the instantaneous budget identity (6′), transversality condition (9) and no-arbitrage condition (13), we also obtain a lifetime budget constraint (Appendix A.2):

$$\int_t^\infty c(\nu, \tau) e^{-R(t,\tau)} \mathrm{d}\tau = k(\nu, t) + p(t)s(\nu, t) + h(\nu, t), \tag{14}$$
$$\text{with} \quad h(\nu, t) = \int_t^\infty [w(\tau) - z(\nu, \tau)] e^{-R(t,\tau)} \mathrm{d}\tau.$$

Thus the present value of the consumption plan at time t of individuals born at ν equals their total wealth of capital, fossil resources and the present values of lifetime labor income and (potentially age-dependent) taxes/transfers.

Solving the Keynes-Ramsey rule (12) for c and substituting this in Equation (14) shows that each individual consumes the same fixed fraction of her total wealth (Appendix A.2):

$$c(\nu, t) = (\rho + \phi)[k(\nu, t) + p(t)s(\nu, t) + h(\nu, t)]. \tag{15}$$

We can now derive the remaining aggregate demand-side quantities according to (4) (see Appendix A.3). Using Equation (7), aggregation of Equation (15) yields

$$C(t) = (\rho + \phi)[K(t) + p(t)S(t) + H(t)]. \tag{16}$$

Aggregate consumption is the same constant fraction of total capital, resource, labor income and transfer wealth as for each individual. For the dynamics of the total capital stock, apply the definition of K, Leibniz' rule and the individual budget constraint ($6'$) to get

$$\dot{K}(t) = w(t) + r(t)K(t) + b(t)\bar{E}(t) - I_A - C(t). \tag{17}$$

The growth rate of aggregate consumption can be derived from the definition of C, using Leibniz' rule and Equations (12) and (15):

$$\frac{\dot{C}(t)}{C(t)} = r(t) - \rho - \phi(\rho + \phi)\frac{K(t) + p(t)S(t)}{C(t)}. \tag{18}$$

The last term is due to the 'generation replacement effect': A share ϕ of the population, owning capital K and resource wealth pS, dies and is 'replaced' by newborns without assets. This continuous turnover of generations of different wealth also affects aggregate consumption growth, since consumption is a fixed fraction $(\rho + \phi)$ of wealth. The effect of newborns' lack of capital and fossil resources is always negative. Note that the dynamics of aggregate quantities are independent of lump-sum taxes Z.[9]

3.1.2 Balanced paths

The differential equations for the aggregate resource stock S, technology A, the resource stock price p, aggregate capital K and aggregate consumption C describe the dynamics of the economy (Equations ($8'$), (3), (13), (17) and (18), respectively). The price of the extracted resource b and capital interest r depend on K, A and S via the production function, so they do not add extra dimensions.

Denote by I_A^* the research investment required to exactly offset resource depletion. Due to (3) and (11), this investment is constant:[10]

$$I_A^* = \sigma/\theta \tag{19}$$

For simplicity, we will contrast below two polar cases of financing R&D, either by permit auction revenues only, or purely by lump-sum taxation. For this reason, we assume that permit auction revenues are by themselves sufficient to finance the research investment level (19) chosen by the government to offset regulated resource depletion (11):

$$\text{There exists a } T^* \in [0;1[\text{ such that } I_A^* \leq T^* b(t)\bar{E}(t) \quad \text{for all } t. \tag{20}$$

See Section 3.1.4 for further discussion of this assumption[11]. The inequality of course also implies that the alternative lump-sum financing of R&D is

[9]For age-dependent *transfers* $-z(\nu, t)$, there is a second 'redistribution' effect: The aggregate population expects lifetime transfers of $-\bar{Z}(t)$, while newborns expect $-\bar{z}(t, t)$. The difference is an additional term in the numerator of the last fraction, the impact of which depends on how transfers redistribute wealth among generations. It *only* disappears for age-independent transfers, $\bar{Z}(t) = \bar{z}(t, t)$ (see also Section 3.3, Appendix A.3 and Edenhofer et al. (2015) for details).

[10]By Equation (3), this implies $A(t) = A_0 e^{\sigma t}$, and thus by Equation (11), we have $A(t)\bar{E}(t) = const. = A_0 E_0$: The 'effective supply' of the fossil resource remains stable.

[11]Empirically, I_A^* can be assumed to be significantly smaller than the mitigation costs of climate change, because these also comprise forgone consumption due to costly transformation of the capital stock (e.g. different power plants). However, the costs of climate

feasible in terms of potential revenues, too, since resource rents are part of each individual's lifetime income. If lump-sum taxes are politically infeasible, the consequence is a trade-off between the beneficial effect described below and distortions from other taxes, which is beyond the scope of the analysis presented here.

Then, with exogenously given depletion (11) and research (19) fixing the evolution of S and A, balanced paths are described by

$$\left\{K(t) = K^*, C(t) = C^*, S(t) = S_0 e^{-\sigma t}, A(t) = A_0 e^{\sigma t}, p(t) = p_0^* e^{\sigma t}\right\},$$

where A_0, S_0 are given and K^*, C^*, p_0^* denote the solution to the following system of equations (using Equations (2))

$$\dot{K} = 0 \rightarrow \quad C_P(K) = F(K) - \delta K - I_A^*, \tag{21}$$

$$\dot{C} = 0 \rightarrow \quad C_H(K) = \phi(\rho + \phi)\frac{K + p_0(K)S_0}{r(K) - \rho}, \tag{22}$$

$$\text{Eq.(13)} \rightarrow \quad p_0(K) = (1 - T)\sigma\frac{b_0(K)}{r(K)}, \tag{23}$$

written here with K as the independent variable for convenience in the subsequent analysis. For the last equation, we substituted $\dot{p}/p = \sigma$ in the no-arbitrage condition, and used that

$$b = F_E = F_{AE}(K, L, AE)A = F_{AE}(K, L, A_0E_0)A_0 e^{\sigma t} \equiv b_0(K)e^{\sigma t}.$$

The crucial policy parameter determining the values of K^*, C^* and p^* is the auctioned share of permits T, since the optimal choice of the extraction rate σ or of the total amount of permits (represented here by the total available resource stock S_0) are assumed to be given.

Equation (21) defines a parabola-shaped curve in the C-K-plane and Equation (22) a hyperbola. The $\dot{K} = 0$ locus is shifted downwards relative to the origin by I_A^*. We assume that I_A^* is sufficiently small so that two intersections of the parabola and hyperbola exist (for empirical plausibility see Footnote 11). While the lower is unstable, the upper is saddle-point stable. In the following, the system is reduced to two dimensions by maintaining $d(pS)/dt = 0$. This projection captures all relevant dynamics.[12] We denote variables on the balanced path (where all three of Equations (21–23) hold) by an asterisk *. In particular,

$$r^* = F_K(K^*) - \delta, \quad b_0^* = F_E(K^*)A_0, \quad p_0^* = (1 - T)\sigma b_0^*/r^*. \tag{24}$$

change are very small compared to aggregate output or capital (in the order of 0.04 to 0.14 percentage points of reduction of annual consumption growth (IPCC, 2014)). Conceptually, our assumptions about the size of I_A are distinctively un-Malthusian, because they insure that the transformation of the economy to a low-carbon state is possible at little cost and without disturbing stability.

[12] This can be shown in the three-dimensional system: Linearizing around the steady states shows that the lower is unstable, while the upper is a saddle point with one stable arm. Since C is a jump variable which instantaneously adjusts such that the optimality and transversality conditions are observed, the system is on the stable path, see Edenhofer et al. (2015) and appendices of Petrucci (2006). We merely subtract here a constant to one of the differential equations of the dynamical system examined previously. The above assumption about I_A^* ensures that this does not change the topology of the phase space and thus also not its stability properties.

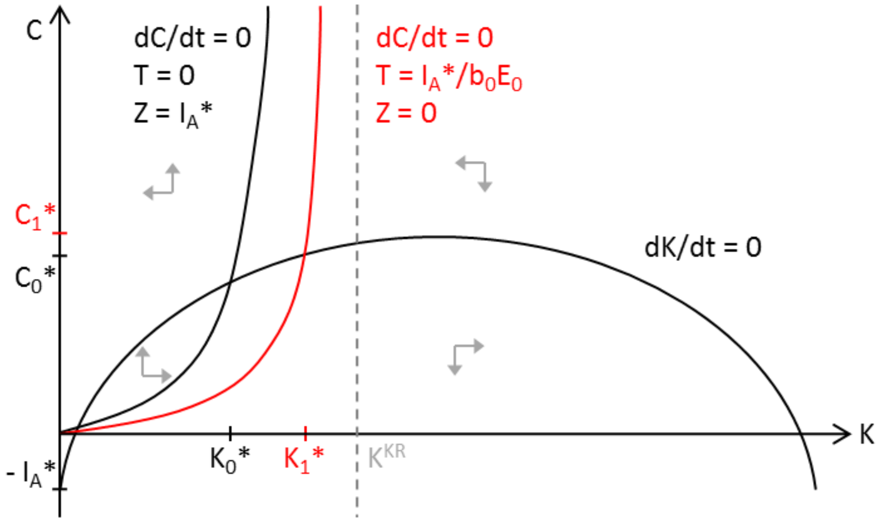

Figure 1: Phase diagram for aggregate consumption C and capital K. K^{kr} denotes the Keynes-Ramsey capital level, given by $F_K(K^{kr}) - \delta = \rho$.

Finally, on the balanced path the growth factor $R(t, \tau)$ simplifies to

$$R(t, \tau) = \int_t^\tau (r(\tilde{t}) + \phi)\mathrm{d}\tilde{t} = (r^* + \phi)(\tau - t).$$

This simplification will be used for the rest of the article wherever balanced-path properties are discussed.

3.1.3 The macroeconomic portfolio effect of carbon pricing (for a permit scheme)

We now show that underaccumulation of capital due to the generation replacement effect can be mitigated by resource rent collection (here, by auctioning of emission permits), which directs investment towards capital, but not by lump-sum taxation.

We first discuss why aggregate capital and consumption are suboptimally low. The reference point for social optimality are the Keynes-Ramsey steady-state levels of consumption $C^{kr}$and capital K^{kr}, which satisfy

$$C^{kr} = F(K^{kr}) - \delta K^{kr} - I_A^* \tag{25}$$

$$\text{and} \quad F_K(K^{kr}) - \delta = \rho. \tag{26}$$

This is derived using the approach of Calvo and Obstfeld (1988), see Appendix A.6.

Equation (22) is essential for analyzing the welfare effects of rent collection, since the position of the parabola (Equation 21) does not change. Solving for the steady state interest rate and using Equations (24) yields

$$r^* = \rho + \phi(\rho + \phi)\frac{K^* + p_0^* S_0}{C^*} = \rho + \phi(\rho + \phi)\frac{K^* + (1 - T)\sigma S_0 b_0^*/r^*}{C^*}. \tag{27}$$

Thus, the interest rate of the decentralized case is higher than the implied price of capital in the socially optimal steady state (Equation 26). From $F_{KK} < 0$ and Equation (2) follows a lower level of capital, $K^* < K^{kr}$. Since K^{kr} is left of the maximum of the parabola (21), a lower capital stock implies that consumption is suboptimal, $C(K^*) < C(K^{kr})$.

We now discuss the two policy cases, corresponding to the two hyperbolas in Figure 1. First, assume that there is no price on fossil resource extraction ($T = 0$) and that technological progress is financed by lump-sum taxation (the government's budget identity (10) becomes $Z^* = I_A^*$, which does not change the aggregate dynamics). Then, the second term in Equation (27) has its maximal value, and capital accumulation and aggregate consumption attain their lowest values (since the intersection of the hyperbola and the parabola is always to the left of the maximum of the parabola).

At the other extreme, with only the collected resource rents to finance technological progress ($Tb\bar{E} = I_A^*$ and $Z = 0$), underaccumulation is reduced relative to the lump-sum tax case, since the tax lowers p_0S_0, so *ceteris paribus* the second term in Equation (27) is smaller. The intuition is that the lower rent earnings make investing in the resource stock less attractive than capital investment, as reflected in the no-arbitrage condition (13), and thus causes a rebalancing of the asset portfolio. Also, a lower resource stock price means less 'missing wealth' for the newborns, and thus a smaller generation replacement effect (but the effect is still non-zero for all T, so the social optimum cannot be reached without additional policies, see next subsection). These effects are of course not isolated, but interact via general equilibrium effects. We thus formalize and prove the effect, also allowing for combinations of both financing options.

Theorem 1. *Suppose that the economy is on a balanced path on which publicly financed technological progress exactly offsets decreasing availability of (extraction) permits, that any share of these permits may be auctioned or allocated for free, and that lump-sum payments are available. Then, the higher the share of permits that is auctioned, the higher is social welfare.*

This result is proved in Appendix A.4 by showing that the higher the auctioned share of permits T, the higher are aggregate capital and consumption. The basic message is that it is welfare-enhancing to fulfill the revenue requirement for R&D investment by distortionary auctioning of permits instead of fulfilling it by non-distortionary lump-sum taxation (which should only close a potential gap if revenues from full auctioning are insufficient). However, the theorem is stronger: It implies that *even if* the revenue requirement can be fulfilled without auctioning all permits, it is still desirable to auction permits to the largest degree possible for efficiency reasons. Revenues in excess of R&D investment needs are redistributed here by a lump-sum transfer that is uniform across all generations; other transfer schemes are explored in the next subsection.

As a direct consequence of Theorem 1, the gross costs of climate policy are reduced if permits are auctioned because the costs of introducing a climate policy regime relative to scenarios in which there is no mitigation (not modeled here) is reduced by the efficiency gain described in our model.

3.1.4 Assumptions underlying the permit scheme model

The above model of an emission trading scheme has been tractable (despite the OLG structure) for two reasons: We assumed that relatively short permit lifetimes allow for a direct control of the emission path. Additionally, we exploited that the degree of rent extraction can be chosen independently from the emission path: by requiring that the revenues equal the investment into resource productivity improvement that is necessary to exactly offset declining fossil resource supply, a balanced path is established. We now discuss the restrictiveness of five underlying assumptions.

First, we chose a specific shape of the permissible extraction path, and resource efficiency improvements: for simplicity, we chose an exponentially declining extraction path ($E(t) = E_0 e^{-\sigma t}$), and accordingly assumed that R&D investment translate into resource efficiency improvements as $\dot{A} = \theta I_A A$, so that $I_A = \sigma/\theta$ leads to $A(t)E(t) = \text{const}$. An exponential extraction path is analytically convenient, but the exact shape of the path is irrelevant for our results as long as technological progress is such that spending no more than a certain fraction of output on R&D can offset the decreasing resource supply (see Bretschger (2005) for a discussion). This assumption about technology, at times considered optimistic, is not crucial and only employed here to obtain an analytical solution.

Second, we require public financing of resource efficiency improvements: An alternative would be to assume exogenous technological progress. We use publicly-financed R&D to underline (1) the necessity of R&D to counter mitigation-induced scarcity, and (2) that even if the mitigation path is given, the government still has a choice regarding R&D investment. The government's optimization problem that should determine this choice is not modeled here: completely offsetting resource scarcity and maintaining a steady state via R&D is chosen merely for simplicity. Furthermore, public investment in resource efficiency improvements could be interpreted to also include investment in infrastructure that matches resource-efficient technologies, such as railways, bike lanes, infrastructure for recharging electric vehicles, or electricity grids and system services required for integrating electricity generation from fluctuating renewable sources.

Third, we assume that to finance public spending on R&D, climate policy revenues can be topped up by lump-sum taxes if necessary. This is analytically convenient because we focus on rent taxation. Introducing distortionary taxation as an additional source of public funds, as for example in Turnovsky (2000), will not change the basic mechanism.

Fourth, we assume short lifetimes of permits to fix the extraction path: due to inertia of the climate system, what matters are the cumulative GHG emissions over longer periods (several decades), not their short-term path (Meinshausen et al., 2009; Ciais et al., 2013). Thus, climate policy will have to regulate GHG emissions over decades, if not centuries. However, practical implementations of climate policy via emission trading schemes, such as the EU ETS and the California Cap-and-Trade scheme, operate on shorter time scales, with emission budgeted over trading periods of eight and three years, respectively. Forward 'banking' of unused permits between trading periods is generally allowed (and is beneficial when the supply of new permits is successively tightened (Rubin, 1996)), but can be neglected if we assume that emission budgets are a binding constraint. More importantly, 'borrowing' of permits to delay mitigation is not possible in California, and restricted to within a trading period in the EU. Thus, when endogenous exhaustion is limited to short time horizons, a succession of many short-term budgets can be approximated well by a fixed path. The fixing of such a long-term mitigation path by the government is not necessarily less efficient than a decentralized solution, depending e.g. on whether individual agents or the government are myopic or not.

Fifth, our analysis starts after climate policy has been credibly imposed and for the long-term (see also Footnote 3): economic actors know and have adapted to the paths for total and auctioned amounts of permits, so it is sufficient to compare balanced paths with different auctioned shares. We do not model the transition to these balanced paths after climate policy is first announced, including the initial one-off devaluation of fossil resource stocks that cannot be exploited anymore at the desired rate.[13] Thus, our analysis cannot be directly applied to an 'extreme' case of a permit scheme: Alternatively to successively issuing smaller budgets of permits as in our model (and in contrast to actual implementations of permit schemes), one may issue (and partly auction) at $t = 0$ the entire budget of permits that are valid to a point far into the future. This would leave the intertemporal allocation problem, which then resembles a standard optimal resource extraction problem, to the market for permits after that. However, this one-off rent collection (a single auction at $t = 0$) then just adds to the one-off devaluation of fossil resource stocks due to the restriction of the extraction path: the effect of such a form of rent collection is transitional and not part of our model.

Overall, this supports our modeling of a GHG emission permit scheme above. Yet it remains to be shown if our hypothesis also holds for a carbon tax (as an alternative carbon pricing instrument that does not fix the emission path), which we consider in Section 4.

3.2 Owning the atmosphere: A 'stock instrument'

The stock-flow structure of our model also suggests an alternative permit-based instrument: Instead of regulating the flow of emissions, one could limit the availability of the stock and make claims on it tradable: Households obtain property rights for the atmosphere and the government regulates to how much annual emissions this entitles them. We first describe what the instrument consists in and subsequently show that it is equivalent to the model presented earlier in this article. We then consider two arguments why the stock instrument may be preferable to a conventional flow-based permit scheme: fossil resources may be less tradable than atmospheric property rights, and a stock instrument may lead to enhanced environmental awareness compared to conventional emission trading.

We suggest a stock instrument for climate policy with the following structure: Assume that households own shares s_a of the atmosphere (instead of shares of fossil resource stocks). Ownership of such shares entitles them to annually obtain emission rights, the amount of which decreases at rate σ. Households can sell these emission rights to firms at a price l and pay taxes on the revenues (they 'rent out' their share of the atmosphere to the firms). They can also trade the shares among each other. Our suggestion is related to the 'long-term permit' component of the McKibbin-Wilcoxen hybrid climate policy (McKibbin and Wilcoxen, 2002), which those authors also allow

[13]See Koethenbuerger and Poutvaara (2009) and Heijdra et al. (2006) for a theoretical analysis of transition effects of introducing a tax on a fixed factor or pollution, respectively.

to embody declining annual emission rights (McKibbin and Wilcoxen, 2007; McKibbin, 2012).[14] However, this type of permit system has not been considered in an analytical model before the present article. It is also related to the case of 'exogenously shrinking' land considered by Buiter (1989) in the context of debt neutrality of taxation of fixed factors.

For this alternative instrument, the model presented in Section 2 is modified as follows: The individual budget becomes

$$\dot{k} + p\dot{s}_a + c = w + rk + [(1-T)l - p\sigma]s_a - z + \phi(k + ps_a). \tag{6'}$$

Here the contribution $-p\sigma s_a$ comes from the annual decrease in emission rights attached to the ownership of an atmospheric stock. The dynamics of the atmospheric stock are controlled by the government and, as above, taken to be

$$\frac{\dot{S}_a}{S_a} = -\sigma. \tag{8'}$$

Its decreasing availability reflects the limited disposal space for emissions. Still, $\dot{S}_a = -E$, so that $E = \sigma S_a$. So σ is both the rate of decline of the atmospheric stock as well as the ratio between emissions used and total available space in the atmosphere. In particular, while households rent out their share of the atmosphere to the firm for one year, E denotes the emissions permitted in production, which are proportional to the current given size of S_a. Hence

$$l = F_{S_a}(K, L, AE(S_a)) = F_E(K, L, AE(S_a))\sigma. \tag{28}$$

The remaining modification to the previous model is Equation (7), which has to be changed to

$$\int_{-\infty}^{t} \dot{s}(\nu, t)\phi e^{-\phi(t-\nu)} \mathrm{d}\nu - \sigma S(t) = \phi S(t), \tag{7'}$$

as the atmospheric stock shrinks without being used. The remaining defining equations of the model are identical. The only change to the dynamics of the model is a no-arbitrage condition between the atmospheric stock and capital:

$$\frac{(1-T)l}{p} + \frac{\dot{p}}{p} = r + \sigma. \tag{13'}$$

As the remaining equations describing the dynamics of the economy are unchanged, the stock instrument will be equivalent to the conventional permit scheme, if $l = b\sigma$. This holds by Equation (28). The equation between prices l and b is true because renting the stock of the atmosphere S_a at rate l, or buying a flow of resources $\bar{E} = \sigma S$ at price b, must have the same value to firms. Thus, the original and modified budget equations are the same. The deeper reason for this equivalence is that our model of the flow-based permit scheme already contains the core of the stock instrument, which is to treat e as proportional to s and thus to prevent endogenous extraction dynamics.

[14]The nature of the 'long-term permits' is not central to the major advantages of the hybrid climate policy propounded by McKibbin and Wilcoxen (2002). In McKibbin and Wilcoxen (2007), the authors attribute the suggestion of embodying declining emission rights into a long-term permit to Rob Stavins, while in McKibbin (2012) some advantages to this specific design are briefly mentioned, see also below.

While the stock- and flow permit schemes are formally equivalent in our model of a closed, competitive economy, where everyone owns resources (or parts of the atmosphere), differences may arise in more realistic settings. The two instruments seem to imply different distributions: While considering the fossil resource stocks underlying an emission trading scheme evokes that 'only resource owners' possess such assets, introducing a new property structure is associated with the idea that 'everyone gets permits'. However, an initial or perpetual reallocation of shares of the stock is in principle possible for *both* instruments, so differences between the two instruments do not arise primarily from different distributions. Instead, we discuss two genuine distinctions:

First, the models of this article rest on the assumption that the fossil resource or atmospheric stocks are fully tradable. Yet in economic reality, there may be several classes of agents, or heterogeneous countries which mostly hold either capital assets or fossil resources. If there are investors that specialize on one class of assets only, or are barred from investing in the alternative class of assets, a portfolio effect may not occur, as fossil resources are not fully traded. A stock instrument, in contrast, creates assets that are (designed to be) fully tradable, overcoming a possible 'separation' of assets that could weaken the portfolio effect if climate policy is implemented as a flow-based permit scheme.

Second, a standard argument against implementing climate policy by an emission trading system is that it crowds out social preferences, namely personal motivation to behave in an environmentally-friendly way (Frey, 1999; Bowles and Polania-Reyes, 2012). An alternative climate policy could attempt to make the scarcity of carbon sinks more tangible to individuals, and provide them with an opportunity to express social preferences directly and visibly for others. A consequence of such a policy may be greater political support for introducing or tightening a cap on emissions (see also McKibbin, 2012). This has been the chief motivation behind the idea of personal carbon trading (PCT) schemes (Hillman, 1998; Fleming, 1997) to which our suggestion of a 'stock instrument' is related. They have been discussed in some theoretical detail (Starkey, 2012a,b) and also received considerable interest from policy makers (Fawcett, 2010). The schemes closest to our model are the Ayres scheme (Ayres, 1997) and the Cap&Share scheme (as described in Starkey, 2012a), where every year, a decreasing amount of tradable emission rights is initially allocated to individuals on an equal per capita basis, and can then be sold on to emitting firms. In addition to this flow market, our suggested instrument involves a 'secondary' stock market where rights to the flow of individuals' future allocations of permits are traded as an asset. Thus, while PCT only differs from conventional emission trading systems by regulating emissions directly at the level of the households, our proposed stock instrument would additionally give households some 'property rights to the atmosphere', with ensuing investment decisions. Whether such a policy may enhance environmental awareness and may be more socially acceptable than conventional emissions trading is a question for future research.

3.3 Non-uniform revenue redistribution and social optimality

As an extension to the basic model above, we now show that if climate policy revenues exceed R&D financing requirements, they can be used for age-dependent transfers that may establish the social optimum.

If resource revenues exceed required R&D investments ($T^* < 1$), it can be seen from Equations (22), (23) and (27) that raising the auctioned share above T^* further reduces the value of the fossil resource and the interest rate, and increases the capital stock and consumption. But due to the missing capital wealth ϕK of the newborns, the generation replacement effect never fully disappears by this price effect alone (the second term in Equation (27) remains positive). It only disappears if the revenues in excess of required R&D investments are used for age-dependent transfers that are received disproportionately by the newborns. This is proved by Edenhofer et al. (2015), whose results apply directly to our case as well, only accounting for the need to finance R&D along with transfers:

If lump-sum payments z that enter individuals' budget constraint (6) are potentially *age-dependent* ($z = z(\nu, t)$, instead of $z(t)$), we obtain a more general expression for aggregate consumption growth (while all other equations for aggregate dynamics remain unchanged; see Appendix A.3):

$$\frac{\dot{C}(t)}{C(t)} = r(t) - \rho - \phi(\rho + \phi)\frac{K(t) + p(t)S(t) - \bar{Z}(t) + \bar{z}(t,t)}{C(t)}. \tag{18'}$$

Thus, for rent collection that (also) finances age-dependent transfers (negative z, which were defined as taxes), there is a 'redistribution effect' additional to the price effect discussed above: The difference between the expected transfers to the aggregate population $\bar{Z}(t)$ and to newborns $\bar{z}(t,t)$ reflects how transfers redistribute wealth among generations, and thus affects the size of the generation replacement effect. Only if transfers are age-independent ($\bar{Z}(t) = \bar{z}(t,t)$), the difference is zero and the redistribution effect disappears.[15] If, on the contrary, transfers are biased towards newborns, the social optimum may be established. For the case in which only newborns receive any transfers, we have

$$\bar{z}_n(t,t) = -\frac{Tb(t)\bar{E}(t) - I_A(t)}{\phi}, \tag{29}$$

$$\bar{z}_n(\nu,t) = 0 \quad \text{for } \nu > t \quad \text{and} \tag{30}$$

$$\bar{Z}_n(t) = 0. \tag{31}$$

The auctioning (or extraction tax) rate that reproduces the social optimum on the balanced path, for which the generation replacement effect disappears, is

$$T^{opt} = \frac{\phi(K^* + p_0 S_0) + I_A^*}{b_0 \sigma S_0} = \frac{\phi(r^* K^* + b_0 \sigma S_0) + r^* I_A^*}{(r^* + \phi) b_0 \sigma S_0}. \tag{32}$$

For age-independent transfers, underaccumulation is mitigated by the price effect, but cannot be fully cured even for $T = 1$. For transfers to newborns only, the additional redistribution effect can compensate newborns' 'missing capital' and establish the social optimum. Both effects together may even lead to overaccumulation, so the optimal auctioning share may be smaller than one. See Edenhofer et al. (2015) for further details and other redistribution schemes.

[15] Thus, the expressions (18) above and $\dot{H} = (r + \phi)H - w + Z$ (with Z defined as a tax), often considered standard results in the literature (Petrucci, 2006; Marini and van der Ploeg, 1988), are in fact a special case.

4 Trading off the beneficial portfolio effect and climate protection: carbon taxes

This section shows that if climate policy is implemented by a carbon tax, it still induces a shift in investment away from fossil resource stocks and towards (previously underaccumulated) capital, so that a beneficial portfolio effect occurs. However, the analysis also reveals a fundamental trade-off between this effect and climate change mitigation: the strongest portfolio effect occurs for a constantly high carbon tax rate, while changing the GHG emission path with a carbon tax requires varying the tax rate. A constant carbon tax only indirectly contributes to emission reductions, because the portfolio effect leads to a higher capital stock, implying lower interest rates and thus slower extraction.

Technically, the main difference of a carbon tax compared to a permit scheme is that the fourth of the assumptions in Section 3.1.4 is relaxed, i.e. the extraction path is determined endogenously, and it may be affected by the path of the tax. We start by modifying the resource extraction part of our continuous OLG model for a carbon tax instead of a permit scheme.

We then show that a government aiming to establish a balanced path with constant aggregate capital and consumption not only needs to invest into technological progress to offset resource scarcity as before, but also has to keep the carbon tax constant. In such a setting, the full dynamical system resembles the permit case, so Theorem 1 can be extended: a higher constant carbon tax level leads to higher social welfare.

Thus, there is some climate change mitigation even under a constant carbon tax: Although it does not *directly* affect the path of resource extraction and GHG emissions (Dasgupta and Heal, 1979), the portfolio effect leads to a higher capital stock and lower interest rate, so extraction is slower.

Finally, we briefly consider scenarios where the system is not on a balanced path, because effective climate policy is imposed by a non-constant carbon tax (which implies different growth rates of the resource stock and the resource stock price, so that the OLG-specific generation replacement effect is non-constant). Even then, a macroeconomic portfolio effect can be conjectured to occur; but the carbon tax remains less flexible than a permit scheme, independent of assumptions about technological progress, since choosing a mitigation path fixes the path of revenues from rent collection.

Assume an OLG model with two assets, capital and an exhaustible resource, as above, but endogenous extraction under a (potentially time-dependent) carbon tax instead of an exogenously given extraction path implemented by a permit scheme. The carbon tax is interpreted as an ad-valorem tax on resource extraction. Again, carbon pricing revenues are used to finance resource efficiency improvements.

The firms' problem remains unchanged. On the demand side, with individual resource extraction e as an independent control variable, the individual budget identity (6) does not simplify to (6′), and the path of the aggregate resource stock is endogenous according to (8). Individual optimization yields a simpler no-arbitrage condition than before, identical to the well-known Hotelling rule, and an additional condition on resource prices (we suppress time dependencies in the following):

$$\dot{p}/p = r, \tag{13$''a$}$$
$$p = (1 - T)b. \tag{13$''b$}$$

Thus, while resource extraction e and resource stock ownership s can be chosen separately, their prices are not independent. However, they may grow at different rates: Combining the two conditions gives

$$\dot{b}/b = r + \psi \quad \text{with} \quad \psi := \dot{T}/(1 - T), \tag{13$''c$}$$

so a decreasing auctioned share ($\psi < 0$) implies that p grows faster than b. From the firms' first-order conditions (2), we have

$$\frac{\dot{b}}{b} = \frac{\dot{F}_E(K, L, A, E)}{F_E(K, L, A, E)} = \frac{\dot{A}}{A} + \frac{\dot{K} F_{EK}}{F_E} + \frac{(\dot{A}E + A\dot{E})F_{EE}}{AF_E}. \tag{33}$$

Substituting this into (13$''c$) and solving for $\dot{E}$ shows that *ceteris paribus* (in particular for constant K), the resource extraction rate depends on the *rate of change* of the tax rate, but not on the rate itself.

The dynamics of aggregate capital and aggregate consumption remain almost unchanged:

$$\dot{K} = w + rK + bE - I_A - C, \tag{17$''$}$$
$$\frac{\dot{C}}{C} = r - \rho - \phi(\rho + \phi)\frac{K + pS}{C}. \tag{18}$$

Compared to the case with permits, only the government-controlled extraction $\bar{E}(t)$ has been replaced by $E(t)$, which is determined endogenously from the households' problem above.

The government takes into account the firms' and households' first-order conditions (thus being the leader in a Stackelberg game) when it chooses the tax rate T and public investment I_A in resource efficiency improvements governed by (3). These are balanced in the government's budget (10) by lump-sum taxes or transfers Z, if necessary.

Assume that the government seeks to establish a balanced path with $K(t) = K^*$, $C(t) = C^*$. It follows from Equation (17$''$) that this requires the marginal resource productivity to grow as fast as resource supply declines (otherwise output is not constant), while for the generation-replacement effect in Equation (18) to stay constant, the resource stock price has to grow as fast the resource stock declines, so we have

$$\frac{d}{dt}(AE) = 0, \tag{34}$$
$$\frac{d}{dt}(pS) = 0. \tag{35}$$

Appendix A.5 shows that these conditions can be satisfied on a balanced path by choosing

$$I_A = 1/\theta(-\dot{E}/E), \tag{36}$$
$$\psi = 0, \tag{37}$$

so a balanced path only exists under a carbon tax if the tax rate is constant. On such a balanced path, we have

$$\dot{b}/b = \dot{p}/p = \dot{A}/A = -\dot{E}/E = -\dot{S}/S = r(K^*), \tag{38}$$

since as long as the carbon tax and R&D investment are constant, the resource stock and resource extraction change at the same rate, so the price for the extracted resource and the stock also need to evolve at the same rate. A non-constant carbon tax would drive a wedge between them ($\dot{p}/p = r = \dot{b}/b - \psi$).

A balanced path is consistent with a constant carbon tax *of any level* (except $T = 1$, for which the resource stock market would collapse). On such a path, the contribution of resource wealth to the generation replacement effect is constant, but smaller for a higher carbon tax ($pS = (1-T)b_0(K^*)S_0$). Thus, the following result holds (proved in Appendix A.5):

Corollary 2. *Assume that production can be described by a Cobb-Douglas function. Suppose the decreasing availability of fossil resources is exactly off-set by technological progress, which is publicly financed by the revenues of a constant carbon tax and, if necessary, lump-sum taxes. Then, the higher the absolute level of the constant carbon tax, the higher is social welfare.*

Finally, consider a *non-constant* carbon tax that affects the endogenous extraction path (Dasgupta and Heal, 1979). The tax will need to decrease to provide an incentive for resource conservation and thus mitigation (Sinclair, 1994). As we saw above, this does not result in a balanced path in a continuous OLG setting (so we cannot apply the same analytical method as above). Nevertheless, *some* part of the fossil resource rent still is extracted by the carbon tax, the value of the fossil stock is reduced and saving in producible capital becomes more attractive, so the basic effect can be expected to hold for a non-constant carbon tax as well:

Conjecture 3. *The macroeconomic portfolio effect still holds under a time-dependent carbon tax.*

Even a time-dependent carbon tax is still less flexible than a permit scheme: If the extraction path is fixed by the carbon tax, the path of tax revenues is also fixed - in contrast to a permit scheme, in which the amounts available for extraction can be chosen independently from the auctioning rates (which may be constant, as above, or vary over time). Without this additional flexibility, it is not possible to implement a given mitigation path *and* arbitrary rent collection simultaneously. Instead, there is a trade-off: the macroeconomic portfolio effect induced by a time-dependent carbon tax is weaker than under a permit scheme to the extent that the mitigation incentive of a falling tax rate is given priority.

5 Conclusion

In his seminal contribution on rent taxation, Feldstein (1977, p.356) wrote that *"[i]ncreasing the effective rate of tax on natural resources creates a capital loss for the current owners and thus induces additional capital accumulation"*. For the case of climate policy, this effect has so far been unexamined. Given the scale of the challenge of decarbonisation with implications at the macroeconomic level, we deem the Feldstein effect of primary importance for future political attempts to put a price on carbon.

The present article therefore has studied the impact of climate policy on aggregate investment behavior. It revealed differences between standard policy instruments to regulate emissions. For a conventional emission trading system, auctioning of permits was proved to induce a shift of investment away from fossil resource stocks towards producible capital. If capital is underaccumulated – a plausible assumption if capital is broadly conceived and includes human capital – this 'macroeconomic portfolio effect' increases efficiency and thus social welfare. The effect implies that the gross costs of climate policy are lower compared to cases in which rent extraction is allocation-neutral, and provides a new reason for the old conclusion that permits should not be allocated for free. If imperfect intergenerational altruism is the source of capital underaccumulation, using the revenues from rent-extracting policies to the benefit of the young may even establish the social optimum.

The portfolio effect relies on the assumption that the resource stocks affected by the conventional,'flow-based', permit scheme are tradable assets directly competing with capital goods. If this is not the case, and in particular in settings with several countries or classes of agents with different resource endowments, a 'stock-based' scheme that introduces ownership of a share of perpetually renewed emission rights may offer a remedy: while being formally equivalent to the conventional permit scheme, the new asset may be more liquid and more widely available. Furthermore, environmental awareness and political feasibility of stringent climate policy could be enhanced by distributing atmospheric property rights instead of implementing an upstream emissions trading system.

A similar effect occurs for the case of a carbon tax. The carbon tax is however not equivalent to the permit schemes: the tax rate is the only policy variable and the resource extraction path is endogenous, while under a permit scheme the share of permits to be auctioned and the total amount of permits can be chosen separately.

Our results similarly apply to resource rents more generally, so we confirm Feldstein's original conjecture and extend it: extracting resource rents has dynamic investment effects, and since these are efficient, resource rent extraction is desirable not only for distributional reasons.

Even more generally and beyond climate economics, our results support the view of Stiglitz (2015) that rents and their taxation are pivotal to understanding and addressing current trends of growth and distribution.

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A Appendix

A.1 Derivation of the Keynes-Ramsey rule and the arbitrage condition

The budget constraint (6′) can be split into a constraint in monetary terms and another in terms of the fossil resource by defining $d(\nu,t) = \phi s(\nu,t) - \dot{s}(\nu,t) - \bar{e}$, where $\bar{e} = \bar{E}/Ss = \sigma s$. Dropping the time arguments, we obtain:

$$\dot{k} = w + [r+\phi]k + (1-T)\sigma bs + pd - z - c \tag{39}$$

$$\dot{s} = \phi s - d - \sigma s. \tag{40}$$

Individuals maximise utility given by Equation (5) by choosing $c(\nu,t)$ and $d(\nu,t)$, subject to Equations (39), (40) and the transversality condition (9). Writing λ and μ for the multipliers of (39) and (40) in the current value Hamiltonian H_c, we obtain the following first order conditions:

$$\frac{\partial H_c}{\partial c} = \frac{1}{c} - \lambda = 0 \tag{41}$$

$$\frac{\partial H_c}{\partial d} = \lambda p - \mu = 0 \tag{42}$$

$$\frac{\partial H_c}{\partial k} = (\rho+\phi)\lambda - \dot{\lambda} \quad \Rightarrow \quad \lambda(r+\phi) = (\rho+\phi)\lambda - \dot{\lambda} \tag{43}$$

$$\frac{\partial H_c}{\partial s} = (\rho+\phi)\mu - \dot{\mu} \quad \Rightarrow \quad \lambda(1-T)\sigma b + \mu(\phi-\sigma) = (\rho+\phi)\mu - \dot{\mu}. \tag{44}$$

Inserting the time derivative of (41) into Equation (43) yields the Keynes-Ramsey rule (12). Using Equation (42) and its time derivative to replace μ and $\dot{\mu}$ in Equation (44) and applying Equation (43) gives the arbitrage condition for investing in fossil resources or capital (13).

A.2 Individual lifetime budget constraint and consumption level

First, to derive the lifetime budget constraint (14), regrouping terms in (6′) and adding $\dot{p}s - (r+\phi)ps$ on both sides gives:

$$\dot{k} + p\dot{s} + \dot{p}s - (r+\phi)(k+ps) = w + (1-T)\sigma bs - p\sigma s + \dot{p}s - rps - z - c = \\ = w - z - c.$$

The last equality follows from (13). This leads to

$$\frac{d}{d\tau}\left[(k+ps)e^{-R}\right] = (w-z-c)e^{-R}$$

$$\Rightarrow \int_t^\infty \frac{d}{d\tau}\left[(k+ps)e^{-R}\right]\mathrm{d}\tau = \int_t^\infty (w-z-c)\,e^{-R}\mathrm{d}\tau$$

$$\Rightarrow -k(\nu,t) - p(t)s(\nu,t) = \bar{w}(t) - \bar{z}(\nu,t) - \int_t^\infty c(\nu,\tau)e^{-R}\mathrm{d}\tau,$$

which is the lifetime budget constraint (14), written here in the more general form with age-dependent transfers/taxes $z(\nu,t)$. For the integration of the left-hand side in the last step, we used $\exp(-R(t,t)) = 1$ and Equation (9).

Then, the individual consumption level follows from solving the Keynes-Ramsey rule for c, which gives

$$c(\nu,\tau) = c(\nu,t)\exp\left(\int_t^\tau (r(\tau)-\rho)\mathrm{d}\tau\right),$$

and substituting this into the lifetime budget equation,

$$\begin{aligned}k(\nu,t)+p(t)s(\nu,t)+\bar{w}(t)-\bar{z}(\nu,t) &= \int_t^\infty c(\nu,t)e^{\int_t^\tau [r(\tilde{t})-\rho]\mathrm{d}\tilde{t}}e^{-R(t,\tau)}\mathrm{d}\tau = \\ &= c(\nu,t)/(\rho+\phi).\end{aligned}$$

Hence, individual consumption is a fixed fraction of wealth.

A.3 Aggregate solution

We derive the aggregate quantities for general age-dependent transfers $z(\nu,t)$, and then simplify them for uniform transfers to obtain the relations given in the main text.

The aggregate consumption level $C(t)$ for general transfers is obtained directly from aggregation of Equation (15), as given by Equation (16) in the main text.

The dynamics of the total capital stock (17) are obtained by applying Leibniz' rule to

$$K(t) = \int_{-\infty}^t k(\nu,t)\phi e^{\phi(\nu-t)}\mathrm{d}\nu,$$

replacing $\dot{k}$ by its expression from the individual budget constraint (6′), and using Equation (7) for aggregate changes in resource ownership:

$$\begin{aligned}\dot{K}(t) &= \underbrace{k(t,t)}_{=0}\phi e^{\phi(t-t)} - 0 + \int_{-\infty}^t \frac{\mathrm{d}}{\mathrm{d}t}\left[k(\nu,t)\phi e^{\phi(\nu-t)}\right]\mathrm{d}\nu = \\ &= -\phi K(t) + \int_{-\infty}^t \dot{k}(\nu,t)\phi e^{\phi(\nu-t)}\mathrm{d}\nu = \\ &= w(t)+r(t)K(t)+[1-T(t)]\sigma b(t)S - p(t)\sigma S + \\ &\quad + p(t)\underbrace{\left[\phi S - \int_{-\infty}^t \dot{s}(\nu,t)\phi e^{\phi(\nu-t)}\mathrm{d}\nu\right]}_{=\bar{E}=\sigma S} - C(t) - \underbrace{\int_{-\infty}^t z(\nu,t)\phi e^{\phi(\nu-t)}\mathrm{d}\nu}_{=-T(t)b(t)\sigma S+I_A} = \\ &= w(t)+r(t)K(t)+\sigma b(t)S - I_A - C(t).\end{aligned}$$

The government budget constraint (10) was used in the last step, to the effect that the aggregate result does not directly depend on the transfer scheme $z(\nu,t)$. However, it may have an indirect effect via prices, stock levels and consumption.

Similarly, we derive the dynamics of aggregate consumption, first for the case of general, age-dependent transfers $z(\nu,t)$:

$$\begin{aligned}\dot{C}(t) &= c(t,t)\phi e^{\phi(t-t)} - 0 + \int_{-\infty}^t \frac{\mathrm{d}}{\mathrm{d}t}\left[c(\nu,t)\phi e^{\phi(\nu-t)}\right]\mathrm{d}\nu = \\ &= \phi(\rho+\phi)[h(t,t)] - \phi C(t) + \underbrace{\int_{-\infty}^t \dot{c}(\nu,t)\phi e^{\phi(\nu-t)}\mathrm{d}\nu}_{=(r(t)-\rho)C(t)} = \\ &= [r(t)-\rho]\,C(t) - \phi(\rho+\phi)[K(t)+p(t)S-\bar{Z}(t)+\bar{z}(t,t)].\end{aligned}$$

The first equality follows from Leibniz' rule. For the second, $c(t,t) = (\rho + \phi)[k(t,t) + p(t)s(t,t) + h(t,t)] = (\rho + \phi)[h(t,t)]$ is used. In the third step, $\phi C(t)$ is replaced using Equation (16). Alternatively, we could have directly differentiated Equation (16) and used that, by Leibniz' rule, $\dot{H} = (r + \phi)H - w + Z + \phi(\bar{Z} - \bar{z}(t,t))$. We thus obtain

$$\frac{\dot{C}(t)}{C(t)} = r(t) - \rho - \phi(\rho + \phi)\frac{K(t) + p(t)S(t) - \bar{Z}(t) + \bar{z}(t,t)}{C(t)}.$$

This is the general result (18′) used in Section 3.3. For the special case of uniform, age-independent transfers,

$$z(\nu, t) = z_u(t), \tag{45}$$

we have $\bar{Z}(t) = \bar{z}(t,t) = \bar{z}_u(t)$ and Equation (18′) simplifies to Equation (18) in the main section.

A.4 Formal proof of the portfolio effect

Proof of Theorem 1. The idea of the proof is to compare the steady state of the decentralized equilibrium for two different auctioned shares of permits (or tax rates on resource extraction revenues): It will be shown that although for a *fixed* capital stock, consumption, and thus social welfare, is lower with a higher auctioned share, both the consumption and the capital stock are higher in the steady state, the higher the auctioned share is. This is illustrated in Figure 1.

Consider two auctioning shares, $0 \leq T_1 < T_2 \leq 1$. Let the steady state defined by Equations (21) and (22) for the two shares be denoted by (K^{1*}, C^{1*}) and (K^{2*}, C^{2*}). The superscripts 1 and 2 also indicate the respective cases for the parabola and the hyperbola. From the definition of social welfare given in Section 3.1, it is sufficient to prove that

$$C^{1*} < C^{2*}.$$

The parabola (21) (defined by $\dot{K} = 0$) is not affected by the auctioned share. However the hyperbola (22) (defined by $\dot{C} = 0$) changes: It is equivalent to the following expression

$$C_H^i(K) = \phi\frac{\rho + \phi}{r(K) - \rho}\left\{K + \frac{\sigma b_0(K)S_0}{r(K)} - T_i\frac{\sigma b_0(K)S_0}{r(K)}\right\} \tag{46}$$

for $i = 1, 2$. As the last term in the curly bracket is negative, it follows that $C_H^2(K) < C_H^1(K)$ for all $K \in [0, K^{kr}]$. In Figure 1, the hyperbola for T_2 is below that for T_1.

For any $K < K^{1*}$, we also have $C_H^1(K) < C_P^1(K)$ and $C_P^1(K) = C_P^2(K)$ since the parabola is independent of T. Hence $C_H^2(K) < C_P^2(K)$ for $K < K^{0*}$. Moreover, $C_H^i(K)$ is positive for all $K \leq K^{kr}$, and thus tends to $+\infty$ as K approaches K^{kr}. Thus the (non-trivial) intersection of parabola and hyperbola for T_2 must occur at a capital stock K^{2*} with $K^{1*} \leq K^{2*} < K^{kr}$. In this interval, $C_P(K)$ is increasing in K, thus $K^{1*} < K^{2*}$ and also $C^{1*} < C^{2*}$, as required. □

A.5 Dynamical system and portfolio effect for constant carbon tax

We first show that a carbon tax needs to be constant for a balanced path to exist. From Equations (17) and (18), we saw that $K(t) = K^*, C(t) = C^*$ requires $d/dt(AE) = 0$ and $d/dt(pS) = 0$. From the first condition and Equation (3) follows that the government needs to set $I_A = 1/\theta(-\dot{E}/E)$ on a balanced path. The second condition can be rewritten with the help of Equation ($13''b$) as $d/dt[(1-T)bS] = 0$. So the government needs to choose $\psi(t)$ such that the following system of differential equations is solved:

$$\begin{aligned}
&\dot{S}/S = -E/S,\\
&\dot{b}/b = \psi - \dot{S}/S \quad \text{(for } (1-T)bS \neq 0),\\
&\dot{b}/b = \psi + r.
\end{aligned}$$

The last two conditions are only both satisfied if $\dot{S}/S = -r$, which is constant on the balanced path. From the first equation then follows that

$$\dot{E}/E = \dot{S}/S = -r.$$

Furthermore, using the balanced-path conditions $d/dt(AE) = 0$ and $\dot{K} = 0$ in (33), and again $\dot{E}/E = -r$, we have

$$\dot{b}/b = \dot{A}/A = -\dot{E}/E = r.$$

This can only hold simultaneously with the fifth equation above if

$$\psi = 0.$$

We now show that Theorem 1 extends to the case of a constant carbon tax (or long-term permit scheme). For the aggregate dynamics under a general carbon tax, we obtained in Section 4:

$$\dot{S} = -E, \tag{8}$$

$$\dot{p}/p = r \quad \text{and} \quad p = (1-T)b, \tag{$13''a$}$$

$$\dot{b}/b = r + \psi \quad \text{with} \quad \psi := \dot{T}/(1-T), \tag{$13''c$}$$

$$\dot{K} = F(K, L, AE) - \delta K - I_A - C, \tag{17}$$

$$\dot{C}/C = r - \rho - \phi(\rho + \phi)(K + pS)/C, \tag{18}$$

$$\dot{A} = \theta I_A A. \tag{3}$$

The first five equations represent the behavior of the private agents, the last equation the government's resource efficiency investment. Assume that the government implements a tax which is constant ($\psi = 0$), implying that $\dot{p}/p = \dot{b}/b = r$. Furthermore, assume that it uses the revenues for R&D investment that exactly offsets resource extraction, $I_A = 1/\theta(-\dot{E}/E)$, so that $AE = const.$ and $\dot{A}/A = -\dot{E}/E$. Then, the essential dynamics of the system are captured by just four differential equations (without the second and the last equation above).

Finally, for simplicity we assume that production can be described by a Cobb-Douglas function, $Y = F(K, L, AE) = K^{\alpha}(AE)^{\beta}L^{(1-\alpha-\beta)}$. Using Equation (33), we then have

$$\frac{\dot{b}}{b} = \frac{d/dtF_E(\cdot)}{F_E(\cdot)} = \frac{\dot{A}}{A} + \alpha\frac{\dot{K}}{K}.$$

The essential dynamical system can now be written as

$$\dot{S}/S = -E/S, \tag{47}$$
$$\dot{E}/E = \alpha\dot{K}/K - r(K), \tag{48}$$
$$\dot{K}/K = \left[F(K) - \delta K - C + \dot{E}/(\theta E)\right]/K, \tag{49}$$
$$\dot{C}/C = r(K) - \rho - \phi(\rho+\phi)\left[K + (1-T)\beta F(K)S/E\right]/C. \tag{50}$$

Substituting (48) into (49) and defining $\epsilon := E/S$, we obtain

$$\dot{S}/S = -\epsilon, \tag{51}$$
$$\dot{\epsilon}/\epsilon = \epsilon + \alpha\dot{K}/K - r(K), \tag{52}$$
$$\dot{K}/K = \left[F(K) - \delta K - C - r(K)/\theta\right]\theta/(\theta K - \alpha), \tag{53}$$
$$\dot{C}/C = r(K) - \rho - \phi(\rho+\phi)\left[K + (1-T)\beta F(K)/\epsilon\right]/C. \tag{54}$$

The last three equations are a dynamical system in ϵ, C and K. Its fixed point satisfies

$$\epsilon = r(K), \tag{55}$$
$$C = F(K) - \delta K - r(K)/\theta, \tag{56}$$
$$C = \phi(\rho+\phi)\left[K + (1-T)\beta F(K)/r(K)\right]/\left[r(K) - \rho\right]. \tag{57}$$

In the C-K-plane, the last two equations describe a parabola and hyperbola as before (cf. Equations (21) and (22)). The fixed point is stable, since the same argument as in Footnote 12 applies (in this case with two jump variables, C_0 and $\epsilon_0 = E_0/S_0$ chosen such that the transversality conditions are met). Thus, the occurence of a macroeconomic portfolio effect under a carbon tax can be proved in a similar way as for the permit scheme:

Proof of Corollary 2. Similar to the proof of Theorem 1 with Equation (46) modified to

$$C_H^i(K) = \phi\frac{\rho+\phi}{r(K)-\rho}\left\{K + \frac{\beta F(K)}{r(K)} - T_i\frac{\beta F(K)}{r(K)}\right\}.$$

□

A.6 Socially optimal solution

The social planner solution represents a normative benchmark to evaluate the adequacy of the climate policies discussed in the article. The application of the approach of Calvo and Obstfeld (1988) to the social planner problem is as in Edenhofer et al. (2015), we restate it here to make this article self-contained.

We here define social welfare as the (discounted) preference satisfaction of the heterogeneous households. The socially optimal rate of pure time preference is assumed to equal the private rate of pure time preference for simplicity.

Social welfare V at time t is defined as follows:

$$\begin{aligned} V(t) = &\int_{-\infty}^{t}\left\{\int_t^\infty \ln c(\nu,\tau)e^{-\rho\tau}\phi e^{-\phi(\tau-\nu)}\mathrm{d}\tau\right\}\mathrm{d}\nu \\ &+ \int_t^\infty\left\{\int_\nu^\infty \ln c(\nu,\tau)e^{-\rho\tau}\phi e^{-\phi(\tau-\nu)}\mathrm{d}\tau\right\}\mathrm{d}\nu. \end{aligned}$$

which is the social welfare function considered by Calvo and Obstfeld (1988) when the private equals the social rate of pure time preference.

We now apply the two-step procedure of Calvo and Obstfeld (1988) for social planner problems with overlapping generations to determine the socially optimal level of aggregate capital and consumption: (i) the optimal static distribution is derived for every point in time, (ii) the intertemporally optimal solution is chosen independently.

(i) Define $U(C(t))$ as the solution to the *static maximization problem*:

$$U(C(t)) = \max_{\{c(\nu,t)\}_{\nu=-\infty}^{t}} \int_{-\infty}^{t} \ln c(\nu,t)\phi e^{-\phi(t-\nu)} \mathrm{d}\nu \tag{58}$$

$$\text{subject to:} \quad C(t) = \int_{-\infty}^{t} c(\nu,t)\phi e^{-\phi(t-\nu)} \mathrm{d}\nu. \tag{59}$$

The solution to this problem is:

$$U(C(t)) = \ln(C(t)).$$

The result is true since all agents have the same utility function. Intuitively, distributing the fixed amount $C(t)$ among all living agents at time t thus makes giving an equal share to each of them optimal. As population is normalized to 1, the share given to the individual equals the total amount of consumption, $C(t)$, so that total utility is $\ln(C(t))$.

Proof. Solving the maximization problem (58) with integral constraint (59) and writing λ as multiplier to that constraint, one obtains the current-value Hamiltonian

$$H_c = \phi \ln c(\nu,t) + \lambda\phi c(\nu,t)$$

and thus finds the first-order conditions:

$$\frac{\partial H_c}{\partial c} = \frac{\phi}{c(\nu,t)} + \lambda\phi = 0 \tag{60}$$

$$(t-\nu)\lambda = (t-\nu)\lambda - \dot{\lambda}. \tag{61}$$

The last equation implies that λ is constant, so from Equation (60) it follows that the optimal $c(\nu,t)$ is constant for all ν, too. Setting $c(\nu,t) = c'(t)$ in Equation (59) implies

$$C(t) = c'(t).$$

Inserting this in Equation (58) gives the result. □

(ii) The *intertemporal maximization problem* of the social planner is then the following problem:

$$\max_{C(t)} \int_{t=0}^{\infty} U(C(t))e^{-\rho t} dt \tag{62}$$

$$\text{with} \quad U(C) = \ln(C)$$

$$\text{s.t.} \quad \dot{K}(t) = F(K(t), L(t), A(t)E(t)) - \delta K(t) - I_A^* - C(t).$$

The corresponding rule for socially optimal aggregate consumption growth is thus the Keynes-Ramsey rule

$$\frac{\dot{C}(t)}{C(t)} = F_K(K(t), L(t), A(t)E(t)) - \delta - \rho. \tag{63}$$

We therefore take the Keynes-Ramsey level of consumption and capital as the reference point for social optimality in the main part of the paper.

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Chapter 6

Keeping Pigou on tracks: second-best carbon pricing and infrastructure provision[1]

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Keeping Pigou on tracks: second-best carbon pricing and infrastructure provision

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Abstract

Long-lived public infrastructure (for example roads) complements private goods (cars) and may perpetuate carbon-intensive demand patterns and technologies far into the future. Thus, climate policy must combine 'direct' instruments such as carbon taxation with public investment shifts (from roads towards rails or bicycle paths). This is particularly important and complex because infrastructure supply changes slowly and carbon taxation may be politically constrained:

This paper shows that if carbon taxation is non-optimal, infrastructure provision should be used to actively change private behavior. Nevertheless, if one instrument is restricted, the other may also have to be less ambitious: Intuitively, if clean infrastructure provision is non-optimal, polluting should also be penalized less (and vice versa), unless welfare gains from environmental quality are large.

More precisely, for two public goods complementing private goods in utility, general second-best policy conditions are derived and applied to a specific utility function. Constrained public spending composition leaves the (Pigouvian) tax rule unchanged, but constrained taxation implies that the environmental externality enters the condition for public spending composition. Nevertheless, the second-best *level* of either policy instrument is below its first-best when 'dirty' consumption is sufficiently important in utility.

JEL classification: H23, H41, H54, R48

Keywords: infrastructure, public spending, carbon price, environmental tax, second-best, transport

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1 Introduction

The feasibility and costs of climate change mitigation crucially depend on how fast capital stocks can be adapted to low-carbon technologies. This importantly includes public capital stocks without direct greenhouse gas (GHG) emissions: public goods that complement private goods may perpetuate GHG-intensive demand patterns and technologies. For example, transport infrastructure and related urban form affect GHG emissions via the number and distance of trips and transport mode choice (Sims et al., 2014; Seto et al., 2014). These perpetuating effects are amplified by particularly long lifetimes of most types of infrastructure (Jaccard and Rivers, 2007; Shalizi and Lecocq, 2010). As a consequence, staying within an 'emissions budget' consistent with a 2 °C target may even require the retirement of *existing* infrastructure (Guivarch and Hallegatte, 2011). Thus, infrastructure policies are important mitigation instruments, along with financial incentives or regulations that address GHG emissions directly (Shalizi and Lecocq, 2010), and both types of instruments need to be adjusted to each other. For example in transport, a fuel tax is inefficient at reducing car use if there are no viable alternatives. Therefore, sufficient infrastructures for public and non-motorized transport are required (May and Roberts, 1995), potentially at the expense of road investments. Similarly, subsidies for buying or using electric vehicles are ineffective without a network of publicly accessible charging stations

Nevertheless, the role of infrastructure in environmental policy is often neglected both by environmental and public economics.[1] Indeed, there is a 'division of labor' between environmental and infrastructure policy in a first-best world: if a tax can be used to fully internalize environmental damages, the infrastructure just needs to match the resulting demands, but it has no role as an environmental policy instrument. This division of labor even holds if the composition of infrastructure provision affects the composition of private consumption. It may break down, however, if either environmental taxation or public spending is restricted, which may be the rule rather than the exception in practical policy-making. Then, if infrastructure cannot be adapted optimally (at least in the short run), should this be compensated by a higher carbon price?[2] Vice versa, if environmental pricing is politically restricted, should more public funds and public space be allocated to infrastructure that supports 'clean transport', and less to roads and parking?

In this paper, I thus analyze the links between two policy variables: an environmental tax, and the ratio of spending on two public goods which are complementary to clean and dirty private consumption goods, respectively.

The first main result establishes public spending as a second-best environmental policy instrument on a par with environmental pricing: whenever an environmental tax does not fully internalize the damages, it is optimal to use public good provision to actively change private behavior, rather than to just 'match demand'. In turn, when public good provision is not optimal, the environmental tax rate changes (but not the tax rule).

[1] For example, the Handbook of Environmental Economics (Mäler and Vincent, 2003) does not consider infrastructure investment or urban planning. The public economics literature is discussed below.

[2] In addition to long lifetimes, infrastructure adaptation may be impeded by long planning and construction times, administrative and legislative obstacles, or public opposition.

The second main result concerns the value of second-best policy variables relative to their first-best: if one policy instrument is restricted, the other instrument should *not* always be reinforced to compensate this, but may have to be set to a less ambitious level as well. More precisely, this holds for the case that dirty consumption relative to clean consumption, and composite consumption relative to environmental quality, are 'sufficiently important' for individuals' utility: then, if either the environmental tax rate or the public spending ratio is constrained below its first-best level, the second-best level of the other policy variable is also *lower* than its respective first-best. Further, a tighter constraint implies an even lower second-best level of the other policy variable.

Intuitively, to the degree that alternative infrastructure (for example for cycling or public transport) that would 'attract' clean consumption cannot be provided to the optimal level, the 'penalty' for polluting behavior (for example by a fuel tax) should also be smaller. Vice versa, if carbon pricing does not provide optimal incentives for a change in private behavior, alternative infrastructure would be oversupplied under the first-best spending composition. (Both under the conditions that environmental quality is endogenous, and that welfare gains from higher environmental quality are not too large.)

The results are formally derived in a static model, but also have an important interpretation in dynamic settings: the speed at which the environmental tax rate should be increased to its first-best is determined by the speed of public capital stock restructuring. Given the often substantial planning lead time and lumpiness of infrastructure investments, they should *precede* environmental tax increases. Such a long-term perspective is not always adopted, as I will illustrate using the example of rail and road infrastructure investments in countries that have committed to climate change mitigation.

The present paper fills a gap in the public economics literature, in which environmental policy is often treated as a topic in optimal taxation: environmental taxes are analyzed as a source of public funds, in settings that are second-best because no lump-sum taxes are available. Models of optimal environmental taxation often include public goods – but they are commonly assumed to be (weakly) separable from private consumption, or there is only one public good (Bovenberg and Goulder, 2002), so the effect of the composition of public spending on the environment cannot be elucidated. As an exception, Bovenberg and van der Ploeg (1994) model two public goods and allow for public-private complementarity. However, they are again mainly interested in optimal levels of taxes or of public goods that are themselves polluting or emission-reducing, while being financed by distortionary taxes. In contrast, the main point here is to bring out as clearly as possible the role of public spending as an environmental policy instrument that affects private behavior, so the revenue-side of the public budget is kept deliberately simple by allowing for lump-sum taxes. Instead, I stress the importance of second-best settings in which environmental policy variables are restricted. Section 5.2 explores potential combinations of distortionary (labor) tax models and the present model.

A few numerical studies on climate change mitigation pathways examine the link between carbon pricing and infrastructure: Waisman et al. (2012, 2013) illustrate that a given abatement target can be achieved by a lower carbon price (and at lower costs) when it is combined with transport-specific policies, including a given recomposition of transport infrastructure investment. In an urban context, Avner et al. (2014) show how public transport infrastructure increases the price elasticity of CO_2 emissions, and thus the efficiency and effectiveness of a carbon- or gasoline tax. However, these studies are numerical, the composition of infrastructure investments are chosen *ad hoc*, and no attempt is made to find the *optimal* public policy to complement carbon pricing.

In the following, Section 2.1 describes a model in which two types of public spending complement a clean and dirty private consumption good, respectively. Section 2.2 shows that a shift towards clean consumption can be induced either by a change in the environmental tax, or by changing the public spending composition.

Section 3 derives general optimal policy conditions, and Section 4 applies them to specific utility function, each for first- and second-best cases:

In the first-best benchmark, a Pigouvian environmental tax fully internalizes environmental damages, and the composition of public spending must be such that marginal utility is equal across public goods, independently of environmental quality or any private-public complementarity (Section 3.1).

In the second-best, a binding constraint on the composition of public spending leaves the Pigouvian *tax rule* intact, but changes the *tax rate* due to equilibrium effects (Section 3.2.1). If the parameters in the exemplary utility function are such that dirty consumption is sufficiently important, the second-best tax is lower than in the first-best. The more the composition of public spending is restricted, the lower the tax (Section 4.2.1). With a binding constraint on the environmental tax rate, the second-best condition for public spending contains the marginal effects of public spending on the environment (via dirty private consumption), reflecting its role as an environmental policy instrument when environmental taxes are too low (Section 3.2.2). Again, if dirty consumption is sufficiently important, the second-best share of 'clean public spending' is lower than in the first-best. The more the environmental tax is restricted, the lower the share (Section 4.2.2).

Section 5.1 discusses implications in a dynamic setting, and demonstrates that transport infrastructure investments in many countries do not yet match long-term climate change mitigation objectives. Section 5.2 discusses variations of the model. Section 6 concludes.

2 A model with two types of infrastructure

This section first sets up a model of household consumption. The key assumption is that clean and dirty private goods are each complemented by a specific public good in utility (rather than being separable), yielding 'green' and 'brown' composite goods, respectively. This could for example be thought of as car-based and public transport services.[3] Second, the households' optimality conditions are used to show that the same private response can be achieved by marginal changes of the environmental tax or of the composition of public goods, depending on the elasticity of substitution between 'green' and 'brown' composite goods, and on the elasticity of the composite goods with

[3]Similarly, a production model can be constructed with clean and dirty private inputs complemented by different public goods and the environment as a weakly separable input.

respect to their respective public input. Later sections will consider optimal policies.

2.1 Production and household consumption

Production in our model is very stylized. There are N identical households each supplying one unit of labor as the only input to production.[4] Output can be used for clean or dirty private goods (C, D) or two corresponding public goods (X, Z). Thus, the commodity market equilibrium is[5]

$$N = NC + ND + X + Z. \tag{1}$$

The representative household's utility is

$$U = U\left\{Q[G(C, X), B(D, Z)], E\right\}. \tag{2}$$

Here, $E = E(ND)$ denotes environmental quality (with $E_{ND} < 0$), which is assumed to be (weakly) separable from all other inputs to utility. In contrast to the standard model, private consumption and public spending are not separable: private goods C, D combined with public goods X, Z yield 'green' and 'brown' composite intermediate goods G, B, respectively, which in turn determine the subutility of consumption Q. Furthermore, assume that $G_i > 0$, $G_{ii} \leq 0$, $B_k > 0$, $B_{kk} \leq 0$, and that C, X and D, Z are complements in the sense that $G_{ij} > 0$ and $B_{kl} > 0$ (with $i, j \in \{C, X\}$, $k, l \in \{D, Z\}$ and $G_i := \partial G/\partial i$, etc.).

Households take prices, public spending and environmental quality as given and maximize (2) subject to their budget constraint

$$C + (1 + \tau)D = 1 - T, \tag{3}$$

where $\tau \geq 0$ is a tax on dirty consumption and T a lump-sum tax. The first-order optimality conditions are

$$U_C = \lambda \quad \text{and} \quad U_D = \lambda(1 + \tau) \tag{4}$$

with λ denoting the marginal utility of income. Thus, the marginal rate of substitution (MRUS) between dirty and clean private goods is

$$\frac{Q_D}{Q_C} = \frac{Q_B B_D}{Q_G G_C} = 1 + \tau. \tag{5}$$

If functions G and B are given, the optimal recomposition of private consumption in response to marginal changes in policy parameters can be derived from this condition under the assumption that Q is homothetic (see Section 2.2).

If additionally, functions U and Q are fully specified, one can use (5) and (3) to obtain demands as explicit functions of policy parameters

$$C = C(\tau, T, X, Z) \quad \text{and} \quad D = D(\tau, T, X, Z). \tag{6}$$

Section 4 discusses an example based on a constant elasticity of substitution (CES) specification for Q.

[4] To focus on the relation between environmental taxation and the composition of public spending, I neglect the private choice between labor and leisure and allow for lump-sum taxation to balance the government's budget.

[5] Units are normalized such that the constant rates of transformation is set to one.

2.2 Households' response to marginal policy variations

If Q is homothetic, the marginal rate of substitution between composites Q_B/Q_G is a function of the ratio of composite goods G/B. Totally differentiating (5) then yields

$$\frac{1}{\sigma}(\tilde{G} - \tilde{B}) - (\tilde{G}_C - \tilde{B}_D) = \tilde{\tau}, \tag{7}$$

where a tilde denotes relative changes (except $\tilde{\tau} := d\tau/(1+\tau)$) and σ is the elasticity of substitution between green and brown composite goods (with $\sigma > 0$). Thus, for a given change in the environmental tax (and public goods X, Z, on which G, B depend), the optimal adjustment in private consumption balances two effects: the change in the ratio of composite goods, and thus in the marginal rate of substitution between composites, which is the first term on the left-hand side (LHS) of (7); and the change in the ratio of the marginal (sub)utilities of private goods. For general G and B, the LHS of (7) can be expressed in terms of changes in private and public goods, weighted by expressions containing the elasticities of G, B, G_C and B_D (see (A1) in Appendix A.1).

To be more specific, I secondly assume that

$$G(C, X) = C^\alpha X^\delta \text{ and } B(D, Z) = D^\alpha Z^\delta, \text{ with } 0 < \alpha, \delta \leq 1. \tag{8}$$

Imposing the same elasticities of G and B with respect to private and public inputs[6] allows us to write (7) in terms of changes in $\Delta := C/D$ and $\Omega := X/Z$, respectively, because we then have

$$G/B = \Delta^\alpha \Omega^\delta, \tag{9a}$$

$$G_C/B_D = \Delta^{\alpha-1}\Omega^\delta, \tag{9b}$$

and thus:

$$\frac{1}{\sigma}\left[\alpha\tilde{\Delta} + \delta\tilde{\Omega}\right] - \left[-(1-\alpha)\tilde{\Delta} + \delta\tilde{\Omega}\right] = \tilde{\tau}. \tag{10}$$

Solving this equation for $\tilde{\Delta}$ shows

Proposition 1 (Private response to marginal policy variations)**.** *The composition of private consumption responds to marginal changes in the environmental tax and the composition of public spending according to*

$$[\alpha + \sigma(1-\alpha)]\tilde{\Delta} = \sigma\tilde{\tau} + \delta(\sigma - 1)\tilde{\Omega}. \tag{11}$$

Thus, the government can achieve a change in the composition of private consumption $\tilde{\Delta}$ by arbitrary combinations of changes in the Pigouvian tax $\tilde{\tau}$, to make the dirty good more or less costly relative to the clean good, and in public spending composition $\tilde{\Omega}$ (with a proportionality factor of $\delta(\sigma-1)/\sigma$), to make the dirty private good more or less 'useful' relative to the clean private good.

The term in the square brackets on the LHS of (11) is always positive: an increase in the ratio of clean and dirty private goods Δ positively affects the ratio of green to brown composites (9a), and thus the marginal rate of substitution between composites (the first term on the LHS of (10) or (7)); it also

[6]For a more general case with different elasticities, see (A2) and (A3) in Appendix A.1.

lowers the ratio of the marginal utilities of private goods (9b), corresponding to the second term on the LHS of (10) or (7). Although they are of different size, both effects work together to increase the MRUS in (5). Such an increase is the optimal response to a higher price of D due to a higher environmental tax ($\tilde{\tau} > 0$, $\tilde{\Omega} = 0$), which thus always leads to a cleaner composition of private consumption ($\tilde{\Delta} > 0$), as expected in the two-good case.

More interestingly, a shift of public spending towards the public good complementary to clean consumption ($\tilde{\Omega} > 0$, $\tilde{\tau} = 0$) does only lead to a 'greening' of private consumption if G and B are substitutes ($\sigma > 1$), and otherwise to an unchanged (for $\sigma = 1$) or even more emission-intensive consumption bundle (for $\sigma < 1$). The reason is that an increase in Ω affects the marginal rate of private substitution via the same two channels as described above for Δ – but they now have opposite signs (the effect via the ratio of marginal utilities of private goods is negative), and their relative size is governed by σ (cf. (10)). For $\sigma < 1$, the positive effect via the marginal rate of substitution between composites is stronger and the overall effect of $\tilde{\Omega}$ is positive. This implies that Δ then needs to decrease for the optimality condition to hold.

3 General optimality conditions for taxation and public spending composition

The results so far hold for arbitrary values of the policy variables. Based on Section 2.1, we now derive general optimality conditions for the government's choice of taxes and public spending composition. We start with the government's general welfare maximization problem and then derive optimality conditions for the first-best case when all policy variables (including a lump-sum tax) can be freely chosen, and for two second-best cases when either the public spending composition or the environmental tax are restricted. In Section 4, we will impose more structure on utility to gain further insights for each policy case.

We approach the government's optimization problem by using indirect utility, obtained by substituting the demand functions (6) in (2):

$$V = U\left\{Q\left[G(C(\tau, T, X, Z), X), B(D(\tau, T, X, Z), Z)\right], E(ND(\tau, T, X, Z))\right\}. \tag{12}$$

This a function of the policy variables (τ, T, X, Z), which are chosen by the government to maximize social welfare NV, subject to a budget constraint

$$X + Z = NT + N\tau D \tag{13}$$

and potential restrictions on policy instruments:

$$S \leq \bar{S}, \quad S := X + Z \tag{14a}$$

$$\Omega \leq \bar{\Omega}, \quad \Omega := X/Z \tag{14b}$$

$$\tau \leq \bar{\tau}. \tag{14c}$$

The first-order conditions (simplified by using Roy's Identity, $U_Q Q_\tau = -\lambda D$, and $U_Q Q_T = -\lambda$) are

$$(\lambda - \mu)D - \mu(\tau - \tau_p)D_\tau = \nu/N, \tag{15a}$$
$$(\lambda - \mu) - \mu(\tau - \tau_p)D_T = 0, \tag{15b}$$
$$U_Q Q_X + \mu(\tau - \tau_p)D_X = (\mu - \xi - \zeta/Z)/N, \tag{15c}$$
$$U_Q Q_Z + \mu(\tau - \tau_p)D_Z = (\mu - \xi + \zeta X/Z^2)/N, \tag{15d}$$

where $\lambda = U_C$ is the marginal utility of income, μ is the marginal utility loss of raising one unit of public funds, ξ, ζ and ν are the multipliers associated with (14a)-(14c), and

$$\tau_p := \frac{NU_E(-E_{(ND)})}{\mu} \tag{16}$$

denotes the 'Pigouvian' environmental tax rate.

3.1 First-best policies

General conditions for the first-best environmental tax and spending composition follow directly:[7] If taxation is unrestricted, that is (14c) is non-binding and $\nu = 0$, (15a) and (15b) yield $\mu = \lambda$ and the optimal tax rate

$$\tau^* = \tau_p. \tag{17}$$

Furthermore, unrestricted public spending on both public goods implies (14a) and (14b) are non-binding and $\xi = \zeta = 0$. Using (17) in (15c) and (15d), we then find that optimal public spending X^*, Z^* must satisfy

$$Q_X = Q_Z, \tag{18a}$$
$$N\frac{Q_X}{Q_C} = N\frac{Q_Z}{Q_C} = 1. \tag{18b}$$

These are standard result for optimal environmental taxation and public spending when lump-sum taxes are available, so that the marginal cost of public funds μ/λ is unity (cf. Bovenberg and van der Ploeg, 1994, ch. 4): The optimal tax on dirty consumption in (17) fully internalizes environmental damages. Condition (18a) ensures the optimal composition of public spending by equating the marginal utility of different public goods. Equation (18b) is the Samuelson condition (with the rate of transformation between public and private goods equal to one).

Interestingly, these results are unaffected by assumptions about the separability of public goods in utility – more generally, they are *independent of how different types of public spending enter utility*: First, the environmental tax rate according to (17) and (16) depends only indirectly on the composition of public spending (via U_E and U_C, which are functions of X and Z). Second, the terms involving D_X and D_Z in (15c) and (15d), representing the environmental effect of public spending due to its effect on private consumption, have disappeared in (18a) and (18b). Thus, there is a 'division of labor' between the two policy instruments in the first-best: it is optimal to use only the tax to internalize environmental damages. Public spending composition has no role as an environmental policy instrument, but should simply match corrected demands.

[7] 'First-best' policies are those that reproduce the social planner's solution, see for example Bovenberg and van der Ploeg (1994); Bovenberg and Goulder (2002).

3.2 Second-best policies

The first-best results above are usually compared to second-best cases in which the government has no access to lump-sum taxes: The second-best environmental tax may then have an additional 'Ramsey component' ($\tau - \tau_p > 0$) due to a revenue-raising motive for differentiated commodity taxation (Sandmo, 1975; Bovenberg and Goulder, 2002). If this is the case, the second-best equivalents of (18a) and (18b) likewise contain terms $(\tau - \tau_p)D_X$ and $(\tau - \tau_p)D_Z$, representing the effect of public spending on revenues from commodity taxation (Bovenberg and van der Ploeg, 1994, ch. 4.2).

In many practical cases, however, environmental policies are further restricted since a full recomposition of public capital stocks takes time (see Section 5.1), or the government's taxation powers may be limited. To focus on this, the second-best analysis in the next two subsections maintains the assumption of lump-sum taxes and considers restrictions on the levels of Ω and τ instead: Limiting Ω does not imply a different rule for optimal environmental taxation, but it affects the tax rate, because the marginal utility of dirty consumption depends on the composition of public spending (Section 3.2.1). Limiting τ does structurally change the condition for optimal public spending, which now depends on $(\tau - \tau_p)$ even in the presence of a lump-sum tax – however, this is now not due to the effect of public spending on tax revenues, but because due to the role of Ω in addressing environmental damages (Section 3.2.2).

3.2.1 Environmental taxation under restricted public spending composition

Assume that the government cannot adjust public spending composition to its first-best value Ω^*, that is (14b) is binding

$$\Omega = \bar{\Omega} < \Omega^* \tag{14b$'$}$$

and $\zeta \neq 0$ in (15c) and (15d). If the government can still choose any tax rate, (14c) is non-binding and $\nu = 0$ in (15a), implying $\mu = \lambda$ and

Proposition 2 (Second-best environmental taxation)**.** *The rule for the second-best environmental tax is identical to the first-best case:*

$$\tau' = \tau_p = \frac{NU_E(-E_{(ND)})}{\lambda}. \tag{17$'$}$$

However, the *level* of the second-best environmental tax τ' will generally be different from the first-best case because restriction (14b$'$) on public spending affects U_E and $E_{(ND)}$.

Appendix A.2.1 derives the remaining conditions for second-best X', Z', T, ξ and ζ, depending on the total spending constraint (14a) being binding or not.

3.2.2 Public spending composition under restricted environmental taxation

Now, assume that the government cannot adjust the environmental tax to its first-best value and environmental damages are not fully internalized by the tax, so (14c) is binding,

$$\tau = \bar{\tau} < \tau^*, \tag{14c$'$}$$

and $\nu \neq 0$ in (15a). Together with (15b), this implies $\mu \neq \lambda$ (see Appendix A.2.2 for an explicit condition).

Constraint (14b) is non-binding and $\zeta = 0$ in (15c) and (15d), which leads to

Proposition 3 (Second-best composition of public spending)**.** *If the environmental tax cannot be set optimally, the composition of public spending should additionally be used to address the environmental externality:*

$$U_Q(Q_Z - Q_X) = \mu(\tau_p - \bar{\tau})(D_Z - D_X). \tag{18a$''$}$$

In contrast to the first-best condition (18a), the effects of public spending on dirty consumption (in the second bracket on the RHS) and thus on the environment now directly enter its second-best equivalent (18a$''$): the composition of public spending assumes a role as an environmental policy instrument. This role becomes more pronounced as the constrained tax level deviates more from the 'recommended' Pigouvian tax level (the first bracket on the RHS). Hence, a 'division of labor' between policy instruments as in the first-best case is no longer optimal.

Appendix A.2.1 derives the remaining conditions for second-best X', Z', T, μ and ξ, depending on the total spending constraint (14a) being binding or not.

4 Results for a specific utility function

Further insights can be gained for specific functional forms for utility and environmental quality. We first state our assumptions (extending those in Section 2.2) and the corresponding results for household behavior. This will then be applied in two subsections on first- and second-best policies, respectively.

Assume that overall utility U is of Cobb-Douglas form, with elasticities m, n. For the utility of composite consumption Q, use a CES function with share parameter β and elasticity of substitution σ. For composite goods G and B, use the Cobb-Douglas specification from (8). Finally, assume that environmental quality E has a constant elasticity ϕ with respect to aggregate dirty consumption:

$$U(Q,E) = Q^m E^n, \tag{19a}$$

$$Q(C,D,X,Z) = \left[\beta G(C,X)^\rho + (1-\beta)B(D,Z)^\rho\right]^{1/\rho}, \tag{19b}$$

$$G(C,X) = C^\alpha X^\delta, \quad B(D,Z) = D^\alpha Z^\delta, \tag{19c}$$

$$E(ND) = (ND)^{-\phi} \quad \text{for} \quad D > 0, \tag{19d}$$

$$\text{with} \quad 0 < m, n < 1, \tag{19e}$$

$$\sigma > 1 \quad \text{and} \quad \rho := (\sigma - 1)/\sigma, \tag{19f}$$

$$0 < \alpha, \delta \leq 1 \quad \text{and} \quad \alpha + \delta < \sigma/(\sigma - 1), \tag{19g}$$

$$\phi > 0. \tag{19h}$$

Parameter condition (19f) implies that G and B are substitutes; the implications of the second part of (19g) (which is satisfied for example if G and B

exhibit constant returns to scale) will become clear below. All results below are derived under this set of assumptions without further mentioning. Furthermore, only interior solutions with $C, D, X, Z > 0$ will be formally analyzed, since otherwise E in (19d), Δ and Ω are not defined.

We now describe households' behavior for this specification. Evaluating the private optimality condition (5) and solving for $\Delta = C/D$ then yields

$$\Delta(\tau, \Omega) = \left[\frac{\beta}{1-\beta}(1+\tau)\Omega^{\delta\rho}\right]^{\eta}, \quad \text{with} \quad \eta := \sigma/(\sigma - \alpha(\sigma - 1)). \tag{20}$$

Equation (20) describes the relation between *any* level (or change) of policy parameters and private consumption composition, while (11) described only *marginal changes*; the intuition remains the same. When private consumption is optimal, η equals the price elasticity of substitution between clean and dirty private consumption[8]. From (19f) follows that $\eta > 1$ and Δ is a convex function of τ. Since we additionally impose (19g), we have $0 < \delta\rho\eta < 1$ and Δ is a concave function of Ω.

Combining (20) and the private budget constraint (3), we obtain the demand functions

$$C(\tau, T, \Omega) = (1-T)\frac{\Delta(\tau, \Omega)}{\Delta(\tau, \Omega) + 1 + \tau}, \tag{21a}$$

$$D(\tau, T, \Omega) = (1-T)\frac{1}{\Delta(\tau, \Omega) + 1 + \tau}, \tag{21b}$$

which are independent of total public spending S. Substituting this back into the utility specification (19) and using $X = \Omega S/(1+\Omega)$ and $Z = S/(1+\Omega)$, we may obtain the indirect utility functions $\hat{Q} = \hat{Q}(\tau, T, \Omega, S)$ (see (A8) in Appendix A.3).

4.1 First-best policies for a specific utility function

To evaluate the first-best tax condition (17), write the Pigouvian tax (16) in terms of elasticities ϵ^{ij} of variable i with respect to j,

$$\tau_p = \frac{\epsilon^{UE}(-\epsilon^{E(ND)})}{\epsilon^{UQ}\epsilon^{QG}\epsilon^{GC}}\Delta(\tau, \Omega). \tag{22}$$

The results of private optimization (20), (21) and (A8) yield

$$\epsilon^{QG} = \Delta(\tau, \Omega)/\left[\Delta(\tau, \Omega) + 1 + \tau\right], \tag{23}$$

while all other elasticities are constant as specified in (19), so

$$\tau_p = \tau_p(\tau, \Omega) = \frac{n\phi}{m\alpha}\left[\Delta(\tau, \Omega) + 1 + \tau\right]. \tag{24}$$

In the first-best, (17) implies that τ on the RHS and τ_p on the LHS are equal.

Furthermore, we can evaluate the first-order condition for the composition of public goods (18a) using the expression for indirect utility (A8).

[8] Similarly, the elasticity of substitution with respect to the composition of public spending is $(d\Delta/\Delta)/(d\Omega/\Omega) = \delta\rho\eta$.

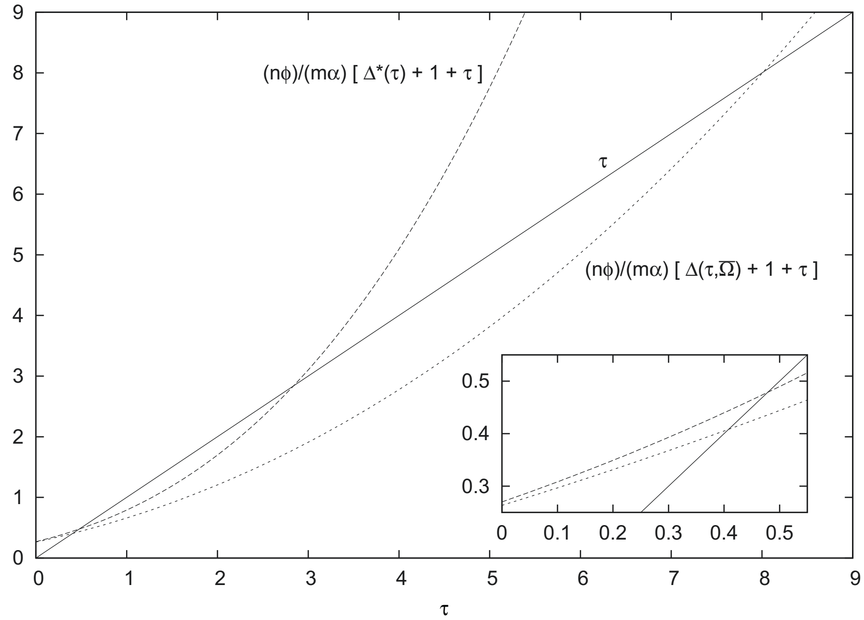

Figure 1: Illustration of the implicit conditions (27) and (31) for the first- and second-best environmental tax. (Parameters: $m = 0.75, n = 0.25, \sigma = 3, \beta = 0.4, \alpha = 0.8, \delta = 0.2, \phi = 0.5, \bar{\Omega} = 0.2$.)

We thus find that the first-best environmental tax and composition of public spending, τ^* and Ω^*, need to satisfy

$$\tau = \frac{n\phi}{m\alpha}\left[\Delta(\tau, \Omega) + 1 + \tau\right], \tag{25a}$$

$$(\Omega)^{1-\delta\rho\eta} = \left[\frac{\beta}{1-\beta}(1+\tau)^{(\eta-1)/\eta}\right]^{\eta}. \tag{25b}$$

Using (20) in (25b) reveals a simple relation between first-best private and public spending patterns:

Lemma 4. *The first-best public spending composition equals the private spending composition:*

$$\Omega^* = \frac{\Delta(\tau^*, \Omega^*)}{1+\tau^*}. \tag{26}$$

Furthermore, substituting (25b) into (25a) yields an implicit (necessary) condition for the first-best environmental tax τ^*:

$$\tau = \frac{n\phi}{m\alpha}\left[\Delta^*(\tau) + 1 + \tau\right], \tag{27}$$

$$\text{with} \quad \Delta^*(\tau) := \left[\frac{\beta}{1-\beta}(1+\tau)^{1-\delta\rho}\right]^{\eta/(1-\delta\rho\eta)}.$$

Here, Δ^* is the ratio of clean to dirty private goods as a function of the first-best environmental tax only. Once τ^* has been determined, the corresponding optimal public spending composition Ω^* can be otained from (25b). Interpreting the left- and right-hand side (LHS and RHS) of (27) as functions of τ permits a qualitative analysis of this condition (see Figure 1):

Assumptions (19f) and (19g) imply that the overall exponent of the $(1+\tau)$-term in the expression for Δ^* exceeds unity, so both Δ^* and the entire RHS of

(27) increase at a growing rate in τ, from a positive value for $\tau = 0$. The term in square brackets on the RHS is always larger than τ on the LHS. Thus, a *necessary* condition for the existence of a solution is that utility is less sensitive to changes in aggregate pollution than to changes in composite consumption,[9] that is, if

$$m\alpha > n\phi. \tag{28}$$

To derive a sufficient condition, note that the existence of a solution to (27) requires that the Pigouvian tax on the RHS does not grow 'too fast' in τ, so that the LHS of (27) is tangent to or intersects the RHS (Fig. 1 illustrates the latter case). To be more precise, define

$$M := \frac{m\alpha}{n\phi}, \quad H := \frac{\eta - \delta\rho\eta}{1 - \delta\rho\eta}, \quad R := \left[\frac{\beta}{1-\beta}\right]^{\eta/(1-\delta\rho\eta)}. \tag{29}$$

Then, we can show

Lemma 5. *The first-order optimality condition* (27) *for the first-best environmental tax* τ^* *has*

$$\left.\begin{array}{l}\textit{two solutions}\\ \textit{one solution}\\ \textit{no solutions}\end{array}\right\} \quad \textit{if} \quad \frac{(M-1)^H}{M^{H-1}} \left\{\begin{array}{c} > \\ = \\ < \end{array}\right\} \frac{H^H}{(H-1)^{H-1}} R. \tag{30}$$

If there are two solutions to (27)*, the smaller one is the solution to the government's welfare maximization problem.*

Proof. The derivation of (30) is technical and moved to Appendix A.4. Identifying the maximum in the two-solution case is more instructive:

The parameter condition (30) implies that there may be two solutions to (27), denoted by τ_L and τ_H with $\tau_L < \tau_H$, if the brown relative to the green composite good and overall consumption relative to environment quality are sufficiently important in social welfare.[10] Additionally, $\tau \to \infty$ by (21) implies ever-decreasing D and ever-increasing E by (19d), so that social welfare goes to infinity by (19a). At the other extreme, an arbitrarily small environmental tax will always yield higher social welfare than $\tau = 0$. Thus, τ_L must *locally* maximize social welfare, τ_H locally minimizes it, and there is only *one finite* solution to the government's unrestricted maximization problem: $\tau^* = \tau_L$, and a low $\Omega^*(\tau_L)$ according to (25b). □

Thus, a low environmental tax rate is preferable to an 'intermediate' tax if dirty consumption contributes relatively strongly to utility. This is only compensated by environmental quality gains if the environmental tax is beyond an upper threshold, which we may denote by τ_{crit}.

That the tax can never be high enough once it is above τ_{crit} is an artifact of our modeling choice for environmental quality (19d). Alternatively, we could for example introduce an upper bound on E (or a lower bound on D), which

[9] Here, the sensitivity to changes in private consumption is measured by $\epsilon^{UQ}\epsilon^{GC} = m\alpha$; since ϵ^{QG} depends on τ and Ω, it does not appear in this condition on parameters. The sensitivity to changes in aggregate pollution is simply the elasticity $\epsilon^{U(ND)} = -n\phi$.

[10] Both the LHS and RHS of (30) increase with σ and α; but if m is large or n and ϕ are small, only the LHS is large, and if β is small, only the RHS is small.
The necessary condition (28) is contained in (30), since the RHS of (30) is always positive but the LHS is non-positive if $M \leq 1$.

would be reached at a finite tax rate $\bar{\tau}$: then, if $\bar{\tau} > \tau_{crit}$, this corner solution replaces the interior solution τ_L as the global optimum.

If the environment or the clean composite good are sufficiently important in utility, (30) implies that (27) has no solution. In this case, a potential loss of utility from composite consumption due to a tax increase is always overcompensated by the corresponding increase in welfare due to higher environmental quality: the local maximum and minimum disappear, an increase in τ always increases welfare, and there is *no finite* solution to the first-best problem. Again, a different specification of (19d) would take care of this.

4.2 Second-best policies for a specific utility function

We now apply the general results of Section 3.2 and analyze scenarios with binding constraints on policy variables.

4.2.1 Environmental taxation under restricted public spending composition

Using (19)-(21) and (A8) in (17′) gives an implicit condition that a second-best environmental tax τ' needs to satisfy:

$$\tau = \frac{n\phi}{m\alpha}\left[\Delta(\tau, \bar{\Omega}) + 1 + \tau\right]. \tag{31}$$

This equation has the same form as (25a) for the first-best case, only that the exogenous parameter $\bar{\Omega}$ replaces Ω^*, so that (31) can be directly compared to (27) (cf. Fig. 1). In analogy to the first-best case, the following sufficient condition for the existence of solutions can be derived:

Lemma 6. *If there is a binding constraint $\bar{\Omega}$ on the composition of public spending, the first-order optimality condition* (31) *for the second-best environmental tax τ' has*

$$\left.\begin{array}{l}\textit{two solutions}\\ \textit{one solution}\\ \textit{no solutions}\end{array}\right\} \quad \textit{if} \quad \frac{(M-1)^{\eta}}{M^{\eta-1}} \left\{\begin{array}{c} > \\ = \\ < \end{array}\right\} \frac{\eta^{\eta}}{(\eta-1)^{\eta-1}} R^{1-\delta\rho\eta}\bar{\Omega}^{\delta\rho\eta}. \tag{32}$$

If there are two solutions, the smaller one satisfies

$$\Delta_{\tau}(\tau', \bar{\Omega}) < \frac{m\alpha}{n\phi} - 1. \tag{33}$$

If there is only one solution, this holds with equality.

Proof. See Appendix A.4. □

The upper bound $\bar{\Omega}$ may be binding either because it is below the first-best solution for public spending composition, or because there is no finite first-best solution (see above).

Again, (32) implies that $m\alpha > n\phi$ (cf. (28)) is a necessary condition for the existence of a second-best τ'. Otherwise, if environmental quality is too important for utility, there is no interior solution (unlike Fig. 1, which illustrates the two-solution case, the curve representing the Pigouvian tax term on the RHS of (31) is then ‘too high and too steep’).

If there are two solutions to (31), by the same reasoning as for the first-best case we identify the smaller value of the tax as the one that locally maximizes social welfare, so it represents the unique (finite) solution to the government's second-best optimization problem.[11] Thus, (33) implies that at the second-best, a change in the private composition of consumption in response to a tax change must not exceed a threshold which again depends on the scaling factor of the Pigouvian tax term on the RHS of (31).

Further, we can show

Proposition 7 (Characteristics of second-best environmental taxation)**.** *If a first-best solution (τ^*, Ω^*) exists, there is a second-best environmental tax τ' for any $\bar{\Omega} < \Omega^*$ with*

$$\tau' < \tau^*. \tag{34}$$

Independent of a first-best solution, if $\bar{\Omega}_1$ permits a solution $\tau'(\bar{\Omega}_1)$, under a tighter constraint $\bar{\Omega}_2 < \bar{\Omega}_1$ there is a solution $\tau'(\bar{\Omega}_2)$ with

$$\tau'(\bar{\Omega}_2) < \tau'(\bar{\Omega}_1). \tag{35}$$

Proof. See Appendix A.4. □

Thus, the more public spending composition is constrained, the more the second-best environmental tax will be below the first-best. Both policy variables affect the private consumption composition in the same direction.

In other words, if clean private consumption contributes too little to utility because there is a lack of matching infrastructure to make it useful, dirty consumption (that is relatively well-supported by infrastructure) should not be penalized as much as under the first-best. To give an intuitive example from transport, car drivers should be penalized somewhat less if alternative transport infrastructure is not sufficient to 'pull' them out of their cars. It should be noted that this is not necessarily an argument for lowering *actually existing* environmental taxes, which may often not even be at the second-best level ($\tau < \tau' < \tau^*$).

The result is illustrated in Figure 1, where the curve representing the Pigouvian tax term on the RHS in (31) is lower than for the first-best case, so its first intersection with the LHS is at a lower τ value. A lower $\bar{\Omega}$ pushes this curve further down.

4.2.2 Public spending composition under restricted environmental taxation

Using (19)-(21) and (A8) first in (A4), and then together with this result in (18a$''$) gives the following implicit equation that the second-best composition of public spending Ω' must satisfy:

$$\Omega = \frac{\Delta}{1+\tau_p}\left[1 + \frac{\eta}{M}\frac{\tau_p - \bar{\tau}}{\tau_p}(1+\Omega)\right], \tag{36}$$

with $\Delta = \Delta(\bar{\tau}, \Omega)$ and $\tau_p = \tau_p(\bar{\tau}, \Omega)$. This expression reflects the assumption that $\tau_p \neq \bar{\tau}$ in two ways: The first fraction on the RHS, the ratio of the marginal total (that is, private and social) costs of clean and dirty consumption, does not equal the private spending ratio (see below). The second term

[11] As for the first-best case, a finite corner solution may result from a limit on E or D.

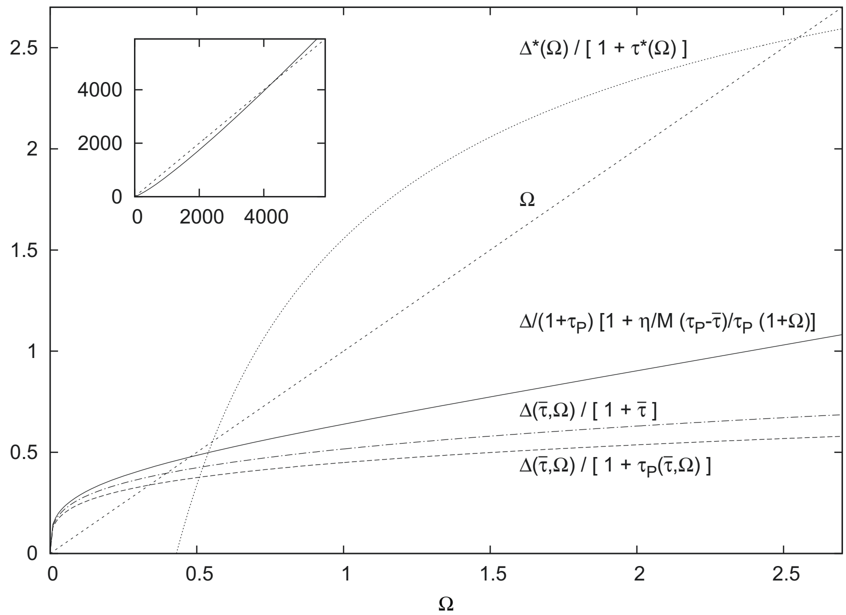

Figure 2: Illustration of the implicit conditions (26) and (36) for the first- and second-best composition of public spending. (Parameters: $m = 0.75, n = 0.25, \sigma = 3, \beta = 0.4, \alpha = 0.8, \delta = 0.2, \phi = 0.5, \bar{\tau} = 0.2$.)

on the RHS, in square brackets, implies that if private consumption composition is not optimally adjusted via an environmental tax, the effect of Ω on private consumption composition should be used as a (partial) compensation, instead of simply 'matching' it to private spending (as implied by the first-best condition (26)). More precisely, we can show that the second term is larger than one, so the second-best composition of public spending must exceed the ratio of the marginal total costs of consumption:

Proposition 8 (Characteristics of second-best public spending composition, part I)**.** *If environmental taxation is constrained to $\bar{\tau}$, (36) may have at most two (non-zero) solutions.*
Any solution Ω' satisfies

$$\Omega > \frac{\Delta(\bar{\tau}, \Omega)}{1 + \tau_p(\bar{\tau}, \Omega)}. \tag{37}$$

Proof. See Appendix A.4. □

Again, the upper bound $\bar{\tau}$ may be binding either because it is below the first-best solution for environmental taxation, or because there is no finite first-best solution.

The complexity of (36) limits the insights that can be proved analytically. For example, we cannot derive a parameter condition similar to (30) or (32) for the number of its solutions. Instead, Proposition 8 only makes a qualitative statement based on the analysis of the shape of the LHS and RHS of (36), interpreted as functions of a general Ω. Figure 2 plots these two functions; their intersections solve the equation.

The same figure illustrates (37), because the curve representing the RHS is above the curve for the ratio of the marginal total costs of consumption at Ω'.[12]

If there are two solutions to (36), it is again the smaller value that locally maximizes social welfare and represents the unique (finite) solution to the government's second-best optimization problem: regardless of any limit on the tax, $\Omega \to \infty$ implies that E goes to infinity, too, and U with it. Thus, the larger value of Ω' must yield a (local or global) minimum of social welfare, and the smaller value a local maximum.[13]

Beyond this, in numerical simulations, I could not find a parameter combination that *qualitatively* changes the relative positions of the intersections of the curves in Figure 2. This leads to

Conjecture 9 (Characteristics of second-best public spending composition, part II)**.** *Assume that environmental taxation is constrained to $\bar{\tau}$.*

Then, first, the second-best public spending composition exceeds the private spending composition:

$$\Omega' > \frac{\Delta(\bar{\tau}, \Omega'_L)}{1+\bar{\tau}}. \tag{38}$$

Second, if a first-best solution (τ^*, Ω^*) exists, there is a second-best compositions of public spending Ω' for any $\bar{\tau} < \tau^*$, with

$$\Omega' < \Omega^*. \tag{39}$$

Third, independent of a first-best solution, if $\bar{\tau}_1$ permits a second-best solution $\Omega'(\bar{\tau}_1)$, under a tighter constraint $\bar{\tau}_2 < \bar{\tau}_1$ there is a second-best $\Omega'(\bar{\tau}_2)$ with

$$\Omega'(\bar{\tau}_2) < \Omega'(\bar{\tau}_1). \tag{40}$$

Condition (38) in the first part of the conjecture is stronger than (37). In contrast to the first-best condition (26), the private spending ratio is lower than the second-best public spending composition because a constrained environmental tax implies that the former is too small, and that the latter plays a role in changing private behavior.

The interpretation of the other two parts of the conjecture is similar to their counterparts in Proposition 6: The more environmental taxation is constrained, the more the second-best composition of public spending will be below the first-best composition. Both policy variables affect the composition of private consumption in the same direction. Returning to the intuitive example from transport, this implies that spending on alternative infrastructure such as rails or bicycle paths should not increase too much if fuel prices cannot be made high enough to 'push' people out of their cars. Again, this is not an argument for lowering *actually existing* spending on clean infrastructure, which may still be below the second-best level in many cases ($\Omega < \Omega' < \Omega^*$; cf. Section 5.1).

Furthermore, Figure 2 illustrates that even though the *solution* Ω' to (36) converges to Ω^* as $\bar{\tau} \to \tau^*$, the RHS of (36) does not converge to the RHS of (26) *for all other* Ω.

[12] For the parameters used in Figure 2, this is even the case for *all* Ω. For other parameter combinations, in particular for $\bar{\tau}$ close to τ^*, this may not be the case for $\Omega < \Omega'$.

[13] As above, a finite corner solution may result from introducing a limit on E or D, and may replace the interior solution as the global optimum if it yields higher social welfare.

5 Remarks and extensions

5.1 Dynamic effects and the example of rail infrastructure investment

We motivated our analysis in the introduction with examples from the transport sector, interpreting public spending as investment in different types of infrastructure. Adjusting the composition of these capital stocks typically takes a long time (Shalizi and Lecocq, 2010): planning and construction of new infrastructure takes many years, and existing infrastructure persists for decades unless maintenance is stopped altogether or it is actively dismantled, which is often politically difficult. Thus, a first-best analysis with a *static* model as in Section 4.1 only describes a very long-run optimum.

However, the short-run is approximated well by the second-best analysis in Section 4.2.1, in which an environmental tax can be immediately adjusted while the composition of public capital is restricted. Then, it was shown that the environmental tax rate may also have to be lower than the first-best. Thus, in a dynamic setting, the speed at which infrastructure stocks can be restructured to lift the restriction also determines the speed at which the environmental tax rate should be increased towards its first-best. In practice, since infrastructure projects often have substantial planning lead times, they should thus be initiated *before* environmental tax increases. Since a larger supply of clean infrastructure increases the (price) elasticities of demand for clean and dirty goods, this would also facilitate subsequent tax increases politically.

However, such a long-term perspective is not always adopted: For example, Figure 3 plots annual investment in rail infrastructure as a share of total (landbound) transport infrastructure investment in countries that have committed to greenhouse gas (GHG) emission reductions under the Kyoto Protocol, before and after ratification of the protocol.[14] Out of 28 countries, 15 *reduced* their relative spending on rail infrastructure, which is unlikely to be optimal when in the long-run, substantial GHG emission reductions will have to come from the transport sector (Sims et al., 2014). Three more countries increased relative spending by less than 5%, and 19 remained below 40% after ratification.

5.2 Model variants

Public goods in the production function

In the present model, environmental quality enters individual utility and public goods affect final demand. But some environmental externalities such as climate change also strongly affect the supply side, and firms' choices between more or less GHG-intensive inputs (such as different transport services) are also affected by public goods and environmental taxes. This would be reflected by a model in which environmental quality and non-separable public goods enter firms' production function. However, for similar functional forms we may expect similar results for second-best taxation and public spending.

[14]The investment data was averaged over several years before the respective country's ratification, and from the ratification year onwards, as far as data was available from the OECD's ITF (2015).

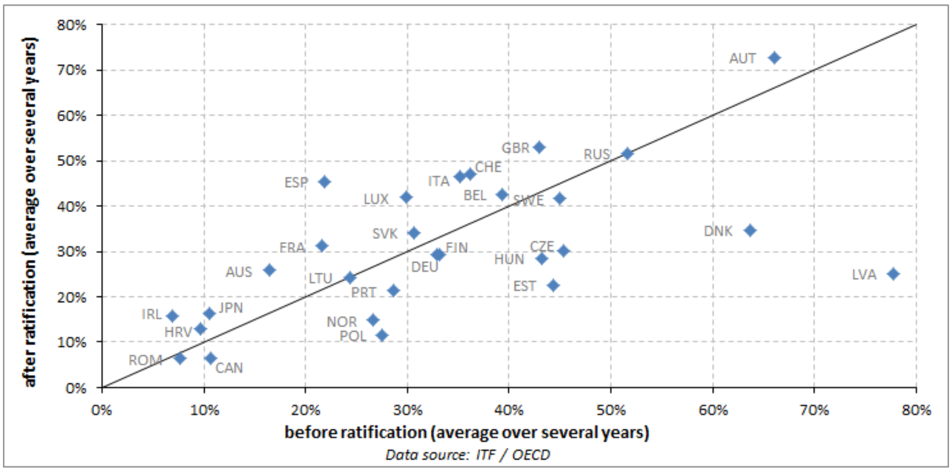

Figure 3: Share of rail investment in total annual transport infrastructure investment before and after ratification of the Kyoto Protocol

Different utility function

The results in Section 4 were derived for a specific utility function. Two assumptions are particularly noteworthy:

First, modeling environmental quality as a function of aggregate dirty consumption by (19d) leads to cases where no finite solution to the government's first- or second-best problem exists. One possible remedy that preserves analytical tractability is to describe environmental quality by (19d) only up to an upper limit, and to keep it constant for lower values of aggregate pollution, as discussed in Section 4.

Second, in (8) or (19c), we imposed the same elasticities of 'brown' and 'green' composite goods with respect to private and public goods (α and δ). A numerical model should drop this assumption, but Appendix A.1 illustrates that the more general case with different elasticities is too complicated for an analytical treatment as in Section 4, and the qualitative insights are unlikely to change.

Network effects

A useful extension for a case-by-case analysis or a numerical model would be to account for network effects in transport infrastructure:

The usefulness of an infrastructure network generally depends on its size, with low marginal benefits of investment for very small or very large networks, and large marginal benefits for intermediate-sized networks. Thus, the elasticities in the model above will not be constant, but functions of the size of the respective network(s), and they will be very different when alternative networks are at different stages of development. This is particularly relevant when considering low-income countries with little infrastructure of any type or economies in transition with major infrastructure investments underway (Shalizi and Lecocq, 2010; Agénor, 2013), where a 'lock-in' on high-emission development pathways may still be avoided.

Labor taxation

To focus on interactions between environmental taxation and public spending, we assumed that lump-sum are available. As mentioned in the introduction, this is in contrast to a large body of public economics literature on environmental taxation in second-best settings in which public funds are costly because they have to be raised via a distortionary (labor) tax (Bovenberg and Goulder, 2002). A central finding of this literature is that the optimal environmental tax rate is below the Pigouvian tax rate, intuitively because it reduces dirty consumption and thus the contribution of the environmental tax to the public budget. More precisely, the optimal tax rate is the Pigouvian tax rate divided by the marginal costs of public funds (MCPF).

We can expect that this still holds when additionally, a constraint on public spending composition is introduced – as in Sections 3.2.1 and 4.2.1, this will only change the *rate*, but not the *structure* of optimal environmental taxation. Vice versa, the other results in 4.2.1 will not change if there is an additional factor (one over the MCPF) in condition (31) for second-best environmental taxation (and all expressions derived from it).

6 Conclusion

This paper analyzed environmental taxation and the composition of public spending when public goods are complementary to private goods. I first demonstrated how either policy instrument can be used to achieve a given change in the composition of private consumption. Then I focused on politically relevant second-best settings in which one of the two instruments is constrained.

In general, if the share of public goods complementary to clean private goods in total public spending cannot be increased to its first-best, this changes the level but not the structure of optimal environmental taxation (which is still Pigouvian). On the contrary, a limit on environmental taxation does structurally change the condition for optimal public spending and thus also its level, because the composition of public spending now plays a role in addressing the environmental externality.

To assess the sign of these changes in second-best policies relative to the first-best, I used a specific utility function. First, I proved that in the first-best, the composition of public spending equals that of private spending. Then, I found that if clean private goods and environmental quality are not too important in utility (in terms of their respective elasticities), a constraint on one policy instrument implies that the level of the other instrument should also be lower than its first-best – and the tighter the constraint, the lower the other policy's second-best level. For the case of second-best taxation, this was formally proved, while the complex second-best condition for public spending composition could only be considered numerically.

These results can most obviously be applied in the transport sector, which is relevant for many environmental concerns such as noise, air quality, climate change, land use and biodiversity (Hensher and Button, 2003): various private transport decisions depend not only on relative prices (that can be influenced by environmental taxes and subsidies), but also on complementary policies such as public spending, or land use management and urban planning.

Examples include, for GHG emission reduction, fossil fuel taxation and a shift of investment from road- towards rail infrastructure; to reduce local (urban) environmental externalities, city tolls complemented by infrastructure investment and land-use management in favor of public and non-motorized private transport modes; and the provision of charging infrastructure to promote electric vehicles.
In particular, since the results suggest that price instruments should be limited as long as the composition of public goods has not been fully adjusted, and since changing settlement patterns, urban form and infrastructure is time-intensive, the latter should be high on the agenda of climate- and environmental policies.

More generally, the results indicate that externality pricing must take into account the infrastructure, and that vice versa, infrastructure spending should not be viewed as a 'downstream' policy, only reacting to private behavior shaped by seemingly more 'direct' instruments such as taxes. On the contrary, public infrastructure can also be used to actively change private behavior, and in realistic settings with constraints on taxes and public spending, integrated environmental policies are required.

Acknowledgements

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A Appendix

A.1 Generalized private response to marginal policy changes

For general subutility functions $G(X, Z)$ and $B(D, Z)$, the total derivative of (5) in the main part is

$$S_C\tilde{C} - S_D\tilde{D} = \sigma\tilde{\tau} - S_X\tilde{X} - S_Z\tilde{Z}, \tag{A1}$$

with

$$\begin{aligned}
S_C &:= (\theta_{GC} - \sigma\theta_{GCC}), \quad S_D := (\theta_{BD} - \sigma\theta_{BDD}),\\
S_X &:= (\theta_{GX} - \sigma\theta_{GCX}), \quad S_Z := (\theta_{BZ} - \sigma\theta_{BDZ}),\\
\text{where} \quad \theta_{FJ} &:= \frac{\partial F/\partial J}{F/J}, \quad \theta_{FIJ} := \frac{\partial F_I/\partial J}{F_I/J},\\
\frac{1}{\sigma} &:= \frac{\partial(Q_B/Q_G)}{\partial(G/B)}\frac{G/B}{Q_B/Q_G}.
\end{aligned}$$

If we choose the specific functions

$$G(C, X) = C^\alpha X^\delta \quad \text{with} \quad 0 < \alpha, \delta \leq 1, \tag{A2a}$$

$$B(D, Z) = D^\beta Z^\gamma \quad \text{with} \quad 0 < \beta, \gamma \leq 1, \tag{A2b}$$

and evaluate all partial derivatives, (A1) becomes

$$[\alpha - \sigma(\alpha - 1)]\tilde{C} - [\beta - \sigma(\beta - 1)]\tilde{D} = \sigma\tilde{\tau} + (\sigma - 1)(\delta\tilde{X} - \gamma\tilde{Z}). \tag{A3}$$

Setting $\alpha = \beta$ simplifies the LHS, and $\delta = \gamma$ the last term on the RHS, so that we obtain (11) in the main text.

A.2 General solutions for second-best policy scenarios

This appendix derives the remaining variables of the general second-best scenarios described Section 3.2.1.

A.2.1 The case of second-best environmental taxation

Subsection 3.2.1 already derived the condition for second-best environmental taxation, Equation (17′). For the remaining conditions, consider first the case when the total spending constraint (14a) is binding. Then, second-best X' and Z' can be determined from (14b′) and

$$X' + Z' = \bar{S}. \tag{14a′}$$

In this case, $\xi \neq 0$ in (15c) and (15d), and (18a) and (18b) are replaced by

$$U_Q(Q_Z - Q_X) = \frac{\zeta}{NZ'}(\bar{\Omega} + 1), \tag{18a′}$$

$$N\frac{U_Q Q_X}{U_Q Q_C} = N\frac{U_Q Q_Z}{U_Q Q_C} = 1 - \frac{\xi}{\lambda} - \frac{\zeta}{\mu Z'}, \tag{18b′}$$

which can be solved for ξ and ζ.

Second, when total public spending is unrestricted, (14a′) does not hold – but (18a′) and (18b′), simplified by $\xi = 0$, still determine the total public spending level (and ζ).

In either case, the lump-sum tax T can be determined as the 'residual' in the public budget (13).

A.2.2 The case of second-best public spending composition

Subsection 3.2.2 assumed the binding constraint $\tau = \bar{\tau} < \tau^*$, so that $\nu \neq 0$ in (15a). Together with (15b), this implies

$$\mu = \frac{\lambda}{1 - (\tau_p - \bar{\tau})D_T} = \frac{\lambda D - \nu/N}{1 - (\tau_p - \bar{\tau})D_\tau}. \tag{A4}$$

Further, since constraint (14b) is non-binding, we have $\zeta = 0$, which lead to (18a″). For the remaining variables, assume first that the total spending constraint (14a) is binding. Then, $X' + Z' = \bar{S}$ and (18a″) determine X' and Z', and $\xi \neq 0$ in (15c) and (15d). Thus, (18b) is replaced by

$$N\frac{U_Q Q_X + (\tau_p - \bar{\tau})D_X}{\mu} = N\frac{U_Q Q_Z + (\tau_p - \bar{\tau})D_Z}{\mu} = 1 - \frac{\xi}{\mu}, \tag{18b″}$$

which can be solved for ξ.

If total public spending is unrestricted, (18a″) and (18b″) simplified by $\xi = 0$ determine the total public spending level.

Again, the lump-sum tax T finally follows from the public budget (13) in either case.

A.3 Private behavior for a specific utility specification

For illustration of Section 2 and reference in Section 4.2, this appendix completes the solution of the private optimization problem for the utility specification in (19). Combining (20) with (3) we obtain the demand functions

$$C(\tau, T, X, Z) = \beta^{\eta} X^{\delta\rho\eta} \frac{1-T}{\pi}, \tag{A5a}$$

$$D(\tau, T, X, Z) = \left(\frac{1-\beta}{1+\tau}\right)^{\eta} Z^{\delta\rho\eta} \frac{1-T}{\pi}, \tag{A5b}$$

$$\text{with} \quad \pi := \beta^{\eta} X^{\delta\rho\eta} + (1-\beta)^{\eta} Z^{\delta\rho\eta} (1+\tau)^{-\alpha\rho\eta}.$$

Since demands are independent of total public spending $S := X + Z$, they can alternatively be expressed as functions of (τ, T, Ω): using

$$X = \Omega S/(1+\Omega), \tag{A6a}$$

$$Z = S/(1+\Omega) \tag{A6b}$$

in (A5) yields the demand functions (21) in the main text.

Substituting (A5) back into (19) yields the indirect utility of composite consumption

$$\hat{Q}(\tau, T, X, Z) = (1-T)^{\alpha} \pi^{1/(\rho\eta)} \tag{A7}$$

Again, using (A6) we can rewrite this as

$$\hat{Q} = \hat{Q}(\tau, T, \Omega, S) = (1-T)^{\alpha} \left[\frac{S}{1+\Omega}\right]^{\delta} \left[\frac{1-\beta}{1+\tau}\right]^{1/\rho} [\Delta + 1 + \tau]^{1/(\rho\eta)}. \tag{A8}$$

A.4 Remaining formal proofs

Derivation of Equation (30) *in Lemma 5.* Since $\sigma > 1$ and $\alpha + \delta < 1/\rho$ by assumptions (19f) and (19g), we have $0 < \rho < 1$, $\eta > 1$ and thus $\delta\rho\eta < 1$. Hence, the RHS of (27) is convex and the LHS is linear.

Equation (27) has exactly one solution if its LHS describes a tangent to its RHS. Thus, denote by $\tau_{||}$ a tax rate for which the derivatives of the LHS and the RHS of (27) with respect to τ are equal, yielding

$$M - 1 = \Delta^*_{\tau}(\tau_{||}) = HR(1+\tau_{||})^{H-1}. \tag{A9}$$

This can be solved for $\tau_{||}$, which equals the solution τ^* if the LHS and the RHS attain the same value: substituting $\tau_{||}$ back into (27) gives Condition (30) with equality.

Equation (27) has two solutions (no solution) if at the tax level $\tau_{||}$ for which the LHS and the RHS are parallel, the LHS is larger (smaller) than the RHS:

$$\tau_{||} > (<) \frac{1}{M} \left[\Delta^*(\tau_{||}) + 1 + \tau_{||}\right]. \tag{A10}$$

Using the solution of (A9) in this expression gives the upper (lower) case of Condition (30). □

Proof of Lemma 6. The derivation of Condition (32) is the same as for (27), see the proof of Proposition 5 above, so we abbreviate it here:

Again, the LHS of (31) is linear and the RHS is convex by (19f) and (19g). By comparing the first derivatives of the LHS and the RHS of (31),

$$1 \left\{ \begin{array}{c} > \\ = \\ < \end{array} \right\} \frac{n\phi}{m\alpha} \left[\Delta_\tau + 1\right], \tag{A11}$$

solving for τ and substituting the result back into (31), we obtain (32).

Furthermore, if there are two intersections of the LHS and the RHS of (31), the slope of the LHS must be larger than that of the RHS at the intersection with the lower τ value. Thus, (33) follows directly from the upper case of (A11).

Similarly, it follows from the 'middle case' of (A11) that (33) holds with equality if there is one solution. □

Proof of Proposition 7. We first show (34): Assume that there is a first-best τ^* satisfying (27). The RHS of (31) is smaller than the RHS of (27) at τ^*, since $\bar{\Omega} < \Omega^*$ implies $\Delta(\tau^*, \bar{\Omega}) < \Delta(\tau^*, \Omega^*)$.

Since the RHS of (31) by (19f) and (19g) monotonously increases in τ at a growing rate, and the LHS of (31) is the identity function as for (27), they must intersect at a smaller tax than for the first-best case: there must be a τ' that solves (31) with $\tau' < \tau^*$.

Since the RHS of (31) starts from $1/M[\Delta(\tau = 0, \bar{\Omega}) + 1] > 0$, and thus above the identity function, we also have $\tau' > 0$.

Relation (35) follows by the same logic, since a lower constraint on Ω implies a smaller Δ at the 'old' intersection. Formally, in the argument above, just replace τ' by $\tau'(\bar{\Omega}_2)$ and $\bar{\Omega}$ by $\bar{\Omega}_2$, as well as τ^* by $\tau'(\bar{\Omega}_1)$ and Ω^* by $\bar{\Omega}_1$. □

Proof of Proposition 8. We first show (37) and then that there are at most two non-zero solutions.

The proof of (37) has two parts: we show that the same relation holds for another specific $\Omega \neq \Omega'$, and then show that this implies the claim.

Define $\hat{\Omega}$ as the solution to

$$\Omega = \frac{\Delta(\bar{\tau}, \Omega)}{1 + \tau_p(\bar{\tau}, \Omega)}. \tag{A12}$$

In Fig. 2, this is the intersection of the linear LHS of (36) and the lowest curve described by the first fraction on the RHS of (36), the ratio of marginal total costs of clean and dirty consumption. For $\Omega \to 0$, this fraction goes to zero (because Δ goes to zero and τ_p towards a finite value), but its slope becomes infinitely large:

$$\lim_{\Omega \to 0} \frac{d}{d\Omega} \frac{\Delta}{1 + \tau_p} = \lim_{\Omega \to 0} \delta\rho\eta \frac{M + 1 + \bar{\tau}}{M(1 + \tau_p)^2} \frac{\Delta}{\Omega} = const. \cdot \lim_{\Omega \to 0} \Omega^{\delta\rho\eta - 1} = \infty,$$

since $\delta\rho\eta < 1$ by (19f) and (19g). Hence, it grows faster than (and is above) the LHS of (A12) near the origin. As Ω increases, it grows monotonously with a decreasing slope towards an upper bound:

$$\lim_{\Omega\to\infty} \frac{\Delta}{1+\tau_p} \overset{\text{l'Hôpital}}{=} \lim_{\Omega\to\infty} \frac{\Delta_\Omega}{1/M\Delta_\Omega} = M. \tag{A13}$$

Thus,

$$\Omega < \frac{\Delta(\bar{\tau},\Omega)}{1+\tau_p(\bar{\tau},\Omega)} \quad \Leftrightarrow \quad \Omega < \hat{\Omega}, \tag{A14}$$

and vice versa for $\Omega > \hat{\Omega}$, so (A12) has exactly one solution.

Now, to show that (37) holds for $\hat{\Omega}$, we need to show that the second term on the RHS of (36), in square brackets, is larger than one at $\Omega = \hat{\Omega}$, which is the case if

$$\tau_p(\bar{\tau},\hat{\Omega}) > \bar{\tau}. \tag{A15}$$

By (24), such a relation holds for *any* Ω if $(M-1)\bar{\tau} < 1$. Otherwise, we need another auxiliary construction:

Define $\tilde{\Omega}$ as the solution to

$$\tau_p(\bar{\tau},\Omega) = \bar{\tau}, \tag{A16}$$

and note that since τ_p is an increasing function of Ω,

$$\tau_p(\bar{\tau},\Omega) > \bar{\tau} \quad \Leftrightarrow \quad \Omega > \tilde{\Omega}. \tag{A17}$$

It follows that if $\tilde{\Omega} < \hat{\Omega}$, (A15) holds. We thus need to show that the left part of (A14) holds for $\tilde{\Omega}$.

To do so, note that (A16) by (24) implies $\Delta(\bar{\tau},\tilde{\Omega}) = (M-1)\bar{\tau} - 1$. Hence, we can rewrite (A14) for $\Omega = \tilde{\Omega}$ as

$$\tilde{\Omega} < \frac{(M-1)\bar{\tau} - 1}{1+\bar{\tau}}. \tag{A18}$$

Substituting $\tilde{\Omega}$ with the help of (20) and reordering (using $(M-1)\bar{\tau} \geq 1$) yields

$$(M-1)\bar{\tau} - 1 < \left[\frac{\beta}{1-\beta}(1+\bar{\tau})^{1-\delta\rho}\right]^{\eta/(1-\delta\rho\eta)}. \tag{A19}$$

Using the definition of Δ^* from (27), we obtain

$$\bar{\tau} < \frac{1}{M}\left[\Delta^*(\bar{\tau}) + 1 + \bar{\tau}\right]. \tag{A20}$$

The RHS of (A20) is a convex function of $\bar{\tau}$ and always positive (see also Fig. 1 and the proof of Proposition 5). Thus, it is larger than the unity function on the LHS up to a potential intersection, which by (27) and Proposition 5 is the first-best τ^*: in this case our second-best assumption $\bar{\tau} < \tau^*$ implies that (A20) is true. If there is no such intersection, (A20) is trivially true (and there is no first-best solution).

Thus, we have shown that (37) holds for $\Omega = \hat{\Omega}$. It remains to be shown that this implies that it also holds for $\Omega = \Omega'$:

The second term on the RHS of (36) in the square brackets is larger than one by (A15) for $\Omega = \hat{\Omega}$, and it keeps growing monotonously with increasing

Ω.[15] We saw above that the first term on the RHS of (36) also grows (towards an upper bound, see (A13)). Thus, if the RHS attains the same value as the LHS, this will be at a value $\Omega' > \hat{\Omega}$, and the term in the square brackets on the RHS will be larger than for $\hat{\Omega}$, so (37) from the main text follows.

Now, consider the number of solutions. Overall, the RHS of (36) grows faster than the LHS for $\Omega \to 0$, and also for $\Omega \to \infty$: Since the term in square brackets grows at a rate that converges to η/M, while the fraction in front of the bracket converges to a constant M, the slope of the entire RHS converges to η, which is larger than one (by $\sigma > 1$) and thus larger than the slope of the LHS. Nevertheless, the derivative of the RHS may fall below that of the LHS 'in between', for example if the growth of the first term on the RHS slows down fast (because this term then itself contributes less to overall growth of the RHS, and because it acts as a weight to the growth contribution of the second term in the square brackets, which will then be small). In this case, the RHS will have a 'curved' shape as in Figure 2: If growth of the RHS increases too fast after the slowdown, it does not have any point in common with the LHS, and there is no solution to (36). If the LHS is tangent to the RHS, there is only one solution. If the RHS has a first intersection with the LHS at Ω'_L, the fact that the RHS becomes steeper afterwards until it reaches a slope larger than that of the LHS implies that there is a second solution at $\Omega'_H > \Omega'_L$ (see inset in Figure 2).

This concludes the proof. □

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[15] More precisely, it grows to infinity at a monotonously decreasing slope that converges to η/M, since

$$\lim_{\Omega\to\infty} \frac{d}{d\Omega}\left[\frac{\tau_p - \bar{\tau}}{\tau_p}(1+\Omega)\right] = \lim_{\Omega\to\infty}\left[\underbrace{\frac{\tau_p - \bar{\tau}}{\tau_p}}_{\to 1} + \frac{\delta\rho\eta\bar{\tau}}{M}\,\frac{1+\Omega}{\Omega}\,\underbrace{\frac{\Delta}{\tau_p^2}}_{\to 0}\right] = 1.$$

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Chapter 7

Synthesis and outlook

The recent Paris Agreement for global climate change mitigation does not define binding emission reduction targets for some or all countries, as was the case under the Kyoto Protocol. Instead, each country independently determines its contribution to climate change mitigation, only the recording and regular assessment of these commitments remains centralized. Under this 'pledge and review' approach to mitigation, domestic motives for climate policy thus take center stage (see Chapter 1). A comprehensive analysis of these domestic mitigation motives needs to include effects beyond avoided climate damages and emission-intensive sectors: at the national level, climate policy interacts with a broad range of non-climate policy goals and instruments. An important example are interactions between national-level climate policies and fiscal policies.

My aim in this thesis was to provide an overview of such interactions, and to theoretically analyze a subset of effects related to rent taxation and public spending. In this final chapter, I first summarize and synthesize the results. Second, I discuss the methods used, potential extensions, and how the analysis of domestic mitigation motives in this thesis informs the analysis of international cooperation under the new regime. Third, I explore the policy implications of my results at the national level for the design and appraisal of climate- and fiscal policies, as well as at the international level.

7.1 Synthesis

This section summarizes the main part of this thesis by relating its results to the research questions posed in Section 1.4 of the introduction:

First, an overview of important interactions between climate- and fiscal policies was provided in Chapter 2, which I will summarize in Subsection 7.1.1 below. Second, three more detailed questions regarding interactions on the revenue-side of the public budget, or more specifically, regarding rent taxation in the context of climate policy, were addressed in Chapters 3 to 5. These are synthesized in Subsection 7.1.2. Third, an effect related to public spending in the context of climate policy was analyzed in Chapter 6, which is the subject of Subsection 7.1.3.

7.1.1 Overview of interactions between national climate policy and public finance

The introductory chapter illustrated that interactions between climate- and fiscal policies can be significant in terms of financial magnitude and welfare impacts, but relied only on a few examples. Thus, to get a better overview, my first question was:

1) What are the most important interactions between national climate policy and public finance? In particular, what are the implications of using carbon pricing for public revenue-raising, how do public spending and climate policy affect each other, and what are the distributional effects of this, both within and across generations? Can and should climate policy and public finance be analyzed in a single framework?

I mainly addressed this in Chapter 2, which started with the observation that the literature on such interactions is scarce: On the one hand, studies of climate change mitigation often focus on technologies in high-emission sectors – both in standard IAMs of optimal mitigation, and in second-best climate policy frameworks. The latter add technology- and sector-specific inefficiencies, rather than inefficiencies related to fiscal policies. On the other hand, many public economists have analyzed a prime example for interactions between climate- and fiscal policies: potential welfare gains from replacing distortionary taxes by carbon pricing revenues, and vice versa, adjustments to carbon prices due to pre-existing distortionary taxes. However, other effects have long been neglected. Thus, an overview was given of recently described further interactions, of which there are three groups:

First, climate policy affects *public revenues*. Direct effects arise from carbon pricing, which is an attractive revenue source for at least two reasons: a carbon price acting as a tax on fossil resources is preferable to a capital tax because it leads to less international relocation of mobile capital (regardless of potential strategic coordination among fossil fuel importers or exporters).

Furthermore, a carbon price acts as a tax on rents from fossil resource stocks. It directs investment away from fossil resource stocks and towards producible capital, which is welfare-enhancing if capital was previously underaccumulated. I elaborated on the second effect in Chapter 5, which is summarized in Section 7.1.2 below.[1]

Second, climate policy interacts with *public spending*. For example, public investment into the right types of transport and energy infrastructure is crucial for GHG mitigation. Thus, climate policy should include changes to the *composition* of public spending along with instruments such as carbon pricing. Both instruments need to be adjusted to each other, in particular when one of them cannot be set optimally. A detailed analysis was provided in Chapter 6, as summarized in Section 7.1.3.

[1]There are also indirect effects of climate policy on public revenues, which were not covered in Chapter 2. For example, as illustrated in Chapter 1, climate policy changes land rents in agriculture, forestry and in cities, and thus affects (potential) revenues from land rent taxation. I further analyzed the potential of either form of rent taxation (carbon pricing acting as a tax on fossil resource rents, or land rent taxes) to finance the optimal level of public investment in Chapter 3, and their potential to implement the social optimum via redistribution in Chapter 4.

Moreover, the aggregate *level* of public spending is affected: due to the revenue-side effects of climate policy, any amount of public funds can be raised at lower costs, and climate change mitigation and adaptation imply additional public spending requirements. Together, this changes the optimal total level of public spending. However, the optimal level may not always be implemented. Among the potential reasons are weak institutions that fail to raise enough taxes, spending choices that do not maximize social benefits, or barriers to large long-term investments (such as political limits on public debt, or limited access of the public sector to credit). To the extent that additional revenues from carbon pricing are less affected by these problems, they offer a possibility to bring public spending closer to the optimum level.

Third, climate policy affects the *distribution* of wealth and income within and across generations, which is also the aim (or side-effect) of a wide range of other public policies.

Regarding *intragenerational* distribution, carbon pricing can for example be regressive when low-income households spend a high income share on carbon-intensive goods, or when carbon-intensive industries employ many low-skilled workers. It has been shown that this can be compensated by using carbon pricing revenues for direct transfers or for cutting other regressive taxes, to the point where the overall reform becomes Pareto-improving. Another revenue-recycling option may be desirable for both normative redistribution motives and efficiency reasons: carbon pricing could finance public spending, for example on education, health care or infrastructure access, in order to reduce inequality of opportunities. In contrast to inequality in returns, which may provide incentives for working and saving, inequality of opportunities may reduce economic efficiency. However, it remains unclear if the regressivity of carbon pricing can be fully compensated by recycling its revenues via public spending.

Regarding *intergenerational* distribution, future generations enjoy most of the benefits from avoided climate damages, while present generations bear most of the costs of mitigation. Thus, to improve political feasibility, some of the costs could be transferred into the future. A Pareto-improving combination of climate change mitigation with intergenerational transfers could be established through different fiscal policies: by public debt (as long as there is no Ricardian equivalence), by diverting funds from long-term capital investment towards mitigation, or by continuously making young generations compensate the concurrent older generations in a pay-as-you-go pension scheme. Theoretically, fixed or durable assets should provide an 'automatic' intertemporal transmission mechanism: expectations of lower climate damages should make current fixed or durable assets more valuable. These gains would then be an issue for intragenerational redistribution again. However, the relevance of this mechanism is unclear because current asset holders do not seem to push for more stringent climate policy.

The descriptions of all these interactions implicitly build on the methodological assumption that the welfare effects of climate policy and public finance can and should be analyzed together. The final part of Chapter 2 supported this assumption: In practice, if decisions in one policy domain significantly impact another policy domain, such as carbon pricing generating large public revenues, these interactions should be included in sound policy appraisal.

However, isolated models of climate policy or public finance cannot capture these non-negligible interactions. Thus, either framework has to be extended – there seem to be no fundamental metaphysical, methodological or normative objections to this. On the contrary, the theory of the second-best (Lipsey and Lancaster, 1956) suggests that the introduction of policies addressing the climate externality will also affect optimal policies in other, seemingly unrelated parts of the economy, and vice versa. Furthermore, an integrated framework is required for a full political economy analysis of the feasibility of climate policy interacting with other policy fields.

The joint welfare analysis of climate policy and its *non-fiscal* co-benefits has sometimes been criticized for co-benefit estimations based on partial models, for their allegedly uncertain magnitudes and difficulties in monetarizing and comparing them. These objections do not apply to fiscal co-benefits of climate policy, which are typically analyzed in general equilibrium models and can be estimated in monetary terms with relatively high robustness.

7.1.2 Public revenue-raising: rent taxation in the context of climate policy

I formally analyzed revenue-side interactions between climate policy and fiscal policies. My focus was on rent taxation: I showed in Section 1.3.1 that despite potentially large impacts of climate policy on rents from fossil resources and land, there has been little analysis of taxes on such rents in the context of national-level climate policy, of their implications for public budgets or of their social welfare effects. I thus explored first the scale of rent taxation revenues relative to national public budgets, second the welfare effects of (fixed factor) rent taxation that is in fact distortionary, and third the applicability of these results to different forms of carbon pricing.

Specifically I began by asking:

2) Is rent taxation theoretically sufficient to fully finance optimal public investment at the national level?

Chapter 3 answers this question based on a standard Ramsey model with production factors including private capital and labor, but also a fixed factor (land) and public capital. The main result is that if the land rent is equal to (or exceeds) the public investment need, the socially optimal level of the productive public good can indeed be financed by full (or partial) land rent taxation alone. Even if no lump-sum taxes are available, there is then no trade-off between distortionary taxation and productive public investment (which otherwise prevents reaching the social optimum). The result similarly applies when land values rather land rents are taxed.

Explicit conditions were derived for a Cobb-Douglas production function: to finance social optimal public investment from rent taxation, it is (more than) sufficient if the national income share of land is greater than the elasticity of output with respect to the public capital stock. This holds in the steady state of a neoclassical growth model, in which there are decreasing returns to scale in private and public capital, and similarly on the balanced growth path of an endogenous growth model with constant returns to private and public capital (under uncontroversial parameterizations of the utility function).

These results can be interpreted as an extension of the 'Henry George Theorem' of local public finance (Stiglitz, 1977; Arnott and Stiglitz, 1979; Arnott, 2004), according to which optimal local public good provision can be financed by a tax that collects all land rents (if population is optimal), to a macroeconomic setting with capital stock dynamics (in which private capital accumulation is optimal). The analogy is particularly close in a model without land, but with firms' profits: taxing the latter can always finance the socially optimal investment in the steady state.

The practical relevance of these results is underlined by empirical data: for many countries, rents from fixed factors and infrastructure investment needs are of a comparable magnitude (Jakob et al., 2016; Fuss et al., 2015).

In sum, Chapter 3 shows that taxes on rents can play a major role for national-level public investment financing. This is of particular relevance in the context of climate policy, which affects land rents and may be used to collect fossil resource rents.

However, the potentially large public revenues and distributional effects of rent taxation related to climate policy also necessitate a careful welfare analysis. In particular, Feldstein (1977) demonstrated that collecting rents from a fixed factor (land) is distortionary, because it shifts investment away from land and towards capital. This aggregate investment effect, which combines efficiency- and distributional aspects, has to be taken into account, suggesting the question:

3) What are the welfare implications of taxing the rents from a fixed factor? Specifically, is the aggregate investment effect beneficial, and how much can additionally be achieved by redistributive recycling of the rent tax revenues?

These questions cannot be answered in a model with a representative infinitely-lived agent (ILA) such as the one employed in Chapter 3: the adjustment of investors' portfolios in response to rent taxation requires that the underlying asset is traded, and this trade only takes place if there is some heterogeneity between agents. One way to introduce heterogeneity is to differentiate agents with respect to age, for example in an overlapping-generations (OLG) model with age-dependent wealth (and without bequests that would neutralize heterogeneity).[2]

Chapter 4 thus used a continuous OLG model based on Yaari (1965) and Blanchard (1985) with a fixed factor (land) and producible capital as alternative assets, a tax on fixed factor returns and potentially age-dependent lump-sum recycling of tax revenues. As they grow older, agents build up wealth, balancing their investment between assets according to a no-arbitrage condition (which is affected by the tax on rents). Wealthy older agents are continuously replaced by newborns, which are fundless as there are no bequests. It is a standard feature of (general-equilibrium) continuous OLG models that this 'generation replacement effect' leads to suboptimally low capital accumulation.

It is proved that rent taxation is then indeed *beneficial*: it both increases the aggregate capital stock and mitigates the missing land wealth of the newborns. This also holds when land owners are compensated, or for uniform transfers – the welfare improvement increases with the tax level. However, the *social*

[2] An OLG model with full bequest motives can be constructed such that the results of the ILA model of dynastic saving are reproduced, in which the aggregate investment effect does not occur (Calvo et al., 1979).

optimum (the dynamically optimal allocation of aggregate consumption and capital) cannot be reached unless additionally, the missing capital wealth of newborns is addressed by a transfer scheme that favors the young.

For transfers to newborns only, a condition for reaching the social optimum was derived: the land rent must be at least as high as the missing capital of the newborns. If it is higher, and transfers are strongly redistributive, a tax level below 100% is optimal. Empirical data confirms that reaching the social optimum by rent taxation and redistribution is actually feasible in many countries.

Alternatively, the social optimum can be reached by recycling the tax revenues as a capital subsidy, under an empirically even weaker condition on the level of land rents (but in contrast to redistribution towards the young, this cannot simultaneously implement the socially optimal distribution across co-existing individuals).

These results show that rent taxation and redistributive revenue recycling are beneficial if capital is otherwise underaccumulated. They also illustrate that efficiency and distribution are inseparable in this context: rent taxation is not only beneficial if one values a more equal distribution of wealth, it also causes distortions that may increase aggregate efficiency. This is not a separate phenomenon, but partly *due to* the redistributive effect of rent taxation. Moreover, additional redistribution via tax revenue recycling can further increase aggregate capital, output and consumption towards their socially optimal levels.

This further strengthens the case for a substantial tax on land rents for public revenue generation – even more so when climate policy increases these rents. However, the arguably most important case of rent collection in the context of climate policy is that of carbon pricing acting as a tax on rents from fossil fuel stocks. Hence, I additionally asked:

4) Does the aggregate investment effect similarly occur for carbon pricing, which acts as a tax on the rents from exhaustible resources? Is there a difference between carbon pricing instruments, such as a permit scheme and a carbon tax?

Chapter 5 modifies the model of Chapter 4 to include an exhaustible fossil resource stock as a tradable asset, instead of a fixed amount of land. Resource owners sell fossil fuels to firms (which directly translates into GHG emissions), thus earning a rent. Some share of this rent is collected by the government, representing carbon pricing by a tax or a permit scheme without full grandfathering. Moreover, to focus on the aggregate investment effect of carbon pricing alone, the public revenues are not used for redistributive recycling in the basic model. Instead, the government invests in R&D for resource efficiency improvements that exactly offset the resource extraction path, to keep the model analytically tractable. In this setting, balanced paths with or without different carbon pricing instruments are compared (abstracting from transition effects after climate policy is first announced).

It is shown that carbon pricing generally induces a beneficial aggregate investment effect when producible capital is otherwise suboptimally underaccumulated. This is similar to the case of fixed factor rent taxation described above. Again, without redistributive recycling of carbon pricing in excess of the R&D financing needs, the social optimum cannot be reached. However, there are important differences between specific policy instruments, most importantly between GHG emission permit schemes and a carbon tax:

Under an emission permit scheme, the amount of GHG emissions depends on the number of permits that are issued over time, while the strength of the investment effect depends on the share of permits that is auctioned. Since these two policy variables can be chosen independently, both the benefits from mitigation and from investment shifting can be maximized by the government. In particular, the auctioned share of permits should be as high as possible. Under a carbon tax, the government can only choose the tax rate (over time). To affect the (endogenous) path of resource extraction and thus of GHG emissions, the tax rate needs to vary – but this also implies that full rent collection at all times is not simultaneously possible.

Another difference may arise between a 'traditional' permit scheme that directly regulates the flow of GHG emissions, and a 'stock-based' permit scheme under which the right to annually obtain a certain share of the total emission budget is a tradable asset: formally, both variants are shown to lead to the same aggregate economic dynamics, including the beneficial investment effect. In practice, however, the underlying assumption that the emission-relevant asset is freely tradable is more likely to hold for newly created property rights to the 'stock of the atmosphere' than for fossil resource stocks. Furthermore, the stock-based permit scheme makes atmospheric limits and climate policy revenues more tangible to individuals, improving the political feasibility of gradually more stringent climate policy.

In sum, all forms of carbon pricing collect fossil resource rents and thus induce a investment shift from exhaustible resource stocks towards capital that is beneficial if capital is otherwise underaccumulated. Carbon pricing could thus be supported for environmental, distributional and efficiency reasons alike – in particular, there is no contradiction between climate change mitigation and capital accumulation.

Although each of Chapters 3-5 uses a formal model tailored to the analysis of a different aspect of rent taxation, their results can be combined:

Regarding the macroeconomic effects of rent taxation, the two-asset OLG models are more realistic because they capture distortions due to rent taxation. Thus, start from the OLG model of Chapter 5, which shows that carbon pricing induces beneficial distortions of investment, but can never reach the social optimum. In this model, carbon pricing revenues are spent on resource efficiency research to maintain a balanced growth trajectory. But assume that carbon pricing yields more revenues than what is needed to finance this research: then, these additional funds could go into transfers biased towards the fundless young generations – to the point where, according to Chapter 4, the social optimum may be reached. This point was discussed in more detail in Section 3.3 of Chapter 5.

Moreover, Chapter 3 shows that the optimal level of productive public capital can be financed by rent taxation if private capital accumulation is optimal. This result carries over to the OLG setting of Chapters 4 and 5 provided that private underaccumulation is cured (by redistributive transfers to the young). Thus, to establish the social optimum in a combined setting with productive public capital and OLG, land (or resource) rent tax revenues need to be sufficient to finance optimal investment into productive public capital *and* transfers that establish the optimal level of private investment (*and* R&D for resource efficiency). See also Section 5.2 in Chapter 3 and Section 4 in Chapter 4.

The sufficiency condition would be somewhat weaker if public investment also had a positive effect on the source of private capital underaccumulation: in our model, less redistribution by transfers would be required if public investment benefited the young more than the old. However, it is unclear whether this is the case (for example, better education for the young would increase their wage also when they are old). Thus, to capture effects of public capital on both productivity and distribution, a model with another source of heterogeneity (rather than just age) may be required.

Overall, this thesis shows that land- and fossil resource rents and their taxation are at the heart of several important interactions between climate policy and and public finance: rent taxation in the context of climate policy can contribute significantly to the public budget, and may have beneficial macroeconomic impacts on capital accumulation.

7.1.3 The role of public spending for climate change mitigation

Climate policy largely focuses on instruments that directly regulate GHG emissions, such as carbon pricing. Because these instruments are similar to non-environmental taxes in some respects, most studies of interactions between climate policy and public finance have focused on the revenue-side of the public budget, and neglected the role of public spending for GHG mitigation. However, adjustments to public spending have a large impact on private behavior and thus on mitigation, for example in the transport and energy sectors. Furthermore, both public spending and carbon pricing (or environmental taxation in general) are often constrained, for example by high inertia in infrastructure capital stocks or political limits to taxation. Thus, I asked:

5) When the provision of different types of infrastructure affects private choices, what is the effect of its non-optimal provision on optimal environmental taxation? Vice versa, how does non-optimal environmental taxation affect optimal infrastructure provision?

In Chapter 6 I considered the case that private choices between polluting and non-polluting goods depend on two publicly provided goods that complement either of the two. An example would be private spending on non-motorized or car transport, and public spending on rails and bicycle paths or roads. Define the composition of public spending as the ratio of spending complementary to clean and dirty consumption. Modifying a standard model of optimal environmental taxation and public spending (Bovenberg and van der Ploeg, 1994), I first showed how marginal changes to the composition of public spending can have the same effect as a tax on pollution.

Second, I showed that compared to the first-best case, the *general formula* for second-best environmental taxation is the same even when the composition of public spending is non-optimal, although the latter will still imply a different second-best *level* of taxation. In contrast, when environmental taxation is constrained, the general formula for the second-best public spending composition does include an additional term that reflects its role in reducing the environmental externality. This is in sharp contrast to the first-best case, in which there is a clear 'division of labor' between price adjustments to address the environmental externality on the one hand, and public spending to match the resulting corrected demands on the other hand.

Third, I applied the general optimality conditions to a specific utility function, under the crucial assumption that polluting private goods are relatively important in utility. I showed that the second-best level of environmental taxation or public spending composition is lower than its respective first-best value if the other policy variable is constrained. For example, if there is a lack of infrastructure for clean non-motorized transport, this should then not be compensated by a higher tax on emission-intensive motorized transport (such as a higher carbon tax on fuels): this would penalize individuals too much without offering a real option for switching to non-motorized transport.

These results are valid in the short run insofar as alleviating infrastructure constraints, or political processes for changes in the tax system, take time. Thus, there is also an implication for the long run: a high priority in environmental policy, and particularly in urgent climate policy, should be given to restructuring public investment. Less public investment should go into roads and other infrastructure that supports emission-intensive transport, and more into rails, waterways, public transport, walkways and bicycle paths, or at least towards publicly accessible charging stations for electric vehicles.

Together, these results challenge the common intuition in much of environmental and public economics that public spending have no role in internalizing environmental externalities. On the contrary, it is shown that public spending should often be used to actively shape private behavior and reduce GHG emissions, and should not just ‘follow’ private demand affected by carbon pricing. Furthermore, the results advise caution against compensating constraints in one policy instrument by stepping up another instrument, which may seem intuitive. Instead, it may be better to work on removing the constraint itself in the long run, depending on the valuation of environmental quality. In fact, the model and results as well as these general conclusions apply not only to climate policy (which motivated the analysis), but to environmental policy at large.

7.2 Methods and Extensions

In this section, I first discuss the formal methods used in Chapters 3 to 6, that is, crucial elements of my analytical models and the validity of the assumptions underlying them. I also discuss alternatives and extensions directly related to the respective method or effect. Second, I consider how the approach and scope of the overview in Chapter 2 could be complemented and extended, and point out additional interactions of climate- and fiscal policy at the national level. Third, I briefly comment on the relation of my analysis to studies concerned with international cooperation.

7.2.1 Model choice and extensions

The theoretical results in Chapter 3 on financing optimal public investment by rent taxation are robust, as they were derived for a neoclassical- and an endogenous growth model, for taxes on land rents or firms’ profits and for different production functions. Section 5 of Chapter 3 further discussed different models of government spending, household heterogeneity and labor- or land-augmenting technological progress. In particular, although the analysis is based on an ILA model in which rent taxation is non-distortionary, the results translate with only minor modifications to settings in which rent taxation is distortionary, such as the OLG models of Chapters 4 and 5 (see Section 7.1.2 above and Section 5.2 in Chapter 3).

An important remaining research question is thus empirical: How large are rents of (unimproved) land relative to optimal public investment, and how does this change over time? Section 5.4 of Chapter 3 presented a first approximation, showing that the income shares of 'non-producible factors' estimated by Caselli and Feyrer (2007) are generally larger than those of *actual* of public investment. However, the former type of data needs to be updated (it was available only for 1996) and decomposed into different factors such as land and fossil resources. Regarding the latter, actual public investment are unlikely to match the *socially optimal* level of public investment (for a given social welfare function).[3]

Chapters 4 and 5 used variants of the continuous OLG model (Yaari, 1965; Blanchard, 1985) with two assets, producible capital and rent-generating land or fossil resource stocks. It was shown that rent taxation induces a 'macroeconomic portfolio effect' which is beneficial, and can be complemented by redistributive revenue recycling to reach the social optimum. These results crucially depend on two model features: agents are *heterogeneous* (by age) and because there are no bequests, the continuous replacement of wealthy older individuals by fundless newborns leads to *capital underaccumulation.* This may then be cured by a tax on rent that redirects investments and further redistribution that makes the young better off.

The occurrence of a portfolio effect is well-established (Feldstein, 1977; Petrucci, 2006; Koethenbuerger and Poutvaara, 2009), the innovation here consists in the evaluation of its welfare effects and its application to climate policy. Accordingly, several (theoretical) robustness checks were provided for these results:

Chapter 4 proved the feasibility of the social optimum for two different redistribution schemes in favor of the young (transfers only to the newborns, or exponentially decreasing with age), compared to uniform recycling, compensation of the rentiers or a capital subsidy. It also explained (in Section 2.2) why the Keynes-Ramsey rule for aggregate consumption growth gives the appropriate benchmark for the dynamically optimal allocation: following Calvo and Obstfeld (1988), the optimal static allocation can be determined separately.

Chapter 4 addressed a potential concern regarding the applicability of the model with fossil resource stocks: there may be barriers to trade in this rent-generating asset, for example between agents in different countries or when large resource stocks are state-owned. However, Section 3.2 of this chapter showed that the beneficial portfolio effect may then be re-established with an innovative climate policy instrument that creates a new asset (a stock-based emission permit scheme with auctioning).

[3]Whether public capital is underprovided is a long-disputed issue, see for example the review by Gramlich (1994). Recent research by Bom and Ligthart (2014) concludes that public capital is under-provided in OECD countries, based on a comparison of output elasticities of public capital to market interest rates. However, this research should be extended to cover more countries – also, it does not take into account private capital formation and employment effects, and it is debatable if market interest rates are the appropriate benchmark.

Nevertheless, there are several important further research questions and extensions:

First, empirical research is needed to determine the size of portfolio effects in the past. For example, the introduction or increase of taxes on land value in different US federal states (Dye and England, 2009) may provide suitable data, including a control group of states without such taxes.

Second, does a beneficial portfolio effect also occur when heterogeneity between agents is modeled differently? Alternative forms of heterogeneity include differences in endowments, access to credit, skills or preferences. With any type of heterogeneity it can be ensured that assets are actually traded (homogeneous agents would hold identical portfolios, so assets have 'hypothetical' prices but no trade occurs). Also, investment choices governed by a no-arbitrage condition will always be affected by rent taxation, so a rebalancing of portfolios in favor of capital can generally be expected. However, not all types of heterogeneity will lead to capital underaccumulation (without rent taxation). In fact, even if heterogeneity in age is modeled differently, it is unclear if there is capital underaccumulation in an economy with capital and land: for discrete OLG models[4] in which finitely-lived agents are either young or old (Diamond, 1965) and with producible capital as the only asset, it has been shown there may be overaccumulation (see for example Acemoglu, 2009). On the other hand, if a fixed factor is the only asset in such a model, this ensures 'dynamic efficiency', that is, Pareto-efficient savings behavior (Homburg, 1991). The discrete OLG model by Feldstein (1977) includes both capital and land, but the question of underaccumulation has not been answered in this setup.

Third, as mentioned towards the end of Section 7.1.2, one may build on the first extension to re-evaluate the condition for reaching the social optimum by taxing and recycling rents in a model with rent-financed public spending (rather than lump-sum transfers) which affects heterogeneous agents differently.

Fourth, there may be other sources of capital underaccumulation than heterogeneity which may also be affected by climate policy, such as inefficient capital markets or bubbles on land markets.[5] Furthermore, empirical research is needed to clarify if private capital is indeed underaccumulated.

Fifth, the relation between a time-varying carbon tax, the dynamics of resource extraction and GHG emissions as well as rent collection could be explored further, for example using a numerical model (which may also be used to verify Conjecture 3 in Chapter 5).

Sixth, carbon pricing may induce other, 'secondary' portfolio effects. For example, it may affect investment choices between fossil resource exploration and R&D of extraction technologies, or R&D in renewable energy and energy efficiency technologies. Since R&D for renewables and energy efficiency may be undersupplied (see for example Jaffe et al., 2003), there is scope for welfare improvements.

Chapter 6 derived formal results on second-best combinations of environmental taxation and public spending. Because there seems to be no other

[4]These are not discretizations of the Yaari-Blanchard continuous OLG, but a separate model class.

[5]See the last point in Section 4, Chapter 4 for details. Additionally, see Galor and Moav (2004) for a distinction between physical and human capital accumulation.

literature on this topic, numerous alternative models and extensions are possible and interesting.

The analysis was based on a well-established model of first- or second-best environmental taxation when environmental quality, and other public goods, enter utility.[6] Thus, an alternative analysis could consider an environmental externality on production, which is particularly important for the case of climate change (Tol and Fankhauser, 1998), and productive public capital.

The first departure from earlier work was to impose a structure on the utility function under which private and public goods are not separable. This seems reasonable for the case of transport, where infrastructure availability is a crucial determinant for private decisions such as transport mode choice (Ewing and Cervero, 2010). The analysis of consumption changes in response to marginal policy changes (to illustrate the equivalence of tax- and infrastructure measures) can be likened to similar approaches in the literate on a potential 'double dividend' of environmental taxation (Bovenberg and De Mooij, 1994).

The second innovation was to consider second-best scenarios that do not focus on the available set of taxes to finance the public budget, but on environmentally relevant restrictions of either the composition of public spending or of the environmental tax. The existence and importance of such restrictions has been shown in the context of climate change mitigation (Shalizi and Lecocq, 2009), which becomes more expensive the longer it is delayed (IPCC, 2014). The derivation of general second-best conditions for these cases (which showed that the second-best formulas are unchanged for the tax, while the public spending composition becomes an environmental policy instrument) is standard and required no further assumptions.

Finally, to determine if policy variables are larger or smaller in the second-best than in the first-best, a set of assumptions was made regarding the functional form of utility and elasticities in this function.[7] Thus, an analytical proof (of a positive difference) was possible for the case of second-best taxation. The case of second-best public spending was explored by numerical experiments. Similarly, modeling a wider range of functional forms and elasticities would only be possible numerically. It seems unlikely that this would yield more insights on a theoretical level. However, calibrating such a numerical model would be useful to evaluate the effect of existing policy restrictions, for example in transport. A difficulty may be to obtain a consistent set of estimates at a macroeconomic level for the elasticity of private transport demands with respect to different types of infrastructure spending. For this, more empirical work may be required.

It would also be important to use the existing theoretical model to explore cases with several constraints, for example on the composition *and total level* of public spending. This would allow for a clearer distinction between income- and substitution effects. Moreover, one may extend the model to capture capital stock dynamics and network externalities, which are particularly im-

[6] I built on the version described by Bovenberg and van der Ploeg (1994), which in turn builds on earlier contributions such as Sandmo (1975); see also Bovenberg and Goulder (2002) and references therein.

[7] In particular, the subutilities from clean or dirty composite goods (interpretable for example as the amount of services obtained from bicycle or car transport) were assumed to have the same elasticities with respect to private and public goods, respectively. The model can then be solved in terms of the ratios (rather than the levels) of private and public spending on clean and dirty goods, respectively.

portant in the transport sector. This could further support the argument that high priority should be given to alleviating infrastructure constraints that obstruct appropriate environmental taxation. This would complement research by Waisman et al. (2013) who demonstrated numerically that a given mitigation target can be reached at lower total costs and by a lower carbon price if this is complemented by different infrastructure spending and spatial reorganization. In their model, the latter policies are chosen *ad hoc*, while the model in the present thesis optimizes infrastructure spending. Another difference is that the model of Chapter 6 endogenized environmental quality, which is then chosen to be lower in a second-best setting. This explains the seemingly contradictory recommendation regarding the carbon price.

7.2.2 A broader view of interactions between climate- and fiscal policies

The overview of interactions between climate policies and fiscal policies given in Chapter 2 was not exhaustive:

First, the overview followed what might be called the 'traditional' paradigm of public economics, assuming a benevolent and perfectly informed government. Some known effects were omitted, as described in the introduction to Section 3 of Chapter 2. Examples are effects related to rigid labor markets (Guivarch et al., 2011) or interactions between different levels of government (Keen, 1998; Williams, 2012). Nevertheless, it has become clear above that even under the traditional, somewhat simplified view of the public sector, more research on climate-fiscal interactions is needed.

Second, much of 'modern' public economics has given up these simplifications about the nature of the government. It has considered informational asymmetry between the state and its subjects (Mirrlees, 1971; Diamond and Mirrlees, 1971; Laffont, 2002) affecting the efficiency and distributional aspects of the tax system, into which carbon pricing has to be integrated. The political economy of public policy has been analyzed (Laffont, 2000), such as the practice of earmarking revenues for specific spending (Anesi, 2006) which is also important in the context of climate policy. More recently, there have also been attempts to integrate behavioral aspects into public finance (McCaffery and Slemrod, 2006) and environmental economics (Shogren and Taylor, 2008). Many of the implications of this literature have yet to be incorporated by climate policy research, or rather the research on climate-fiscal interactions. Positive examples include work by Diederich and Goeschl (2014a,b) on the effect of social preferences on providing public goods such as climate change mitigation. Kallbekken et al. (2011) find in a lab experiment that support for an environmental tax is increased by narrowly targeted revenue recycling, and by labeling it as a 'fee' rather than a tax. Mattauch et al. (2015) point out that the (public) built environment impacts private decision-making in transport. Thus, public spending on transport has behavioral effects that may be important for decarbonizing this sector.

Third, public economics has in turn neglected insights from environmental economics, too: some topics stressed in the field of climate change economics (and in this thesis) are not sufficiently represented in today's public economics literature, such as rent economies and their importance for wealth accumulation and distribution. Stiglitz (2015) has also pointed out the insufficiency of current neoclassical models to deal with the latter, albeit without reference to climate change and its impact on rents.

7.2.3 Relation to economic studies of international cooperation

Voluntary mitigation by individual countries is unlikely to be sufficient for reaching a 2 °C-target, so international cooperation will still be required to prevent or close the remaining gap (Edenhofer et al., 2015). Thus, the question arises how different dynamics at the national level affect international cooperation.

I briefly discuss here how the analysis in this thesis, and work on national mitigation incentives more generally, relates *methodologically* to game theory as the standard analytical framework for the economic analysis of international cooperation: the national-level analysis *complements* methods for the international level. The next section will close with remarks on potential *implications* of national mitigation activities for international cooperation.

Without a central institution to enforce climate change mitigation, non-cooperative game theory can be used to analyze strategic interactions between independent countries. To determine the incentives of individual countries to reduce GHG emissions (or to participate in a global policy regime or smaller coalitions), these models take into account that each country's costs and benefits from mitigation also depend on the behavior of other countries. International climate policy regimes can change the mitigation incentives of countries for example by providing for transfers of money or technology in GHG-intensive sectors (Barrett, 2006). A potential outcome is a 'Nash equilibrium' in which no country has an incentive to deviate from its decision, given that no other country changes its behavior. One may then for example analyze the support for a given international regime, or the endogenous emergence of one or several stable coalitions with more or less broad participation, ambitious mitigation targets and effective compliance.

A broad range of the game-theoretic literature takes stylized representations of nation states as a starting point, namely each country's net benefits as a function of climate policies. Models of these net benefits are more or less complex, ranging from static payoff tables or simple cost- and damage functions, to large numerical IAMs for each country (Lessmann et al., 2009). In most cases however, costs and benefits have so far been framed rather narrowly (see also Section 1.1 in Chapter 1: the main benefits are taken to be avoided domestic damages from climate change (depending on total global mitigation efforts). The main costs are domestic mitigation costs in sectors with high GHG emissions (as in technology-focused IAMs).

Thus, including beneficial climate-fiscal interactions in models of international cooperation is not a challenge to game theory, but a matter of appropriately modeling countries' payoffs: These interactions do not change the nature of the global externality problem, but unilateral incentives for mitigation. In the simplest cases, the entries in payoff tables or parameters in cost- and damage functions would need to be adjusted; in the more complex cases, IAMs for several countries need to be modified or extended to incorporate public finance issues. The approach of this thesis does not compete with, but complements existing approaches on international cooperation – indeed, a comprehensive analysis of international cooperation under a new 'hybrid' paradigm should take into account a broader range of domestic motives, including interactions between climate- and fiscal policies.

7.3 Conclusion: Policy Implications

The results of this thesis have important implications for the design and appraisal of domestic climate- and fiscal policies. They show that rent taxation should play a larger role in both policy fields, and that complementary policies such as infrastructure provision should be treated as a central part of climate policy. Finally, this may strengthen domestic mitigation motives, and thus eventually change the dynamics of international cooperation.

First, a joint evaluation and design of domestic climate- and fiscal policies is required: Interactions between climate policy and other public policies, in particular fiscal policies, are important for two reasons (see also Section 5 of Chapter 2). On the one hand, direct climate policy, such as carbon pricing or R&D policy in favor of low-emission technologies, may yield non-environmental benefits by supporting other public sector goals and functions, such as efficient taxation, growth or equitable distribution. On the other hand, aligning with mitigation objectives a larger set of complementary public policies that have an indirect effect on private behavior and emissions, such as infrastructure spending, may lower the costs of private abatement. Taking both 'directions' into account is important for assessments of the costs of climate change mitigation, for its distributional effects and political feasibility, and for the optimal choice and design of instruments for climate and fiscal policy alike.

Second, my results support a currently increasing political momentum in favor of rent taxation and redistribution (Piketty, 2014), and link these topics to climate change: taxing fossil resource rents (by carbon pricing) as well as land rents (which may increase due to climate change and mitigation policies) may not only raise substantial public revenues and redistribute wealth. It may at the same time make the economy more efficient by inducing higher aggregate investment.[8] This adds to recent observations of diverging wealth (Piketty, 2014) which have already been linked to increasing rents (Stiglitz, 2015), but not in the context of climate policy.

Third, climate policy should better integrate a range of instruments beyond direct regulation or carbon pricing: so far, most climate policies directly address GHG emitters or their clean substitutes, for example by carbon pricing,

[8] There may however be practical obstacles to large-scale rent taxation.
In particular for the case of land rent taxation, separating the value of land from improvements such as buildings may be an isuse: Advanced methods have been developed to measure the land price, for example based on market value for residential property and on capital income for commercial property, see Bell et al. (2009). However, legal requirements of uniform property taxation may be an obstacle for applying different tax rates to land and (desirable) improvements (Coe, 2009). Also, political opposition may arise if a tax on land rents acts as a tax on unrealized capital gains (Bourassa, 2009). An example is a land value tax payable by homeowners that do not receive a regular stream of income from their property. This problem may be exacerbated if complex value assessments are perceived as intransparent and unfair (Bourassa, 2009).
Measuring rents from fossil resources may be much easier, but taxing them is at least as difficult due to the political power of those who benefit from or own the fossil resources (Hammar et al., 2004; Helm, 2010; Lloyd, 2012).

emission standards for cars and power plants, or subsidies and R&D support for renewable energies and electric vehicles. This neglects that many publicly provided goods influence private decisions to pollute or not (sometimes in subtle ways, see for example Thaler and Sunstein, 2008): cars are less attractive with fewer and smaller roads. Switching to public transport requires a good network and service information. Health information campaigns and attractive urban planning increase cycling. And renewable power generation needs to be integrated into the grid and the (highly regulated) energy market. Thus, the adequate provision of public goods is essential for effective GHG emission reductions, and also likely to reduce opposition to measures such as carbon pricing.

Fourth, and beyond this thesis, a crucial question is if the reliance of the Paris Agreement on countries' voluntary mitigation actions will eventually be a 'game changer' for international cooperation: In the introductory chapter, I described how the national level had come into the focus of international cooperation on climate change mitigation, motivating my analysis of effects at this level. Nevertheless, the nature of the global climate externality implies that unilateral incentives for mitigation will be too weak for reaching the $2\,^{\circ}$C-target, and the remaining gap will still have to be closed by international cooperation (Edenhofer et al., 2015). Thus, if interactions between climate- and fiscal policies as well as other domestic effects change benefit-cost considerations, what are the implications for global mitigation? It seems unrealistic that the incentive structure of key players will change so much that a stringent, globally binding agreement becomes possible directly. A weaker position is that countries may start with unilateral mitigation action, but these will be more significant than otherwise. This may increase the likelihood that international cooperation is reinvigorated, for example by technology spillovers, social learning and signaling, or reciprocity (Edenhofer et al., 2015). Finally, a minimal expectation is that if motives for unilateral action are strengthened, these add up to a larger overall mitigation than hitherto expected. While it is unlikely that the initial pledges will add up to the required global mitigation targets, it is important to make at least some progress because mitigation will be more costly the longer it is delayed (IPCC, 2014). Specifically in some countries with high investment into long-lasting capital stocks such as China, there is a closing 'window of opportunity' to prevent lock-in (Shalizi and Lecocq, 2009): If entire cities and infrastructure systems are newly built with reliance on individual car transport and fossil energy provision, decarbonization becomes very difficult and costly.

Thus, realizing interactions between climate policy and public finance may help to maintain the possibility to still reach the two degree target in the future.

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Statement of contribution

Chapter 2: The author and Linus Mattauch designed research, with refinements from all authors. Specifically, Max Franks developed the argument on tax competition and David Klenert developed the argument on inequality reduction. The author wrote the article with major contributions from all authors, specifically to Sections 3.1 and 3.3 by Max Franks, and to Sections 2.2 and 3.5 by David Klenert.

Chapter 3: Linus Mattauch developed the model. Linus Mattauch and the author proved and framed the results. Linus Mattauch wrote the article, with contributions from the author, who also provided the illustration of the empirical relevance and collected the data used there. Ottmar Edenhofer proposed the research question. Ottmar Edenhofer and Felix Creutzig contributed to the results in the case that no balanced growth path exists and to their interpretation. They also provided comments on the manuscript in many discussions.

Chapter 4: Ottmar Edenhofer suggested the model. The author and Linus Mattauch proved the results and wrote the article in very close collaboration. The author provided the empirical estimation, while Linus Mattauch contributed the discussion of normative validity. Ottmar Edenhofer also contributed to several results by refining them in extensive discussions.

Chapter 5: The author and Linus Mattauch developed the model. The author proved the results. He wrote the article, with contributions from Linus Mattauch, in particular to the analysis of the "stock instrument". The author, Linus Mattauch and Ottmar Edenhofer jointly developed the research question. Ottmar Edenhofer provided comments on the manuscript in many discussions.

Chapter 6: The model and the article were entirely developed and written by the author.

Tools and resources

All chapters of this thesis were written with $\LaTeX\,2_\varepsilon$ using Miktex (Schenk, 2012) und Texniccenter (TeXnicCenter Team, 2013). Moreover, in some chapters additional resources have been used for simulations, data analysis and generating graphical output, as indicated:

Chapter 3: Microsoft Excel 2010 (Version 14.0) was used to create Figure 1.

Chapter 4: Microsoft PowerPoint 2010 (Version 14.0) was used to draw Figure 1–3. Microsoft Excel 2010 (Version 14.0) was used to compute the empirical estimates in Section 4.1.

Chapter 5: XPP-Aut (Ermentrout, 2012) was used for numerical explorations that did not enter the final manuscript. Microsoft PowerPoint 2010 (Version 14.0) was used to draw Figure 1.

Chapter 6: Gnuplot (Williams et al., 2014) was used to create Figures 1–3. Microsoft Excel 2010 (Version 14.0) was used to create Figure 4.

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List of publications

Chapters 2 to 6 of this thesis correspond to articles that have been submitted to / published in different journals:

Chapter 2: The fiscal benefits of climate policy: an overview.
In preparation for submission to *CESifo Economic Studies.*
An earlier version has been published as a working paper: Siegmeier, J., L. Mattauch, M. Franks, D. Klenert, A. Schultes and O. Edenhofer (2015). A public finance perspective on climate policy: Six interactions that may enhance welfare. *Fondazione Eni Enrico Mattei, Nota di Lavoro,* 31.2015.

Chapter 3: Financing public capital through land rent taxation: A macroeconomic Henry George Theorem.
In preparation for submission to *Finanzarchiv / Public Finance Analysis.*
An earlier version has been published as a working paper: Mattauch, L., J. Siegmeier, F. Creutzig and O. Edenhofer (2013). Financing public capital through land rent taxation: A macroeconomic Henry George Theorem. *CESifo Working Paper*, No. 4280.

Chapter 4: Hypergeorgism: When rent taxation is socially optimal.
Post-print version of an article published in the journal's formatting as Edenhofer, O., L. Mattauch and J. Siegmeier (2015). Hypergeorgism: When rent taxation is socially optimal. *Finanzarchiv / Public Finance Analysis*, Vol. 71(4): 474-505, doi: 10.1628/001522115X14425626525128.

Chapter 5: Capital beats coal: how collecting the climate rent increases aggregate investment.
To be resubmitted with revisions to the *Journal of Environmental Economics and Management* as Siegmeier, J., L. Mattauch and O. Edenhofer: Capital beats coal: how collecting the climate rent increases aggregate investment.
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Chapter 6: Keeping Pigou on tracks: second-best carbon pricing and infrastructure provision.
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Keeping Pigou on tracks: second-best carbon pricing and infrastructure provision. *MPRA Paper No. 69046*.