Rents, Taxes, and Distribution:
Towards a New Public Economics of Climate Change

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Summary

Economists commonly perceive climate change as a negative environmental externality, and in the political arena, environmental ministries are in charge of finding solutions to the problem of climate change. This thesis departs from the common practice of framing climate change as a problem of environmental pollution. Instead, it takes the perspective of a finance minister, based on the premise that interactions of climate policy with the broader fiscal system cannot be omitted from the economics of climate change. To analyze the manifold interaction effects of climate policy with the broader fiscal system, novel general equilibrium models of intermediate complexity are developed and solved numerically.

This thesis shows that even in the absence of any environmental motive, governments benefit from implementing carbon taxes unilaterally. The reason is that international capital mobility puts downward pressure on corporate taxes, and public capital stocks are thus underfinanced. Unilaterally taxing carbon can solve this problem by enabling governments to appropriate rents associated with the ownership of fossil resources. If the rents are then invested in productive public capital, national welfare increases. As an additional unintended effect, resource owners postpone extraction, and the level of cumulative emissions is reduced – no green paradox occurs. Instead, fiscally motivated carbon taxation constitutes a viable green policy, and could be, moreover, an alternative entry point for the international climate negotiations under the UNFCCC. However, if carbon taxes are implemented unilaterally, jobs in energy-intensive sectors may relocate abroad. This thesis shows that governments can mitigate adverse distributional effects on these sectors by implementing sectoral labor tax cuts instead of carbon tax exemptions. Addressing distributional questions more broadly, this thesis further shows that governments have substantial freedom to reduce wealth inequality without sacrificing output by implementing combinations of taxes on land rents and bequests.

Finally, the thesis provides a systematical discussion of hitherto identified interactions between climate change mitigation and public finance, and thus puts the other main results into perspective. Thereby, this thesis takes first steps towards a *new public economics of climate change*.

Zusammenfassung

Üblicherweise wird der Klimawandel in der Ökonomie als negative Umweltexternalität bezeichnet. Entsprechend delegieren Regierungen die Lösung des Problems an ihre Umweltministerien. Die vorliegende Dissertation weicht von der herkömmlichen Praxis ab, den Klimawandel als ein Umweltverschmutzungsproblem zu behandeln. Stattdessen wird die Sicht eines Finanzministers gewählt, da die Wechselwirkungen zwischen Klimapolitik und dem allgemeinen System der Staatseinnahmen und -ausgaben nicht ignoriert werden können. Um diese mannigfaltigen Wechselwirkungen analysieren zu können, werden neuartige Allgemeine Gleichgewichtsmodelle mittlerer Komplexität entwickelt und numerisch gelöst.

Die vorliegende Dissertation zeigt, dass Regierungen – selbst ohne die Absicht, die Umwelt zu schützen – einen Anreiz haben, CO_2 unilateral zu besteuern. Dies liegt daran, dass internationale Kapitalmobilität zu Steuerwettbewerb führt und Finanzierungsspielräume für öffentliche Investitionen einschränkt. Mit unilateralen CO_2-Steuern können Regierungen ihren Spielraum wieder erweitern, da sie so Knappheitsrenten von fossilen Ressourcen abschöpfen können. Investieren sie nun die Renten in den Erhalt bestehender und den Aufbau neuer Infrastruktur, steigt die nationale Wohlfahrt. Als unbeabsichtigter Nebeneffekt reduzieren Ressourcenbesitzer ihre Förderrate, die kumulativen Emissionen fallen – ein "grünes Paradox" tritt also nicht auf. Stattdessen stellen fiskalisch motivierte unilaterale CO_2-Steuern eine gangbare Umweltschutzmaßnahme dar, und darüber hinaus sogar einen alternativen Einstieg in internationale Klimaverhandlungen im Rahmen des UNFCCC-Prozesses. Ferner wird gezeigt, wie Regierungen negative Verteilungseffekte unilateraler Klimapolitik, z.B. die Abwanderung von Arbeitsplätzen in energieintensiven Sektoren ins Ausland, abfedern können. Anstatt diesen Sektoren CO_2-Steuererleichterungen zu gewähren, sollten sie vielmehr mit niedrigeren Lohnsteuern kompensiert werden. Hinsichtlich allgemeiner Verteilungsfragen zeigt die vorliegende Dissertation, dass Regierungen einen relativ großen Spielraum haben, Wohlstand umzuverteilen, ohne dabei das Bruttoinlandsprodukt zu reduzieren. Dies ist möglich, wenn verschiedene Kombinationen aus Landrenten- und Erbschaftssteuern implementiert werden.

Schließlich werden die in der Literatur bisher identifizierten Wechselwirkungseffekte zwischen Klimapolitik und öffentlicher Finanzwirtschaft diskutiert. So werden die zentralen Forschungsergebnisse der vorliegenden Dissertation in einen breiteren Rahmen eingeordnet. Diese Forschungsarbeit kann daher als ein erster Schritt verstanden werden, die Theorie der öffentlichen Finanzen mit der Ökonomie des Klimawandels zu einem neuen Forschungsfeld zu kombinieren.

List of papers

The four core chapters of this cumulative dissertation (Chapters 2 to 5) are based on individual research papers. They are the result of collaborations in this PhD project between the author of the dissertation, his advisor Ottmar Edenhofer, his Post-Doc advisor Kai Lessmann, and other colleagues.

Chapter 2 is based on Franks, M., Edenhofer, O., Lessmann, K. *Why Finance Ministers Favor Carbon Taxes, Even If They Do Not Take Climate Change into Account*. Environmental and Resource Economics (2015): pp. 1-27. The final publication is available at Springer via http://dx.doi.org/10.1007/s10640-015-9982-1

Chapter 3 is based on Schwerhoff, G., Franks, M., 2015. *Optimal environmental taxation with capital mobility*. Submitted to *Fiscal Studies*.

Chapter 4 is based on Franks, M., Klenert, D., Schultes, A., Lessmann, K., Edenhofer, O., 2016. *Is capital back? The role of land ownership and savings behavior*. Mimeo.

Chapter 5 is based on Siegmeier, J., Mattauch, M., Franks, M., Klenert, D., Schultes, A., Edenhofer, O., 2016. *The fiscal benefits of climate policy: an overview*. Mimeo.

”[The] reference to carbon pricing (...) is somewhat of a concern to us as far as taxing our economies is something that we wish not to see in the decision.”

(Ayman Shasly, Chair of Climate Change Negotiations of the League of Arab States, speaking on behalf of Saudi Arabia, 4th meeting of the Comité de Paris, COP21, Paris)

“We know that the enemy is carbon, and we know its ugly face, we should put a big fat price on it.”

(Ángel Gurria, Secretary-General of the OECD, COP21, Paris)

“Taxes, man, they’re at the center of human history!”

(John Green, Crash Course World History #25)

Contents

Chapter 1

Introduction

The objective of the United Nations Framework Convention on Climate Change (UNFCCC) as defined in Article 2 is to achieve

> "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

The objective is not defined rigorously, as expressions such as "dangerous" and "sustainable" leave room for interpretation. The economics of climate change provide an analytic framework to describe their meaning more precisely and to evaluate different political targets such as limiting global warming to 2°C or even 1.5°C relative to pre-industrial levels. Further, the economics of climate change provide tools to assess the policy options to achieve the stabilization of greenhouse gas (GHG) concentrations. The methods employed involve social cost-benefit analysis, the market and non-market valuation of impacts, and social discounting. Faced with long time scales and uncertainties, a particularly important method is the analysis of scenarios of future environmental, social, and economic changes, and the comparison of different mitigation pathways.

Climate change is usually framed as a stock pollution problem, and the atmosphere is regarded as a limited disposal space for greenhouse gases. That most economists understand climate change as a negative environmental externality was famously expressed by Nicholas Stern, who wrote, "climate change is the greatest market failure the world has ever seen," (Stern et al., 2006).

The prevailing view is thus that the problem can in principle be solved with market-based policy instruments. Any environmental economics textbook explains on a theoretical level how such instruments may internalize externalities and thus move the economy closer to its optimum. Correspondingly, in the political arena, governments delegate the solution of how to internalize the climate externality to their environmental ministries.

In this thesis I depart from the common practice of framing climate change primarily as a problem of environmental pollution. Instead, I take the perspective of a finance minister, who faces a set of challenges that is usually very different from the duties of an environmental minister. Taking a public finance perspective on climate policy is crucial since any measures that are consistent with Article 2 under the UNFCCC will require a massive transformation of the global economy. Therefore, interactions of climate policy with the broader fiscal system cannot be omitted from the economics of climate change – in particular if sound economic policy advice is sought.

Among the most prominent challenges finance ministers face is balancing the national budget. Core duties involve raising and spending of public revenues, both efficiently and equitably. Governments must, for example, trade-off spending public funds on investments in public capital against reducing the national debt. Any choice about fiscal policy has distributional consequences, and thus, governments have to weigh the interests of different societal groups, both along an *intra*-generational as well as an *inter*-generational dimension. Since the financial crisis of 2008, public awareness of social inequality has strongly increased, putting pressure on finance ministers to carefully design adequate tax systems.

In this thesis I discuss three of the challenges finance ministers face in greater detail. First, I analyze the problem of raising public funds efficiently to spend on public capital like infrastructure, education, and health systems when budgets are tight due to tax competition. Next, I show how to manage the distributional consequences of unilateral climate policy policy reforms when capital is mobile and jobs could move abroad. Finally, I take a broader perspective on distributional issues by considering overall wealth inequality in a closed economy. I analyze a government's scope for redistributing wealth without sacrificing output, in particular when land rents are taxed.

Thus, in this thesis, I take first steps towards a new understanding of the economics of climate change. I show how both environmental economics and politics can profit by taking a public finance perspective. Climate policy, in particular in the form of carbon taxation and thus the appropriation of resource rents, does not only serve to protect the environment. It also has beneficial fiscal effects.

In Chapter 2, I argue that even without the policy objective of internalizing an environmental externality, governments have a strong fiscal incentive to implement unilateral climate policy. The reason is that the high degree of international capital mobility puts downward pressure on corporate taxes, which results in a so-called race to the bottom in capital tax rates. If alternative sources for funds are unavailable, for instance due to already very high levels of value-added taxes or payroll taxes, or the inability to incur more debt, public capital stocks are likely to be underfinanced. This problem can be overcome by unilaterally introducing a carbon tax, which enables governments to appropriate rents associated with the ownership of fossil resources. If the rents are then invested in productive public capital, national welfare increases.

The result of the fiscal efficiency of unilateral carbon taxation is meaningful beyond national public finance. For a long time, unilateral climate policy has not been at the center of attention of the global political process guided by the UNFCCC to mitigate climate change. This is also reflected by the fact that economists often frame climate change as global public goods problem. For most of the time, political efforts have focused on reaching a global agreement on how to limit global warming to 2°C relative to pre-industrial levels – a top-down approach. Both politics and academia thought of the yearly negotiations at the Conferences of Parties (COP) as the main entry point for global action against climate change.

My first main result suggests another entry point than international negotiations: the selfish interest of national governments to tax carbon unilaterally for fiscal reasons. I show that following this incentive can lead to an international equilibrium in which resource rents are skimmed off and are invested in public capital. Such an equilibrium turns out not only to yield fiscal benefits to national economies. As an unplanned additional outcome, the global level of cumulative GHG emissions will lie below a counter-factual business-as-usual case without any price on carbon, and thus closer to the level required for achieving the 2°C target. Therefore, unilateral carbon taxation for fiscal reasons does not cause a green paradox (see Sinclair, 1992, 1994; Ulph and Ulph, 1994; Sinn, 2008), but constitutes a viable entry point for green policy.

However, there is concern that unilateral climate policy may have unintended negative consequences. Thus, in Chapter 3, I discuss the problem that unilateral climate policy in an open economy with capital mobility may have adverse distributional consequences for the domestic economy. In particular, policy makers are concerned about the high burden for energy-intensive sectors and the danger of jobs relocating abroad (Fischer and Fox, 2011). Such concern prevents governments from implementing climate policy and motivates sectoral exemptions from climate policy. I argue that governments can mitigate adverse distributional effects on energy-intensive sectors, but they should implement sectoral labor tax cuts instead of carbon tax exemptions.

In Chapter 4, the analysis of policy instruments and their distributional implications concentrates on the more general question of how to deal with overall wealth inequality in a closed economy. Scholars like Thomas Piketty, Emmanuel Saez, and Gabriel Zucman have compiled data and provided first interpretations, giving rise to new interest in income and wealth inequality both in academia and politics (Piketty, 2014; Piketty and Zucman, 2014; Saez and Zucman, 2016).

Robust policy advice is still lacking, though. Piketty's recommendation to implement a global progressive capital tax (Piketty, 2014), which is based on formal modeling of bequest dynamics by Piketty and Saez (2013), does not take into account the crucial distinction between "capital" and "wealth" (Homburg, 2015; Stiglitz, 2015b). In particular, a thorough discussion of the role of fixed factors of production, such as land, and rents associated with the ownership of fixed factors is still missing. In this thesis, I present evidence that if land rents are taken into account (and bequests are the main driver of wealth inequality), then governments have substantial freedom to reduce wealth inequality without sacrificing output.

On a more abstract level, this thesis argues that public finance considerations such as the efficiency and equity aspects of fiscal policy are valuable complements for the research field of environmental economics, and moreover, the conduct of climate politics. Jointly considering carbon pricing and fiscal policy is mandatory for sound policy appraisal. Chapter 5 thus provides a systematical discussion of hitherto identified interactions between climate change mitigation and public finance. By combining this overview with the detailed theoretical analyses of the preceding chapters, this thesis could serve as a blueprint for the research agenda of a new public economics of climate change.

The remainder of this introductory chapter reviews the theory and the empirical findings my thesis builds upon. In Section 1.1, I discuss the most relevant topics that lie within the field of climate change economics. Topics going beyond the field of environmental economics, but rather pertain to public economics are then touched upon in Section 1.2. Section 1.3 justifies the approach of this thesis to join the two fields, and finally, Section 1.4 concludes with a more detailed description of the objectives and an outline of the main part of the thesis.

1.1 Economics of climate change

The prevailing paradigm in environmental economics with respect to pollution problems appeals mainly to environmental ministers. It involves the concept of externalities and ways of how to internalize them, but largely ignores interactions between environmental and fiscal policy. The textbook solution to pollution problems is thus Pigouvian taxation[1], or more broadly, market-based policy instruments such as carbon taxes and emissions trading schemes.

Even without considering aspects of public finance, climate change poses a vastly more complex problem for environmental economics than Pigou's textbook example of sparks from a train that cause a forest fire (Pigou, 1932, Pt. II, Ch. II). Large

[1] Pigou (1932) introduced the concept of externalities. An externality describes a situation in which the market fails to allocate resources, goods, and services efficiently. A negative externality implies that the social costs of a market activity exceed the private costs. This activity distorts the economy. A tax on the distorting market activity is said to be at its Pigouvian level if it realigns incentives such that the private costs reflect the social costs again.

time scales, great uncertainties, and deep path dependencies are involved. To tackle such problems analytically, the original Pigouvian approach has been extended, for example, to general equilibrium, intertemporal analysis, and risk management (Perman et al., 2003).

In this section I review those issues of the economics of climate change that have a direct bearing on the core problems this thesis addresses. In addition, I briefly explain how my thesis is linked to the issues reviewed, and how it sheds a different light on them. The issues discussed here are the lack of international cooperation (Section 1.1.1), the supply side dynamics of fossil resource extraction (Section 1.1.2), and the presence of sizable rents, which are, for example, associated with fossil resources (Section 1.1.3). Public finance aspects beyond the economics of climate change will be discussed in Section 1.2.

1.1.1 Lack of international cooperation

The negotiation efforts so far have not been able to establish a binding global treaty that definitely limits global warming to 2°C relative to pre-industrial levels. An assessment conducted by the Climate Action Tracker finds that under the most optimistic assumptions, the Intended Nationally Determined Contributions (INDC) put forward by the countries (as of December 2015) add up to an expected temperature increase of 2.7°C compared to pre-industrial levels. A projection based on policies currently in place yields a 3.6°C increase (Gütschow et al., 2015).

From a game theoretic point of view, the failure to achieve global cooperation has been explained by modeling the international negotiations as a prisoner's dilemma, thereby accounting for the global public good nature of climate change mitigation (Carraro and Siniscalco, 1993; Barrett, 1994). The free-riding incentive prevents the players of the game, that is, the governments engaged in the UNFCCC process, from achieving the social optimum. The Nash equilibrium of this game implies too little effort to reduce emissions to successfully mitigate dangerous climate change.

Scientists hoping to provide policy advice often made use of the insights from game theory. The Intergovernmental Panel on Climate Change (IPCC) provides several suggestions of how to improve the process of international negotiations in its Fifth Assessment Report (Stavins et al., 2014); a summary of these suggestions can be found, for example, in Kornek (2015, Ch. 1).

However, game theory is not the only conceptual framework used to understand the lack of international cooperation. Levin et al. (2012), for instance, depart from the game theoretic approach, and explain humanity's failure to cooperate with the four elements that characterize so-called 'super wicked' problems: time is running out; those who cause the problem also seek to provide a solution; the central authority needed to address it is weak or non-existent; and policy responses discount the future irrationally. Combined, these elements create a policy-making "tragedy".

Regardless of the theoretical explanations for the lack of cooperation, political efforts to foster cooperation focused on the UNFCCC process of yearly rounds of negotiations at the COPs. Up to the failure of 2009's COP15 in Copenhagen, negotiations centered around binding quantity targets – a top-down approach. Since 2010, more bottom-up features have been considered, leading to the present hybrid system combining top-down and bottom-up elements (Ranson and Stavins, 2013; Edenhofer et al., 2013). This includes the coordination of the INDCs, which are central to the COP21 in Paris.

The focus shift away from negotiated binding targets and timetables towards the coordination of voluntary unilateral contributions is consistent with the pessimistic message of the game theory literature. Further, the focus shift also warrants the need for more research on unilateral climate policy. At this juncture the research presented in this thesis comes into play. The results of Chapter 2 highlight the incentive of governments to unilaterally tax carbon out of their own self-interest to maximize their national economy's welfare. Even without considering the environmental externality, complementing the fiscal policy portfolio with carbon pricing is beneficial from a national perspective. Moreover, from a global perspective, unilateral carbon pricing motivated by fiscal considerations reduces cumulative emissions and could constitute an alternative entry point for international negotiations.

1.1.2 Supply-side dynamics of fossil resource extraction

I have argued that the lack of international cooperation implies the need for additional unilateral efforts. Such policies must be well-designed in order to succeed. The criterion discussed here is that a regulator has to take into account not only the demand side of the market for fossil resources, but also the supply-side dynamics.

If fossil resource owners' reactions to unilateral climate policy are not taken into account in the policy design, these owners may follow their incentive to immediately speed up extraction in anticipation of even stricter future climate policy. The debate between Sinclair (1992, 1994) and Ulph and Ulph (1994), based on the canonical models of Hotelling (1931) and Dasgupta and Heal (1974), made it clear that resource owners' expectations matter. Depending on the time path of a carbon tax, and thus the expected time path of their stream of profits, resource owners may speed up or slow down extraction.

After the Kyoto protocol was ratified, Sinn (2008) revisited this debate and coined the term 'green paradox' to call attention to the problem that good (environmental) intentions do not always breed good deeds. The author's results show how a carbon tax that increases over time induces fossil resource owners to increase their rate of extraction. The question of how to evaluate the dangers of a green paradox has sparked new interest in the economics of depletable resources. Several scholars have contributed to our understanding of the underlying mechanisms of the green paradox.

The current state of knowledge paints a differentiated picture. The green paradox is only one special case among a wider variety of consequences of carbon pricing. Edenhofer and Kalkuhl (2011) modify the partial equilibrium model used by Sinn (2008) to include unit taxes instead of ad valorem taxes. The authors conclude that there is only a low risk of a green paradox, which would occur if a permanently mal-adjusted tax is implemented. The study by Van der Meijden et al. (2015) extends the analysis to general equilibrium and open economies. The authors show in great detail how assumptions about the preferences of resource importers and exporters affect cumulative emissions. Contrasting their results from the previously conducted partial equilibrium analyses, they emphasize the crucial role of the interest rate, which drives decisions about savings, investments, and resource depletion.

The analysis of unilateral climate policy presented in Chapter 2 of this thesis goes even one step further by allowing for strategic interactions between resource importers and exporters. The novel model structure accounts for the fact that national governments face multiple heterogeneous agents, each of which is pursuing different objectives and using different strategies. More precisely, national governments sit at two game tables: First, they have to take into account how households and firms react to their policies. Second, governments of resource importing and exporting countries each take the policies of all other governments as given when making their own decisions.

Varying the assumptions about the strategic behavior of resource importers and exporters reveals a high degree of robustness of the main result of Chapter 2: If a carbon tax is implemented unilaterally based on the fiscal rationale to finance productive public capital, then no green paradox occurs. Thus, even if the negative environmental externality of climate change is not taken into account, the carbon tax constitutes a viable green policy.

1.1.3 Rents associated with fossil resources and land

Studying the supply-side dynamics of fossil resource extraction not only shows the potential danger of a green paradox. It also reveals the importance of economic rents, in particular those associated with the ownership of fossil resources, but also, under a broader perspective, those arising from fixed factors like land.

Economic rents are usually understood as any income from an input factor in excess of the cost required to bring that factor into production. A typical example for economic rents is the income that arises from fixed factors like land, which is in fact the historical origin of the concept of economic rents (Dwyer, 2014). In contrast to the productive economic activity of providing labor, or investing into capital, providing land for production implies no opportunity costs for its owner. Fossil resources, unlike land, may not be fixed if they are regarded as a flow resulting from extracting activity, only their total stock is indeed a fixed quantity. However, the crucial characteristic of rent income that is important for depletable resources is that it emanates from “free gifts of nature” (Dwyer, 2014, Ch. 2.1).

The economic analysis of rents is important for this thesis for three reasons. First, rents constitute a substantial share of the economy of many countries. Caselli and Feyrer (2007), for example, calculate that the income share of the stocks of land and natural resources lies between 6% (in Belgium) and 47% (in Ecuador) with a median of 14% for a sample of 49 countries. In other OPEC countries like Saudi Arabia or the United Arab Emirates, which were not included in the latter study, this income share is even higher. Moreover, there is new empirical evidence that in several advanced economies land prices, and thus land rents, have followed a hockey-stick pattern over the last century – remaining constant over the 19th up to the mid-20th century, and sharply rising in the second half of the 20th century (Knoll et al., 2014). Thus, the rising importance of resource and land rents in many countries highlights the necessity to take them into account.

Second, climate policy will necessarily devalue the rents of fossil resource owners by reducing demand for these resources. At the same time, the implementation of stringent climate policy will create new rents. In order to limit global warming to 2°C relative to pre-industrial average temperature levels with a probability of 50%, only a cumulative amount of 1440 Gt CO_2 can be released into the atmosphere over the period from 2000 to 2050 (Meinshausen et al., 2009). Implementing such a ‘carbon budget’ (WBGU, 2009) would imply a new artificial scarcity of the disposal space of the atmosphere. It would create a new rent associated with the right to use part of the atmosphere. Depending on the specific design of the climate policy, the fossil resource rent would thus be transformed into a climate rent, and transferred to new owners. There is evidence that the value of the climate rent may exceed the amount by which the resource rents are devalued (Bauer et al., 2013). Thus, resource owners could in principle be compensated for their loss in order to win their support for climate policy (Kalkuhl and Brecha, 2013). In any case, the large scale of such a transformation, the size of the wealth transfer in the form of rents, and the risk of distributional conflicts show their importance for the economics of climate change.

The third reason for the significance of rents lies in their relevance for a broader economic topic: the dynamics of the distribution of wealth. With his very influential book, Piketty (2014) sparked new interest in distributional questions and summarized findings of 15 years of mostly empirical research on the dynamics of wealth and its distribution in several OECD countries. Saez and Zucman (2016), for instance, find that wealth concentration in the United States has followed a U-shaped evolution over the last 100 years, consistent with the evolution of the capital-income ratios of several developed countries (Piketty and Zucman, 2014).

The empirical work cited above constitutes an extremely valuable contribution to economics in general. However, there seems to be a lack of robust theories capable of explaining the mechanisms and causalities underlying the observations. In a recent series of working papers, Stiglitz (2015b) convincingly argues that standard growth models cannot explain the evolution of wealth-income ratios, and thus that wealth and capital must not be treated as equal – in contrast to, for example, Piketty and Saez (2013), or Piketty (2014). While the data on housing and land prices compiled by Knoll et al. (2014) are mirrored in those unearthed by Piketty, Saez, and Zucman, the latter fail to adequately account for their significance (Homburg, 2015). Accordingly, (Stiglitz, 2015b, p. 3) strongly emphasizes that rents play a central role:

> "Solow, and those working in the neoclassical tradition, assumed markets were competitive, and that output was produced with labor and capital, with a constant returns to scale production function. In that theory, rents played no role, because under those assumptions, there were no rents. We argue, however, that changes in rents, broadly defined – including land rents, exploitation rents, and rents on intellectual property – may be at the center of what has been happening; and that economic analysis should focus on how changes in technology (...) institutions, and policy may have increased these rents."

To account for the observed trends in the distribution of income and wealth, new models that include rents and heterogeneous agents are needed. The present thesis takes first steps in this direction by studying the taxation of the carbon content of fossil resources in a setting of international factor mobility, and by taking land rents in overlapping generations models into account.[2] This thesis develops new arguments for rent taxation – primarily from a fiscal, but also from an environmental point of view. In Chapter 2, I show that taxing carbon in open economies enables governments to appropriate resource rents and to finance public capital, while mitigating the negative fiscal externality of corporate tax competition and avoiding a green paradox. Further, in Chapter 4, taxing land rents is shown to have beneficial growth implications. This is due to a portfolio effect first described by Feldstein (1977), and further analyzed by Edenhofer et al. (2015): Asset owners rebalance their portfolio in reaction to land rent taxes by shifting their investments away from land and towards capital, which increases macroeconomic output. In addition, Chapter 4 extends the analysis to heterogeneous savings behavior and shows that land rent taxation has a moderate progressive effect on the distribution of wealth.

In considering the relevance of economic rents, a link between the economics of climate change and public finance becomes clear. The most direct connection between the two fields is established by studying the transformation of the fossil resource rent to the climate rent due to governmental intervention.

[2] Recent examples of further studies that have taken first steps in the direction suggested by Stiglitz (2015a) include Mattauch et al. (2014), Klenert et al. (2014), Edenhofer et al. (2015), and Siegmeier et al. (2015).

Land rents, while presently less associated with climate change, can be expected to play an important role in the future. Once the economy anticipates significant land use change – either due to efforts to mitigate dangerous climate change (Hertel, 2011), or the harmful impacts of unmitigated climate change (IPCC WGII, 2014) – one can expect large-scale changes in level, distribution, and structure of land rents.

In Working Group 3's contribution to the Fifth Assessment Report of the IPCC, Clarke et al. (2014, Ch. 6) name three key forces driving land-use change that are associated with mitigation: (1) bioenergy demand, (2) the demand to store carbon in land, and (3) reductions in non-CO_2 greenhouse gas emissions by changing management practices. There is strong variation between the scenarios of the model comparison summarized in Clarke et al. (2014, Figure 6.19). Nevertheless, most of the scenarios imply substantial land use change around the order of magnitude of 1000 million hectares.

The impacts of unmitigated climate change are subject to even greater uncertainties. However, the IPCC confirms that "increasing magnitudes of warming increase the likelihood of severe, pervasive, and irreversible impacts" (IPCC WGII, 2014) – in particular, this includes impacts on both urban and rural areas, and impacts on food security and food production systems.

Schultes et al. (2016) confirm that land rents are important for the economics of climate change. The authors describe how negative impacts, in particular land-biased damages are linked to land rents: First, land-biased damages increase future scarcity rents, thereby distorting capital accumulation today, and thus reducing growth. Second, current generations expect higher future scarcity rents if climate change is not mitigated. This yields a disincentive for the current generation to implement more stringent climate policy.

1.2 Public finance

In general, the theory of public finance is concerned with the proper role of government in the economy. Important forms of governmental activity are fiscal policy, that is public revenue raising and spending, and monetary policy. Public finance studies how governmental activities affect the "four major spheres of (1) allocation of scarce productive resources among competing multiple uses, (2) distribution of income and wealth among the people, (3) economic stability (...), and (4) economic growth (...)" (Jain, 1989).

In the preceding section, I have argued that resource and land rents constitute one of several links between environmental economics and public finance. Already today, governments must take rents into account in their fiscal policy. Rents play an important role in the national income of many countries, and, due to climate change, their importance can be expected to increase. Moreover, understanding rents is crucial for the analysis of the wealth distribution.

In this section I consider three further topics of public finance, and discuss how the present thesis links them to the economics of climate change. Thus, I will discuss tax competition and underprovision of public capital (Section 1.2.1), distributional impacts of climate policy (Section 1.2.2), and, more generally, wealth inequality (Section 1.2.3).

1.2.1 Tax competition and the underprovision of public goods

Global problems demand global solutions. Thus, studying the economics of climate change is crucially tied to the analysis of international economics. Next to the lack of international cooperation (Section 1.1.1) and trade in fossil resources (Sections 1.1.2 and 1.1.3), topics that have been studied so far include carbon leakage, the pollution haven hypothesis, and how trade patterns determine the carbon footprint of different countries.

In this thesis, though, I depart from the typical topics of international environmental economics. Instead, I focus on public finance considerations by studying the international capital market and its relation to climate policy. In particular, the problems of international tax competition and the consequential underprovision of public capital will be analyzed in detail.

Tax competition

The awareness that national tax policies may cause economic activity to relocate abroad has been documented at least as early as 1763, when Catherine the Great used tax exemptions to attract foreign businesses (Weightman, 2010). More recently, as data compiled by Bénassy-Quéré et al. (2010) for instance show, tax competition as a problem seems to emerge in the late 1970s, reflecting the more general tendency towards globalization over the last couple of decades (see also Zodrow, 2010; Rodrik, 2011; Keen and Konrad, 2013). Ongoing global political processes, for example the OECD/G20 Project on Base Erosion and Profit Shifting (OECD, 2015a) discussed by the G20 Finance Ministers in October 2015, or the efforts of the EU towards tax harmonization show the relevance of studying this problem.

While Oates (1972) already discusses capital mobility and how it may lead to tax competition, the two seminal papers by Zodrow and Mieszkowski (1986) and Wilson (1986) are the first to use formal models to describe the fiscal externality of the race to the bottom. Both publications show that in the Nash equilibrium of the game played by the governments of several jurisdictions, capital tax competition leads to inefficiently low tax rates. Thus, governments do not provide enough local public goods for the social optimum of the whole economy to be achieved. The reason for the underprovision is that the individual governments do not take into account the effect of their domestic tax policy on the welfare of other jurisdictions. Increasing the capital tax rate unilaterally in one jurisdiction would cause a positive externality in all other jurisdictions. The tax increase would lead to an outflow of capital to all other regions and increase their welfare.[3]

There are cases in which also inefficient *over*provision of public goods may arise. Noiset (1995), for instance, shows how relaxing a specific assumption about the production function made by Zodrow and Mieszkowski (1986) could lead to such an overprovision of public goods that benefits firms instead of households. In response, Matsumoto (1998) argues that this case is of limited importance. However, Dhillon et al. (2007) revisit the same critical assumption and discuss in greater detail and analytical clarity how the choice of the production function determines whether there is inefficient over- or underprovision. Further, taking into account environmental quality (Bayındır-Upmann, 1995), congestion effects (Bjorvatn and Schjelderup, 2002), or agglomeration effects as studied by economic geography (Baldwin and Krugman, 2004) reveals additional mechanisms leading to the overprovision of public goods.

In sum, the result of the underprovision of public goods seems to hold under quite general assumptions, and it is furthermore consistent with empirical evidence of falling corporate tax rates and falling shares of public investments (Bénassy-Quéré et al., 2010; Zodrow, 2010). However, there is a body of literature that puts forward important caveats (Wilson and Wildasin, 2004).

Underprovision of public goods

Public goods appear in a very stylized and abstract way in most of the models in the tax competition literature. Distinctions are usually only made between those goods and services that increase households utility directly, and those that increase firms output. Environmental protection, health benefits from public parks, and education are examples for the former, and finding metrics to express their beneficial effects in monetary terms is quite difficult. The latter, however, are more tangible with respect to measuring their beneficial effects.

There are several studies that quantify the impact of investments in public capital on the general performance of the economy. Public capital is comprised of the government-owned fixed assets – core infrastructures such as roads, electricity grids, public buildings, etc. They are generally considered to increase productivity (Romp and de Haan, 2007). Early empirical research provides some evidence that investments in public capital in the U.S. since 1970 had been suboptimally low (Aschauer, 1989; Gramlich, 1994). More recent publications based on data from multi-country studies confirm the finding that public capital is underprovided in many economies around the world (Bom and Ligthart, 2013; Calderón et al., 2015).

[3] For an overview over the tax competition literature see, e.g. Wilson (1999), Genschel and Schwarz (2011), or Keen and Konrad (2013).

The underprovision of public capital is the point of departure for the analysis in Chapter 2. When tax competition constrains governments' ability to raise funds by taxing capital, they need alternative funding sources. Combining the analysis of international capital markets with fossil resource markets shows that unilaterally introducing a carbon tax enhances efficiency – and at the same time contributes unintentionally to climate change mitigation. Chapter 3 will focus on the consequences of capital mobility for the distributional impacts of climate policy and their policy implications. A more general discussion of the interaction of climate policy with public spending on infrastructure is provided in Sections 5.3.3 and 5.3.4.

1.2.2 Distributional impacts of climate policy

The fear of adverse distributional impacts constitutes a serious obstacle to more stringent climate policy. Besides reshuffling the structure of rents and their ownership on the international level (see Section 1.1.3), there are further ways in which climate policy has distributional impacts on the national and sub-national level. Widely held concerns are, for example, that climate policy would have regressive effects on the distribution of household incomes (Fullerton, 2009; Bento, 2013). Energy-intensive goods make up a higher fraction in the typical composition of relatively poor households' spending on consumption. Thus, by increasing the price of such goods, climate policy would reduce the disposable income of relatively poor households by a greater fraction than that of more affluent ones.[4]

According to the survey by Bento (2013), there is overall very little research on revenue-recycling options to achieve distributional goals. Nevertheless, a few recent exceptions show on a theoretical level that the regressive effect can be offset by well-designed fiscal policy, for example by simultaneously decreasing the wage tax and increasing its progressivity (Chiroleu-Assouline and Fodha, 2014). Further, Klenert and Mattauch (2015) show that the existence of a subsistence level of polluting consumption is a strong driver of the regressivity, but that recycling tax revenues as uniform lump-sum transfers may render the tax reform progressive again.

Another example for a possible distributional side-effect of climate policy is that if abatement technologies are capital-intensive, then climate policy will likely cause firms to use more capital. If this shifts demand away from labor towards capital, then the relative wage reduction may also harm low-income households (Fullerton, 2009). Similarly, low-income households would also suffer if under an emissions trading scheme permits would be grandfathered instead of auctioned. The reason is that freely allocating permits to businesses yields windfall profits to shareholders who tend to be rather high-income households (Dinan and Rogers, 2002; Rose and

[4]Sterner (2012) highlights that the distributional effects of carbon taxation are ambiguous. They depend on country background, but also measurement methodology and interactions with other policies. In very low-income countries, for example, poorer people have little or no access to fossil fuel energy and hence fossil fuels taxes may become progressive.

Oladosu, 2002; Parry, 2004).

Further, Fullerton (2009) also highlights distributional effects that occur during transitional phases in which polluting sectors, for example those that are very carbon intensive, shrink. Thus, laid-off workers who have accumulated human capital in the form of specific skills are hurt due to the devaluation of their human capital. Moreover, workers laid off by impacted firms might have to accept lower wages at another firm, but also "the very sharp pain of disruption, retraining, and months or years of unemployment between jobs" (Fullerton, 2009, p. xii). Finally, due to highly integrated global markets, jobs in energy-intensive and trade-exposed sectors are more strongly endangered of being moved abroad in case of unilateral climate policy (Fischer and Fox, 2011).

In Chapter 3 this thesis takes up the latter two problems by providing a theoretical analysis of an open economy with heterogeneous sectors. It is shown that in the short run, when workers cannot move freely between sectors, inequality-averse governments should implement labor tax exemptions for the energy-intensive sector instead of a differentiated carbon price.

1.2.3 Wealth inequality

I argued above that the impact of climate policy on the distribution of income, and thus also welfare between different households is of crucial importance since it constitutes a major obstacle to more stringent climate policy. Distributional issues lie at the heart of many political processes, which thus justifies a more general inquiry into the impact of policy instruments on the distribution of wealth. This is reinforced by the current trend of rising wealth inequality in several OECD countries (Saez and Zucman, 2016). Wolff (2011), for example, finds that in the U.S., the wealthiest 5% of the population owned about 65% of total wealth in the year 2009, increasing from roughly 62% in 2007. The situation in other OECD countries is similar (OECD, 2015b).

In Section 1.1.3, I have argued that the role of rents has not been appreciated enough in the debate about the dynamics of the wealth distribution. A further aspect that is crucial for the understanding of the dynamics of wealth inequality is heterogeneous savings behavior (Stiglitz, 2015a), and in particular, heterogeneity in preferences for leaving bequests (Cagetti and De Nardi, 2008; Kopczuk, 2013; De Nardi and Yang, 2014).[5] Taking bequests into account is important since they make up a substantial fraction of current wealth. In the U.S. , this fraction is estimated to be approximately 35% to 45%, and it tends to be greater in other countries (Davies and Shorrocks, 2000).

[5]There is strong empirical evidence for the heterogeneity of bequest motives; see, for example, Hurd (1989), Laitner and Juster (1996), Light and McGarry (2004), Arrondel and Masson (2006), Kopczuk and Lupton (2007), and Ameriks et al. (2011).

Other mechanisms also contribute to forming the shape of the wealth distribution. Standard incomplete market models based on the seminal contributions by Bewley (1983), Aiyagari (1994), and Huggett (1996), for instance, use exogenous uninsurable idiosyncratic earnings shocks to model wealth distributions. Since these models fail to generate a high concentration of wealth at the top of the distribution (Castañeda et al., 2003), heterogeneous bequests are regarded as a key ingredient for theoretical models to be able to reproduce the observed data (Suen, 2014).[6]

One objective of this thesis is to explore the policy implications of the recent findings outlined above. Chapter 4 discusses how different policy instruments influence the wealth distribution and GDP in the steady state of an overlapping generations model with two non-standard features: land ownership and heterogeneity in preferences for bequests.

1.3 Beyond watertight compartments

After having reviewed the topics of the economics of climate change and public finance that are relevant for this thesis, I now review the previous literature that combines the two fields. In particular, this includes the double dividend hypothesis and environmental tax competition. Moreover, I will discuss why it is important to bridge the gap between the two fields, argue for a systematic approach, and explain how this thesis constitutes a first step towards that objective.

First of all, taking interactions between climate policy and the broader fiscal system into account is important since the revenue streams associated with policy measures consistent with the 2°C target would be sizable (Metcalf, 2007; Bauer et al., 2013; Carbone et al., 2013). Simply neglecting them would lead to unsound policy advice. Moreover, broadening the perspective to include more interactions opens up the policy space, and yields a richer set of possible solutions to the problem of mitigating dangerous climate change, as the results of Chapters 2 and 3 show. In a more general discussion, Chapter 5 systematizes further interactions and synergies in addressing environmental and fiscal objectives simultaneously.

The double dividend hypothesis

In an early contribution, Gordon Tullock (1967) criticized that "[economists], like everyone else, sometimes keep ideas in watertight compartments." In his short note, he anticipated the idea of the double dividend by arguing that taxes implemented to internalize an externality should serve the dual purpose of (a) correcting the market

[6]Further factors that shape the distribution of wealth include income inequality, the type of earnings risk at the top of the distribution (Cagetti and De Nardi, 2008; De Nardi, 2015), and differences in education (Pfeffer and Killewald, 2015). This thesis, however, concentrates on heterogeneity in preferences for bequests as the key source of wealth inequality.

failure, and (b) generating public revenue; such taxes would be more efficient than other distortionary taxes.

More than twenty years after Tullock's note, the debate about the double dividend hypothesis produced the first attempt to formally analyze the interactions of environmental policy with the broader tax system. The hypothesis contends that environmental policy may not only benefit the environment (the first dividend), but the revenues it generates may be used to reduce other distortionary taxes and thus to reduce the gross costs of environmental policy (see e.g. Goulder, 1995 and Bovenberg, 1999).[7]

The double dividend hypothesis was initially rejected. However, a number of assumptions leading to its rejection have been criticized. A double dividend is thus more likely to occur if the pre-existing tax system is inefficient, if environmental quality is non-separable in the utility function, or if the environmental externality affects the production function (see Section 5.2.2). The results presented in Chapter 2, for instance, confirm the existence of a strong double dividend – the details are discussed in Section 2.6.

The debate about the double dividend is limited in its scope with respect to bridging the gap between environmental economics and public finance. In most cases, only revenue-neutral tax reforms are considered, and the only public finance feature is to analyze the efficiency of the tax system. A full assessment of how climate policy and the broader fiscal system interact must include a much broader spectrum of non-climate inefficiencies and policy objectives. This includes, for example, a more general discussion of public spending, and intra- and intergenerational distribution. In Section 5.2.2, a detailed account of the double dividend hypothesis and how the research of this thesis goes beyond that debate is given.

Environmental tax competition

A very recent strand of literature bridges the gap between public finance and environmental economics by analyzing unilateral environmental policy in the presence of international factor mobility. Ogawa and Wildasin (2009), for instance, analyze transboundary pollution when capital is mobile, and surprisingly find that decentralized decision making leads to an efficient outcome. In response, Eichner and Runkel (2012) show that the efficiency result critically hinges on the rather unrealistic assumption that the capital supply is fixed. Once relaxed, the more intuitive result of underprovision of the public good is restored again. Further, Withagen and Halsema (2013) find a race to the top in environmental policies when capital mobility is taken into account. Their finding stands in contrast to Schmidt and Runkel

[7] This definition refers to the 'strong' double dividend. Its 'weak' form occurs under a less strict condition: It holds if an environmental policy involves lower costs when its revenues are used to reduce pre-existing distortionary taxes than when revenues are recycled in a lump-sum fashion (Goulder, 2013).

(2015), who come to the opposite conclusion in a model that combines the analysis of the free-rider problem in climate policy with tax competition.

This thesis also contributes to the latter strand of literature, as capital mobility is a key feature in both Chapters 2 and 3. However, the analysis of this thesis does not only provide specific examples of how the gap between the economics of climate change and public finance can be bridged. It also discusses the combination of the two fields on a meta-level by providing a systematic overview over a variety of other important interactions (Chapter 5), synthesizes the findings, and makes suggestions for future research (Chapter 6). Therefore, this thesis also contributes to the literature by taking a first step towards a new public economics of climate change.

1.4 Objectives and outline

In this thesis I argue for a new perspective on environmental policy and the economics of climate change. Due to the breadth and the complexity of the problem, sound policy analysis in search of sustainable solutions must take into account public finance considerations, such as tax competition, public goods provision, and distributional aspects. The objective of this thesis is thus to take first steps towards a *new public economics of climate change* by answering the following four main research questions.

1. When the world is reluctant to engage in a joint effort to implement stringent climate policy, do national governments still have a fiscal incentive to tax carbon?

2. If a government unilaterally implements environmental policy, how should adverse distributional impacts on workers in energy-intensive sectors be mitigated?

3. What is the scope of action for a government to redistribute wealth without sacrificing macroeconomic output?

4. What can be learned from combining the economics of climate change and public economics in general?

The objective of Chapter 2 is to introduce a novel multi-region model of tax competition and resource extraction, and to use it to rigorously assess the *fiscal* incentive of imposing a tax on carbon rather than on capital. The aim is to show that when carbon is taxed, the resource rents can be captured and invested in infrastructure. It is shown that this leads to higher welfare than if only capital taxation is available, which gives rise to harmful tax competition. Further, the supply-side dynamics of fossil resource extraction are taken into account in order to assess whether a green paradox may occur.

The model incorporates a decentralized market economy with several representative agents and strategically interacting governments. There are two symmetric resource-importing countries and a third region that sells fossil resources. The tax instruments, which governments use to finance productivity enhancing infrastructure stocks, are determined endogenously for both cooperative and non-cooperative behavior among the resource-importing countries in the Nash equilibrium. Capital and fossil resources may be traded on explicitly modeled international markets.

The model structure allows for an extensive robustness analysis with respect to different assumptions about the strategic behavior of governments. The robustness of the main results is assessed by varying the assumptions about cooperation among resource-importing countries, and the ability of the resource-exporting region to interact strategically on the international resource market.

Chapter 3 continues the integrated analysis of environmental and fiscal policy in a setting of tax competition. Here, in addition to considering fiscal efficiency, the emphasis lies on the distributional impacts of unilateral climate policy, which are often considered as a major obstacle to implementing more stringent climate policy. In particular, the objective of Chapter 3 is to address the concern that households employed in energy-intensive sectors might be affected disproportionally due to international capital mobility. Assuming that workers cannot move freely between sectors, this concern is reproduced in a conceptual model. A uniform carbon tax is found to cause more inequality between the sectors when capital is mobile than when it is not. The study shows that affected households can be relieved more effectively with sector-specific labor taxes than with sector-specific carbon tax exemptions.

In Chapter 4, the policy analysis with respect to distributional issues is then continued with a focus on the distribution of wealth within a closed economy. This chapter provides a policy instrument analysis by comparing the economic impacts of taxes on capital, land rents, and bequests – both on GDP and the distribution of wealth. Similar to the policy conclusions of Chapter 2, the results presented in Chapter 4 provides new arguments for the taxation of rents. The objective is to explain how a government can gain considerable freedom in reducing wealth inequality without sacrificing output. It is shown how combining the taxation of land rents and bequests enables a government to reduce wealth inequality substantially, while leaving the steady state level of macroeconomic output at the same level. Calibrating the model to currently observed OECD average data on wealth quintiles, the range of possible Gini coefficients of the wealth distribution lies between 0.52 and 0.63. In particular, the analysis shows that the land rent tax is not neutral, but enhances output due to a portfolio effect, and reduces wealth inequality slightly.

Further, different spending options for the tax revenues are considered. The analysis in Chapter 4 shows that using the tax revenues to finance infrastructure investments only raises the steady-state level of output, but does not change the distribution of wealth. If public revenues are instead recycled as lump-sum transfers to households, both output and the distribution of wealth are affected: The more a government directs the transfers to the young, the higher the level of output in the steady-state will be and the more equal wealth will be distributed. Moreover, by allowing for intragenerational transfers, it is shown that the Kaldor-Hicks criterion[8] is fulfilled when governments tax land rents, which suggests that rent taxation could indeed be welfare-improving. This is consistent with further new evidence that taxing rents is not neutral, but actually increases social welfare, and may be necessary for achieving the social optimum (Edenhofer et al., 2015).

The aim of Chapter 5 is to take a bird's eye perspective and shows how taking into account interactions between environmental and fiscal objectives may enhance welfare and change the distribution of mitigation costs within and across generations. Chapter 5 shows that jointly considering carbon pricing and fiscal policy is legitimate and mandatory for sound policy appraisal. A systematic discussion of the hitherto identified interactions between climate change mitigation and public finance puts the results presented in the preceding chapters into perspective, and could thus serve as a blueprint for the research agenda of a new public economics of climate change.

Finally, Chapter 6 provides a synthesis of the findings and discusses the methods used. The chapter also discusses the policy relevance of the main findings, and gives an outlook on possible future research based on the results put forward by this thesis.

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[8] In an economy with multiple agents, a policy reform is said to fulfill the Kaldor-Hicks criterion if the theoretical possibility exists that appropriate transfers from the winners of the reform to the losers could render the reform Pareto-improving. In other words, the winners of the reform should be able to compensate the losers and still remain better-off after the reform. The Kaldor-Hicks criterion is weaker than the criterion for a Pareto improvement since the transfers only have to be possible in theory. For a more detailed discussion, see Hindriks and Myles (2013, p. 877ff).

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Chapter 2

Why finance ministers favor carbon taxes, even if they do not take climate change into account[1]

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Why finance ministers favor carbon taxes, even if they do not take climate change into account*†

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Abstract

Fiscal considerations may shift governmental priorities away from environmental concerns: Finance ministers face strong demand for public expenditures such as infrastructure investments but they are constrained by international tax competition. We develop a multi-region model of tax competition and resource extraction to assess the fiscal incentive of imposing a tax on carbon rather than on capital. We explicitly model international capital and resource markets, as well as intertemporal capital accumulation and resource extraction. While fossil resources give rise to scarcity rents, capital does not. With carbon taxes the rents can be captured and invested in infrastructure, which leads to higher welfare than under capital taxation. This result holds even without modeling environmental damages. It is robust under a variation of the behavioral assumptions of resource importers to coordinate their actions, and a resource exporter's ability to counteract carbon policies. Further, no green paradox occurs – instead, the carbon tax constitutes a viable green policy, since it postpones extraction and reduces cumulative emissions.

JEL Classification: F21, H21, H30, H73, Q38
Keywords: Carbon pricing, Green paradox, Infrastructure, Optimal taxation, Strategic instrument choice, Supply-side dynamics, Tax competition

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1. Introduction

The economic integration of national economies has had beneficial impacts on the world in several ways. Nevertheless, we also observe how the economic forces of globalization constrain democratic governments increasingly. According to Dani Rodrik, the world faces a triangle of impossibility: We cannot have democracy, national sovereignty, and hyperglobalization at the same time (Rodrik, 2011). Hyperglobalization impinges on democratic choices within sovereign nations by giving rise to corporate tax competition, which "restricts a nation's ability to choose the tax structure that best reflects its needs and preferences" (ibid., p. 193). National governments find themselves competing for capital through their choice of taxes. Evidence for the resulting race-to-the-bottom[1] in national tax policies is found in declining corporate tax rates (Benassy-Quere et al., 2007; Zodrow, 2010).

The race-to-the-bottom constrains a government's ability to raise sufficient funds, which has far reaching consequences. Sufficient government funds are required for providing public infrastructure, which is underfinanced in many countries (Bom and Ligthart, 2013) even though it has been shown to increase productivity significantly (see e.g. Romp and de Haan, 2007, or Calderón et al., 2014). This raises the question how governments can reduce their exposure to tax competition and generate sufficient funds to finance essential public goods.

In this study, we identify taxes on the use of carbon resources as a superior alternative to taxes on capital income in terms of fiscal efficiency. Even though fossil resources are also traded on international markets, there is an asymmetry in efficiency between capital and resources as tax base. While ownership of fossil resources gives rise to a scarcity rent, capital does not. Taxes on either input factor cause an interregional reallocation by driving economic activity out of the country with the higher tax rates, and into countries with lower taxes. The carbon tax has the advantage, though, of capturing part of the resource rent

[1] Wilson (1986) and Zodrow and Mieszkowski (1986) have conceptualized the underlying economic mechanism. For an overview of the literature on tax competition see e.g. Zodrow (2010), Wilson (1999), and Keen and Konrad (2013).

which is held initially by resource owners. Governments can use the appropriated rent for infrastructure investments that increase the productivity of the domestic economy, which in turn attracts investments in domestic capital stocks.

A tax reform that substitutes carbon taxation for capital taxation has effects beyond improving fiscal efficiency. The supply side dynamics of carbon taxation may have the adverse environmental effect of causing a green paradox[2]. Further, appropriating the resource rents may meet resistance by the rent owners.

However, we find that financing infrastructure investments optimally does not require the carbon tax to increase at a higher rate than the interest rate, which is known to be a necessary condition for the green paradox to occur (Edenhofer and Kalkuhl, 2011). Carbon taxes thus do not cause a green paradox, but constitute a viable green policy, even if governments' motivation to tax fossil resources is based exclusively on their fiscal needs. Further, we explore options for strategic behavior of both buyers and sellers of carbon resources. We show that both the fiscal and the environmental implications remain beneficial regardless of whether resource importers cooperate or not, and regardless of whether resource exporters can influence the resource price strategically with an export tax.

Our contribution is twofold. To the best of our knowledge, our model is the first to combine several key features which allow us to precisely assess the opportunity costs of optimal tax portfolios. It enables us to bridge the gap between the tax competition literature and the economics of exhaustible resources. We implement a decentralized market economy with several representative agents and strategically interacting governments. The tax instruments, which governments use to finance productivity enhancing infrastructure stocks, are determined endogenously for both cooperative and non-cooperative behavior among resource importing nations in the Nash equilibrium. Capital and fossil resources may be traded on explicitly modeled international markets. The use of fossil resources in

[2] The phrase "green paradox" was introduced by Sinn (2008) to describe a situation in which the implementation of carbon taxes leads to an acceleration of resource extraction and an increase of cumulative emissions by the owners of fossil fuel resources. This would counteract the purpose of the environmental policy. The idea originates in a debate lead by Sinclair (1992, 1994) and Ulph and Ulph (1994).

production is assumed to cause no harmful externality. Finally, we include the intertemporal dynamics of capital accumulation and resource extraction. Households' savings behavior is based on a Ramsey model, and a Hotelling model of the resource exporting sector determines the timing of resource extraction.

Second, we use our model to shed light on the supply side dynamics of fossil resource extraction. Most of the research on the conditions under which a green paradox occurs has used partial equilibrium analysis as, for example, in Edenhofer and Kalkuhl (2011), Gerlagh (2011), or van der Ploeg and Withagen (2012). Recently, this strand of research has been extended to general equilibrium models (van der Ploeg and Withagen, 2014; van der Meijden et al., 2014). Now, we are able to go even one step further. Our model allows us to introduce strategic interactions between fossil fuel exporting and importing regions, as well as among the governments of importing countries themselves.[3] A novel insight which we derive from opening up the analysis to such interactions is the possibility of a beneficial race-to-the-top in carbon taxes. The conditions under which it occurs in our model are that capital taxes are not available and that the resource exporter strategically increases the resource price with high domestic export taxes.

The idea to study environmental policy in the form of carbon taxes in a dynamic setting and under the assumption of capital mobility has been taken up recently by two publications. First, Withagen and Halsema (2013) find inefficiently strict environmental policy. They assume that capital and demand for environmental quality are complements. Therefore, the race-to-the-bottom in capital taxes translates via the thusly stimulated higher capital supply into a race-to-the-top in environmental policy – a different mechanism from the one which causes the race-to-the-top in our analysis. While the authors also study tax competition in an intertemporal general equilibrium framework, they neglect the dynamics of resource extraction.

[3] Irrespective of the literature on the green paradox, it is already known that a cooperating bloc of resource importing countries can appropriate a certain fraction of the exporters' resource rent, as discussed, for example, by Karp (1984), Amundsen and Schöb (1999), or Liski and Tahvonen (2004). We are able to reproduce this result and compare it to the outcome under non-cooperative importers.

Closer yet to the present study is Habla (2014). The author implements an analytical two-period general equilibrium model of tax competition and resource extraction. The main finding consists in the discovery of an additional channel through which governments, that take environmental damages into account, may counter a green paradox. By raising a positive tax on capital unilaterally, governments can decrease the global interest rate. Through the Hotelling rule, the decrease of the interest rate translates into a lower future price of fossil resources. The price signal, thus, stimulates a shift in demand away from present and towards future resource use.

Our analysis differs from Habla (2014) in three respects, which highlight the relevance of our results for policy making. First, we assume that the primary motivation for taxation is demand for public infrastructure rather than environmental concern.[4] By focusing on infrastructure as motivation we account for both the income and the expenditure side of fiscal policy. Omitting environmental damages in our analysis accounts for the currently hesitant and incomplete environmental policies to address climate change. Second, we distinguish between a resource seller and resource buyers, opening up the analysis to a richer set of strategic interactions. Finally, the design of our model allows us to quantify the opportunity costs of various tax portfolios under different assumptions. In particular, we can determine the differential impacts of various assumptions about the strategic behavior of resource importing and exporting countries.

The rest of the paper is structured as follows. After explaining the model in Section 2, we present our results on the comparison of different tax portfolios in Section 3. In Section 4 we assess the impact of different policy choices on the supply side dynamics of resource extraction. In Section 5 we describe how different assumptions about the strategic behavior of the governments change our results. We conclude with Section 6.

[4] This point is also an example of how we differ from the related literature on the double dividend hypothesis (see e.g. Bovenberg, 1999, and Goulder, 2013, for surveys), in which usually only the income and not the expenditure side of fiscal policy is considered, and which concentrates on flows and not on stocks.

2. The model

We implement a differential game based on a Ramsey-type general equilibrium growth model. There are two symmetric countries, each populated by an identical set of economic agents, as well as a group of resource owners who reside outside of the two countries. These resource owners as agents in our model can be thought of as a third country which is endowed with a stock of fossil resources. The economic activity of this third country consists of exporting the resource to the other two countries in exchange for final goods and of consuming these.

The model is calibrated to represent two countries of the developed world which import substantial amounts of fossil resources (see, for example, the U.S. Energy Information Administration's list of the *Top World Oil Net Importers*, EIA, 2014) and which already have in place a relatively high amount of publicly held fixed assets. The initial endowment with infrastructure is extrapolated from US data.[5] The details of the calibration can be found in the Appendix A.

2.1. International markets

The symmetric importing countries are labeled by the index $j \in \{1, 2\}$. They are linked by the international markets for capital and fossil resources. We distinguish between firm j's demand for capital $K^d_{j,t}$ and resources $R^d_{j,t}$ at time t, household j's assets, that is, the capital supply $K^s_{j,t}$, and the exporter's resource supply R_t. Households own only the domestic firms but rent out their accumulated capital to any firm, domestic or abroad. Renting to a firm abroad does not afford them any ownership claims abroad, and we assume that capital and resources move around until the prices for each factor are equal in all countries. Thus, the international

[5] Developing countries usually have a much lower endowment with infrastructure and thus the marginal benefit of additional tax income should be higher than found using our model. Here, we would expect the advantage of the carbon tax to be even higher.

capital market is described by

$$K_{1,t}^s + K_{2,t}^s = K_{1,t}^d + K_{2,t}^d \quad \forall t, \tag{1}$$

$$r_{1,t} = r_{2,t} = r_t \quad \forall t, \tag{2}$$

where r is the interest rate. For the resource market and the price of fossil resources p, we have

$$R_t = R_{1,t}^d + R_{2,t}^d \quad \forall t, \tag{3}$$

$$p_{1,t} = p_{2,t} = p_t \quad \forall t, \tag{4}$$

Labor is significantly less mobile than capital or fossil resources. Thus, we assume in our model that labor is fixed in supply and may not move across country borders. A further market for final goods is not included as we assume that there is only one final goods producing sector. Firms pay the households and resource owners with their output of the final good.

2.2. Agents of the national economy

A large number of households live in each of the two importing countries. Output is produced by a large number of competitive firms which use labor, private capital, and publicly provided infrastructure as well as fossil resources as inputs to produce a homogeneous final consumption good. The two countries are not endowed with any fossil resource, thus the firms have to import them. Fossil resources are extracted by a large number of resource owners who sell them on the international resource market to the firms in the two resource importing countries.

We assume that all households, all the firms producing final goods, and all the resource owners are identical. We thus focus on the aggregated behavior of representative agents. Therefore, each of the two resource importing countries has one representative household and one representative firm, as well as a benevolent government. Resources are extracted and exported to these two countries by one representative resource owner. The governments of the importing countries influence the economy by implementing policy instruments. They are assumed to have perfect knowledge of all agents' objectives and their reactions to the policy instruments, that is, they act as Stackelberg leaders.

In presenting our results, we make different assumptions about the resource extracting and exporting country. In Section 3 we focus on the comparison between different policy instrument portfolios in the importing countries. Here, we assume that the only control variable of the resource exporting country is the rate of extraction, rendering it a Stackelberg follower. In Section 4, we then introduce a government of the exporting country in addition to the (private) resource owner. We implement this government as a third Stackelberg leader next to the importing countries' governments to analyze the impact of strategic interaction between importers and the exporter.

The following optimization problems characterize the individual economic agents' behavior. Their respective first order conditions can be found in Appendix B.

The representative household

The representative household in country j derives instantaneous utility from per capita consumption according to the constant intertemporal elasticity of substitution (CIES) utility function

$$U(C_{j,t}/L_t) = \frac{(C_{j,t}/L_t)^{1-\eta}}{1-\eta}, \tag{5}$$

where $1/\eta$ is the intertemporal elasticity of substitution, $C_{j,t}$ denotes aggregate consumption in country j at time t, and L_t is labor. The supply of labor is given exogenously and we assume it is equal in the two importing countries.

To improve readability, we will omit the country index j in the description of the representative household, the representative firm, and the government. The household maximizes its welfare W subject to the budget constraint (7) and the equation of motion of the capital it supplies, K^s (8).

$$\max_{C_t/L_t} \quad W = \sum_{t=0}^{T} U(C_t/L_t)\left(\frac{1}{1+\rho}\right)^t \tag{6}$$

$$\text{s.t.} \qquad C_t(1+\tau_{C,t}) = r_t K_t^s + w_t L_t - I_t + \Pi_t^F + \Gamma_t \tag{7}$$

$$\text{and} \qquad K_{t+1}^s = K_t^s(1-\delta) + I_t. \tag{8}$$

The capital stock depreciates at the annual rate δ. The household in country j discounts future utility according to its pure rate of time preference ρ. It rents out the capital that it supplies (K^s) on the global capital market and earns income according to the world interest rate r. Further, the household receives labor income according the exogenously given time path of labor and the endogenously determined wage rate w. The profits of the firm Π^F accrue to the household. The government may use tax revenue for lump sum transfers $\Gamma \geq 0$ to the household and it may charge a tax on consumption, τ_C.

The production sector

The representative firm in the importing country j is assumed to be a price taker. Its output is given by a neoclassical production function, which depends on four input factors – capital, infrastructure, labor, and fossil resources, denoted by $Y = F(K^d, G, L, R^d)$. For our calculations we use a nested constant elasticity of substitution (CES) function. On the lowest level, private capital K^d, which the firm may demand on the global capital market, and publicly financed infrastructure G are aggregated to an intermediate input, $\mathbf{Z}(K^d, G)$. This *general capital*, resembling governmental and private fixed assets used to produce output, is then combined with labor on the intermediate level in a further composite input $\mathbf{X}(\mathbf{Z}, L)$. Finally, on the top level, fossil resources R enter in production. We choose this specific structure since the empirically determined values for the substitution elasticities $\sigma_i,\ i = 1, 2, 3$ differ from each other. The production function takes the form

$$F(K_t^d, G_t, L_t, R_t^d) = A_t \left[\alpha_1 (A_{R,t} R_t^d)^{s_1} + (1-\alpha_1)\mathbf{X}(\mathbf{Z}, L_t)^{s_1}\right]^{\frac{1}{s_1}}, \qquad (9)$$
$$\text{where} \qquad \mathbf{X}(\mathbf{Z}, L_t) = \left[\alpha_2 \mathbf{Z}(K_t^d, G_t)^{s_2} + (1-\alpha_2)(A_{L,t} L_t)^{s_2}\right]^{\frac{1}{s_2}}.$$
$$\text{and} \qquad \mathbf{Z}(K_t^d, G_t) = \left[\alpha_3 (K_t^d)^{s_3} + (1-\alpha_3)(A_G G_t)^{s_3}\right]^{\frac{1}{s_3}}.$$

The exponents s_i, $i = 1, 2, 3$, are determined by the respective elasticities of substitution σ_i via $s_i = \frac{\sigma_i - 1}{\sigma_i}$. We assume $\sigma_1 < 1$,[6] and for the share parameters it holds that $\alpha_i \in (0, 1)$, $i = 1, 2, 3$. A_t denotes total factor productivity, while $A_{\zeta,t}$ is the productivity of the factor $\zeta = R, G, L$.

The production technology (9) exhibits constant returns to scale in all four inputs. Since the firm only pays for the three privately provided inputs, profits are non-zero, that is, there are economic rents caused by the unpaid factor. The public input in our analysis is assumed to be of the *firm-augmenting* type.[7]

The firm produces output with the technology given by (9), rents capital at the market interest rate r_t, pays workers their wage w_t, and pays the price p_t for the fossil resources it uses in each period. In addition, we assume that it may have to pay corporate taxes, which we approximate by an ad valorem tax on capital τ_K, a payroll tax τ_L on the use of labor, or a source based carbon tax τ_R, to the government.[8] We have based our choice to model τ_K and τ_L as ad valorem and τ_R as unit tax on reality: The political debate about CO_2 taxes focuses on unit taxes; corporate tax rates, which are approximated by the capital tax, and

[6] See Appendix A for more details on the calibration and choice of model parameters.

[7] The alternative assumption that it is of the *factor-augmenting* type, which means that G affects total factor productivity, would imply that the production technology exhibits increasing returns to scale. The solution of the non-linear program then would become technically more challenging. Using the factor-augmenting type would thus complicate matters unnecessarily, since we expect that it would not change our results qualitatively: Matsumoto (1998) addresses the technical difference between the two types in the context of tax competition.

[8] One could also implement τ_K or τ_L as a unit tax, or τ_R as an ad valorem tax. Whether unit, or ad valorem taxes are chosen for the respective input factors has only a relatively weak impact on our results – they are robust with respect to this choice. Determining the differences in detail, though, is a research question that goes beyond the scope of this paper. For a general discussion see Suits and Musgrave (1953). Studies focusing on this question in the light of capital mobility are Lockwood (2004) and Hoffmann and Runkel (2015).

payroll taxes are usually given in ad valorem terms.

The firm's objective is to choose the amount of capital, labor, and fossil resources it demands in each period which maximizes profit for all points t in time,

$$\max_{K^d,L,R^d} \Pi^F = F\left(K^d, G, L, R^d\right) - r\left(1+\tau_K\right)K^d - w(1+\tau_L)L - (p+\tau_R)R^d.$$

Differentiation with respect to K, L, and R yield the three first order conditions, which equate the marginal product of the private input factors with their respective after-tax prices:

$$F_K = r(1+\tau_K) \quad (10)$$

$$F_L = w(1+\tau_W) \quad (11)$$

$$F_R = p+\tau_R \quad (12)$$

The fossil resource sector

The representation of the resource extraction sector is based on the classical models of Hotelling (1931) and Dasgupta and Heal (1974). The resource owner depletes the finite stock S of a generic fossil resource according the equation of motion

$$S_{t+1} - S_t = -R_t, \ S_0 \text{ given}, \quad (13)$$

and sells the quantity R_t in each period on the international resource market at the price p_t. The generic fossil resource can be thought of as coal, oil, and gas. In reality, fossil resources are widely dispersed across the surface of the earth. In particular this holds true for coal. Nevertheless, we abstract from a symmetric endowment with coal among all countries, since our results would not change qualitatively. In general, differentiating between different types of fossil resources would improve model realism, but it would also complicate the analysis substantially and, thus, lies beyond the scope of the present study.

The extraction costs c_t are assumed to increase with cumulative extraction

$S_0 - S_t$, as the most accessible resources are depleted first:

$$c_t(S_t, r_t) = r_t \left(1 + \frac{\chi_2}{\chi_1}\left((S_0 - S_t)/S_0\right)^{\chi_3}\right) \tag{14}$$

We implement the same cost function used in the model PRIDE (see e.g. Kalkuhl et al., 2012), which is based on the assessment of world hydrocarbon resources by Rogner (1997). An overview of the parameter values used can be found in the Appendix in Table 5.

The resource owner's profits in each period are given by

$$\Pi_t^R = (p_t - c_t - \tau_{RO})R_t + \Psi = (p_t - c_t)R_t. \tag{15}$$

We assume that the government of the resource exporting country recycles the tax revenue $\tau_{RO,t}R_t =: \Psi_t$ as lump-sum transfer to the resource owner, thus (15) simplifies again. However, the resource owner does not anticipate her influence on Ψ, but takes it as given, which matters for the first oder conditions (see Appendix B). In maximizing her intertemporal stream of profits (16) she discounts profits by the market interest rate net of depreciation $r_t - \delta$, which she takes as given. She takes into account the resource constraint (17), the equation of motion for the stock (13), the extraction costs (14), and possibly the unit tax τ_{RO} on exports.

$$\max_{R_t} \sum_{t=0}^{T} \Pi_t^R \left(\frac{1}{1 + r_0 - \delta} \cdot ... \cdot \frac{1}{1 + r_t - \delta}\right) \tag{16}$$

$$\text{s.t.} \quad \sum_t R_t \leq S_0. \tag{17}$$

The government

The firms, the resource owner, and the households take all taxes as given. The government of a resource importing country balances the marginal benefits of additional infrastructure investments with the marginal costs of distorting the economy with additional taxes. In the market equilibrium of the decentralized economy, the government acts as Stackelberg leader. It optimizes the representative household's welfare by choosing the tax paths, and how to spend the tax revenues.

Note that the policy instruments – except the payroll tax – are not allocation neutral. Non-zero taxes on capital, and consumption always distort the decisions of the households in our model. On the other hand, a carbon tax path $\{\widetilde{\tau}_{R,t}\}_{t\in\{1,\dots,T\}}$ under which the extraction path remains unchanged does exist.[9] In practice, though, the timing on the income side of governmental fiscal policy does not match the optimal timing on the expenditure side in general: The result of such a path $\{\widetilde{\tau}_{R,t}\}_{t\in\{1,\dots,T\}}$ would be inefficient over- and underprovision of infrastructure at different points in time.[10]

The government anticipates the general equilibrium response of the economy. It takes into account all first order conditions, budget constraints, terminal conditions, etc. from the other agents' optimization problems when deciding on the tax paths. The government distributes a fraction d_t of total tax revenue $\mathcal{T}_t = r_t \tau_{K,t} K_t^d + w_t \tau_{L,t} L + \tau_{C,t} C_t + \tau_{R,t} R_t^d$ to the domestic households as lump sum transfers Γ_t and a fraction $1 - d_t$ to investments in the infrastructure stock I_t^G.[11] The infrastructure stock evolves according to the equation of motion

$$G_{t+1} = G_t + I_t^G - \delta G_t. \tag{18}$$

[9] In the Hotelling model it is possible to show that the extraction path remains unchanged if the resource price and the unit tax grow at the same rate.

[10] Theoretically it would be possible to decouple the income and the expenditure sides: Governments could use positive tax transfers Γ as a buffer to adjust the carbon tax path such that it would be allocation neutral. Any excess in tax revenue that would not be needed for the optimal financing of infrastructure would be transferred to households as lump sum transfers. In practice, though, such an excess revenue will be competed away through a race-to-the-bottom in carbon taxes.

[11] We implement the possibility of lump-sum transfers in order to avoid that our results are dominated by unrealistic timing effects due to the optimal timing of infrastructure investments. The average value of the distribution parameter d_t is 75% (average over time and all possible policy scenarios). Across different policy cases the time average does not vary by more than six percentage points.

The government's problem thus reads

$$\max_{\tau_K,\tau_L,\tau_C,\tau_R,d} \quad W = \sum_{t=0}^{T} L_t U\left(C_t/L_t\right)\left(\frac{1}{1+\rho}\right)^t$$
$$\text{s.t.} \quad \Gamma_t = d_t \mathcal{T}_t,$$
$$I_t^G = (1-d_t)\mathcal{T}_t,$$

and Equations (1), (2), (7) – (13), (17), (18), and (B.1) – (B.6).

2.3. Equilibria of the economy

We frame the optimization problem as a non-linear program and solve the economy for the Nash equilibrium using the GAMS software (Brooke et al., 2005). The solution algorithm is described in Appendix C, the program code is contained in the supplementary material.

All economic agents take the strategies of the other agents as given. The two governments of the importing countries and the government of the exporting country have an advantage, though, as they are assumed to be Stackelberg leaders and may move first, or, to formulate it in different terms, they anticipate the reactions of firms, households, and the resource owner. We assume that they can commit to the policies they announce.[12]

We analyze two different solutions: the case of cooperative and non-cooperative importers, by which we mean that welfare is maximized jointly and separately, respectively. This way we can construct a counterfactual to reality in which countries actually do compete for mobile factors. Comparing the two equilibria, we can isolate the effects of harmful tax competition, which disappear when importers cooperate.

[12] Due to the Stackelberg structure of the game, at least in theory time inconsistencies could arise. However, we have checked whether governments have an incentive to deviate from the initially announced tax paths and found no significant deviations (see Appendix E for more details).

Non-cooperative importers

Each country's government faces its local agents and anticipates their reaction, that is, it acts as a Stackelberg leader here. We further assume that the government also anticipates the reactions of each foreign household, firm, and the external resource owner. This makes the government a Stackelberg leader of the resource owner and firms and households, both domestic *and* foreign.[13]

At the same time, one country's government also faces the other countries' governments, Stackelberg leaders of the global economy as well.[14] Thus, governments sit at two game tables – here a Stackelberg and there a simultaneous move game. In the former sub-game, the importers' governments have to make decisions about financing local infrastructure and they strive to balance the benefits from additional infrastructure with the policy costs of the distortionary taxes. The exporters' government only maximizes profits. In the latter, all governments can interact strategically with each other through the choice of policy instruments.

Each government takes the strategies of the other governments as given when choosing its own strategy. In doing so, it anticipates the international movement of capital and fossil resources, but also the behavior of domestic and foreign households, firms, and the resource owner in response to the policy instrument choice.

More formally, the objective of a government of an importing country j is to maximize its payoff, that is, its welfare W_j. The objective of the exporter's government is to maximize the discounted sum of profits given by equation (16). The strategies of the importers' governments are $\{d_t^j, \tau_{\zeta,t}^j\}$ where $t \in \{1, ..., T\}$ and $\zeta \in \{K, L, C, R\}$. The exporter's government chooses only the path of the export tax $\{\tau_{RO,t}\}$. Each government takes as given the respective other govern-

[13] This assumption is crucial for the present study in order to ensure that governments anticipate how mobile capital will be absorbed by firms abroad. It also seems more realistic than the case in which the domestic government forms no expectations about foreign agents at all. Introducing imperfect knowledge would add further parameters and raise questions which lie beyond the scope of the present study.

[14] Strictly speaking, the national governments are only Stackelberg leaders of the subgame in which they determine their own policy instruments optimally, taking the other governments' policy instruments as given and taking the reactions of all other economic agents into account. In the present study the term Stackelberg leader always refers to this specific meaning.

ments' strategies. Note that throughout Section 3 we assume that the exporter's government may not use any taxes, in order to concentrate on the assessment of different tax portfolios in resource importing countries.

The cooperative solution

The Stackelberg game structure described above remains the same, both in the non-cooperative and the cooperative solution. In contrast to non-cooperation, though, we obtain the cooperative solution by calculating those policies $\{d_t^j, \tau_{\zeta,t}^j\}$, where $j = 1, 2,\ t \in \{1, ..., T\}$, and $\zeta \in \{K, L, C, R\}$, that maximize the joint welfare of both importing countries, $W_1 + W_2$.

3. Optimal tax policies and portfolios

In this section, we assess the performance of different tax instruments in a setting of tax competition. We first consider tax portfolios in which both importing countries may use only one type of instrument, and the government of the exporting country does not implement any taxes. Then, we allow the use of a mixed tax instrument portfolio. Finally, we show how our results depend on the choice of two key parameters. In particular, we vary the substitution elasticity between fossil resources and the composite of all other inputs, as well as the substitution elasticity between capital and infrastructure.

Throughout this section we assume that the resource exporter does not interact strategically and that the governments of the importing countries do not cooperate.

3.1. Single instrument portfolio

We compare the outcome of the Nash game that the two importers' governments play. For exposition, both governments may only use one and the same of the following tax instruments: resource tax τ_R; payroll tax τ_L; consumption tax τ_C; capital tax τ_K. Table 1 shows welfare measured in balanced growth equivalents[15], and presents the relative difference between the carbon tax on the one hand, and the capital tax, the consumption tax, and the payroll tax on the other.

We find that welfare is highest under the carbon tax, followed by the payroll tax, and then the capital tax. Welfare is lowest under the consumption tax. The the carbon tax is the most efficient choice for the government of an importing country.

Further, when the carbon tax is implemented, the net present value[16] of profits

[15] Balanced growth equivalents (BGE) are a commodity measure of welfare. The BGE of a given welfare level is the value of initial consumption which yields – under a constant annual growth rate – the given level of welfare. It translates the unit-less welfare into more tangible consumption levels in dollars, and thus facilitates comparisons of policy instrument portfolios. It has been introduced by Mirrlees and Stern (1972). Since our model uses discrete time steps, we follow the accordingly modified method of Anthoff and Tol (2009). In calculating the BGE, we assume a constant annual growth rate of 2%.

[16] The net present value of any flow variable X_t is calculated as the sum over the entire time

of the resource owner are lowest. By implementing the carbon tax, resource importing countries capture part of the resource rent, which they then invest in their local infrastructure. The other tax instruments do not give this advantage to the importing countries. Even though we model labor as fixed in supply, and thus the payroll tax does not distort the economy, governments cannot use it to capture the resource rent. The consumption tax and the capital tax also lack this advantage. In addition, they distort the households' decisions how much to save or to consume, which is why they are inferior to the payroll tax.

	BGE [tril. US$ / year]	Welfare relative to policy case τ_R	$NPV(\pi_R)$ [tril. US$]
τ_R	24.86	–	84
τ_L	24.30	-2.3 %	119
τ_K	24.28	-2.4 %	151
τ_C	24.13	-3.0 %	124

Table 1: Welfare comparison in balanced growth equivalents (BGE) of policy cases in which importers' governments only use one instrument: Carbon tax τ_R, capital tax τ_K, payroll tax τ_L, or consumption tax τ_C. Welfare losses are measured relative to the case in which governments use only carbon taxes. The net present value of the resource owners profits $NPV(\pi_R)$ is measured in trillion US$. An extended version of this table showing the impact of different taxes on capital and infrastructure stocks, as well as on interest rate and resource price is included as Table 6 in Appendix D.1.

Thus, when we compare the two internationally mobile factors capital and fossil resources as tax bases, we see a fundamental asymmetry. The endowment with fossil resources gives rise to a scarcity rent (evident in the profits of the resource sector in our model), while private capital does not. Therefore, the carbon tax performs much better in importing countries when their governments have to take into account both the income and the expenditure side of their fiscal policy, as well as the international integration of factor markets.

horizon, discounted by the interest rate net of depreciation $r - \delta$, that is,

$$NPV(X) = \sum_t \frac{X_t}{\Pi_s^t (1 + r_s - \delta)}.$$

3.2. Mixed tax portfolios

By allowing the use of only one single tax instrument in the preceding section, we have identified the possibility to capture part of the Hotelling rent with the carbon tax. We now turn to the more realistic case in which governments use a combination of all tax instruments.

In order to focus the role international factor mobility plays for the design of tax portfolios in resource importing countries, we restrict our analysis to those taxes which have mobile factors as tax base, that is, capital and resources. Thus, for the rest of the paper, we make the assumption that the payroll tax and VAT rates are fixed at a specific level, respectively, which is based on data compiled by the World Bank (2014) and the OECD (2014). For more details see Appendix A. Governments may determine only the tax rates on the use of carbon and capital optimally.

A comprehensive discussion including the role of consumption and payroll taxes lies beyond the scope of this paper, because the simultaneous calculation of the optimal time path of four different instruments causes complex tax interaction effects. Further, political economy reasons suggest to focus on carbon and capital taxes. Payroll taxes and VAT are already relatively high and up to now have been used to compensate fiscal losses from lowered corporate income taxes (see e.g. Sinn, 2003, p. 20). Our point of departure is thus a situation where governments are much more constrained in their ability to raise payroll taxes or the VAT than to raise environmental taxes.

Figure 1 shows how the tax income of an importing country evolves over time in absolute terms. The revenues from the fixed labor and consumption tax rates are quite high. Further, the amount of income generated with the carbon tax exceeds by far the income from taxing capital. The net present value of tax income generated by the carbon tax in an importing country amounts to about \$33 trillion over the period from 2010 to 2065, while the capital tax generates only \$3 trillion over that time horizon.

The outcome confirms our insight from Section 3.1. Because the carbon tax

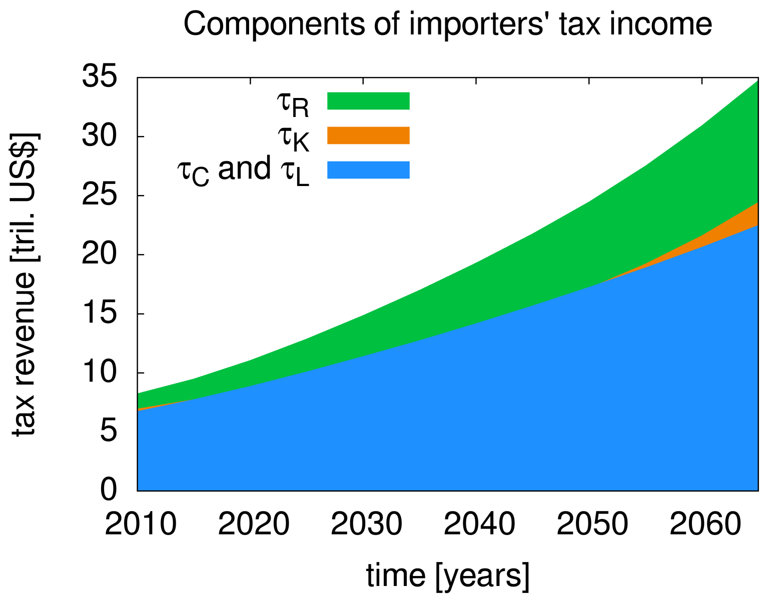


Figure 1: Tax income, decomposed into contributions by the endogenously determined carbon tax τ_R and capital tax τ_K, as well as the fixed consumption and payroll tax ($\tau_C = \tau_L = 0.16$), respectively. For the underlying data, see the corresponding table in Appendix D.2.

can capture part of the Hotelling rent, it plays a decisive role in the unilaterally chosen tax portfolio of an importing nation. Note that this result is robust under the variation of the exogenously fixed rates for the tax on consumption or on labor.

3.3. Substitution elasticities

A sensitivity analysis of the model to assumptions about parameter values showed no particular sensitivity toward any one parameter.[17] To explore the robustness of our findings, we therefore focus on the two parameters which are critical to the characterization of the tax bases of capital tax and carbon tax, namely the parameters governing their factor substitution possibilities. We begin by analyzing how welfare depends on the elasticity of substitution σ_1 between fossil resources and

[17] We have conducted a local sensitivity analysis by varying all parameters one-at-a-time. A parameter variations of $\pm 5\%$ resulted in changes of the net present value of aggregate consumption of the same or smaller order of magnitude.

the composite input $\mathbf{X}(K, G, L)$, which combines private and public capital with labor. Then, we perform the same experiment for σ_3, the elasticity of substitution between private capital and infrastructure. Two policy cases are subject to our comparison, one in which governments determine the capital tax endogenously and do not use the carbon tax, and vice versa.[18] The taxes on consumption and labor remain at their constant level, as discussed in Section 3.2.

Substitution elasticity between fossil resources and composite $\mathbf{X}$
Table 2 summarizes welfare measured as balaced growth equivalents (BGE) in importing countries for the two policy cases. We would like to highlight two observations. First, when the two inputs are assumed to be complementary, that is, $\sigma_1 < 1$, the carbon tax always performs better than the capital tax. Our standard value for the elasticity is $\sigma_1 = 0.5$ (for a discussion of the empirical literature see Appendix A).

	τ_R [tril. US$]	τ_K [tril. US$]	relative difference
0.3	23.03	22.10	4.19 %
0.4	24.17	23.37	3.44 %
0.5	**24.96**	**24.26**	**2.86 %**
0.6	25.52	24.92	2.42 %
0.7	25.95	25.41	2.09 %

Table 2: Comparison of the policy cases in which the importers' governments only determine the carbon tax τ_R or only the capital tax τ_K endogenously. The numbers give welfare measured as balanced growth equivalents. The column on the right shows the relative difference between the second and the third column.

Second, with a smaller elasticity of substitution, the advantage of the carbon tax over the capital tax increases, as indicated by the increasing difference in welfare between the two policy cases. The explanation for the latter observation lies in the shape of the demand functions for the input factors. The lower the elasticity of substitution in any CES production function is, the more inelastic demand for the inputs becomes.[19] When demand is relatively inelastic, fossil

[18] The case in which both instruments are optimized does not yield any further insights.

[19] The derivation of the demand functions from a given CES production function can be

resources R and the composite input $\mathbf{X}(K,G,L)$ become relatively fixed factors and taxes on these factors distort the market outcome less. Within the composite input, though, substitution between the inputs is still possible – more precisely, infrastructure can be substituted for capital, even when the elasticity σ_1 is low. Thus, capital remains relatively more elastic in supply when the elasticity σ_1 decreases, while fossil resources become a relatively fixed factor and can be taxed at lower costs than capital.

Substitution elasticity between capital and infrastructure

Varying σ_3, the elasticity of substitution between private capital and infrastructure, has a rather moderate impact on the model results, when we compare it with the above result on σ_1. In table 3 we present this finding.

Nevertheless we observe a trend in the difference between the two policy cases. The harder it gets to substitute capital for infrastructure, the greater is the difference in welfare losses relative to the benchmark case. In other words, the more inelastic the demand for infrastructure is, the more pronounced becomes the advantage of the carbon tax.

	τ_R [tril. US$]	τ_K [tril. US$]	relative difference
0.7	24.36	23.59	3.262%
0.9	24.73	24.05	2.864%
1.1	**24.96**	**24.26**	**2.863%**
1.4	25.16	24.48	2.785%
1.7	25.29	24.61	2.734%

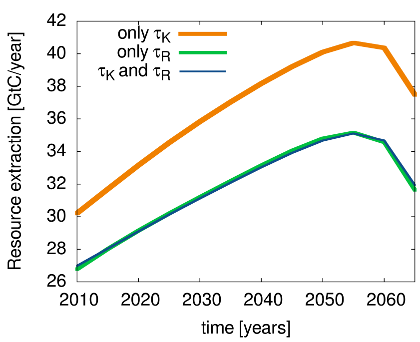
Table 3: Comparison of the policy cases in which the importers' governments only determine the carbon tax τ_R or only the capital tax τ_K endogenously. The numbers give welfare measured as balanced growth equivalents. The column on the right shows the relative difference between the second and the third column.

found in Allen (1938), p. 369 ff.

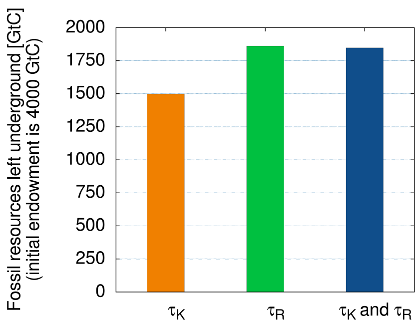
4. Supply side dynamics of resource extraction

In the preceding sections we showed that a carbon tax is superior to capital taxation because the carbon tax has the ability to appropriate part of the resource rent. The argument in favor of carbon taxation was based exclusively on the goal of fiscal efficiency in resource importing countries.

In this section, we consider environmental aspects by identifying the impact of carbon taxation on the supply side dynamics of fossil resource extraction. We compare three tax portfolios. Again, we focus on mobile tax bases, thus the taxes on consumption and labor remain at their fixed level. Governments may either only specify the capital tax, or only the carbon tax, or both the capital and the carbon tax.



(a)



(b)

Figure 2: Timing and volume effects of different policy instrument portfolios. Compared to the case in which importing governments only determine the capital tax optimally, portfolios which include an optimally determined carbon tax lead to both a lower rate of extraction and lower cumulative extraction.

Figures 2a and 2b show the time path of resource extraction for the three different policy cases, as well as the amount of fossil resources left underground at the end of the time horizon, respectively. Note that fossil resources will never be exhausted fully due to the assumption that extraction costs are convex. We observe that the use of a carbon tax postpones extraction and also leads to a lower level of cumulative extraction over the entire time horizon, that is, it causes a conservative volume effect. In other words, the use of carbon taxes to finance infrastructure investments causes no green paradox, but constitutes a viable green policy.

The reason for the above result lies in the time profile of the demand for infrastructure, which determines the time profile of the optimal carbon tax. We find that the annual growth rate of the optimal carbon tax is always less than the interest rate net of depreciation, with which the resource owner discounts her profits (see Table 4). However, a necessary condition for the green paradox to occur is that the annual growth rate of the carbon tax is greater than the discount rate used by the resource owner (see e.g. Edenhofer and Kalkuhl, 2011, Table 1, for an overview over these conditions). Thus, the conditions for a green paradox to occur are not fulfilled.

year	τ_R [$/tC]	γ_{τ_R}	$r-\delta$
2010	77	0.000	0.039
2020	124	0.049	0.069
2030	194	0.043	0.067
2040	277	0.034	0.063
2050	369	0.028	0.061
2060	483	0.028	0.062

Table 4: Time profile of the optimal carbon tax τ_R in dollars per ton of carbon, the annual growth rate of the carbon tax γ_{τ_R}, and the annual interest rate net of depreciation $r-\delta$ for the case in which governments optimize only the carbon tax.

5. Assumptions about strategic behavior

In the two preceding sections we have shown our main results. Resource importing countries prefer to finance their infrastructure by using the carbon tax rather than the capital tax. If they do so, fossil resource extraction is postponed and cumulative emissions are reduced. The aim of the present section is to show that our two main results are robust under a variation of the behavioral assumptions of the resource importers to coordinate their actions, and the resource exporter to counteract carbon policies. Further, in Section 5.3, we also identify a special case in which competition among the importing countries leads to a beneficial race-to-the-top in carbon taxes.

Our premise that resource importing countries compete in their policies for mobile factors is based on the empirical evidence for tax competition around the world. However, the prospect of valuable resource rents as suggested by our analysis may motivate importers to negotiate coordinated policies. Furthermore, nations are already negotiating about climate policy striving for a coordinated price on carbon emissions, which would have similar implications for resource imports.

Therefore, we ask how the Nash equilibrium of our modeled economy changes, when the governments of the importing countries could actually cooperate to maximize their joint welfare. It is known from the theoretical literature that a resource buyers' cartel can exercise monopsony power and capture a greater portion of the resource rent (see Karp, 1984, Amundsen and Schöb, 1999, and Liski and Tahvonen, 2004). Our analysis confirms the result for the case of an exporter that does not act strategically, and we provide an estimate of the magnitude.

Conversely, resource suppliers may not remain idle when policies are implemented that deprive them of their rent income. One option for the resource exporting country is to use domestic tax instruments to interact strategically on the international resource market (this is equivalent to the assumption that resource sellers exercise market power, e.g. as cartel or monopoly). When importers charge a tax for the use of fossil resources, the government of the exporting country has an incentive to tax its exports to prevent the rent from being captured by the importers.

5.1. Volume effects

The first result we would like to highlight concerns the volume effect of a carbon tax. In Figure 3 we present an overview over the three policy cases already considered in Section 4 and all four combinations of assumptions about strategic behavior of the importers' and exporter's governments.

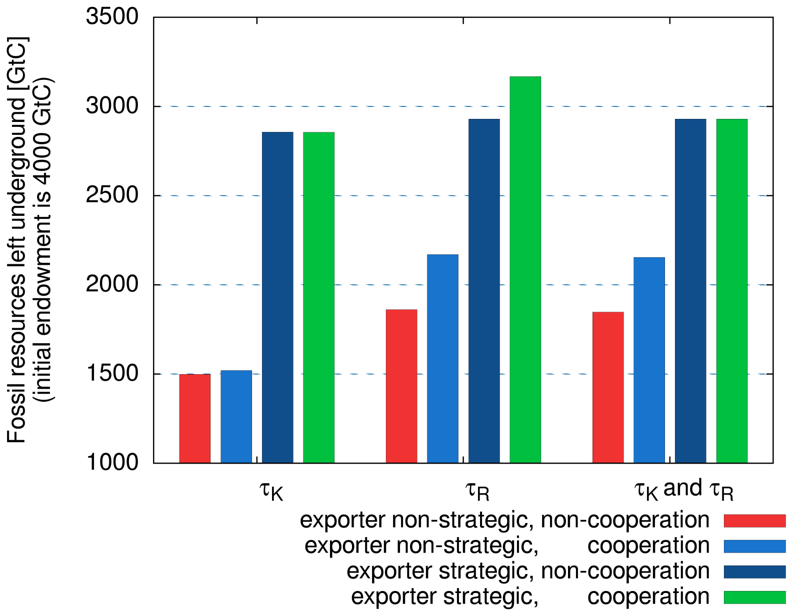


Figure 3: Amount of fossil resources left underground at the end of the time horizon. For the corresponding table, see Appendix D.3, Table 8.

In most cases we see that allowing cooperation among importers leads to an increase of the amount of fossil resources left underground. The assumption about the strategic behavior of the exporter's government has a much greater impact, though. When the exporter's government reacts to the importers' policies by taxing resource exports, we see a strong increase in the amount of resources left underground. The exporter's government has an incentive to implement very high tax rates in order to retain the resource rent. Thus, the consumer price of fossil resources increases and the quantity sold on the market decreases.

The result from the previous section on the dependence of the volume effect on the policy instrument portfolio is robust under the varying assumptions about strategic behavior of the governments. Importers may cooperate or not, and the exporter may act strategically or not – in all cases we observe that when the importers include a carbon tax in their portfolio to finance their infrastructure, more resources are left underground than if only the capital tax is used. A green paradox occurs in none of the four cases.

5.2. The resource rent

In Figure 4 we summarize our findings for the dependence of the resource rent on the tax portfolios of the importers and our assumptions about the strategic behavior of the different governments. The graph shows the net present value of the resource owner's profits.

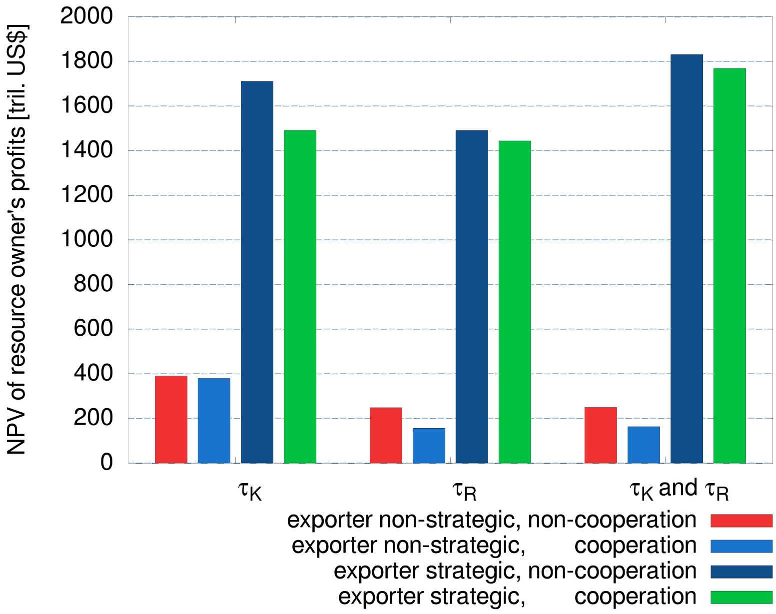


Figure 4: Net present value (NPV) of resource owner's profits. For the corresponding table, see Appendix D.3, Table 9.

We see that cooperation among importers always reduces the exporter's profits. When governments cooperate, they design their policies such that the exporter has to accept market conditions that are similiar to those which would be caused by monopsony power.[20] When we compare the carbon and capital tax rates, we observe that both increase significantly if the importing countries cooperate. Under cooperation, no harmful tax competition occurs.

The effect of the assumption whether importers cooperate is much smaller, though, than the impact of allowing the government of the exporting country to interact strategically. When we allow it to tax resource exports, it is quite successful in retaining more of the resource rent. As we have seen above, the quantity sold decreases significantly, but the increase in the resource price caused by the export tax overcompensates the reduction in quantity. It comes as no surprise that opening up the policy space for the exporter's government should increase the resource owner's payoff.[21]

Further, when the exporter does not interact strategically, the availability of the carbon tax in importing countries unambiguously leads to a reduction of the resource owner's profits. This is the result already obtained above that the carbon tax captures the resource rent. When the exporter interacts strategically, the choice of the policy instrument portfolio has ambiguous impacts on the resource owner's profits. Replacing the capital tax with the carbon tax still has the intuitive effect of reducing the exporters' profits due to rent capturing. However, if the carbon tax is used in addition to the capital tax, the exporter's profits actually increase. The increase occurs because the importers' governments use the carbon tax to subsidize fossil resources to counter the exporter's high price policy. Revenues for financing the subsidies and infrastructure investments are then raised with the capital tax.

[20] Since the governments are not identical with the agents who buy the resource, we cannot directly refer to the effect as monopsony. The firms, which are the ones that buy the resource, are assumed to be price takers and have no market power by themselves.

[21] The exporter's government could theoretically also reduce the price or create fluctuation to increase the dependence of importing economies. However, our model does not capture this possibility since we already assume complementarity between fossil resources and all other input factors, and since we assume that there is no backstop technology available. Both assumption imply a relatively inelastic demand in importing countries.

5.3. Welfare

To complete the assessment of the impact of different assumptions about strategic behavior and tax portfolios, we present an overview of the welfare in an importing country in Figure 5.

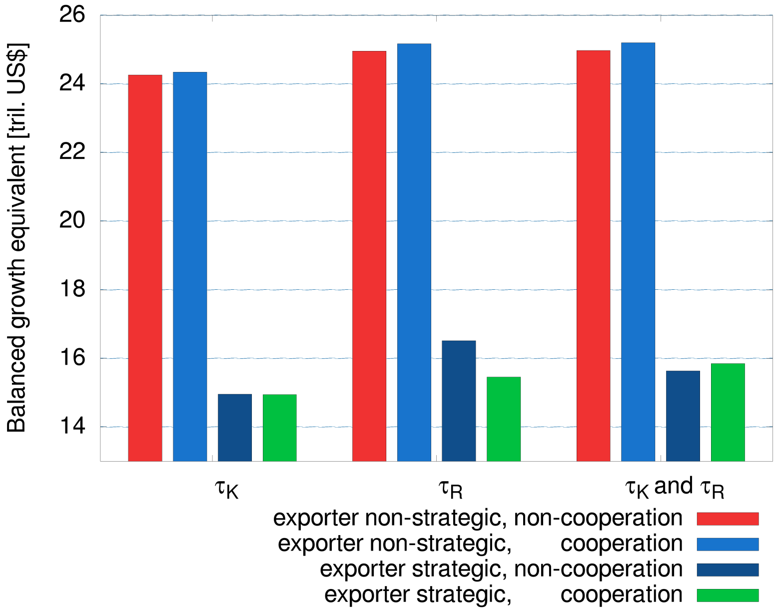


Figure 5: Social welfare in importing countries, measured as balanced growth equivalent. For the corresponding table, see Appendix D.3, Table 10.

In most cases, cooperation among importers and strategic behavior of the exporter result in Nash equilibrium outcomes we would expect intuitively. When importers cooperate, they are able to increase their welfare slightly.

However, when only the carbon tax is available and exporters may interact strategically, cooperation decreases welfare in the importing countries significantly. When importers do not cooperate, but instead compete against each other, the average carbon tax rate increases by approximately 20 percent relative to the case of cooperation. One rationale behind the low carbon tax rate in case of cooperation is the incentive to try to keep the carbon price at the lowest level possible, since it is already driven up very high due to the strategic actions of the exporter. Further, the presence of productivity enhancing infrastructure gives importers which do not cooperate an additional incentive to engage in a race-to-the-top in carbon tax rates. Greater infrastructure stocks make the domestic economy more attractive for capital investments. Accordingly, the net present value of infrastructure investments is one and a half times higher if importers do not cooperate relative to the case of cooperation. Thus when only the carbon tax is optimized and the exporter interacts strategically, importers are better of if they do not cooperate.

Strategic behavior of the exporter's government has a much stronger impact on welfare in the importing countries than cooperation among importers. When we allow for an export tax to be levied, welfare in an importing country decreases by around 60%, independent of the assumptions about cooperation and the policy instrument portfolio.

Most importantly, regardless of the assumptions about strategic behavior the use of a carbon tax increases welfare relative to a tax portfolio which only uses a capital tax, ceteris paribus. This confirms the results we have presented in Section 3: The carbon tax gives governments the possibility of capturing the resource rent and thus increases the potential to raise revenue for infrastructure investments. Resource importing countries prefer to tax carbon instead of capital.

6. Conclusion

We have used an intertemporal numerical general equilibrium model to calculate the opportunity costs of implementing different tax portfolios to finance productive infrastructure investments.

We have two main results. First, we find that the carbon tax is superior to the capital tax with respect to social welfare in the resource importing countries. The reason is that while the ownership of fossil resources gives rise to a scarcity rent, capital does not. Thus, the former can be taxed more efficiently than the latter. This efficiency result is also robust under different assumptions about the strategic behavior of the different governments. The carbon tax is the superior tax, regardless of whether the governments of the importing countries cooperate or not, or whether the government in the exporting country may interact strategically on the resource market or not.

Second, the unilateral implementation of carbon taxes does not cause a green paradox. Quite the contrary, under all assumptions about the strategic behavior of governments listed above, unilaterally imposing a carbon tax postpones extraction and reduces the amount of cumulative emissions. This is because financing infrastructure investments optimally does not require the carbon tax to increase at a higher rate than the interest rate, which is known to be a necessary condition for the green paradox to occur (Edenhofer and Kalkuhl, 2011). A carbon tax thus constitutes a viable green policy option.

Before drawing final conclusions we discuss applicability and scope of our model. First note that it applies to the short to medium run. In the long run we expect that carbon pricing has effects which our model does not capture. First, carbon pricing will increase the substitution elasticity between fossil resources and other inputs, e.g. through the availability of clean backstop technologies. Further, unilaterally implemented carbon taxes constitute a good entry point for climate policy and render an international agreement on climate change mitigation more feasible. Both long run effects reduce demand for fossil resources, and would consequently reduce the value of resource rents.

Further, our analysis of the assumptions about the strategic behavior of the importers and the exporter of fossil resources has shown that the interaction of the economic agents can become quite complex. Similarly, the interactions of several optimally determined tax instruments (i.e. not only the capital and the carbon taxes, but also the VAT and in particular the payroll tax) implies a high degree of complexity. A characterization of the additional effects lies beyond the scope of the present paper. Incorporating at least a subset of these effects, however, could be an avenue for future research.

Another interesting possibility to extend our model would be to include distributional effects of carbon taxes. This could be done, e.g. by differentiating between a 'clean' and an energy-intensive final goods sector and by allowing for competition on the market for these goods. In such a model it would also be possible to trace more precisely the relative strength of the so-called 'tax interaction effect', through which higher prices of carbon intensive products reduce factor returns. De Mooij and Bovenberg (1994) identified the tax interaction effect to be the main obstacle to the existence of a strong double dividend[22]. In our model a strong double dividend does occur.[23] Two reasons for its occurrence, which Goulder (2013) for instance highlights, are that the carbon tax captures rents (also found by Bento and Jacobsen, 2007) and the initial tax system (in which only the capital tax is optimized) is inefficient due to the intertemporal and interregional mobility of capital. Therefore, the strong double dividend might still

[22] There is an extensive strand of literature discussing the so-called (strong) double dividend hypothesis: Environmental policy may not only benefit the environment (the first dividend), but the revenues it generates may be used to reduce other distortionary taxes and thus to reduce the gross costs of environmental policy (see e.g. Tullock, 1967, Goulder, 1995, Bovenberg, 1999).

Its weak form is widely accepted to hold, i.e. efficiency gains may be attained when the use of revenues from environmental policy is shifted away from lump-sum transfers to households towards reductions in other distortionary taxes.

Our approach goes beyond the standard assumptions of the double dividend literature in several ways: Instead of distortionary labor taxes, we consider capital taxes; we do not include environmental quality in households' utility; we model environmental policy to capture resource rents; we do not limit ourselves to revenue neutral tax reforms but consider instead endogenously determined optimal infrastructure investments.

[23] To see this, compare the case in which only the capital tax is optimized with the case in which in addition also the carbon tax is available and set optimally. Then, with the carbon tax overall (non-environmental) welfare increases and carbon emissions are reduced through both a timing and a volume effect.

hold, even if final goods sectors were differentiated, and additional trade-offs for the use of tax revenues were considered.

Going beyond our model and its non-environmental scope, we can draw an important conclusion from our results. Even when governments do not intend to address the climate externality in any way, they have a strong incentive to implement a carbon tax to improve the efficiency of their fiscal policy. When only fiscal aspects are considered, the introduction of a carbon tax nevertheless contributes to the effort of mitigating the adverse effects of climate change.

Our results suggest to rethink the role of carbon taxes. We conclude that not only the environmental ministers are the ones who should favor carbon taxes, but also the ministers of finance.

Appendix

A. Calibration and implementation of model

We assume that resource importing countries are characterized by the same economic parameters. The model should apply to countries with comparable endowments and production technologies, which compete on international capital markets. These could be member states of the EU, or China and the USA. Each resource importing country's initial endowment of public and private capital is given by the same share of the initial global endowment. Table 5 summarizes the parameters used in the model. If not otherwise indicated, we have chosen their values in accordance with the closely related model PRIDE[24], as introduced in Kalkuhl et al. (2012), and the model comparison exercise referenced therein, Edenhofer et al. (2010).

We estimate the initial global level of infrastructure G_0 according the ratio of public to private fixed assets from US data published by the Bureau of Economic Analysis (BEA, 2013). The tax rate on consumption of 16 % is calculated as weighted average over all countries of 2013 rates taken from data of the OECD (2014), where the respective countries are weighted according to their GDP. The average payroll tax rate of 16 % is taken from the World Banks' world development index on labor tax and contributions (World Bank, 2014).

The parameters of the production function are calibrated according to the empirical literature. We insert the elasticities of substitution between the respective factors directly. The share parameters α_i, $i = 1, 2, 3$ are chosen such that the observed output elasticities reported in Calderón et al. (2014), Bom and Ligthart (2013), and Caselli and Feyrer (2007) are matched.

The variation of σ_1, the elasticity of substitution between the fossil resource R and general capital $\mathbf{Z}$, is a key method to generate part of our results. In particular, results are relatively sensitive to variations of σ_1. Therefore, we have calibrated the CES production function to a specific baseline point (Klump and Saam, 2008). As standard

[24] Both our model and PRIDE are capable of calculating 2nd best solutions in a decentralized economy with several different economic actors. Both models are formulated as non-linear programs which are implemented with the GAMS software (Brooke et al., 2005). While PRIDE involves a more detailed energy sector and a broader set of policy instruments, it does not represent multiple countries, but only one global closed economy.

value, we choose $\sigma_1 = 0.5$, which is in line with the literature on CGE models (see for example Burniaux et al., 1992; Babiker, 2001; Burniaux and Truong, 2002; Paltsev et al., 2005; Edenhofer et al., 2010).

As the benchmark case for the elasticity of substitution between public and private capital, σ_3, we have implemented a value of 1.1. The empirical literature gives mixed evidence about the substitutability between public and private capital and identifies both cases of relatively high and low substitutability between the two factors. It turns out that the results presented in this paper are quite robust under variation of σ_3, cf. Section 3.3.

Description	symbol	value	range	sources
Intertemporal elasticity of substitution	η	1.1		
Pure rate of time preference	ρ	0.03		
Annual depreciation rate of capital	δ	0.025		
Share parameter of fossil resource	α_1	0.05		Edenhofer et al. (2005)
Elasticity of substitution between $\mathbf{X}$ and R	σ_1	0.5	0.25 – 0.92	Hogan and Manne (1979)
				Kemfert and Welsch (2000)
				Burniaux et al. (1992)
				Markandya and Pedroso-Galinato (2007)
Share parameter of general capital $\mathbf{Z}$	α_2	0.42		Caselli and Feyrer (2007)
Elasticity of substitution between $\mathbf{Z}(K,G)$ and L	σ_2	0.7		
Share parameter of private capital K	α_3	0.7		
Elasticity of substitution between K and G	σ_3	1.1	0.5 – 4	Baier and Glomm (2001)
				Coenen et al. (2012)
				Otto and Voss (1998)
Total factor productivity	A	1		
Initial labor productivity	$A_{L,0}$	6		
Initial growth rate of A_L	$\gamma_{L,0}$	0.026		
Decline rate of labor productivity	d_L	0.006		
Initial resource use productivity	$A_{R,0}$	1		authors' calibration
Initial growth rate of A_R	$\gamma_{R,0}$	0.005		"
Decline rate of resource use productivity	d_L	0.001		"
Productivity of infrastructure	A_G	2		"
Initial world capital [tril. US$]	K_0	165		
Initial world infrastructure [tril. US$]	G_0	50		
Initial world resource stock [GtC]	S_0	4000		
Initial world population [bill.]	L_0	6.5		
Population maximum [bill.]	L_{max}	9.5		
First period [year]	t_0	2010		
Last period [year] [years]	T	2085		
Time step [years]	Δ	5		
Scaling parameter	χ_1	20		
Scaling parameter	χ_2	700		
Slope of Rogner's curve	χ_3	2		

Table 5: List of model parameters. If source not indicated otherwise, values are chosen in accordance with Kalkuhl et al. (2012) and Edenhofer et al. (2010).

A.1. Exogenously given growth rates

The productivity of labor A_L and fossil resources A_R are assumed to increase over time due to exogenous technological change. The parameters are chosen in accordance with empirically observed output and consumption growth rates:

$$\gamma_{\zeta,t} = \gamma_{\zeta,0} e^{-d_\zeta t}$$
$$A_{\zeta,t+1} = A_{\zeta,t} \left(1 + (\frac{\gamma_{\zeta,t}}{1-\gamma_{\zeta,t}})\right), \quad A_{\zeta,0} \text{ given,}$$

where $\zeta = L, R$.

B. First order conditions of representative agents

To determine the first order conditions, we use a maximum principle for discrete time steps as given in Feichtinger and Hartl (1986). We use their concept of the *discrete Hamiltonian* which is more convenient than the equivalent formulation of the optimization problems with Lagrangians. In the following we shall use the term *Hamiltonian* in this sense.

Household

The household maximizes its intertemporal welfare (6) taking into account the budget constraint (7) and the equation of motion for his assets (8). Since the economic impact of a single household on the total of all profits is small, the representative household takes Π^F and governmental transfers Γ as given. The Hamiltonian is given by

$$\mathcal{H}_t^{HH} = U(C_t/L_t) + \lambda_t \left[(1 + (r_t - \delta))\, K_t^s + w_t L_t + \Pi_t^F + \Gamma_t - C_t(1 + \tau_{C,t})\right],$$

and thus the first order and terminal conditions for the control and costate variables C and λ are

$$\frac{L_t^{\eta-1}}{C_t^{\eta}} = \lambda_t(1 + \tau_{C,t}), \tag{B.1}$$

$$\lambda_{t-1}(1 + \rho) = \lambda_t\,(1 + r_t - \delta)\,, \tag{B.2}$$

$$(I_T - (1 - \delta)K_T^s)\,\lambda_T = 0. \tag{B.3}$$

Resource extraction sector

The resource owner maximizes her intertemporal stream of profits (16) taking into account the resource constraint (17), the equation of motion for the stock (13), and possibly a unit tax τ_{RO} on exports. We assume that the government of the resource exporting country recycles the tax revenue $\tau_{RO,t}R_t =: \Psi_t$ as lump-sum transfer to the resource owner. The resource owner does not anticipate its influence on Ψ, but takes it as given. The Hamiltonian then reads

$$\mathcal{H}_t^{RO} = \left(p_t - \frac{r_t}{\kappa_t(S_t)} - \tau_{RO,t}\right) R_t + \lambda_t^R(S_t - R_t) + \Psi_t,$$

and thus the first order and terminal conditions for the control and costate variables R and λ^R are

$$\lambda_t^R = p_t(1 - \tau_{RO,t}) - \frac{r_t}{\kappa_t}, \tag{B.4}$$

$$\lambda_t^R - \lambda_{t-1}^R(1 + r_t - \delta) = -\frac{r_t R_t \chi_2 \chi_3}{\chi_1 S_0}\left(\frac{S_0 - S_t}{S_0}\right)^{\chi_3 - 1}, \tag{B.5}$$

$$\lambda_{T-1}^R S_T = 0. \tag{B.6}$$

C. Solution algorithm

We solve the model in four phases:

Phase 1: Find good initial values.

Phase 2: Find symmetric policy variables with Nash algorithm.

Phase 3: Solve model with fixed policy variables to find good lower bound for investment in last period.

Phase 4: Find symmetric policy variables with Nash algorithm and fixed lower bound for last-period investment.

To find a Nash equilibrium, we use the following algorithm:

```
until policy instruments converge
    repeat for each player j:
        unfix policy variables
        optimize player j's payoff/welfare
        fix player j's newly found policy variables
```

D. Additional data

D.1. Extension of Table 1

	Welfare relative to policy case τ_R	$NPV(\pi_R)$ [tril. US$]	$\overline{K^d}$ [tril. US$]	$\overline{G}$ [tril. US$]	$\overline{r}-\delta$ [1/a]	$\overline{p}$ [$/tC]
τ_R	0%	84	137.1	122	0.063	517
τ_L	-2.3 %	119	136.9	123	0.067	714
τ_K	-2.4 %	151	124.4	100	0.066	757
τ_C	-3.0 %	124	151.0	126	0.061	675

Table 6: Extended version of Table 1. Comparison of policy cases in which importers' governments only use one tax instrument. Impact of carbon tax τ_R, capital tax τ_K, payroll tax τ_L, and consumption tax τ_C on welfare (measured relative to the case in which governments use only the carbon tax), the net present value of the resource owners profits $NPV(\pi_R)$, the stocks of capitel $\overline{K^d}$ and infrastructure $\overline{G}$, the average annual interest rate net of depreciation $\overline{r}-\delta$, and the average resource price $\overline{p}$.

D.2. Data table corresponding to Figure 1

year	r	τ_K	K^d [tril. US$]	$r\tau_K K^d$ [tril. US$]	τ_R [$/tC]	R^d [GtC]	$\tau_R R^d$ [tril. US$]
2010	0.060	0.068	83	0.34	74	13.1	1.0
2020	0.094	0.002	75	0.01	124	14.0	1.7
2030	0.093	-0.020	100	-0.19	198	15.1	3.0
2040	0.089	-0.024	131	-0.28	283	16.0	4.5
2050	0.086	-0.016	162	-0.23	374	17.0	6.3
2060	0.087	0.021	184	0.33	472	17.6	8.3

Table 7: Underlying data for Figure 1. Interest rate r, capital tax rate τ_K, capital demand K^d, capital tax revenue $r\tau_K K^d$, carbon tax rate τ_R, resource demand R^d, and carbon tax revenue $\tau_R R^d$. Data for consumption tax τ_C and payroll tax τ_L are omitted since they are fixed exogenously.

D.3. Data tables corresponding to Figures 3 to 5

	non-strategic exporter		strategic exporter	
	no cooperation	cooperation	no cooperation	cooperation
τ_K	1498	1521	2857	2856
τ_R	1862	2171	2931	3169
τ_K and τ_R	1848	2155	2931	2931

Table 8: Amount of fossil resources left underground at the end of the time horizon in gigatons of carbon, GtC (corresponds to Figure 3).

	non-strategic exporter		strategic exporter	
	no cooperation	cooperation	no cooperation	cooperation
τ_K	391	380	1712	1492
τ_R	249	157	1491	1444
τ_K and τ_R	250	164	1832	1769

Table 9: Net present value of of resource owner's profits in trillion US$ (corresponds to Figure 4).

	non-strategic exporter		strategic exporter	
	no cooperation	cooperation	no cooperation	cooperation
τ_K	24.26	24.35	14.96	14.94
τ_R	24.96	25.17	16.52	15.46
τ_K and τ_R	24.97	25.21	15.64	15.85

Table 10: Social welfare in an importing country measured as balanced growth equivalent (corresponds to Figure 5).

E. Time consistency

To check whether governments have an incentive to deviate from the tax paths they have announced at the beginning of the first period, we have performed the following experiments. First, we calculate the tax paths of two standard benchmark cases in which the governments may only use the carbon tax or only the capital to finance the infrastructure investments, $\{\tau_R\}_t$ and $\{\tau_K\}_t$, respectively. Then, we run the model again, but fixate the respective tax rate in the first n time periods to the value we have found in the benchmark case. Now, we compare the benchmark tax paths with the newly found ones $\{\widetilde{\tau_R}\}_t$ and $\{\widetilde{\tau_K}\}_t$, respectively.

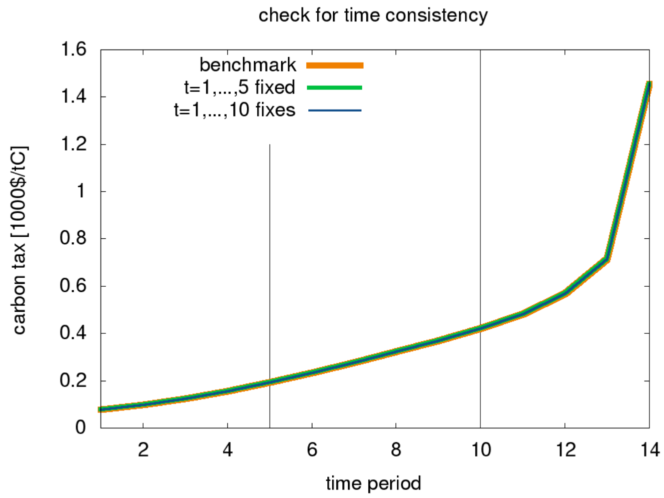


Figure 6: Governments have no incentive to deviate from the initially announced carbon tax path.

For the carbon tax it turns out that governments do not deviate at all from the announced tax path (Figure 6). For the capital tax we observe minor unsystematic deviations (Figure 7). Measured in tax revenues, we find that on average this difference is less than 0.01 percentage points if $n = 5$ and less than 0.26 percentage points if $n = 10$. Here, we express the relative difference in fractions of GDP. More precisely, for each period t we calculate the difference as

$$\Delta = \frac{\tau_K r K^d}{GDP} - \frac{\widetilde{\tau_K}\tilde{r}\widetilde{K^d}}{\widetilde{GDP}}.$$

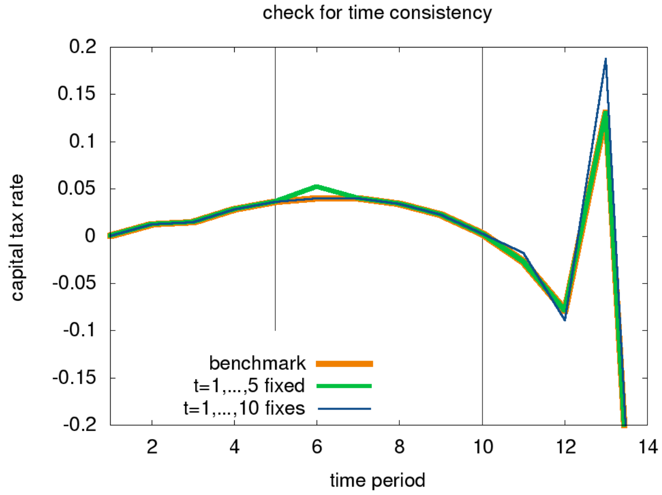


Figure 7: Governments deviate only to an insignificant extent from the initially announced capital tax path.

Conflict of interest

The authors declare that they have no conflict of interest.

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Chapter 3

Optimal environmental taxation with capital mobility[1]

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Max Franks

[1] Submitted to *Resource and Energy Economics*

Optimal Environmental Taxation with Capital Mobility

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September 29, 2015

Abstract

Climate policy exemptions for energy intensive sectors are often justified with distributional concerns. One concern is that households employed in energy intensive sectors might be affected disproportionally due to (international) capital mobility. By assuming that workers cannot move freely between sectors we can reproduce this concern: a uniform carbon tax causes more inequality between the sectors when capital is mobile than when it is not. We find, however, that affected households can be relieved more effectively with sector specific labor taxes than with sector-specific climate policy. The reason for this finding is that households benefit more directly from sector-specific labor tax cuts than from carbon tax exemptions. Keeping climate policy uniform across sectors has the added benefit of creating incentives for long-term decarbonization. In addition, we find that the differential effect of capital mobility depends on the government's degree of inequality aversion: Redistribution is more expensive when capital is mobile.

JEL classification: H21, H23, Q52

Keywords: capital mobility, climate policy, tax competition, equity

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1 Introduction

How should a government take capital mobility into account when designing climate policy? There is a strong concern[1] that climate policy affects energy intensive sectors disproportionally when capital is mobile. This concern motivates policy exemptions for the most affected sectors. Previous research considering sectoral exemptions usually considers one representative household. They find that exemptions are not optimal and conclude that carbon taxes should be uniform across sectors. In this paper we consider sector-specific policy as a means of addressing the sector-specific distributional effects created by the interaction of climate policy and capital mobility.

We build a model with two sectors of different energy intensity. To reflect the distributional concern we assume sectoral rigidity in labor mobility. The government maximizes a social welfare function which aggregates utility of the households working in the two sectors. The environmental objective is to reduce domestic carbon emissions, motivated for example by the objective to fulfill a carbon reduction target. We then compare the effect of environmental policy with and without capital mobility. We find that indeed climate policy introduces a bigger difference in utility of the households employed in the two sectors when capital is mobile. Based on this we determine the optimal policy package for reconciling distributional and environmental objectives. We find three major results.

The first result is that sector specific labor taxes are the most suitable instrument to redistribute among the sectors. Sector specific carbon taxes can indeed be justified, but the difference should be very small. In optimum, redistribution between sectors is mainly achieved through relatively large differences in labor taxes. When labor taxes are optimally differentiated between sectors, the difference between utility of the households employed in the different sectors is much smaller than in the scenario where labor taxes are constrained to be uniform.

The second result is that the reaction of the government depends strongly on its inequality aversion. A utilitarian government achieves a higher welfare under capital mobility since it benefits from the gains of (capital) trade. A strongly inequality averse government faces high

[1] "[I]mposing a price (cost) on carbon in the United States at a time when some other countries (in the developing world) are not taking comparable actions raises concerns about negative impacts on the competitiveness of U.S. industry, particularly in energy-intensive, trade-sensitive sectors" (Stavins, 2009). Peter Altmaier, German minister of the environment, justified exemptions in the energy intensive sector with the objective to "maintain jobs in the energy sector in Germany" (BMU, 2013).

cost of countering the inequality increasing effect of climate policy under capital mobility. The cost of redistribution might be so high that it could even be better off without capital mobility.

The third result is that climate policy creates a greater difference between capital and labor income under capital mobility than in autarky. The government's ability to counter this shift through labor tax cuts is weakened through capital mobility since the reduced demand for pollution means that carbon tax revenues are lower under capital mobility than in autarky.

The literature considers two related motivations for carbon tax exemptions, carbon leakage and reduced competitiveness. Neither of these, however, are found to justify differential carbon taxes when other policy instruments are available. Carbon leakage can better be addressed with border tax adjustment (Hoel, 1996) and reduced competitiveness can be addressed with wage subsidies (Böhringer and Rutherford, 1997) or generally labor market policy (Babiker et al., 2003). We consider a third motivation for sector-specific policy, which is the distributional effects among households employed in different sectors.

Climate policy raises a number of distributional issues, depending on the type of heterogeneity considered, see Fullerton (2011) for an overview. Jacobs and de Mooij (2015) consider households with different types of productivity as in the model of Mirrlees (1971). Fullerton and Heutel (2007) consider the effect of climate policy on capital and labor income. Related to this is the work of Babiker and Eckaus (2007) and Guivarch et al. (2011) who consider the effect of climate policy under labor market rigidities. As Babiker and Eckaus (2007) we model sectoral rigidity in labor mobility, thus considering distributional effects across sectors. While all these models assume capital to be immobile we determine the difference made by capital mobility.

De Mooij and Bovenberg (1998) describe, for both mobile and immobile capital, how environmental taxation can make the tax system more or less efficient depending on the relative taxation of capital and labor. Goulder (2013) points out that this "strong" double dividend can only occur when the tax system was initially inefficient. We rule out the strong double dividend by letting the government set taxes optimally. A "weak" double dividend of using carbon tax revenues to reduce other distortionary taxes remains of course. The question of efficiency adds an additional aspect: When factors are not freely mobile between sectors, a constraint to tax factors uniformly can constitute an inefficiency. Welfare gains can then be made by allowing differential taxes.

The nature of our analysis requires us to consider two sectors with three production factors each in at least two heterogeneous countries. Given the complexity of the results in the case of three plus two production factors in a closed economy in Fullerton and Heutel (2007) we consider the setup beyond of what is analytically tractable. We thus solve the model numerically and ensure generality by conducting robustness checks with parameter variations.

Section 2 describes the model and the scenarios with and without capital mobility. Section 3 describes the results in four steps with an increasing number of policy instruments, which allow the government to take distributional effects of climate policy into account. Section 4 considers the effect of inequality aversion on the relative welfare in autarky and under capital mobility. In Section 5 optimal taxation in the long run, that is with full labor mobility across sectors, is determined. Further results are summarized in Section 6. These include robustness checks, the effect of a capital tax harmonization and carbon leakage. Section 7 concludes.

2 The Model

There are S different countries, each with two sectors of different energy intensity. There is a long-run equilibrium in which all countries maximize "blue" welfare, consisting of consumption of the goods produced in the two sectors, leisure and public good consumption. In this long run equilibrium workers can move between sectors so that there is a unique economy-wide wage. Country 1 then wants to achieve an emission reduction target by maximizing "green welfare" which includes blue welfare plus a term accounting for domestic emissions. In the short run workers cannot move between sectors. The introduction of environmental policy thus introduces sector-specific household utility and wages.

The subindex indicates the country of a variable. K_s^i for example is the amount of capital employed in sector $i \in \{E, N\}$ in country s. The subindex is dropped wherever possible in order to ease notation when no confusion is possible.

Firms. There are two sectors, one of which is energy intensive, E. Firms employ capital K^i, labor L^i and pollution Z^i to produce output $Y^i = f^i(K^i, L^i, Z^i)$. They pay taxes on capital τ^K and sector-specific taxes on labor, τ^{Li}, and pollution, τ^{Zi}. The prices corresponding to the production factors are the interest rate plus tax $r + \tau^K$, the wage plus tax $w^i + \tau^{Li}$

and the pollution tax τ^{Zi}. The profit function of the firm is

$$\Pi^i = p^i f^i(K^i, Z^i, L^i) - (r + \tau^K)K^i - \tau^{Zi}Z^i - (w^i + \tau^{Li})L^i, \quad \forall i \in \{E, N\} . \tag{1}$$

The first order conditions of the firm are

$$p^i f^i_K - (r + \tau^K) = 0 \tag{2}$$

$$p^i f^i_Z - \tau^{Zi} = 0 \tag{3}$$

$$p^i f^i_L - (w^i + \tau^{Li}) = 0 \tag{4}$$

Final good producers. Final good producers combine intermediate goods $Y = F(Y^E, Y^N)$. The profit function of the final good producers is

$$\Pi = pF(Y^E, Y^N) - p^E Y^E - p^N Y^N . \tag{5}$$

First order conditions thus are

$$pF_{Y^E} - p^E = 0 \tag{6}$$

$$pF_{Y^N} - p^N = 0 \tag{7}$$

Households. Household utility depends on consumption C^i, leisure V^i and public goods G,

$$U^i = U(C^i, V^i, G) . \tag{8}$$

The only endogenous choice of the household is the supply of labor. Households thus face the standard labor/leisure trade-off.

A share M^i of households is employed in sector i, so that the $M^E + M^N = 1$. How M^i is determined depends on whether the short or long term is considered, see Section 2.3. Households receive net wages w^i. In addition, all households earn an equal share of capital income from asset holdings A. Household use their income to buy consumption

$$pC^i = w^i L^i + M^i rA . \tag{9}$$

There are M^i workers in sector i. Each has a time budget of 1, so that the total amount of leisure enjoyed in sector i is given by $V^i = M^i - L^i$. The household optimization is

$$\max_{V^i} U\left(\frac{1}{p}\left(w^i L^i + M^i r A\right), V^i, G\right) . \tag{10}$$

The optimality condition is thus

$$\frac{w^i}{p} U_{C^i} = U_{V^i} . \tag{11}$$

In reality, a negative demand shock for labor (induced by climate policy) can cause unemployment. Voluntary unemployment is included in our model in the form of increasing leisure. However, we use wage reductions as an indicator of lower labor demand instead of involuntary unemployment. Modeling involuntary unemployment would strongly complicate the model without adding much insight: both wage reductions and involuntary unemployment reduce utility of affected households and can be addressed by incentives to increase labor demand.

Government. There are two possible notions of welfare the government may use as its objective function. "Blue" welfare W^b considers a weighted sum of utility from consumption, leisure and public good provision. "Green" welfare W^g considers environmental quality in addition,

$$W^b = \sum_{i \in \{E,N\}} M^i \frac{1}{\rho} \left(U\left(\frac{C^i}{M^i}, \frac{V^i}{M^i}, G\right)\right)^\rho \tag{12}$$

$$W^g = \sum_{i \in \{E,N\}} M^i \frac{1}{\rho} \left(U\left(\frac{C^i}{M^i}, \frac{V^i}{M^i}, G\right) - \delta(Z^E + Z^N)^\varphi\right)^\rho . \tag{13}$$

ρ is the degree of inequality aversion. The instruments available to the government are environmental taxes τ^{Zi}, labor taxes τ^{Li} and capital taxes τ^K. For technical reasons (otherwise pollution would be infinite) we assume that there is a minimum for the pollution tax, $\tau^Z \geq \tau^Z_{\text{min}}$. The government purchases the final to provide the public good. The government budget is thus

$$pG = \tau^K K + \sum_{i \in \{E,N\}} \left(\tau^{Li} L^i + \tau^{Zi} Z^i\right) . \tag{14}$$

The environmental objective of the government is to reduce *domestic* emissions. See Section 6.3 for a discussion of this policy objective.

Market clearing and numeraire. The amount of pollution used in production is chosen by the firms. The price for pollution is fixed by the government to τ^Z.

The total amount of capital used in production is given by the international supply of capital,

$$\sum_{s=1}^{S} A_s = \sum_{s=1}^{S} (K_s^E + K_s^N) \ . \tag{15}$$

The final good is consumed by the two households and the government for public good production. In addition it can be traded internationally, so that countries effectively exchange capital and the final good.

$$Y - Y^X = C^N + C^E + G \ . \tag{16}$$

Y^X is the amount of the final good exported. It is positive if the country exports the final good and negative when it imports.

The numeraire good is the final good,

$$p = 1. \tag{17}$$

To close the model, further restrictions are needed. The restrictions depend on the scenario, which will be specified in the next three subsections. One scenario dimension is whether or not capital is mobile internationally. The second scenario dimension is whether the governments objective function is blue or green welfare. The third scenario dimension is whether labor is mobile between sectors or not.

2.1 Capital Mobility

Case 1: Autarky. In case of autarky, total domestic capital is limited by the domestic capital endowment,

$$A_s = K_s^E + K_s^N \quad \forall s \in S \ . \tag{18}$$

Case 2: Capital Mobility. When capital is mobile, borrowed capital must be compensated with the final good Y. The equation for balanced trade thus reads

$$r(K_s^N + K_s^E - A_s) = pY^X \quad \forall s \in S \ . \tag{19}$$

The prices for capital and the final good, r and p, are identical across countries due to the law of one price.

2.2 Environmental Policy

We assume that all governments except in country 1 maximize blue welfare in any case. Country 1 can either maximize blue welfare as well or unilaterally introduce climate policy by maximizing green welfare.

Case 1: No environmental policy. All governments maximize blue welfare,

$$\max_{\tau_s^{Li},\tau_s^{Zi},\tau_s^{K}} W_s^b \quad s.t. \quad p_s G_s = \tau_s^K K_s + \sum_{i\in\{E,N\}} (\tau_s^{Li} L_s^i + \tau_s^{Zi} Z_s^i) \quad \forall 1 \le s \le S \,. \tag{20}$$

Case 2: Environmental policy. Government 1 maximizes green welfare while all other governments maximize blue welfare,

$$\max_{\tau_1^{Li},\tau_1^{Zi},\tau_1^{K}} W_1^g \qquad s.t. \qquad p_1 G_1 = \tau_1^K K_1 + \sum_{i\in\{E,N\}} (\tau_1^{Li} L_1^i + \tau_1^{Zi} Z_1^i), \tag{21}$$

$$\max_{\tau_s^{Li},\tau_s^{Zi},\tau_s^{K}} W_s^b \qquad s.t. \qquad p_s G_s = \tau_s^K K_s + \sum_{i\in\{E,N\}} (\tau_s^{Li} L_s^i + \tau_s^{Zi} Z_s^i) \quad \forall 2 \le s \le S \,. \tag{22}$$

2.3 Labor mobility

There is a long run equilibrium in which workers allocate freely across sectors. In addition, there is a short run equilibrium in which workers are attached to their sectors. In this case worker shares are fixed to the level they had in the long run equilibrium without environmental policy. This reflects a situation in which a government switches from maximizing blue to maximizing green welfare and workers cannot quickly adapt.

Case 1: Long run equilibrium. The share of workers employed in a sector is equal to the amount of labor employed in this sector,

$$M_s^i = \frac{L_s^i}{L_s^E + L_s^N}, \quad i \in \{E, N\} \,. \tag{23}$$

Case 2: Short run analysis. The allocation of workers is exogenously fixed to the long-run level $M_s^i(LR)$, which corresponds to the worker share obtained in case 1.

$$M_s^i(SR) = M_s^i(LR), \quad i \in \{E, N\} \,. \tag{24}$$

2.4 Functional forms and parameter values

The calibration of the model is based on Fullerton and Heutel (2007). They assume factor shares of 25%, 30% and 45% for pollution, capital and labor, respectively, in the energy intensive sector. We also follow this paper on assuming that the N sector accounts for 80% of factor income. Concerning the N sector we assume that the factor share of pollution is 10% and keep a K/L share of roughly 2/3. We also follow Fullerton and Heutel (2007) by setting the elasticity of substitution for both the factor inputs in the N sector and between the energy intensive and N goods to unity. For the substitution elasticity of factor inputs in the energy intensive sector Fullerton and Heutel (2007) work with several different values (and they allow the elasticities between the three inputs to be different). We choose an intermediate case of $\sigma_E = 0.4$ and provide a robustness test in Section 6.1.

Parameter values for all countries are assumed to be identical. In the numerical solution of the model in section 2, we specify the functional forms as follows:

$$f^N(K^N, L^N, Z^N) = \left(0.55(L^N)^{\frac{\sigma_N-1}{\sigma_N}} + 0.35(K^N)^{\frac{\sigma_N-1}{\sigma_N}} + 0.1(Z^N)^{\frac{\sigma_N-1}{\sigma_N}}\right)^{\frac{\sigma_N}{\sigma_N-1}}, \quad (25)$$

$$f^E(K^E, L^E, Z^E) = \left(0.45(L^E)^{\frac{\sigma_E-1}{\sigma_E}} + 0.3(K^E)^{\frac{\sigma_E-1}{\sigma_E}} + 0.25(Z^E)^{\frac{\sigma_E-1}{\sigma_E}}\right)^{\frac{\sigma_E}{\sigma_E-1}}, \quad (26)$$

$$F(Y^E, Y^N) = \left((0.2Y^E)^{\frac{\varepsilon-1}{\varepsilon}} + (0.8Y^N)^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}}, \quad (27)$$

$$U(C^i, V^i, G) = (C^i)^{1-\gamma_1-\gamma_2}(V^i)^{\gamma_1}(G)^{\gamma_2}. \quad (28)$$

Parameter values $\sigma_N = 1$ and $\varepsilon = 1$ are taken from Fullerton and Heutel (2007). We normalize $A = 1$. The values of $S = 2, \gamma_1 = \gamma_2 = 0.15, \delta = 0.1, \varphi = 2$ and $\tau^Z_{\min} = 0.05$ are set by the authors and have been found to not impact results qualitatively. The values for $\rho = 1$ and $\sigma_E = 0.4$ are set by the authors and subjected to robustness tests in Sections 4 and 6.1.

3 Optimal taxes in the short run

We obtain our results by comparing a set of scenarios which are determined by the scenario dimensions discussed in Sections 2.1 to 2.3 as well as the availability of taxes. In this section we present results for the short run case, meaning that whenever we consider environmental policy we assume to be in the case of no labor mobility. Section 3.1 presents the baseline scenarios with uniform labor and carbon taxes and no capital taxes. The following sections allow for progressively more instruments: differential labor taxes, differential carbon taxes and capital taxes. Differential capital taxes are not considered since experiments highlight that the optimizing government makes very little use of this additional possibility when given the choice. Notice that the numbers resulting from the numerical simulation are not meaningful as such. We analyze the relative change between the numbers.

The main results are presented in Tables 1 to 4 in the text. For a more detailed list of results, see the extended Tables 6 to 9 in the Appendix.

3.1 Baseline scenarios with minimal policy instruments

In the baseline scenarios we constrain the government to set uniform pollution and labor taxes across sectors, $\tau^{ZN} = \tau^{ZE}$ and $\tau^{LN} = \tau^{LE}$ and exclude capital taxes, $\tau^{K} = 0$. The objective is to reflect the concern voiced by politicians that climate policy causes disproportional harm to workers in the energy intensive sector.

Table 1 shows the results for country 1 for the four scenarios in the baseline. In columns 1 and 2 the countries are autarkic, while capital is mobile in columns 3 and 4. In column 1 and 3, country 1 maximizes blue welfare, in columns 2 and 4 it maximizes green welfare. When moving from column 1 to column 2, we see that the change in objective function causes country 1 to introduce a carbon tax above the minimum value. As an immediate consequence, green welfare increases while blue welfare decreases. Since sector E is more pollution intensive and workers cannot move between sectors, utility for workers in sector E is lower than for workers in sector N due to climate policy. There is almost no difference between columns 1 and 3. The small difference stems from a “race to the bottom” in labor taxes which are used to increase the marginal productivity of capital. The difference is very small, however, since countries are identical and thus all employ the same amount of capital.

The differential effect of capital mobility under climate policy can thus be analyzed by comparing columns 2 and 4. An immediate effect of capital mobility under climate policy is that some capital moves abroad and goods are imported in return. Due to the loss of capital, the complementary production factor labor is employed less. The reduced demand for pollution allows the government to achieve its environmental objectives at a lower carbon price.

On the aggregate, green welfare is higher in the scenario with capital mobility. This aggregate welfare gain is due to the gains of trade effect. There are also distributional effects, however. We compare the green welfare of the respective households, $W^g(i) = U^i - \delta(Z^E + Z^N)$. Households employed in the N-sector benefit from capital mobility and households in the energy-intensive sector experience a small decrease in welfare. This could be seen as a confirmation of the political concern mentioned in the introduction: Under capital mobility, climate policy introduces a larger difference between households employed in the two sectors than it would in autarky.

Even more dramatic is the effect of capital mobility on factor income. Total labor income (LI) decreases due to capital mobility and capital income (KI) benefits greatly. The reason is that capital earns the high international interest rate while labor productivity suffers from the loss of the complementary production factor. The interest rate is endogenously determined in the model, but since we consider that only country 1 implements environmental policy, the marginal productivity of capital is equalized when the other countries absorb some of the capital owned by country 1.

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.19472	0.27019	0.19469	0.27033
W^b	0.31659	0.28610	0.31659	0.28593
$W^g(N)$	0.31659	0.27425	0.31659	0.27453
$W^g(E)$	0.31659	0.25454	0.31659	0.25412
τ^K	0.00000	0.00000	0.00000	0.00000
τ^{ZN}	0.05000	0.15084	0.05000	0.14428
τ^{ZE}	0.05000	0.15084	0.05000	0.14428
τ^{LN}	0.04686	0.02825	0.04615	0.03153
τ^{LE}	0.04686	0.02825	0.04615	0.03153

Table 1: Numerical results for the baseline scenarios. See Table 6 for the extended version.

3.2 Differential labor taxes

Starting from the baseline effect we now consider the effect of additional tax instruments in order to equalize the inequality between the workers in the two sectors caused by carbon taxes. As a first redistribution policy we consider differential labor taxes. In order to isolate this effect we continue to impose uniform carbon taxes $\tau^{ZN} = \tau^{ZE}$ and zero capital taxes, $\tau^K = 0$.

Comparison of Tables 1 and 2 shows that sector-specific labor taxes allow the government to make utility $W^g(i)$ across the two sectors more equal. This raises total welfare since utility is concave. The availability of a redistribution instrument makes the introduction of carbon taxes less regressive. The government thus chooses a higher carbon tax and achieves a lower level of total pollution than in the baseline, both in autarky and in capital mobility.

In Table 2 labor taxes are further apart in column 4 than in column 2. Differential labor taxes are thus used to counter the inequality-increasing effect of capital mobility. They allow the government to support the energy intensive sector, which is affected by capital mobility much more than the N-sector. By incentivizing more labor input through lower labor taxes in the energy intensive sector, differential labor taxes also allow retaining more capital in the domestic economy.

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.19472	0.27024	0.19469	0.27039
W^b	0.31659	0.28609	0.31659	0.28593
$W^g(N)$	0.31659	0.27174	0.31659	0.27200
$W^g(E)$	0.31659	0.26445	0.31659	0.26414
τ^K	0.00000	0.00000	0.00000	0.00000
τ^{ZN}	0.05000	0.15147	0.05000	0.14503
τ^{ZE}	0.05000	0.15147	0.05000	0.14503
τ^{LN}	0.04686	0.03585	0.04615	0.03947
τ^{LE}	0.04686	-0.00241	0.04615	-0.00072

Table 2: Numerical results for differential labor taxes. See Table 7 for the extended version.

3.3 Differential carbon taxes

In addition to sector specific labor taxes we now allow for sector specific carbon taxes as well. This effectively means that the government can give carbon tax exemptions to the individual sectors.

Results in Table 3 show that differential carbon taxes are employed both in autarky and in capital mobility. The additional freedom to design tax policy increases utility for workers in both sectors and consequently aggregate welfare (the difference is too small to reflect in the five digit precision used in the Tables). Distributional effects thus do justify differential carbon taxes.

The differences in optimal carbon taxes, however, are much smaller than in the optimal labor taxes. Labor taxes are thus the better suited instrument of redistribution. While differentiated labor taxes result in a large welfare increase compared to the baseline, the additional welfare increase through differentiated carbon taxes is very small.[2] Distributional concerns thus do not justify large tax exemptions and should rather be seen as a possible tool for detailed refinement of tax policy secondary to differentiated labor taxes.

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.19472	0.27024	0.19469	0.27039
W^b	0.31659	0.28609	0.31659	0.28593
$W^g(N)$	0.31659	0.27174	0.31659	0.27200
$W^g(E)$	0.31659	0.26445	0.31659	0.26414
τ^K	0.00000	0.00000	0.00000	0.00000
τ^{ZN}	0.05000	0.15129	0.05000	0.14527
τ^{ZE}	0.05000	0.15207	0.05000	0.14428
τ^{LN}	0.04686	0.03584	0.04615	0.03949
τ^{LE}	0.04686	-0.00267	0.04615	-0.00038

Table 3: Numerical results for differential labor and carbon taxes. See Table 8 for the extended version.

In order to gain an intuitive understanding of *why* differential labor taxes are preferable as a tool for redistribution we conduct the following experiment. We take the baseline scenario with uniform taxes, autarky and green welfare maximization, which is familiar from the second column in Table 6. In a first experiment we then reduce carbon taxes in the E-sector until net wages for households working in the E-sector have increased by 1%. In a second experiment we start again at the baseline and then reduce labor taxes in the E-sector until net wages for households working in the E-sector have increased by 1%. Government budget balance is achieved by reducing public good provision.

As we can see in Table 11 both experiments do achieve redistribution of utility from the N-sector to the E-sector. The results of the two experiments concerning consumption and leisure for the two households as well as for public good provision are extremely close (less than 0.15% deviation). The sector-specific reduction in labor taxes, however, results in a much smaller increase in total pollution (0.89% less). Both tax reductions thus achieve an increase in equality, but the labor tax reduction does so at a lower level of pollution and thus at a higher level of utility.

[2]We also conducted the experiment with differential carbon taxes and uniform labor taxes. The results are very similar to the ones presented here: The optimizing government makes very little use of the possibility to differentiate carbon taxes and achieves hardly any improvement in utility with it.

3.4 Capital subsidies

In Sections 3.2 and 3.3 we were concerned mainly with redistribution between sectors. A second important aspect, however, is the redistribution effect of climate policy from labor to capital income. In principle, it would be possible to use capital subsidies to keep capital in the domestic economy. However, these subsidies need to be financed. Higher carbon taxes would counteract the capital subsidies by reducing the marginal productivity of capital. Higher labor taxes would reduce the net return on labor and thus counteract the objective to redistribute from capital to labor income. In this section we thus allow the full set of policies: sector specific labor and carbon taxes as well as capital taxes or subsidies.

Results in Table 4, column 3, show that capital mobility causes a race to the bottom in capital taxes and inefficiently low public good provision as described in Zodrow and Mieszkowski (1986) and others. The scenario with environmental policy (column 4) shows that an optimizing government does subsidize capital and is able to retain more capital than in the scenario without the capital tax. Due to the capital subsidy labor taxes are increased, but the net effect of capital taxes on labor income is positive (since more domestic capital increases the demand for labor).

The retained capital increases utility for both types of household and is thus a beneficial tool for the government and thus aggregate welfare. On the other hand it increases inequality since almost all of the gains go to the household working in the N sector. Notice that we chose two countries which are identical except in their policy objective. If countries are chosen to be different, in particular with respect to their capital endowment, the scenario with capital mobility will provide higher utility than the scenario of autarky since countries benefit from gains of trade. Our main result here is that a utilitarian government benefits more from capital mobility more than a highly inequality averse government. This continues to hold when non-identical countries are considered.

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.18656	0.27041	0.19581	0.27042
W^b	0.31776	0.28633	0.31619	0.28591
$W^g(N)$	0.31776	0.27165	0.31619	0.27209
$W^g(E)$	0.31776	0.26558	0.31619	0.26399
τ^K	0.66476	0.15480	-0.05178	-0.02759
τ^{ZN}	0.05000	0.15335	0.05000	0.14612
τ^{ZE}	0.05000	0.15335	0.05000	0.14612
τ^{LN}	-0.04582	0.00848	0.05886	0.04449
τ^{LE}	-0.04582	-0.03110	0.05886	0.00549

Table 4: Numerical results for the differential labor and carbon taxes and capital taxes. See Table 9 for the extended version.

4 The role of inequality aversion

In equation (13) we defined welfare as an aggregate of utility in the two sectors. The parameter $\rho \leq 1$ indicates the degree of risk aversion by the government. The smaller ρ, the higher the inequality aversion of the government. For $\rho = -\infty$ this yields Rawlsian preferences, for $\rho = 1$ we have unweighted utilitarian preferences. So far, we have worked with the utilitarian case. We use this as our reference, since the concavity of the utility function gives an incentive to redistribute to the government. We now explore the effect of inequality aversion on our results.

In the utilitarian case, aggregate welfare is higher under capital mobility, but while households in the N-sector benefit from capital mobility, households in the E sector have lower welfare, see Table 9, columns 2 and 4. Notice that the welfare gain of capital mobility for an individual household in the N sector is smaller than the welfare loss for an individual household in the E sector. Aggregate welfare increases nevertheless through capital mobility, because there are more households employed in the N sector. Capital mobility thus increases efficiency (by allowing gains of trade) at the expense of higher inequality. This raises the question if capital mobility is an advantage or an obstacle for a government when it is more inequality averse than a utilitarian government.

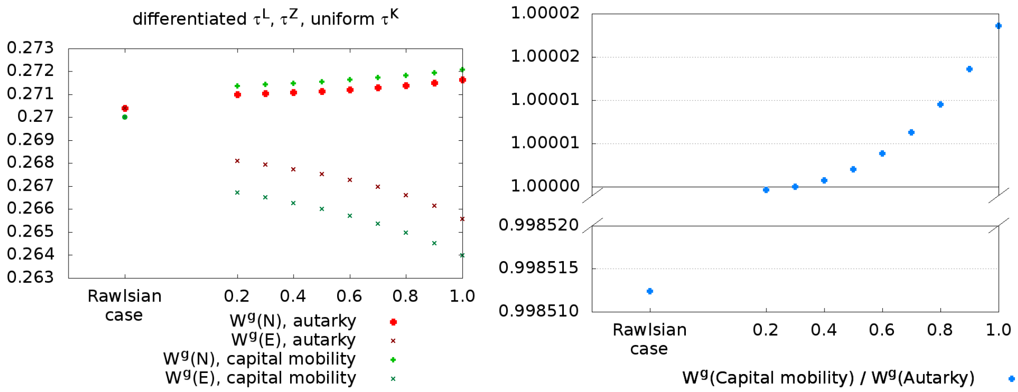

Figure 1: Welfare for different values of inequality aversion

To generate Figure 1 we considered values of ρ of $-\infty, 0.2, 0.3, ..., 1$. The left panel shows the values of $W^g(N)$ and $W^g(E)$ in the scenario with autarky and capital mobility for each value of ρ. The right panel shows the ratio of aggregate welfare of the two scenarios for the different values of ρ. From the left panel we can see that the distribution of utility is always more equal in autarky. In addition, the distribution is more equal for smaller values of ρ. From the right panel we can see that the government would be better off in autarky when it has Rawlsian preferences and in capital mobility when $\rho \geq 0.2$.

Taken together, we can conclude that environmental policy causes higher inequality when capital is mobile. This, however, causes lower aggregate welfare only when the government has an extreme aversion to inequality.

5 Optimal taxes in the long run

The political justification for sector specific policy was that climate policy caused a disproportional burden on the energy intensive sector when capital is mobile. We reproduced this skewed effect of climate policy by assuming sectoral rigidity in the labor market. In this section we show that no sector specific policy is necessary when labor markets adjust freely and we determine the adjustment of optimal policy to capital mobility.

In the long run, households will move from the more energy intensive to the less energy intensive sector. The wage differential between households in the two sectors in column 4 in Table 4, for example, should provide sufficient incentive to do so, in spite of the government subsidies for the energy intensive sector. Table 5 provides the results for the scenario in which the government has all policy options available (as in Section 3.4) and households can move freely between sectors.

Comparing column 4 of Tables 4 and 5 shows that the efficient allocation of labor has the expected effects. A higher share of production factors labor, capital and pollution are used in the N sector in the long run. Production consequently shifts from the E to the N sector as well. The more efficient use of production factors allows the government to attain higher welfare. As households can move into the better paying sector, there is no more need to use sector-specific policy.

Comparing columns 2 and 4 in Table 5 shows how the government optimally adjusts to capital mobility in the long run. The optimal pollution tax is lower under capital mobility since demand for pollution is lower. In addition, labor taxes are decreased while capital taxes are increased, which is an adjustment to capital mobility hardly related to the presence of pollution.

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	Yes	Yes	Yes
W^g	0.18656	0.27064	0.19581	0.27072
W^b	0.31776	0.28628	0.31619	0.28588
$W^g(N)$	0.31776	0.28628	0.31619	0.28588
$W^g(E)$	0.31776	0.28628	0.31619	0.28588
τ^K	0.66476	0.16822	-0.05178	-0.02939
τ^{ZN}	0.05000	0.15221	0.05000	0.14442
τ^{ZE}	0.05000	0.15221	0.05000	0.14442
τ^{LN}	-0.04582	0.00000	0.05886	0.03849
τ^{LE}	-0.04582	0.00000	0.05886	0.03849

Table 5: Numerical results for the long run scenario where households are fully mobile between sectors (shown here are the scenarios where the government can use the full set of policy options: differential labor and carbon taxes and capital taxes). See Table 10 for the extended version.

6 Further Results

6.1 Robustness Checks

We find qualitative results to be robust to changes in parameters. Sector specific policy, however, is necessary only when sectors are affected differently by environmental policy. When the substitution elasticity between production factors is high, the energy intensive sector reacts to higher emission prices by simply substituting emissions with capital. As a consequence, wages across sectors remain similar. The left panel of Figure 2 illustrates this. When the elasticity of substitution increases from $\sigma_E = 0.4$, as it is in the results discussed above, to higher values, the difference between sectors disappears.

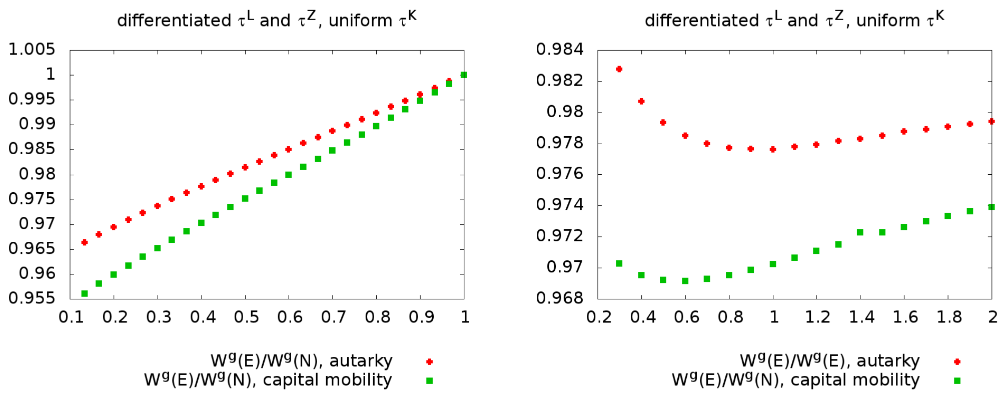

Figure 2: Relative welfare of the sectors for different values of parameters σ_E (left panel) and ε (right panel)

As the right panel of Figure 2 shows, the same does not hold for the substitution elasticity between sectors. The gap between sectors remains at a roughly similar level for a wide range of substitution elasticities.

6.2 Tax Harmonization

Zodrow and Mieszkowski (1986) identified a race to the bottom in capital taxes which causes inefficiently low public good provision. This effect can be found in the results in Table 9 by comparing columns 1 and 3. When capital is mobile, capital is subsidized instead of taxed, public good provision is lower and blue welfare is reduced. The effect is less visible in column 4. Aside from the negative effect of tax competition, capital mobility has the positive effect of improving the international allocation of capital whenever countries are not identical. In column 4 countries are not identical because of different policy objectives. Public good provision is thus higher in column 4 than in column 2 since the benefits of capital mobility outweigh the cost.

Comparing Tables 8 and 9 shows what could be achieved by international capital tax harmonization. Results in Table 8 could be seen as the outcome of an international agreement to set capital taxes to zero. Zero is an arbitrary number for the tax harmonization as it is not the socially optimal amount. It serves as a useful experiment nevertheless. For the scenario without environmental policy and with capital mobility (column 3) the scenario with tax harmonization has more public good provision and higher blue welfare. Tax harmonization is thus efficiency enhancing.

When capital is mobile and country 1 pursues environmental policy (column 4), tax harmonization still increases public good provision. Nevertheless, green welfare in country 1 is lower in the scenario with tax harmonization. Higher public good provision increases the demand for output and the lower domestic capital is substituted with pollution to some extent. Both of these effects increase pollution, so that blue welfare increases and green welfare decreases through the tax harmonization.

6.3 Leakage

Throughout the paper we assumed that country 1 considers only domestic emissions as environmental variable. This is designed to reflect a country's consideration of how much emissions to reduce unilaterally. The aim of such a unilateral policy could be to set a good example. See Schwerhoff (2015) for possible motivations to implement policy unilaterally.

In spite of this explicit domestic policy focus we can consider the amount of leakage caused by climate policy as designed in Table 9 for example. Domestic emissions are reduced by 0.704 and foreign emissions increased by 0.048, implying a leakage rate of 6.8%. The leakage rate is thus within the range of 5% to 20% typically identified in the literature (Gerlagh and Kuik, 2007; Branger and Quirion, 2014). We consider it suitable that our results are at the lower end of this range, since some models find even negative leakage rates (Barker et al., 2007; Elliott and Fullerton, 2014) and econometric studies find no significant effect at all (Branger and Quirion, 2014). We thus follow the conclusion of Bernard and Vielle

(2009) that carbon leakage "does not represent a real concern, with a magnitude of at most a few percent of GHG abatement by Annex B countries". The unilateral reduction of domestic CO2 emissions without regard for leakage therefore appears to be a legitimate and reasonable policy objective.

7 Conclusion

This paper considers the differential effect of capital mobility for climate policy and possible policy reactions. We find that capital mobility can indeed amplify the unequal impact of climate policy across sectors. The ideal policy instrument to compensate households employed in the energy intensive sector, however, are not sectoral carbon tax exemptions. Sector-specific labor taxes are a much more direct way of relieving their burden, since it benefits them directly and motivates a larger labor input. Distributional concerns can justify sector specific carbon taxes, but when labor taxes can be made sector specific, carbon taxes should be at almost the same level in the two sectors.

The paper also contributes to the understanding of the welfare effect of capital mobility. Capital mobility makes it more difficult for a government to redistribute. Taxing capital and pollution drives capital abroad so that it is difficult to raise funds to reduce labor taxes. This additional cost implies that capital mobility is less beneficial for governments with a high degree of inequality aversion, so that it might even be better to not have capital mobility.

In the long run, however, the wage differential between the sectors provides an incentive for workers to move away from the energy intensive sector. The sector specific policy should then be phased out. This constitutes another advantage of redistribution through differential labor taxes. Carbon tax exemptions provide no incentive for capital and labor to allocate across sectors in the way it would be optimal in the long run.

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A Results

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.19472	0.27019	0.19469	0.27033
W^b	0.31659	0.28610	0.31659	0.28593
$W^g(N)$	0.31659	0.27425	0.31659	0.27453
$W^g(E)$	0.31659	0.25454	0.31659	0.25412
G	0.08956	0.08090	0.08906	0.07979
Y	0.52006	0.46218	0.52013	0.44117
Y^N	0.68147	0.60840	0.68156	0.57894
Y^E	0.17639	0.15392	0.17642	0.14876
Y^X	0.00000	0.00000	0.00000	-0.01730
C^N	0.43050	0.30971	0.43108	0.30796
C^E	0.43050	0.07157	0.43108	0.07072
M^N	0.79439	0.79439	0.79440	0.79440
M^E	0.20561	0.20561	0.20560	0.20560
L	0.73333	0.73452	0.73350	0.72300
L^N/L	0.79439	0.79800	0.79440	0.79899
L^E/L	0.20561	0.20200	0.20560	0.20101
$K^N + K^E$	1.00000	1.00000	1.00000	0.89593
K^N	0.82357	0.83641	0.82356	0.74307
K^E	0.17643	0.16359	0.17644	0.15286
Z^N	0.83210	0.24513	0.83221	0.24462
Z^E	0.27184	0.15364	0.27188	0.15040
$L^N w^N + L^E w^E$	0.28805	0.24731	0.28809	0.23524
$(K^N + K^E)r$	0.17681	0.15472	0.17684	0.16624
K^N/L^N	1.41372	1.42697	1.41337	1.28630
K^E/L^E	1.17011	1.10253	1.17000	1.05186
Z^N/L^N	1.42836	0.41821	1.42823	0.42345
Z^E/L^E	1.80290	1.03547	1.80283	1.03490
w^N	0.39280	0.34694	0.39276	0.33603
w^E	0.39280	0.29622	0.39276	0.28296
r	0.17681	0.15472	0.17684	0.16624
τ^K	0.00000	0.00000	0.00000	0.00000
τ^{ZN}	0.05000	0.15084	0.05000	0.14428
τ^{ZE}	0.05000	0.15084	0.05000	0.14428
τ^{LN}	0.04686	0.02825	0.04615	0.03153
τ^{LE}	0.04686	0.02825	0.04615	0.03153
p	1.00000	1.00000	1.00000	1.00000
p^N	0.61052	0.60773	0.61052	0.60962
p^E	0.58966	0.60053	0.58966	0.59312

Table 6: Numerical results for the baseline scenarios

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.19472	0.27024	0.19469	0.27039
W^b	0.31659	0.28609	0.31659	0.28593
$W^g(N)$	0.31659	0.27174	0.31659	0.27200
$W^g(E)$	0.31659	0.26445	0.31659	0.26414
G	0.08956	0.08090	0.08906	0.07981
Y	0.52006	0.46208	0.52013	0.44117
Y^N	0.68147	0.60709	0.68156	0.57756
Y^E	0.17639	0.15508	0.17642	0.15019
Y^X	0.00000	0.00000	0.00000	-0.01722
C^N	0.43050	0.30534	0.43108	0.30350
C^E	0.43050	0.07584	0.43108	0.07508
M^N	0.79439	0.79439	0.79440	0.79440
M^E	0.20561	0.20561	0.20560	0.20560
L	0.73333	0.73479	0.73350	0.72341
L^N/L	0.79439	0.79564	0.79440	0.79605
L^E/L	0.20561	0.20436	0.20560	0.20395
$K^N + K^E$	1.00000	1.00000	1.00000	0.89648
K^N	0.82357	0.83573	0.82356	0.74276
K^E	0.17643	0.16427	0.17644	0.15371
Z^N	0.83210	0.24404	0.83221	0.24335
Z^E	0.27184	0.15405	0.27188	0.15095
$L^N w^N + L^E w^E$	0.28805	0.24696	0.28809	0.23489
$(K^N + K^E)r$	0.17681	0.15481	0.17684	0.16631
K^N/L^N	1.41372	1.42951	1.41337	1.28980
K^E/L^E	1.17011	1.09398	1.17000	1.04184
Z^N/L^N	1.42836	0.41743	1.42823	0.42257
Z^E/L^E	1.80290	1.02595	1.80283	1.02308
w^N	0.39280	0.34777	0.39276	0.33708
w^E	0.39280	0.29068	0.39276	0.27638
r	0.17681	0.15481	0.17684	0.16631
τ^K	0.00000	0.00000	0.00000	0.00000
τ^{ZN}	0.05000	0.15147	0.05000	0.14503
τ^{ZE}	0.05000	0.15147	0.05000	0.14503
τ^{LN}	0.04686	0.03585	0.04615	0.03947
τ^{LE}	0.04686	-0.00241	0.04615	-0.00072
p	1.00000	1.00000	1.00000	1.00000
p^N	0.61052	0.60891	0.61052	0.61108
p^E	0.58966	0.59591	0.58966	0.58750

Table 7: Numerical results for differential labor taxes

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.19472	0.27024	0.19469	0.27039
W^b	0.31659	0.28609	0.31659	0.28593
$W^g(N)$	0.31659	0.27174	0.31659	0.27200
$W^g(E)$	0.31659	0.26445	0.31659	0.26414
G	0.08956	0.08090	0.08906	0.07981
Y	0.52006	0.46208	0.52013	0.44118
Y^N	0.68147	0.60718	0.68156	0.57747
Y^E	0.17639	0.15499	0.17642	0.15030
Y^X	0.00000	0.00000	0.00000	-0.01721
C^N	0.43050	0.30534	0.43108	0.30350
C^E	0.43050	0.07584	0.43108	0.07508
M^N	0.79439	0.79439	0.79440	0.79440
M^E	0.20561	0.20561	0.20560	0.20560
L	0.73333	0.73479	0.73350	0.72341
L^N/L	0.79439	0.79564	0.79440	0.79605
L^E/L	0.20561	0.20436	0.20560	0.20395
$K^N + K^E$	1.00000	1.00000	1.00000	0.89653
K^N	0.82357	0.83578	0.82356	0.74275
K^E	0.17643	0.16422	0.17644	0.15378
Z^N	0.83210	0.24434	0.83221	0.24296
Z^E	0.27184	0.15376	0.27188	0.15133
$L^N w^N + L^E w^E$	0.28805	0.24693	0.28809	0.23494
$(K^N + K^E)r$	0.17681	0.15480	0.17684	0.16631
K^N/L^N	1.41372	1.42958	1.41337	1.28979
K^E/L^E	1.17011	1.09362	1.17000	1.04232
Z^N/L^N	1.42836	0.41793	1.42823	0.42190
Z^E/L^E	1.80290	1.02397	1.80283	1.02570
w^N	0.39280	0.34777	0.39276	0.33709
w^E	0.39280	0.29043	0.39276	0.27671
r	0.17681	0.15480	0.17684	0.16631
τ^K	0.00000	0.00000	0.00000	0.00000
τ^{ZN}	0.05000	0.15129	0.05000	0.14527
τ^{ZE}	0.05000	0.15207	0.05000	0.14428
τ^{LN}	0.04686	0.03584	0.04615	0.03949
τ^{LE}	0.04686	-0.00267	0.04615	-0.00038
p	1.00000	1.00000	1.00000	1.00000
p^N	0.61052	0.60882	0.61052	0.61119
p^E	0.58966	0.59625	0.58966	0.58706

Table 8: Numerical results for differential labor and carbon taxes

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.18656	0.27041	0.19581	0.27042
W^b	0.31776	0.28633	0.31619	0.28591
$W^g(N)$	0.31776	0.27165	0.31619	0.27209
$W^g(E)$	0.31776	0.26558	0.31619	0.26399
G	0.09520	0.08255	0.08801	0.07961
Y	0.53945	0.46779	0.51690	0.44315
Y^N	0.70655	0.61509	0.67738	0.58052
Y^E	0.18331	0.15649	0.17526	0.15049
Y^X	0.00000	0.00000	0.00000	-0.01458
C^N	0.44425	0.30898	0.42889	0.30308
C^E	0.44425	0.07626	0.42889	0.07504
M^N	0.79669	0.79669	0.79401	0.79401
M^E	0.20331	0.20331	0.20599	0.20599
L	0.77798	0.75128	0.72615	0.72132
L^N/L	0.79669	0.79744	0.79401	0.79577
L^E/L	0.20331	0.20256	0.20599	0.20423
$K^N + K^E$	1.00000	1.00000	1.00000	0.91336
K^N	0.81979	0.83490	0.82420	0.75819
K^E	0.18021	0.16510	0.17580	0.15517
Z^N	0.86312	0.24403	0.82703	0.24262
Z^E	0.28228	0.15489	0.27013	0.15094
$L^N w^N + L^E w^E$	0.29793	0.24973	0.28644	0.23617
$(K^N + K^E)r$	0.11068	0.13585	0.18519	0.16830
K^N/L^N	1.32265	1.39359	1.42948	1.32087
K^E/L^E	1.13936	1.08490	1.17531	1.05333
Z^N/L^N	1.39256	0.40734	1.43440	0.42267
Z^E/L^E	1.78468	1.01782	1.80594	1.02466
w^N	0.38295	0.34356	0.39446	0.33969
w^E	0.38295	0.28850	0.39446	0.27954
r	0.11068	0.13585	0.18519	0.16830
τ^K	0.66476	0.15480	-0.05178	-0.02759
τ^{ZN}	0.05000	0.15335	0.05000	0.14612
τ^{ZE}	0.05000	0.15335	0.05000	0.14612
τ^{LN}	-0.04582	0.00848	0.05886	0.04449
τ^{LE}	-0.04582	-0.03110	0.05886	0.00549
p	1.00000	1.00000	1.00000	1.00000
p^N	0.61080	0.60842	0.61046	0.61070
p^E	0.58858	0.59784	0.58987	0.58896

Table 9: Numerical results for the differential labor and carbon taxes and capital taxes

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	Yes	Yes	Yes
W^g	0.18656	0.27064	0.19581	0.27072
W^b	0.31776	0.28628	0.31619	0.28588
$W^g(N)$	0.31776	0.28628	0.31619	0.28588
$W^g(E)$	0.31776	0.28628	0.31619	0.28588
G	0.09520	0.08264	0.08801	0.07953
Y	0.53945	0.46831	0.51690	0.44190
Y^N	0.70655	0.62636	0.67738	0.58984
Y^E	0.18331	0.14635	0.17526	0.13922
Y^X	0.00000	0.00000	0.00000	-0.01582
C^N	0.44425	0.38567	0.42889	0.37819
C^E	0.44425	0.38567	0.42889	0.37819
M^N	0.79669	0.81706	0.79401	0.81777
M^E	0.20331	0.18294	0.20599	0.18223
L	0.77798	0.75318	0.72615	0.72154
L^N/L	0.79669	0.81706	0.79401	0.81777
L^E/L	0.20331	0.18294	0.20599	0.18223
$K^N + K^E$	1.00000	1.00000	1.00000	0.90597
K^N	0.81979	0.84095	0.82420	0.75790
K^E	0.18021	0.15905	0.17580	0.14807
Z^N	0.86312	0.24614	0.82703	0.24479
Z^E	0.28228	0.14930	0.27013	0.14457
$L^N w^N + L^E w^E$	0.29793	0.25219	0.28644	0.23777
$(K^N + K^E)r$	0.11068	0.13348	0.18519	0.16820
K^N/L^N	1.32265	1.36652	1.42948	1.28446
K^E/L^E	1.13936	1.15432	1.17531	1.12608
Z^N/L^N	1.39256	0.39997	1.43440	0.41487
Z^E/L^E	1.78468	1.08355	1.80594	1.09951
w^N	0.38295	0.33484	0.39446	0.32952
w^E	0.38295	0.33484	0.39446	0.32952
r	0.11068	0.13348	0.18519	0.16820
τ^K	0.66476	0.16822	-0.05178	-0.02939
τ^{ZN}	0.05000	0.15221	0.05000	0.14442
τ^{ZE}	0.05000	0.15221	0.05000	0.14442
τ^{LN}	-0.04582	0.00000	0.05886	0.03849
τ^{LE}	-0.04582	0.00000	0.05886	0.03849
p	1.00000	1.00000	1.00000	1.00000
p^N	0.61080	0.59814	0.61046	0.59935
p^E	0.58858	0.63999	0.58987	0.63484

Table 10: Numerical results for the long run scenario where households are fully mobile between sectors (shown here are the scenarios where the government can use the full set of policy options: differential labor and carbon taxes and capital taxes)

	Capital mobile? No Welfare: Green Households mobile? No	Experiment 1 (carbon tax cuts)	Experiment 2 (labor tax cuts)
W^g	0.27019	0.27019	0.27020
W^b	0.28610	0.28639	0.28611
$W^g(N)$	0.27425	0.27406	0.27404
$W^g(E)$	0.25454	0.25525	0.25538
G	0.08090	0.08047	0.08045
Y	0.46218	0.46277	0.46226
Y^N	0.60840	0.60830	0.60839
Y^E	0.15392	0.15501	0.15407
Y^X	0.00000	0.00000	0.00000
C^N	0.30971	0.31022	0.30978
C^E	0.07157	0.07209	0.07203
M^N	0.79439	0.79439	0.79439
M^E	0.20561	0.20561	0.20561
L	0.73452	0.73465	0.73472
L^N/L	0.79800	0.79781	0.79778
L^E/L	0.20200	0.20220	0.20222
$K^N + K^E$	1.00000	1.00000	1.00000
K^N	0.83641	0.83577	0.83633
K^E	0.16359	0.16423	0.16367
Z^N	0.24513	0.24544	0.24517
Z^E	0.15364	0.15703	0.15374
$L^N w^N + L^E w^E$	0.24731	0.24802	0.24733
$(K^N + K^E)r$	0.15472	0.15504	0.15476
K^N/L^N	1.42697	1.42597	1.42683
K^E/L^E	1.10253	1.10561	1.10162
Z^N/L^N	0.41821	0.41876	0.41828
Z^E/L^E	1.03547	1.05715	1.03472
w^N	0.34694	0.34741	0.34701
w^E	0.29622	0.29890	0.29569
r	0.15472	0.15504	0.15476
τ^K	0.00000	0.00000	0.00000
τ^{ZN}	0.15084	0.15084	0.15084
τ^{ZE}	0.15084	0.14451	0.15084
τ^{LN}	0.02825	0.02825	0.02825
τ^{LE}	0.02825	0.02825	0.02503
p	1.00000	1.00000	1.00000
p^N	0.60773	0.60861	0.60785
p^E	0.60053	0.59708	0.60006

Table 11: Results on the differential effects of carbon and labor tax cuts. See Section 3.3 for a discussion.

Chapter 4

Is capital back? The role of land ownership and savings behavior[1]

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Is Capital Back?
The Role of Land Ownership and Savings Behavior.

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Abstract

Wealth inequality is one of the major political concerns in most OECD countries. Under this premise we analyze different policy instruments in terms of their impact on wealth inequality and output. We use a general equilibrium model in which we disaggregate wealth in its capital and land components, and savings in their life-cycle and bequest components. Households are heterogeneous in their taste for the 'warm glow' of leaving bequests. We show that a government has considerable freedom in reducing wealth inequality without sacrificing output: A land rent tax enhances output due to a portfolio effect and reduces wealth inequality slightly. The bequest tax has the highest potential to reduce inequality, and its effect on output is very moderate. By contrast, we confirm the standard result that a tax on capital income reduces output strongly, and show that it only has moderate redistributive effects. Furthermore, we analyze different revenue recycling options and find that lump-sum recycling of the tax revenue to the young generation enhances output the most and further reduces wealth inequality.

JEL Classification: D31, E62, H23, H24, Q24

Keywords: Fiscal policy, Wealth distribution, Capital tax, Bequests, Land rent tax

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1. Introduction

In many OECD countries wealth-to-income ratios are rising (Piketty and Zucman, 2014) and inequality is relatively high, which is a matter of concern to policy makers. Saez and Zucman (2015) for instance find that the US wealth concentration is high by international standards and has considerably increased in recent decades. To counteract the concentration of wealth Benhabib et al. (2011) and Piketty and Saez (2013)[1] recommend taxes on capital. However, capital taxes discourage investment and reduce economic growth. Further, these authors do not distinguish between capital and wealth (Homburg, 2015), which is inconsistent with empirical findings as Stiglitz (2015) points out. In particular, Stiglitz highlights the fundamental role of land rents for the distribution of wealth.[2] Therefore, we compare taxes on capital income, land rents, and bequests in an overlapping generations model in which we disaggregate wealth into capital and land.

We show that governments have considerable freedom in reducing wealth inequality without sacrificing output. There is a range of combinations of land rent and bequest tax rates under which output remains unchanged, but public revenues and the wealth distribution can be varied.

Explicitly distinguishing the stocks of land and capital is crucial due to their inherently different dynamics. While capital is reproducible, land is fixed. The differing evolution of the capital and housing shares of wealth underline this point: In several developed economies, the increase of the wealth-to-GDP ratio in the post-WWII era is caused by an increase of the value of land (see, e.g., Homburg, 2015, Fig. 3).

In analogy to Piketty and Saez (2013), we choose preferences for bequests as the source of heterogeneity in our analysis. We do so since bequests are a key

[1] Although Piketty and Saez (2013) is titled *A Theory of Optimal Inheritance Taxation*, the tax on bequests which they analyze is equivalent to a capital tax (p. 1854, Footnote 4). Accordingly, the title of their working paper version Piketty and Saez (2012) is *A Theory of Optimal Capital Taxation*.

[2] In contrast to Stiglitz (2015), Homburg (2015) seems to dismiss the distributional implications of the dynamics of land rent ownership in the conclusion of his article.

determinant of wealth inequality (Cagetti and De Nardi, 2008), and intergenerational transfers of wealth make up approximately half of total capital formation (Gale and Scholz, 1994), yet "theoretical implications of inequality in received inheritances are not yet fully understood and are likely to lead to arguments for positive taxation of bequests" (Kopczuk, 2013, p. 332).[3]

Next to Benhabib et al. (2011) and Piketty and Saez (2013) there are many other studies which analyze the distributional effects of taxation in heterogeneous agent models. Two classic papers on optimal taxation, Judd (1985) and Chamley (1986), establish that capital taxes are inefficient, and should not be used to redistribute wealth when households have heterogeneous preferences. More recently, Chiroleu-Assouline and Fodha (2014) implement heterogeneity through differences in skill among workers. They find that if capital taxes (interpreted in their analysis as environmental taxes) are regressive, a complementary change of the income tax rules is Pareto efficient and renders the tax system progressive again.

To our knowledge, the only other study with heterogeneous agents that takes land into account apart from ours is Stiglitz (2015). However, the author takes only the polar case of two types of households into account: workers, who save only for consumption during their own old age, and capitalists, who save only to leave bequests to their offspring. He finds that taxing capital income cannot reduce wealth inequality since the capitalists always shift the tax burden to workers.

By contrast, we model heterogeneity in greater detail. We let different households have both savings motives, but to differing degrees. Thus, our framework

[3] We are aware of exceptions in the literature: In their empirical contributions Wolff and Gittleman (2014) and Bönke et al. (2015) find that bequests are not an important driver of wealth inequality. However, both studies do not take the top 1% of the wealth distribution fully into account. Further, the results of Wolff and Gittleman (2014) rest on the assumption that "(...) if wealth transfers are eliminated, there would be no effect on the savings behavior of those who have received transfers or are expecting them and that there would be no effect on the savings of those who intend to give a bequest." (p. 465). Due to the methodological difference from Wolff and Gittleman (2014) we are able to take exactly that counterfactual case into account in which transfers are eliminated and households actually change their savings behavior.

is flexible enough to be calibrated to the empirical data on the distribution of wealth compiled by the OECD (2015). Due to our assumptions of endogenous saving and bequest heterogeneity instead of class membership, a capital income tax in our model reduces inequality in wealth.

We show that in fact all three instruments considered in our study reduce wealth inequality. However, they differ strongly in their effect on output (and thus also households' incomes). Taxing capital income has a negative effect on output levels for two reasons: The tax reduces households' incentive to save in general, but it also shifts investments away from capital towards land – a macroeconomic portfolio effect. Conversely, land rent taxation shifts private savings and investments away from land and towards capital, thereby enhancing output.[4] Bequest taxes do not affect the composition of the households' portfolio, so they have a significantly smaller effect on output. For the benchmark calibration, bequest taxes reduce output slightly. In that case, the reduction of income is stronger than the increased demand for leaving bequests. In other words, the income effect dominates the substitution effect. In the robustness analysis of our results, however, we also discuss cases in which the opposite is true, and bequest taxes slightly increase output.

Further, the savings behavior of households determines the redistributive effect. Each of the three tax instruments discourages savings to a certain extent, and thus also reduces bequests to the following generation. Since wealthy households' income consists of a relatively high amount of bequests, a reduction of the latter decreases their income more strongly than that of poorer households. The potential to redistribute wealth using land rent and capital income taxation is only moderate compared to bequest taxes, which directly target the

[4] Feldstein (1977) was the first to identify the portfolio effect, which Petrucci (2006) later formalized in an OLG. Edenhofer et al. (2015) extend the analysis of the portfolio effect by introducing a social welfare function as benchmark for evaluating fiscal policy, in particular land rent taxes. The present paper focuses on the economic impacts of fiscal policy and does not consider a social welfare function. Nevertheless, we find that under land rent taxation the winners of the policy could theoretically compensate the losers. Thus, land rent taxation fulfills the Kaldor-Hicks criterion (see Appendix D).

source of inequality. Once all land rents are taxed away, or capital investments are choked, respectively, no further redistribution of wealth is possible.

Finally, different ways of recycling tax revenues to the economy have different impacts. Using the tax revenues to finance infrastructure investments only raises the steady state level of output, but does not change the distribution of wealth. If public revenues are instead recycled as lump-sum transfers to households, we find an impact both on output and on the distribution of wealth: The more a government directs the transfers to the young, the higher the level of output in the steady state will be and the more equal wealth will be distributed. Our finding thus gives support to the proposal of the stakeholder society (Ackerman and Alstott, 1999), also voiced by Corneo (2011), Atkinson (2015), and Edenhofer et al. (2015).[5]

The rest of the paper is structured as follows. In Section 2 we introduce a simplified version of our model with sequential generations. Here, we highlight the importance of endogenous prices to justify our choice of a deterministic model with complete markets – an approach which we understand as complementary to Piketty and Saez (2013) and Benhabib et al. (2011), who model individual households' rate of return on capital and the distribution of wealth as determined by stochastic processes. In Section 3 we introduce overlapping generations and land, and perform the policy instrument analysis which is central to our paper. Sensitivity and robustness of our results are tested in Section 4. Section 5 concludes.

[5] Inspired by the idea of the stakeholder society, the United Kingdom introduced Child Trust Funds in 2005, which were replaced by Junior ISAs in 2011.

2. A simple model of bequest heterogeneity

In the present section, we develop a simple model of bequest heterogeneity to explain fundamental mechanisms at work. In particular, we want to demonstrate the importance of the impact of taxes on the interest rate for the distribution of wealth. Land as a production factor and the life cycle savings motive are omitted here and will be introduced in the next section.

Our simple model is based on Acemoglu (2008). To the best of our knowledge, it is the most parsimonious model of an economy in which new generations enter the economy each period and leave bequests to the next generation.

In each period t a new generation arrives in the economy and the old generation leaves the economy. There are N different types of households in each generation, which differ in their preferences. Each type of household $i \in \{1, ..., N\}$ lives for one period, during which it receives income $y_{i,t}$. It divides its income between consumption $c_{i,t}$ and bequests for the next generation $b_{i,t}$, which are taxed at the uniform rate τ_B. A household derives utility from consumption and the "warm glow" (Andreoni, 1989) of leaving net-of-tax bequests:

$$u_{i,t} = \log(c_{i,t}) + \beta_i \log(b_{i,t}(1 - \tau_B)). \tag{1}$$

The budget equation is given by

$$y_{i,t} = w_t + (1 + R_t(1 - \tau_K))b_{i,t-1}(1 - \tau_B) = c_{i,t} + b_{i,t}, \tag{2}$$

where w denotes wage income, R is the rate of return on inherited wealth, that is, the bequests from the previous generation, and $0 < \beta_i < 1$ determines the preference for leaving bequests for the household of type i of the next generation $t + 1$. We assume that capital does not depreciate after use,[6] and that the offspring of a household has the same preferences as its parents.[7] Households

[6] Assuming positive depreciation does not alter the results qualitatively.

[7] This simplifying assumption may be justified by recent findings on the determinants of intergenerational wealth transmission which suggest potential roles for intergenerational

may have to pay taxes τ_K on capital income or taxes τ_B on the bequests they receive.

Production is given by a standard neoclassical production function in intensive form $f(k)$ that satisfies the usual conditions. Then, for the equilibrium wage rate we have,

$$w_t = f(k_t) - f'(k_t)k_t, \tag{3}$$

and

$$R_t = f'(k_t).$$

We assume that all bequests are invested in capital k used for production:

$$k_{t+1} = \frac{1}{N}\sum_i b_{i,t}.$$

2.1. Basic properties

Households choose the levels of consumption and bequests in order to maximize their utility (1) subject to their budget equation (2). This yields the first-order conditions

$$b_{i,t} = \frac{\beta_i}{1+\beta_i} y_{i,t} = \varphi_i \Big(w_t + (1 + R_t(1-\tau_K)) b_{i,t-1}(1-\tau_B) \Big) \quad \forall t, \tag{4}$$

where $i \in \{1, ..., N\}$ and $\varphi_i := \frac{\beta_i}{1+\beta_i}$.

With (4) it is possible to deduce a condition on the curvature of the production function which ensures the existence of a steady state (see Appendix A). This condition is, for instance, fulfilled by CES-type production functions. Then, the steady state level of bequests is given by

$$b_i^* = \frac{w^* \beta_i}{1 + \beta_i - \beta_i \big(1 + R^*(1-\tau_K)\big)(1-\tau_B)}, \tag{5}$$

transmission of preferences (Black et al., 2015).

where asterisks denote steady state levels. Further, if a steady state exists, it follows directly from (5) that households with relatively high preference parameters β_i for bequests have higher steady state levels of bequests than households with relatively low preferences for bequests.[8]

2.2. Fiscal policy

We consider a linear tax on capital income or on bequests which is implemented in the first time period of the model and remains constant for the whole time horizon. The main aim here is to highlight that the impact of the tax on the interest rate is crucial for how the tax affects wealth distribution.

Lemma 1. *Assume a steady state exists (cf. Corollary A, Appendix A).*

1. *An increase in the bequest tax leads to a decrease in wealth inequality, if and only if*

$$\frac{\mathrm{d}R^*}{\mathrm{d}\tau_B} < -\frac{1 + R^*(1-\tau_K)}{(1-\tau_K)(1-\tau_B)}. \tag{6}$$

2. *An increase in the capital income tax leads to a decrease in wealth inequality, if and only if*

$$\frac{\mathrm{d}R^*}{\mathrm{d}\tau_K} < \frac{R^*}{1-\tau_K}. \tag{7}$$

By a decrease in wealth inequality we understand a decreasing steady state bequest ratio b_i^*/b_j^* of households i and j whenever $\beta_i > \beta_j$ (i.e. household i has a higher preference for leaving bequest than household j).

Proof. Let $i, j \in \{1, ..., N\}$ such that $\beta_i > \beta_j$ and thus $b_i^* > b_j^*$ holds. We define $\psi_i := 1 + \beta_i - \beta_i\big(1 + R^*(1-\tau_K)\big)(1-\tau_B)$. Using (5) it is straightforward to calculate whether a marginal increase of a tax increases or decreases the ratio of steady state bequest levels:

1. $\frac{\mathrm{d}}{\mathrm{d}\tau_B}\left(\frac{b_i^*}{b_j^*}\right) = \overbrace{\frac{\beta_i}{\beta_j}(\beta_i - \beta_j)\psi_i^{-2}}^{>0}\left[\big(1 + R^*(1-\tau_K)\big) + \frac{\mathrm{d}R^*}{\mathrm{d}\tau_B}(1-\tau_K)(1-\tau_B)\right]$

2. $\frac{\mathrm{d}}{\mathrm{d}\tau_K}\left(\frac{b_i^*}{b_j^*}\right) = \underbrace{\frac{\beta_i}{\beta_j}(\beta_i - \beta_j)\psi_i^{-2}(1-\tau_B)}_{>0}\left[\frac{\mathrm{d}R^*}{\mathrm{d}\tau_K}(1-\tau_K) - R^*\right]$ □

[8] In other words, if $\beta_i > \beta_j$ for $i, j \in \{1, ..., N\}$, then $b_i^* > b_j^*$. To see this, note that $\frac{\mathrm{d}b_i^*}{\mathrm{d}\beta_i} > 0$ for constant w^* and R^*.

The intuition behind conditions (6) and (7) is that wages, which all households receive equally and which are linked to the interest rate R via equation (3), should not decrease too much. If conditions (6) or (7) hold, there is an upper bound for the marginal product of capital $f'(k)$, and thus a lower bound for the capital stock, output, and wages.

Our interpretation of the above lemma is that prices matter for a comprehensive policy instrument analysis. Any statement about the impact of taxes on the distribution of wealth should consider how the taxes affect factor prices endogenously. In Section 3 we will build on this insight to derive more precisely how taxes affect an economy with heterogeneous agents and land when prices are endogenous. Thereby, our study can be understood as complementary to Benhabib et al. (2011) and Piketty and Saez (2013), who assume that the interest rate is exogenously given.

Further note, that Lemma 1 alone does not make a statement whether it is possible to alter the ranking of households' steady-state levels of bequests by fiscal policy.

3. The role of land rents and savings behavior for the economic impact of fiscal policy.

We extend the analytical model described in Section 2 by introducing land and by assuming that agents live for two periods instead of only one. Thus, in each period there are two generations that overlap. We make this assumption to differentiate between the life-cycle savings motive and the savings motive for leaving bequests, and also in order to have a market for land, on which old households may sell their land to young ones. Land thus serves both as a fixed factor of production and an alternative asset for households' investments.

We first give a model description. Then, in Section 3.2, we show how taxes on capital income, land rents, and bequests affect output and the wealth distribution in the steady state, without taking the spending side into account. Finally, in Section 3.3, we consider different ways of using the public funds generated by fiscal policy.

3.1. Model

The economy consists of N different types of households, which differ with respect to their preferences and live for two periods. Further, there is one representative firm and the government. The different preferences of each type of households imply different levels of wealth. Similar to the analytical model of sequential generations in Section 2, we observe that also in the model with overlapping generations, higher preferences for bequests imply higher steady state levels of wealth. For the rest of the paper we set $N = 5$ and use the index i to identify the household belonging to the ith wealth quintile, where households are ordered from lowest to highest preferences for bequests. We assume that the offspring of a household has the same preferences as its parents. Further, we shall assume a finite time horizon, i.e. $t \in \{1, ..., T\}$, where one time step represents a period of 30 years (one generation). All variables are stated in per capita terms.

3.1.1. Households

The utility of households is given by an isoelastic function with elasticity parameter η. It depends on their consumption when young $c^y_{i,t}$, consumption when old $c^o_{i,t+1}$, and net bequests left to their children $b_{i,t+1}(1-\tau_B)$, on which the government may levy bequest taxes.

$$u\left(c^y_{i,t}, c^o_{i,t+1}, b_{i,t+1}\right) = \frac{(c^y_{i,t})^{1-\eta} + \mu_i (c^o_{i,t+1})^{1-\eta} + \beta_i \left(b_{i,t+1}(1-\tau_B)\right)^{1-\eta}}{1-\eta} \quad (8)$$

For the parameters we assume that $\mu_i, \beta_i \in (0,1)$. Households maximize their utility subject to the following budget equations.

$$\begin{aligned} c^y_{i,t} + s_{i,t} &= w_t + b_{i,t}(1-\tau_B) \\ s_{i,t} &= k^s_{i,t+1} + p_t l_{i,t+1} \\ c^o_{i,t+1} + b_{i,t+1} &= (1 + R_{t+1}(1-\tau_K))k^s_{i,t+1} + l_{i,t+1}(p_{t+1} + q_{t+1}(1-\tau_L)) =: v_{i,t+1} \end{aligned}$$

In period t a young household i earns wage income w_t, receives bequests from the currently old generation, and pays taxes on the bequests. The household uses its income to consume or save. Savings $s_{i,t}$ can be invested in capital $k^s_{i,t+1}$ or land $l_{i,t+1}$, which are assumed to be productive in the next period and may be taxed at rates τ_K and τ_L, respectively. We assume that capital is the numeraire good and land has the price p. When households are old, they receive the return on their investments according to the interest rate R_{t+1}, the price of land p_{t+1}, and the land rent q_{t+1}. We define household wealth $v_{i,t}$ as the sum of the values of the stocks of capital and land, and also the returns to investments in these stocks. Old households use their wealth to consume or to leave bequests for the next generation.

The first-order conditions of the households' optimizations are given by

$$(c^o_{i,t+1})^\eta = \mu_i (1 + R_{t+1}(1-\tau_K))(c^y_{i,t})^\eta \quad (9)$$

$$\beta_i (1-\tau_B)^{1-\eta} (c^o_{i,t+1})^\eta = \mu_i b^\eta_{i,t+1} \quad (10)$$

$$\frac{p_{t+1} + q_{t+1}(1-\tau_L)}{p_t} = 1 + R_{t+1}(1-\tau_K). \quad (11)$$

Note that the no-arbitrage condition (11) can be reformulated as the discounted sum of future rents:

$$p_t = \sum_{i=1}^{T} \frac{\widetilde{q}_{t+1}}{\prod_{j=T-i+1}^{T}(1+\widetilde{R}_{t+j})},$$

where $\widetilde{q}_t := q_t(1-\tau_L)$ and $\widetilde{R}_t := R_t(1-\tau_K)$, and we assume that in the final period T the price of land is zero, $p_T = 0$, since there is no following generation to buy the land. The no-arbitrage condition ensures that households invest in capital and land in such a way that the returns are equalized across the two assets. The returns are determined by the aggregate quantities of the input factors. Beyond this, the no-arbitrage condition does not impose any restrictions on how the asset portfolios of individual households are composed.[9]

3.1.2. Firm

The representative firm produces one type of final good using capital k, land l and labor, where the latter two are assumed to be fixed factors. We assume that the production function is of CES type. In intensive form it is defined as

$$f(k_t) = A_0[\alpha k_t^{\sigma} + \gamma l^{\sigma} + 1 - \alpha - \gamma]^{\frac{1}{\sigma}},$$

where A_0 is total factor productivity and $\sigma = \frac{\epsilon-1}{\epsilon}$ is determined by the elasticity of substitution ϵ. The firm's demand for capital k_t equals the aggregate of capital that is supplied by households $k_{i,t}^s$. The clearing of factor markets is described by

$$k_t = \frac{1}{N}\sum_{i=1}^{N} k_{i,t}^s \quad \text{and} \quad l = \frac{1}{N}\sum_{i=1}^{N} l_{i,t}.$$

[9] We shall make use of the convention that all households choose the same asset composition. More precisely, in every period t there is an $X_t > 0$ such that $X_t = k_{i,t}^s / l_{i,t}$ for all $i \in \{1, ..., N\}$. We use this convention because there is an infinite continuum of possible combinations of individual asset portfolio compositions of each household i which have no bearing on any of our results.

In each period the firm maximizes its profit, which we assume to be zero due to perfect competition. Thus, the first-order conditions are

$$f_k(k_t) = R_t \quad \text{and} \quad f_l(k_t) = q_t,$$

and wages are given by $w_t = f(k_t) - R_t k_t - q_t l$.

3.1.3. Government

The government levies taxes on capital income τ_K, land rents τ_L, or bequests τ_B. Throughout Section 3.2, we assume that public revenues g_t are used for public consumption which has no effect on the economy. In Section 3.3 we relax this assumption and analyze alternative recycling schemes.

$$g_t = \tau_K R_t k_t + \tau_L q_t l + \frac{1}{N} \sum_i \tau_B \, b_{i,t}.$$

3.2. The revenue side of fiscal policy

The heterogeneity in household preferences and the introduction of land as an additional factor of production yield complex results, which go beyond that which is analytically tractable. Thus, we solve the model numerically using GAMS (Brooke et al., 2005). The parameter values are chosen such that the level of output and the distribution of wealth in the steady state match recent OECD data on the distribution of wealth (OECD, 2015).[10] In the present section we focus on the revenue side of fiscal policy and assume that the public revenues are not used for a specific purpose.

3.2.1. The policy-option space of output, redistribution, and public revenue

We evaluate fiscal policy along three dimensions: Their impact on output, their consequences for the wealth distribution, and their potential to raise public revenue.

We summarize our main result in Figure 1. The graphs show the feasible combinations of output f^*, the Gini coefficient of the wealth distribution

[10] For a description of the calibration procedure and parameter values, see Appendix B. The robustness of our results with respect to different parametrizations is assessed in Section 4.

$\{v_i^*\}_{i=1,\ldots,5}$, and the magnitude of public revenues g^* in the steady state if only one of the three tax instruments is used at a time. If taxes are set to zero, per capita output is about 1 million US$ per time step (30 years) and the Gini coefficient of the wealth distribution has a value of about 0.63. This point is marked by the intersection of the two dashed lines.

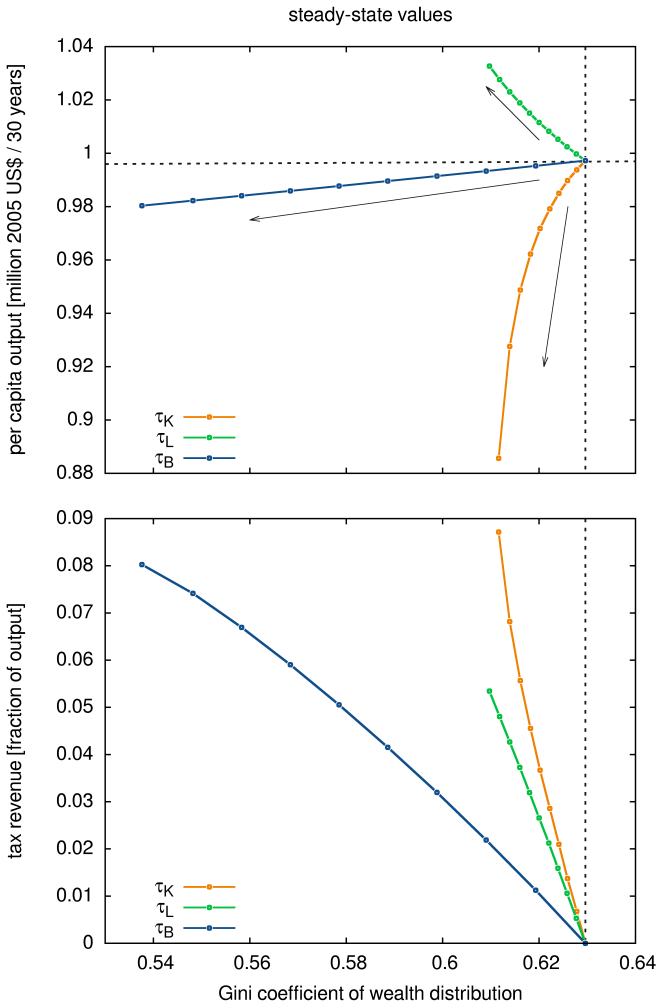

Figure 1: Depending on which tax instrument is used, the government may achieve different coordinates in the policy-option space of output, redistribution, and public revenue. Each curve represents the set of coordinates which are achievable with the use of one single tax instrument. The arrows in the upper panel indicate increases in the respective tax rate. The data points are chosen for tax rates in steps of 10%. They range from 0% to 100% for the land rent tax, and from 0% to 90% for the capital income and the bequest tax. Note that capital income and bequest tax rates of 100% produce extreme results which we have left out here for expositional reasons.

As the tax rates are increased above zero, respectively, we observe that all taxes reduce the Gini coefficient. Output increases under the land rent tax and decreases under the capital income tax. The bequest tax reduces output only slightly. Capital income and bequest taxes achieve higher public revenues than the land rent tax.[11]

The distribution of wealth depends on how fiscal policy affects the two components of the young households' income, i.e., wages and bequests. Rich households draw a higher proportion of their income from bequests than the poor. When a tax affects the two sources of income differently, the distribution of wealth will change accordingly. It turns out that the capital income tax and the land rent tax reduce the after tax return to savings $1 + R^*(1 - \tau_K) = 1 + \frac{q^*}{p^*}(1 - \tau_L)$, which discourages savings and thus reduces bequests. Moreover, bequest taxes reduce households' income, and thus they also reduce bequests via the income effect. Households whose income consists of a comparably high share of bequests are affected more strongly by the bequest tax than households who receive most of their income as wages. As a consequence, each tax instrument reduces the income of richer households by a higher proportion than the income of poorer ones – all taxes have a progressive effect on the distribution of wealth (see Table 1).

[11] In the robustness analysis of our results in Section 4.1.1, we will show that the potential to raise public revenues with the bequest tax crucially depends on the elasticity parameter η of households' utility function.

	Household i	$\tau_K = 0.2$	$\tau_L = 0.2$	$\tau_B = 0.2$	$\tau_K = 0.7$	$\tau_L = 0.7$	$\tau_B = 0.7$
Income y^*							
	1	0.990	1.007	0.995	0.938	1.03	0.98
	2	0.990	1.007	0.995	0.938	1.03	0.98
	3	0.989	1.005	0.989	0.934	1.02	0.96
	4	0.987	1.003	0.975	0.925	1.01	0.91
	5	0.974	0.989	0.910	0.882	0.97	0.73
Bequests b^*							
	1	0.957	0.972	1.014	0.819	0.90	1.03
	2	0.957	0.972	1.014	0.819	0.90	1.03
	3	0.956	0.970	1.008	0.816	0.89	1.01
	4	0.954	0.968	0.994	0.808	0.88	0.97
	5	0.941	0.955	0.928	0.771	0.84	0.77

Table 1: Different tax instruments and rates imply different reductions in the steady state levels of income and bequests. We assume that only one tax is implemented at a time. The numbers give the respective fractions of the case in which no taxes are implemented. All tax instruments reduce the income and the received bequests of rich households by a greater fraction than that of poor households.

The level of output is influenced by households' choices on whether to invest in land or capital. Since land and labor are fixed, fiscal policy that stimulates (hampers) investment in capital will unambiguously increase (decrease) output. While a bequest tax only indirectly affects asset prices, taxes on capital income and land rents have a relatively strong impact. As the relative prices of assets change, households will react by changing the composition of their portfolio.[12] Since the tax on land rents shifts investment toward capital, output actually increases. The capital income tax has the exact opposite effect.

While the observed effects of land rent and capital income taxation are quite straightforward, the effects of the bequest tax are governed by the interplay of households' incomes and their substitution behavior. The immediate effect of increasing the bequest tax is to reduce households' income, which follows from the budget equations. A second immediate effect of bequest taxes is that they also increase demand for bequests relative to consumption in both periods of life, which follows from households' first-order conditions.

Table 1 reveals that for relatively rich households the income effect out-

[12] For a graphical exposition of this fact, see Appendix C, Figure C.1.

weighs the substitution effect, while for the poorer households the opposite is true. Since the bequest tax discourages the rich from saving for the purpose of leaving bequests, but encourages the poor to do so,it has a strong potential for wealth redistribution from the rich to the poor. With the bequest tax the Gini coefficient can, thus, be reduced to a significantly lower level than with the taxes on land rents or capital income.

The latter two have natural limits. Once all land rents are taxed away, there is no more scope for further tax increases and wealth redistribution. As capital income taxes are increased, investment in the main source of productivity is choked, and the economy collapses.

3.2.2. Output-neutral tax reform.

Figure 1 suggests that several combinations (τ_L, τ_B) of land rent tax and bequest tax rates can redistribute wealth while at least maintaining the same steady state level of output. In Figure 2 we show how the Gini coefficient changes under different combinations of bequest and land rent tax rates which do not reduce the steady state level of output below the level of the benchmark case in which $\tau_K = 0.2$, and $\tau_L = \tau_B = 0$. The assumed fixed capital income tax rate of 20% is roughly in line with the corresponding average tax rate in OECD countries.

It turns out that a typical OECD government has considerable freedom in choosing the desired value of the Gini coefficient without having to bear any costs in terms of forgone output. In our experiment, the Gini coefficient may be reduced from its benchmark value 0.63 down to almost 0.52, and public revenues increase from 1.4% to about 11% of output, as Table 2 shows.

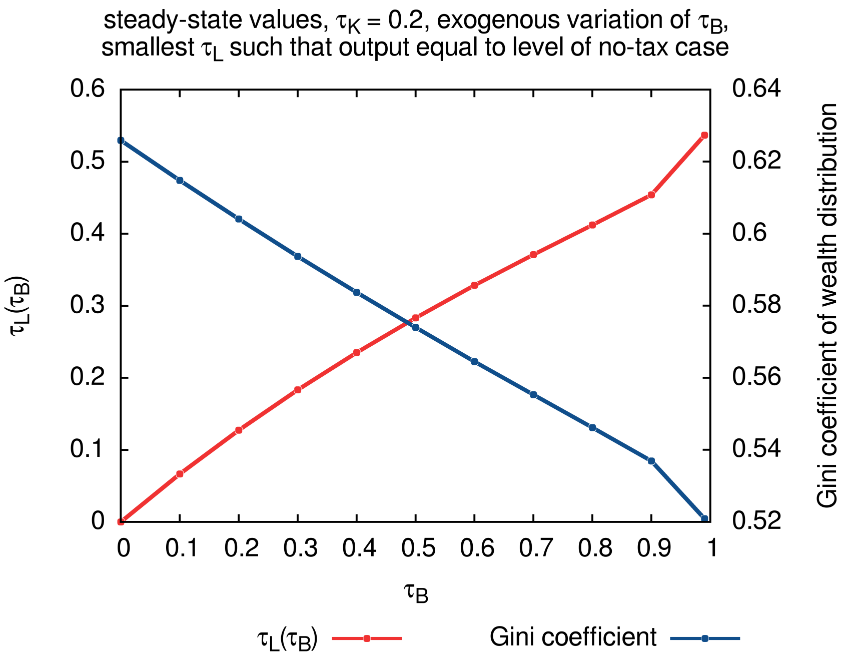

Figure 2: Combinations of bequest- and land rent taxes that imply the same steady-state level of output as in the benchmark case in which $\tau_K = 0.2, \tau_L = \tau_B = 0$.

τ_B	τ_L	Gini	public revenue per capita [10^3 2005 US$/30 years]	[fraction of output]
0.00	0.00	0.63	14	1.4%
0.10	0.07	0.62	28	2.8%
0.20	0.13	0.60	40	4.0%
0.30	0.18	0.59	52	5.3%
0.40	0.24	0.58	63	6.4%
0.50	0.28	0.57	73	7.4%
0.60	0.33	0.57	82	8.3%
0.70	0.37	0.56	91	9.2%
0.80	0.41	0.55	98	9.9%
0.90	0.45	0.54	105	10.6%
0.999	0.54	0.52	104	10.5%

Table 2: Combinations of bequest and land rent taxes that imply the same steady-state level of output ($f^* = 0.99$ million 2005 US$ / 30 years) as in the benchmark case in which $\tau_K = 0.2, \tau_L = \tau_B = 0$.

3.3. The spending side of fiscal policy

So far, we have only considered the revenue side of fiscal policy. Thereby we have assumed that the public revenues do not feed back into the economy. However, since public revenues are an endogenous variable and can become quite substantial, we now turn to the analysis of alternative uses of these revenues. Here, we show how different ways of recycling the revenues as lump-sum transfers to young and old households affect the policy-option space. In Section 4.2, we also consider the alternative case of productivity enhancing public spending, for example through infrastructure investments.

3.3.1. Lump-sum transfers to young and old households

We analyze the impacts of different transfer schemes by varying the distribution parameter $\delta \in [0, 1]$. Its value indicates the fraction of total transfers going to the old generation. Now, the budget equations of the young and the old households living in period t are given by

$$c^y_{i,t} + s_{i,t} = w_t + b_{i,t}(1 - \tau_B) + (1 - \delta)g_t,$$
$$c^o_{i,t} + b_{i,t} = (1 + R_t(1 - \tau_K))k^s_{i,t} + l_{i,t}(p_t + q_t(1 - \tau_L)) + \delta g_t.$$

As Figure 3 shows, it makes a significant difference whether the government transfers the public revenues only to young households ($\delta = 0$), only to old households ($\delta = 1$), or to both[13]. The more the government directs transfers to the young, the higher the level of output in the steady state will be and the more equal wealth will be distributed.

If a transfer increases a young household's income, it directly increases consumption as well as savings (an income effect), and thus also capital supply and output. By contrast, a transfer to old households can in principle increase savings only indirectly. Through the direct income effect the old consume more and leave more bequests. Leaving more bequests, as second-order effect, increases the income of the descendants. If bequests are taxed, then the second-order

[13]Here, we use $\delta = \frac{1}{2}$. In general, of course, any $0 < \delta < 1$ implies transfers to both.

increase of the income of descendants is even smaller. However, it turns out that transfers to the old actually reduce savings through a substitution effect: Since young households anticipate the higher income in old age, they save less. The substitution effect is stronger for those households that have relatively low preferences for leaving bequests (and, thus, for savings). An overcompensation of the income effect through the substitution effect explains why the Gini coefficient increases and the output level decreases with δ.

It is worth mentioning that there is a relatively low threshold for the percentage of transfers which go to the old ($0 < \delta < 0.5$) above which the substitution effect is so strong, that steady state output falls below the case in which public revenues are not even fed back into the economy (see Appendix C, Figure C.3).

If the government uses the bequest tax, public revenues are highest under recycling scheme $\delta = 1$. The more transfers are directed to the young, the lower the bequest tax revenues become. Revenues from land rent and capital income taxes show no substantial change under variation of δ.[14] This difference is due to the fact that, unlike with the factor taxes, the choice of the redistribution parameter δ directly changes the tax base of the bequest tax.

[14] See Appendix C, Figure C.2 for a graphical exposition of this fact.

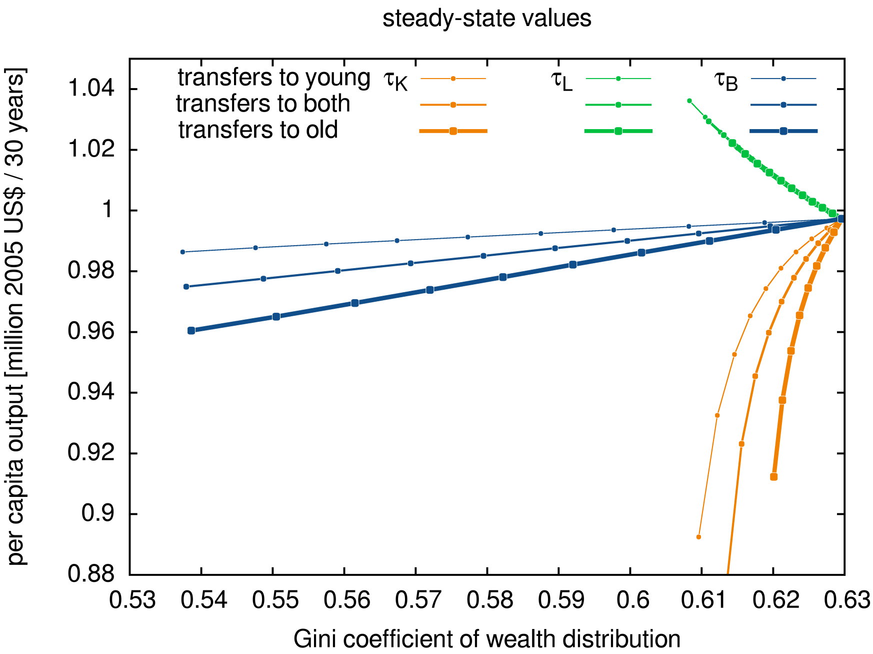

Figure 3: Impact of different recycling schemes on output and the distribution of wealth.

4. Robustness checks and sensitivity analysis

This section shows the robustness of our main results with respect to different assumptions about model specifications. In Section 4.1, we describe how the policy option space (cf. Figure 1) changes under different parameter choices. Then, in Section 4.2, we discuss the alternative assumption that the government finances infrastructure investments with the tax revenues – instead of recycling them as lump-sum transfers.

4.1. Sensitivity analysis of the impacts of fiscal policy

We have calibrated the model parameters to match observed data on the distribution of wealth in OECD countries (OECD, 2015) under the assumption that the capital income tax rate τ_K is 20%, while land and bequests are not taxed – we shall refer to this as the standard policy case. To test the sensitivity of our results to the parameter choice, we have performed a one-at-a-time variation of all model parameters. For each variation of one specific parameter we have subsequently recalibrated all other parameters such that the standard policy case reproduces the observed data again.

For most tested parameters, we find that a variation has no significant qualitative nor quantitative effect on our results. However, the elasticity parameters of the utility function η and of the production function ϵ reveal a non-trivial relationship between parameter choice and model results. Thus, in the following we only present the results of separate variations of η and ϵ. Neither the simultaneous variation of the latter two parameters, nor simultaneous variations of multiple other randomly chosen parameters provided any further insights.

4.1.1. Utility function

The elasticity parameter of the utility function η has a significant impact on the distribution of wealth and, moreover, on output, even when taxes are not taken into account (see Figure 4). Ceteris paribus, the steady state level of output increases with η, while the Gini coefficient decreases. The reason is that households' substitution behavior depends on η. The first-order conditions

(9) and (10) determine the relative demand for consumption and bequests. It turns out that higher values of η induce poorer households to save more, while it does not discourage rich households from leaving bequests significantly. Taken together, total wealth increases, in particular capital, and thus also output.

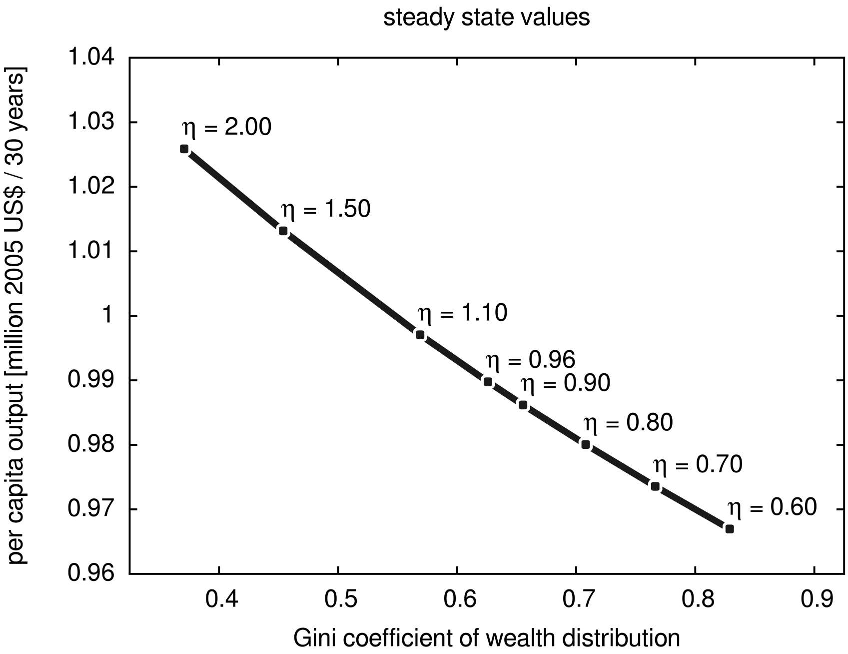

Figure 4: Variation of preference parameter η without recalibration to observed data. Benchmark case: $\eta = 0.96$.

Now, consider the parameter variation under recalibration of all other parameters. Figure 5 shows that the behavior of the economy in reaction to fiscal policy is sensitive to changes in the elasticity parameter. First, note that the potential to redistribute wealth with the capital income or the land rent tax increases with the elasticity parameter η. This is because increasing η implies that the tax-induced reduction in the after tax rate of return to savings $1 + R^*(1 - \tau_K) = 1 + \frac{q^*}{p^*}(1 - \tau_L)$ induces a stronger behavioral response. This means that for higher η, households reduce their savings more strongly in reaction to increases in capital income or land rent taxes. As discussed in Section

3.2.1, richer households' incomes are thus reduced by a higher factor than poorer households' incomes.

In contrast, the government's scope for wealth redistribution via the bequest tax decreases as η increases. The bequest tax is progressive due to the income effect it induces.[15] For higher values of η, however, the substitution effect gains in importance relative to the income effect, and thus, the bequest tax becomes less progressive.

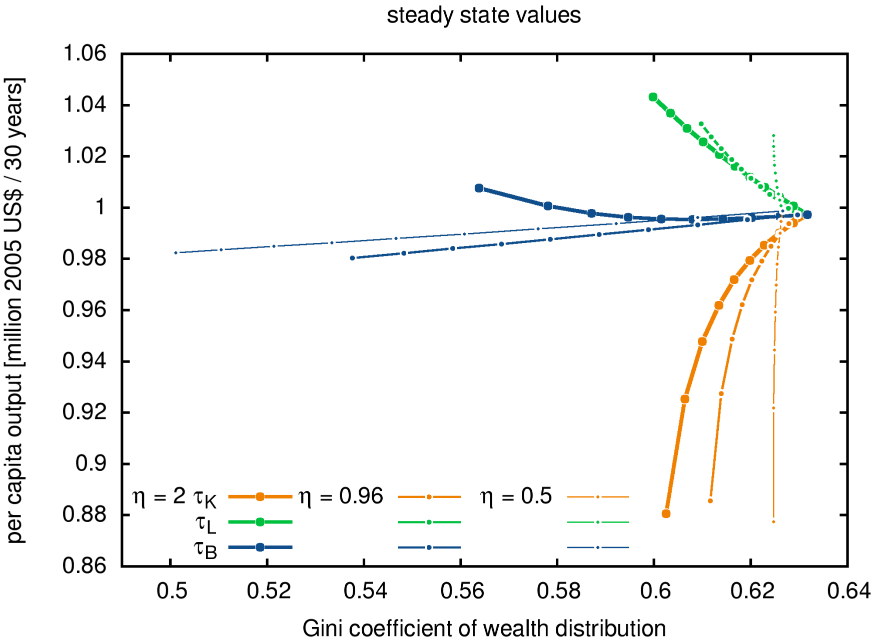

Figure 5: Policy-option space under variation of preference parameter η and subsequent recalibration of all other parameters such that the case of $\tau_K = 0.2, \tau_L = \tau_B = 0$ remains invariant under the variation of η.

Further, Figure 5 reveals that reactions to the bequest tax in term of steady-state levels of output are qualitatively different for different values of η. When η is relatively high, the bequest tax has the tendency to increases output, in

[15] As explained in Section 3.2.1, rich households' income includes a higher proportion of bequests. Bequest taxes thus reduce their income by a higher factor than the incomes of poorer households.

particular for higher tax rates. The opposite is the case for lower values. The variation illustrated in Figure 5 shows us how η determines the relative size of income and substitution effects of the bequest tax (see also the discussion in Section 3.2.1). For high η, the tax-induced substitution effect outweighs the income effect, households redirect their income away from consumption towards leaving bequests. Thereby they save more, which implies more capital, and thus a higher output level. For low η the opposite is the case.

Finally, in Figure 6 we see that the potential to raise public revenues with the bequest tax τ_B strongly depends on the choice of the elasticity parameter η. The higher η is, the greater the revenue raising potential of the bequest tax becomes. In contrast, revenues from capital income and land rent taxation remains almost unchanged when η changes.

The mechanism that drives this behavior is again the interplay of the income and substitution effects. For a high elasticity parameter η, the substitution effect outweighs the income effect. In that case, increasing the bequest tax also increases the demand for leaving bequests, and thus increases the tax base. In analogy, for low values of η, the opposite is the case.

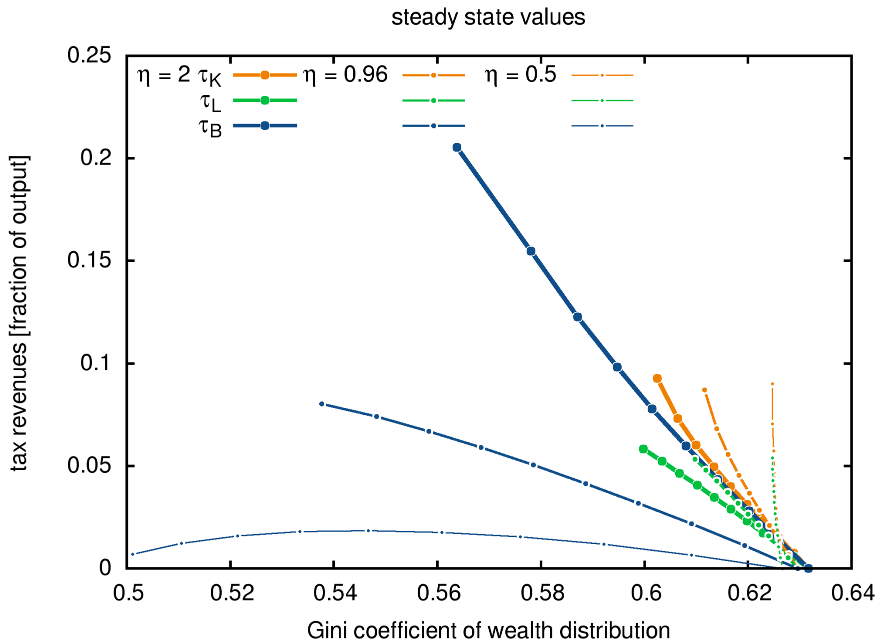

Figure 6: Tax revenues and Gini coefficient under variation of preference parameter η and subsequent recalibration of all other parameters such that the case of $\tau_K = 0.2, \tau_L = \tau_B = 0$ remains invariant under the variation of η.

4.1.2. Production function

Figure 7 shows that varying the substitution elasticity ϵ (and subsequently recalibrating all other parameters) has no greater qualitative impact. However, the graph shows clearly the intuitive result that varying the elasticity does change the results quantitatively. The higher the substitution elasticity is, the greater is the impact of bequest and capital income taxes on output and the wealth distribution. In contrast, the impact of land rent taxation on the wealth distribution is slightly reduced.

Varying ϵ changes the elasticity of capital supply with respect to capital income and bequest taxes. Hence, we observe a relatively strong increase in the impact of the two instruments if ϵ is increased. Since land is a fixed factor, changes in the effects of land rent taxation are much less pronounced when ϵ is varied.

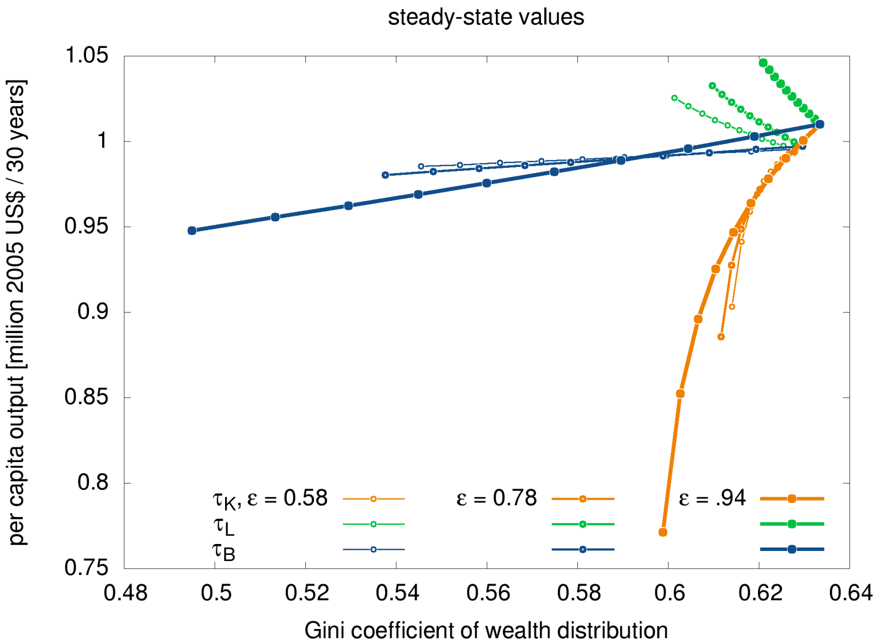

Figure 7: Policy-option space under variation of substitution elasticity ϵ and subsequent recalibration of all other parameters such that the case of $\tau_K = 0.2, \tau_L = \tau_B = 0$ remains invariant under the variation of ϵ. Benchmark case: $\epsilon = 0.78$.

The elasticity of substitution determines the potential to raise public revenues in a similar way (see Figure 8 and Table C.4 in Appendix C). Thus, the potential of the land rent tax remains invariant. Under relatively high values of ϵ, the bequest tax has a higher tendency to erode its tax base. Consequently, increasing ϵ reduces the tax revenues collected with the bequest tax. Finally, the capital tax also erodes its tax base more strongly under higher values of ϵ. However, the decrease of the capital stock k^* is less than the increase of the interest rate $R^* = f_k(k^*)$. Therefore, capital income tax revenues $k^*R^*\tau_K$ increase if the elasticity of substitution ϵ increases.

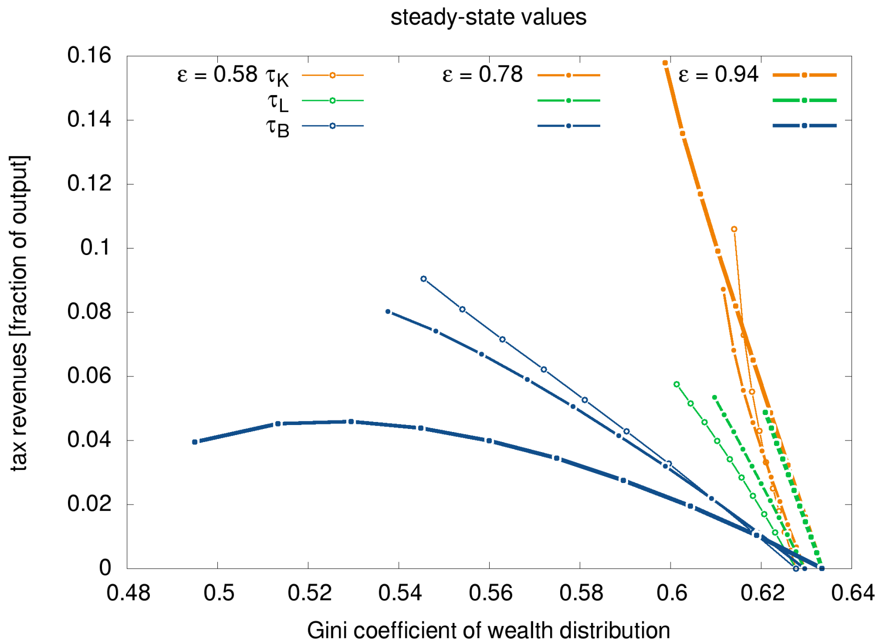

Figure 8: Tax revenues and Gini coefficient of wealth distribution under variation of substitution elasticity ϵ and subsequent recalibration of all other parameters such that the case of $\tau_K = 0.2, \tau_L = \tau_B = 0$ remains invariant under the variation of ϵ. Benchmark case: $\epsilon = 0.78$.

4.2. Alternative spending option: Infrastructure investments

In Section 3.3 we considered different ways of recycling tax revenues as lump-sum transfers to the households. Here, we briefly show how results change under the alternative assumption that the government spends tax revenues to enhance firms' productivity, for example through infrastructure investments. In the following, we assume a simple linear relationship between public revenues and total factor productivity A:

$$A_t = A_0 + x_1 g_t$$

The impact of varying the efficiency parameter x_1 on output and the distribution of wealth are summarized in Figure 9. Independent of which tax instrument is used, an increase in the efficiency of public expenditures also increases the steady state level of output.

While output is quite sensitive to changes in x_1, the wealth distribution remains almost unchanged. The reason is that increasing x_1 raises incomes for all types of households equally. The so-caused increase in total factor productivity does not only increase wages, but also the return on savings. In sum, the incomes of all households increase by almost the same factor and the wealth distribution remains virtually unchanged.

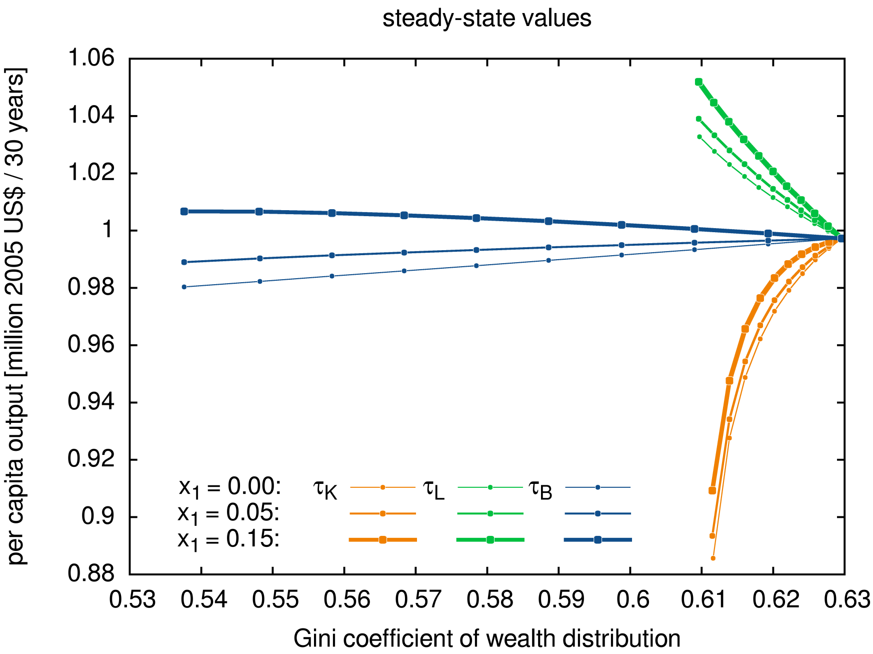

Figure 9: Impact of different degrees of effectivity of infrastructure on output and the wealth distribution

5. Conclusion

Is capital back? Thomas Piketty and Gabriel Zucman claim that this is the case by highlighting that the currently observed increased levels of inequality are due to a concentration of capital ownership at the top (Piketty, 2014, Piketty and Zucman, 2014). Recent literature, however, suggests that land ownership and bequest heterogeneity play a more important role in the process of wealth concentration (Homburg, 2015; Stiglitz, 2015; Cagetti and De Nardi, 2008). We illustrate this in an overlapping generations model that accounts for both features.

Our conclusions differ from Piketty's. Life-cycle saving (when invested in capital) should be left untaxed, while taxing bequests has a higher scope for redistribution at lower policy costs. Further, taxing the land rent component of wealth has a moderate scope for redistribution and strongly enhances output, due to a beneficial portfolio effect: Households shift investments away from the fixed factor land towards capital. The increase in capital investments directly increases output. Accordingly, capital income taxes reduce output since they discourage capital investments.

Atkinson (2015) takes up the idea of the stakeholder society (Ackerman and Alstott, 1999) and proposes, among other measures, to reduce inequality by endowing young households with a one-time transfer at adulthood. That transfer, according to Atkinson, should be financed by a wealth or inheritance tax. We demonstrate that financing such a transfer indeed reduces inequality. We find that the more the transfers are directed to the young and the less they are directed at the old, the higher output in steady state is and the more equal the wealth distribution is. In this case, reducing inequality goes hand in hand with enhancing output.

While heterogeneity in bequests is a key driver of the wealth distribution, it is not the only one which has been suggested by the literature. Entrepreneurial risk taking, income inequality, or the type of earnings risk at the top of the distribution (Cagetti and De Nardi, 2008; De Nardi, 2015), as well as differences in education (Pfeffer and Killewald, 2015) also may play an important role in determining the shape of the distribution and how it changes over time. The quantitative importance of each factor is still an open research question, and the design of tax policies crucially depends on its answer. Accordingly, our results will differ from findings based on other assumptions about the drivers of wealth inequality. Extending our analysis of policy instruments to a framework with multiple drivers of wealth inequality, as used for instance by De Nardi and Yang (2014), could yield valuable insights.

There is a further promising avenue for future research based on the present article. The policy instrument analysis conducted here has focused only on the impact of exogenously determined tax reforms on the steady state. It would be desirable to embed our analysis within a framework of optimal taxation and social welfare maximization, and thus combine the theory of optimal taxation with the literature on household heterogeneity.

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A. Mathematical tools

Here we develop some mathematical tools to analyze the simple model from Section 2.

Lemma A. *If there exists a period t' such that for all $i \in \{1, ..., N\}$ it holds that $b_{i,t'} = b_{i,t'+1} > 0$, then there are b^* and k^* such that $k_{t'+l} = k^*$ and $b_{i,t'+l} = b_i^* \quad \forall l \geq 1$.*

Proof. Let t' be such that $b_{i,t'} = b_{i,t'+1}$ $\forall i$. Then it follows that

$$k_{t'+2} = \frac{1}{N} \sum_i b_{i,t'+1} = \frac{1}{N} \sum_i b_{i,t'} = k_{t'+1},$$

which implies $w_{t'+1} = w_{t'+2}$ and $R_{t'+1} = R_{t'+2}$. Using this we have

$$\begin{aligned} b_{i,t'+2} &= \varphi_i\Big(w_{t'+2} + (1 + R_{t'+2}(1 - \tau_K))b_{i,t+1}(1 - \tau_B)\Big) \\ &= \varphi_i\Big(w_{t'+1} + (1 + R_{t'+1}(1 - \tau_K))b_{i,t}(1 - \tau_B)\Big) \\ &= b_{i,t'+1}. \end{aligned}$$

The iteration of these two steps closes the proof. □

Corollary A. *If the condition*

$$\lim_{k \to \infty} f''(k)(\beta_i f(k) - k) = 0 \tag{A.1}$$

holds for all i (e.g., when the production function is of CES- or Cobb-Douglas type), there exists a steady state with capital-labor ratio k^*, bequest levels $b_i^* = \frac{w^* \beta_i}{1 - \beta_i R^*}$, and factor prices w^*, R^*.

Proof. Considering Lemma A we have to show that for some $t' \in \mathbb{N}$ the equations

$$b_i := b_{i,t'} = b_{i,t'+1} > 0, \quad i \in \{1, ..., N\} \tag{A.2}$$

have a solution, respectively. To see this, we use Equation (4), which states that

$$b_{i,t'+1} = \varphi_i\Big(w_{t'+1} + (1 + R_{t'+1}(1 - \tau_K))b_{i,t}(1 - \tau_B)\Big).$$

W.l.o.g. we assume that $\tau_B = 0 = \tau_K$. Plugging in Equation (A.2), we have

$$
\begin{aligned}
& b_i = \varphi_i(w_{t'+1} + (1 + R_{t'+1})b_i) \\
\iff \quad & b_i = \frac{\varphi_i w_{t'+1}}{1 - \varphi_i(1 + R_{t'+1})} \quad \forall i.
\end{aligned} \tag{A.3}
$$

When Equation (A.2) holds, we always have $\varphi_i(1 + R_{t'+1}) < 1$. This can be seen by using Equation (4), from which follows that

$$
\begin{aligned}
b_i = \varphi_i(w_{t'+1} + (1 + R_{t'+1})b_i) &\iff (1 + R_{t'+1})b_i\varphi_i = b_i - \varphi_i w_{t'+1}, \\
&\iff (1 + R_{t'+1})\varphi_i = 1 - \underbrace{\frac{\varphi_i w_{t'+1}}{b_i}}_{>0} < 1.
\end{aligned} \tag{A.4}
$$

It remains to be shown that under condition (A.1) the Equations (A.3) have a solution. To see this, let's define

$$
\psi(b_i) := \frac{\varphi_i w_{t'+1}}{1 - \varphi_i(1 + R_{t'+1})}.
$$

Due to constant returns to scale in the production function we have

$$
\psi(b_i) = \varphi_i \frac{f(k_{t'+1}) - f'(k_{t'+1})k_{t'+1}}{1 - \varphi_i(1 + f'(k_{t'+1}))}.
$$

It is straightforward to calculate the first derivative of ψ with respect to b_i. Note that $k_{t'+1} = \frac{1}{N}\sum_j b_j$, so $\frac{\mathrm{d}}{\mathrm{d}b_i}k_{t'+1}(b_i) = \frac{1}{N}$. Thus it holds that

$$
\psi'(b_i) = \underbrace{\frac{\varphi_i f''(k_{t'+1})}{(1 - \varphi_i(1 + f'(k_{t'+1})))^2 N}}_{<0} \left[\varphi_i f(k_{t'+1}) - k_{t'+1}(1 - \varphi_i)\right],
$$

and

$$
\psi'(b_i) \begin{cases} > 0\,, & \text{if } 0 > \varphi_i f(k_{t'+1}) - k_{t'+1}(1 - \varphi_i) \\ = 0\,, & \text{if } 0 = \varphi_i f(k_{t'+1}) - k_{t'+1}(1 - \varphi_i) \\ < 0\,, & \text{if } 0 < \varphi_i f(k_{t'+1}) - k_{t'+1}(1 - \varphi_i) \end{cases}
$$

Due to the monotonicity of the production function, there is only one non-zero value of $k_{t'+1}$ at which it is equal to $\frac{\varphi_i}{1-\varphi_i} f(k_{t'+1})$. Thus, as b_i increases from 0 on, ψ first falls monotonically, then reaches its minimum, and from then on increases monotonically. Depending on the values of the other b_j, $j \neq i$, the capital stock $k_{t'+1}$ could already be greater than $\varphi_i f'$ when $b_i = 0$. Now taking the limit of ψ', we see that

$$\lim_{b_i \to \infty} \psi'(b_i) = \lim_{b_i \to \infty} \frac{\beta_i}{N} f''(\beta_i f - k_{t'+1}).$$

So if Equation (A.1) holds, then ψ approaches some constant value. From Equation (A.4) we know that ψ is always positive. Thus, it must have at least one intersection with the function that maps b_i to itself, which is equivalent to the existence of a solution to Equation (A.3). □

B. Model parameters and calibration

To calibrate the model, we fix the steady state levels of output and wealth to average OECD data (OECD, 2015), the capital income tax rate at its approximate OECD average, and set the land rent and bequest tax rates to be zero. Then we solve for the parameters which describe household preferences and production technology. Table B.3 summarizes these values.

The calibration algorithm is implemented as an optimization problem. More precisely, we find the preference and technology parameters by minimizing the weighted sum of the Euclidean norm of the differences between the OECD data and the steady state levels of output and wealth.

Preferences	Elasticity parameter	η	0.96
	Preferences for consumption when old	μ_1	0.070
		μ_2	0.070
		μ_3	0.095
		μ_4	0.152
		μ_5	0.468
	Preferences for leaving bequests	β_1	0.0001
		β_2	0.0001
		β_3	0.025
		β_4	0.082
		β_5	0.398
Production	Share parameter of capital	α	0.2
	Share parameter of land	γ	0.08
	Elasticity of substitution	ϵ	0.78
	Total factor productivity	A_0	481.9
Tax rates	Capital income tax	τ_K	0.2
	Land rent tax	τ_L	0
	Bequest tax	τ_B	0
Other	Time horizon	T	40

Table B.3: Benchmark parameters that reproduce observed data on the wealth distribution in OECD countries.

C. Additional figures and data

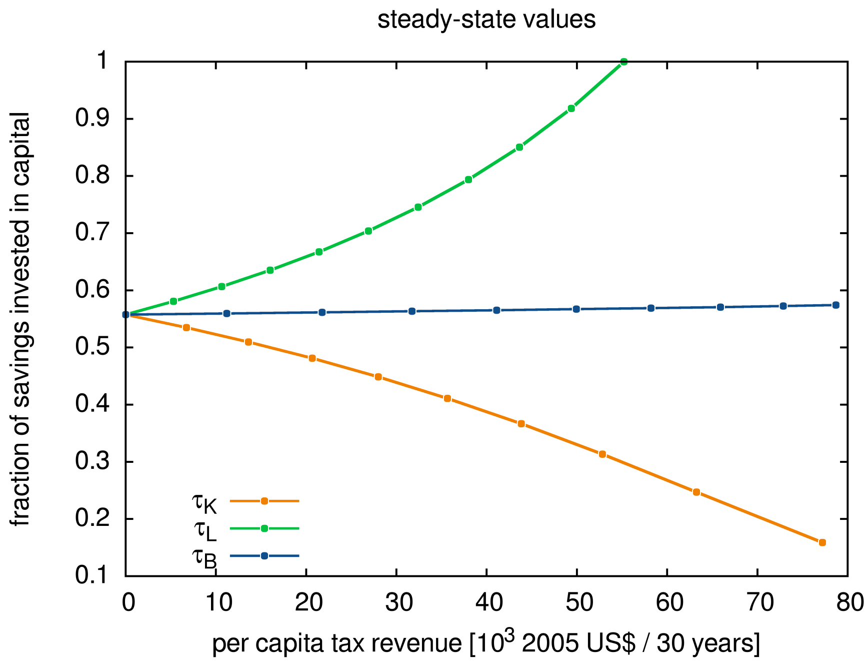

Figure C.1: Aggregate composition of assets (cf. Footnote 12) under variation of fiscal policy. Fiscal policy that stimulates (hampers) investment in capital will unambiguously increase (decrease) output. While a bequest tax only indirectly affects asset prices, taxes on capital income and land rents have a relatively strong impact. As the relative prices of assets change, households react by changing the composition of their portfolio. Since the tax on land rents shifts investment toward capital, output actually increases. The capital income tax has the exact opposite effect.

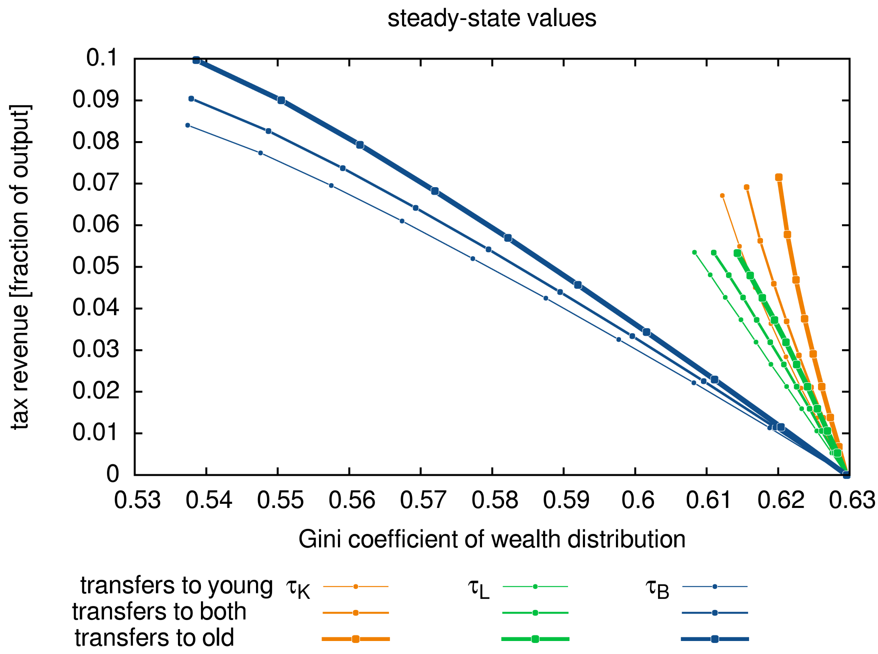

Figure C.2: The revenue raising potential of fiscal policy depends on the recycling scheme used. For all policy instruments, public revenues are higher the higher the share of transfers to the old. However, this effect makes a visible difference only in the case of the bequest tax τ_B. Figure 3 shows how the choice of the transfer scheme affects output.

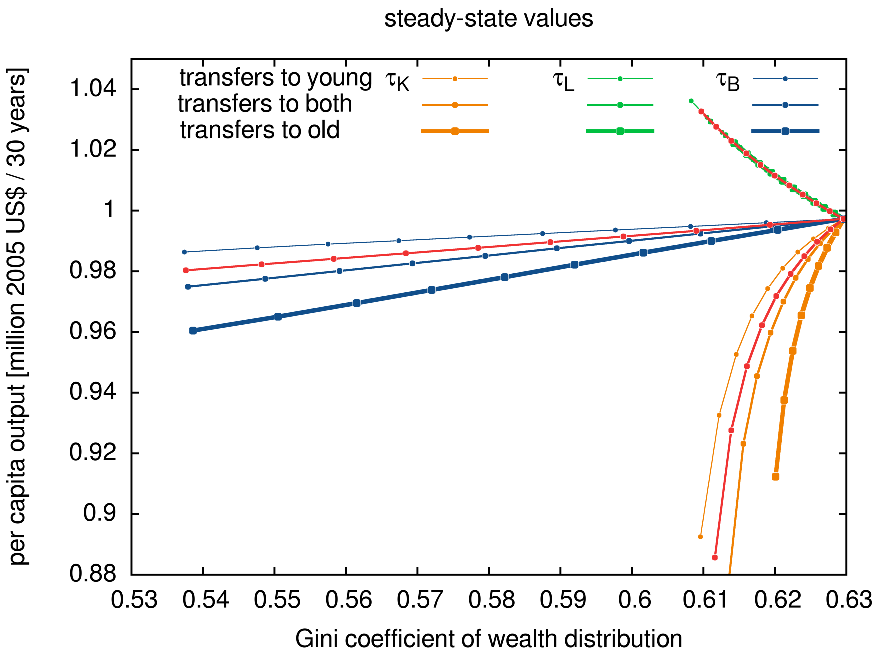

Figure C.3: Impact of different recycling schemes on output and on the wealth distribution (cf. Figure 3). The red lines mark the option space for the case in which public revenues are not redistributed.

	tax rate	tax revenue			output		
		τ_K	τ_L	τ_B	τ_K	τ_L	τ_B
$\epsilon = 0.58$	0.2	11	6	22	990	999	993
	0.5	24	29	52	977	1007	990
	0.7	53	40	71	959	1013	987
$\epsilon = 0.94$	0.2	32	10	19	990	1016	996
	0.5	78	25	39	947	1026	975
	0.7	105	35	44	896	1034	962

Table C.4: Steady-state level of tax revenues and output per capita [10^3 2005 US$ / 30 years] for variation of substitution elasticity ϵ under subsequent recalibration of all other parameters.

D. Kaldor-Hicks criterion

Even though we find that recycling all public revenues to the young as lump-sum transfers enhances output and reduced inequality, a Pareto improvement is not possible. However, we find that at least there are cases in which the Kaldor-Hicks criterion is fulfilled. Consider, for instance, the case in which all land rents are skimmed off and redistributed to the young ($\tau_L = 1$, $\delta = 0$) shown in Figure D.4. Absent any additional transfer mechanism between winners and losers, the households belonging to the first old generation always bear the burden, except those in the lowest wealth quintile $i = 1$, whose utility does not change under the 100% land rent tax. Further, not only the first old generation, but in fact all generations belonging to the top wealth quintile $i = 5$ suffer under the tax.

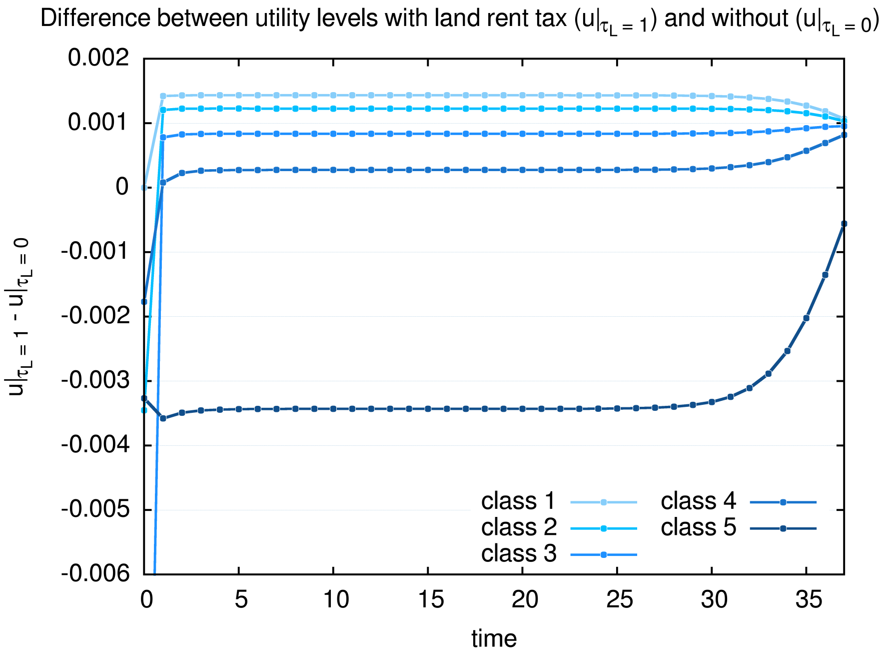

Figure D.4: When land rents are taxed at 100% and recycled as lump-sum transfers to the young, the first old generation and the richest households bear the burden. Their utility under taxation is less than without taxation, i.e., $u|_{\tau_L=1} - u|_{\tau_L=0} < 0$. All other households benefit from the policy.

Now, we introduce a mechanism which allows intertemporal transfers between households. Instead of the lump-sum transfers from public revenues g_t, young and old households may now receive a transfer or have to pay a lump-sum tax X. Their budget equations thus are

$$c^y_{i,t} + s_{i,t} = w_t + b_{i,t}(1 - \tau_B) + X^y_{i,t}$$
$$c^o_{i,t} + b_{i,t} = (1 + R_t(1 - \tau_K))k^s_{i,t} + l_{i,t}(p_t + q_t(1 - \tau_L)) + X^o_{i,t}.$$

Further, we assume that funds can be shifted over time via banking and borrowing at the market interest rate R. Then, for the total volume of the transfers it has to hold that

$$\sum_t \frac{g_t}{\Pi^t_{s=1}(1 + R_s)} \geq \frac{1}{N} \sum_{i,t} \frac{X^y_{i,t} + X^o_{i,t}}{\Pi^t_{s=1}(1 + R_s)}.$$

Our numerical experiments confirm that there are feasible combinations of $\{X^y_{i,t}, X^o_{i,t}\}_{i=1,\ldots,N,\ t=1,\ldots,T}$ such that the winners of the 100% land rent tax can compensate the losers, i.e., that

$$u_{i,t}|_{\tau_L=1} \geq u_{i,t}|_{\tau_L=0} \quad \forall i, t.$$

Chapter 5

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

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[1] submitted to *Environmental and Resource Economics*

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

[1]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).

to capture some of these effects (e.g. Hope (2006), Nordhaus (2007)).[2] 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 substitution possibilities between physical capital and environmental services (Stern, 2008; 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.[3]

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.

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

[3] 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.

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 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), Mattauch et al. (2012), Kalkuhl et al. (2011), Kalkuhl et al. (2013); 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 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).[4]

More controversial is a stronger version of the hypothesis: an environmental

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

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).

For the case of a carbon tax, early numerical simulations supported these findings (Goulder (1995a,b); see also the review by 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 (Schwartz and Repetto (2000); substantial positive health co-benefits of climate policy due to local air quality improvements have been found e.g. by Thompson et al. (2014)). 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) or Tol and Fankhauser (1998)), a strong double-dividend also becomes more likely (Bovenberg and de Mooij, 1997).[5] 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 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

[5] 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.*"

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,[6] 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.

[6] 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.

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 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); or 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 co-operation 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 countrys 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 of 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., 2013a). 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.[7] 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 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

[7]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.

technologies deteriorates vis-à-vis R&D in resource productivity or substitutes for fossil fuels, for example renewable sources of energy.[8] 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. Efficient 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 todays 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,[9] such as the wider electricity system and transport infrastructure. These parts of the capital stock are often publicly financed or subsidized,

[8] 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.

[9] 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.

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.[10]

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

[10]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) 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.

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 climate 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 mitigation costs, in particular in the long run: Beyond the mid-2030s, 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 (2015) in a simple static model considers the optimal composition of public spending to accompany environmental taxation when two publicly provided goods are complementary to clean and dirty private consumption goods, respectively.

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 (Shalizi and Lecocq, 2010, cf.): (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

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).[11] 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, 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.[12] 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 Aschauers study for the US and finds

[11] 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'.

[12] 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.

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 from other taxes cannot be changed, the new revenues from climate policy can be allocated freely to different spending options, at least initially.[13]

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

[13]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.

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 countrys 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:

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 is an argument regarding inter-generational distribution, 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.[14]

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 households transfers and cutting distorting taxes with climate policy revenues to mitigate regressivity: Chiroleu-Assouline and Fodha (2011, 2014) use an overlapping generations approach where agents have different income sources and skills, and thus income levels, as well as different time preference rates. They show that for any degree of progressivity of a carbon tax, there is a labor tax-cutting redistribution mechanism that renders the tax reform Pareto-improving. In their framework, climate policy is acting like a capital tax and the regressivity of this tax is not caused by any of the drivers listed above, but rather by the design of the pre-existing labor tax system.

Klenert and Mattauch (2015) and Klenert et al. (2015) 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 the poorer a household, the more of its income it spends 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.

[14] 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.

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.[15]

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 crises in the U.S., 1929 and 2007, which both were foreshadowed by a strong increase in wealth and welfare inequality.[16]

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

[15] 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).

[16] 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).

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. (2014) and Klenert et al. (2014) 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[17] 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. (2015)), 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 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.

[17]Attanasio (1994), Dynan et al. (2004) and Browning and Lusardi (1996) demonstrate that the savings motive varies across income classes. Quadrini and Ríos-Bull (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.

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 todays 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[18] 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.

A second 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.

However, one may doubt whether such a model captures the relevant features of asset-holders behavior. The premise that future generations would pay todays proprietors higher prices for assets if future rents were higher due to miti-

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

gation 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 model, 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.

A third, 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 standard discounted utilitarianism, if (intragenerational) equality is valuable as such (see Section 3.5) one may find that welfare gains are larger compared to evaluations under discounted utilitarianism. 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.[19]

From a practitioners 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 practitioners 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 ones 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:

[19] 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.

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 government 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 practitioners 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 if climate policy is 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 practitioners 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., 2015).[20] 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 merging 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., 2013b, 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 en-

[20]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).

vironmental 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:

Concerning the assessment of climate policy, IAMs have generally been designed to include as many effects relevant climate change mitigation as possible.[21] 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.

[21] 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 6

Synthesis and Outlook

Scholars of climate change economics have studied many obstacles to achieving the goal formulated in the UNFCCC to prevent dangerous climate change – the "greatest market failure the world has ever seen" (Stern et al., 2006). This thesis approaches the problem from a different angle by taking first steps towards a new *public* economics of climate change. It demonstrates that taking a public finance perspective on climate policy yields new scientific insights and new policy conclusions. By carrying out detailed policy analyses of different tax instruments, this thesis contributes to a better understanding of governments' scope of action to achieve their social, environmental, and fiscal goals. In the four main chapters, respectively, I have shown the following main results.

1. Even if finance ministers do not take climate change into account, they still have a fiscal incentive to unilaterally implement carbon taxes in order to skim off resource rents and to finance infrastructure investments. Following the incentive to tax carbon unilaterally does not cause a green paradox. Instead, it constitutes a viable green policy.

2. When governments unilaterally implement carbon taxes, they should mitigate adverse distributional impacts on workers in energy intensive sectors by granting sectoral exemptions from labor taxes instead of the carbon tax.

3. Governments have considerable freedom in reducing wealth inequality without sacrificing output by taxing land rents and bequests.

4. On a more abstract level, the interactions of climate policy with other governmental objectives of public finance yield beneficial fiscal effects.

The remainder of this chapter is organized as follows. In Section 6.1, I will synthesize my main findings. Subsequently, in Section 6.2, I will discuss the methods used to obtain my results. In Section 6.3, I will critically discuss the novelty of the arguments put forward in favor of rent taxation. Finally, Section 6.4 suggests directions for future research, and Section 6.5 gives a cautiously optimistic outlook.

6.1 Rents, taxes, and distribution

One of the main contributions this thesis makes as a whole is to show the importance of *rent taxation* for environmental and fiscal policy: first, by arguing that in a globalized economy finance ministers favor carbon taxes over capital taxes, since the former can capture resource rents for the purpose of infrastructure investments (Chapter 2); and second, by showing that land rent taxes in combination with bequest taxes give governments substantial freedom in redistributing wealth without sacrificing GDP (Chapter 4).

The overall policy instrument analysis provided by this thesis puts, in fact, considerable emphasis on tracing out the *distributional impacts* of environmental and fiscal policy. While Chapter 2 puts forward a strong fiscal argument for the efficiency of unilateral carbon taxation when capital is internationally mobile, Chapter 3 scrutinizes the scope of action of national governments to relieve those workers who suffer disproportionately under such climate policy. In contrast to Chapter 3, in which the more specific question of equity and efficiency in an open economy with unilateral environmental policy is analyzed, Chapter 4 studies distributional aspects on a rather general level by considering the overall distribution of wealth, albeit within a closed economy. Taken together, the policy analysis in this thesis contributes to a better understanding of policy options for national governments to address distributional issues.

There are several examples of climate policy's fiscal benefits, and in Chapter 5, this thesis provides a systematic, yet non-exhaustive overview by grouping the discussed interactions into three categories. The interactions concern, first, public revenue generation, as climate policy may appropriate resource rents and induce macroeconomic portfolio effects. Second, they concern public expenditures, since both composition and level of governmental spending need to be adjusted in the presence of climate policy. Finally, distributional effects are also included, because intragenerational equity depends on appropriate revenue recycling, and intergenerational Pareto improvements are possible through intertemporal transfers. By putting the individual research questions and results into perspective, this chapter can also serve as the basis for a broader research agenda.

6.2 Innovative, tractable, and flexible models for policy instruments analysis

A further main contribution of this thesis is the development of new models for each of the Chapters 2, 3, and 4. The individual research questions of these chapters are all motivated by the need for sound policy advice in the light of real economic and political problems. Thus, the newly developed models need an intermediate degree of complexity, for which numerical solution methods are ideally suited.

Numerical models of intermediate complexity are especially well-suited to answer questions that involve multiple interaction effects. Chapter 2 involves the joint analysis of intertemporal and interregional distortions, as well as the simultaneous analysis of the income and the spending side of fiscal policy with multiple tax instruments. Chapter 3, while only implicitly taking the time dimension into account, necessitates the simultaneous analysis of two countries, two sectors, three input factors, and preferences for three types of goods in households' utility. In both of these chapters, the newly developed models are capable of calculating the optimal tax portfolio; only the model of Chapter 4 does not involve normative analysis, since no social welfare function is employed. However, analyzing the economic impacts of taxes on capital income, land rents, and bequests again involves multiple dimensions, because it considers intertemporal growth dynamics, intra-generational wealth distributions, and inter-generational savings behavior.

While the increased degree of complexity does not yield the clarity of more highly stylized analytical models, it is still possible to reveal and isolate underlying economic mechanisms. A case in point is the analysis of different assumptions about the strategic behavior of resource-importing and -exporting countries in Chapter 2. The robustness and generality of the key results is ensured by comparing the behavior of cooperative and non-cooperative importers, and of strategically and non-strategically interacting exporters. Further examples for the potential to gain in-depth insights about fundamental mechanisms are the extensive comparisons of different scenarios along three different dimensions in Chapter 3, and the detailed monitoring of income and substitution effects in Chapter 4.

On the other hand, limiting the degree of complexity to an intermediate level allows for more freedom and flexibility, both for the purposes of robustness analysis, and for adaptation to future research endeavors. All three models developed for this thesis could be easily modified, extended, or re-calibrated to answer different research questions, which could, for example, pertain to different countries, policy instruments, and sectors. Sections 2.6 and 4.5, respectively, give some examples of possible future research questions that could be addressed using modified versions of the individual models. Further examples, along with a discussion of how combining the individual models could also yield new insights, will be given in Section 6.4.1.

6.3 Is arguing for rent taxation water under the bridge?

This thesis argues for rent taxation, even though it is already well-known that taxing rents is beneficial. However, there seems to be a lack of appreciation of the fact that, in general, rent taxation is not neutral. Thus, in this section, I trace the analysis of rent taxation back to its historical origins, and critically discuss the novelty of my arguments for rent taxation presented in Chapters 2 and 4.

Adam Smith already endorsed land rent taxation based on the idea that it would be non-distortionary (Smith, 1904, Book V, Ch. 2, §75). David Ricardo, whose work on the subject of differential land rents is a famous classic, supported this view, too (Ricardo, 1821, Ch. 10, §1). A further noteworthy proponent of rent taxation is Henry George, who claimed that one single tax on the unimproved value of land is sufficient to finance all governmental activity (George, 1920). Henry George even inspired a political movement promoting the "Single-Tax" that, despite his success as a scholar, is considered to have failed – partly due to the substantial opposition it managed to arouse (Candeloro, 1979).

Notably, Georgism declined as a political movement during a period in which land rents were comparably small. In their recent working paper, Knoll et al. (2014) show for the case of 14 advanced economies (including the U.S.) that land prices remained constant from the 19th to the mid-20th century, but rose sharply after the Second World War. According to the authors, an important explanation for the stagnating land prices is the so-called transport revolution, which substantially augmented the supply of land up to the mid-20th century. The decline of transport costs subsided in the second half of the 20th century, land increasingly became a fixed factor, and thus, prices started to increase.

Perhaps the long period of stagnating land prices can help to explain the fact that research in economics has largely abstracted from land and other fixed factors over the course of the 20th century, and rent taxation played a comparatively little role in the fiscal policy of most governments.[1] The commonly held view was that of Adam Smith, namely that taxes on rents associated with fixed factors are neutral – taxing rents would not distort economic decisions. A corollary of this view would have been to dismiss any newly conducted research arguing for rent taxation as water under the bridge.

However, taxing rents is not neutral. Feldstein (1977) was the first to discuss the mechanisms of how a tax on land rents may in fact be distortionary. In a discrete overlapping generations model (OLG), he showed, for instance, that if land owners can also hold other assets they may rebalance their portfolio by directing investments into other accumulable assets. Feldstein's portfolio effect does not seem to have been widely appreciated immediately. It was formalized only much later in continuous OLGs by Petrucci (2006) and Edenhofer et al. (2015b); the latter au-

[1] Other reason why governments do not rely more on land rent taxation may include the difficulties to distinguish between the value of the land rent and the value of the improvements to the land. Further, the political economy can be expected to play an important role, too. Taxing land rents would require governments to balance the interests of winners and losers in an equitable way. Moreover, land rent taxation would likely raise strong opposition from landowners, in many countries an influential lobby.

thors even show that taxing land rents can be socially optimal if the proceeds are recycled appropriately.

The analysis conducted within this thesis in Chapter 4 confirms that taxing rents is not neutral. The model used does not involve a social welfare function and, thus, statements about social optimality may not be derived from it. Nevertheless, it corroborates the finding of Edenhofer et al. (2015b) by showing that when a government taxes land rents, the Kaldor-Hicks criterion[2] is satisfied, and Pareto improvements are theoretically possible.

Chapter 2 also presents a new argument in favor of rent taxation by showing how it can help to overcome fiscal externalities. The novelty lies in jointly considering tax competition and the dynamics of fossil resource extraction, and the politically relevant results. However, the design of the specific model is indeed consistent with neutrality of rent taxation.

Beyond the scope of this thesis, revisiting fixed factors and rent taxation is of general interest, and does not only contribute to a better understanding of the public economics of climate change. It is, in fact, key to consistently interpreting the data on wealth inequality collected, discussed, and widely disseminated by Thomas Piketty, Emmanuel Saez, and Gabriel Zucman (see e.g. Piketty, 2014; Piketty and Zucman, 2014; Saez and Zucman, 2016), as Homburg (2015) and Stiglitz (2015) have shown. Moreover, Mattauch (2015) even argues that distinguishing fixed factors and their rents from accumulable capital income is crucial to making sense of the two mutually exclusive narratives of capitalism – liberation or exploitation.

6.4 Next steps towards a new public economics of climate change

The specific research questions presented in Chapters 2, 3, and 4 follow the leitmotif of bridging the gap between the economics of climate change and public economics. Further, the overview of beneficial interactions of climate policy with the broader fiscal system in Chapter 5 is an attempt to systematize the overlaps between the two research fields. These efforts can only be first steps, though, and the overview cannot claim to be exhaustive. So, if the research presented in this thesis is to inspire a new public economics of climate change, then it must also explain how to continue the endeavor.

Therefore, in Section 6.4.1, I will consider the models used in the individual chap-

[2]In an economy with multiple agents, a policy reform is said to fulfill the Kaldor-Hicks criterion if the theoretical possibility exists that appropriate transfers from the winners of the reform to the losers could render the reform Pareto-improving. In other words, the winners of the reform should be able to compensate the losers and still remain better-off after the reform. The Kaldor-Hicks criterion is weaker than the criterion for a Pareto improvement since the transfers only have to be possible in theory. For a more detailed discussion, see Hindriks and Myles (2013, p. 877ff).

ters and discuss how modifying and combining them could yield further insights. Then, in Section 6.4.2, I will discuss how combining horizontal and vertical fiscal federalism could be the next bold step.

6.4.1 Combining individual models developed for this thesis

Each model developed in Chapters 2, 3, and 4 considered on its own could be enhanced to answer new research questions. Some examples are given in Sections 2.6 and 4.5. Building on the results of Chapter 2, another next step could be to include the analysis of asymmetric regions. We already have a basic understanding of how the standard results about tax competition change when there are heterogeneous jurisdictions. If, for example, jurisdictions are of different *size*, then there is an “advantage of smallness” in tax competition; if countries differ in domestic policy constraints, those with fewer such constraints are more successful in attracting capital (Genschel and Schwarz, 2011). However, these insights remain on a conceptual level. By including empirical data, a model based on the analysis of Chapter 2 could evaluate the relative importance of the actual differences between countries more realistically. Such an evaluation could show whether asymmetries tend to exacerbate or rather attenuate the negative fiscal externality of tax competition.

Furthermore, including empirical data could reveal the bargaining positions of individual countries in international negotiations, for example on climate change, but also on fiscal harmonization. This indicates another possible bold next step for future research that would integrate public finance consideration in the economics of climate change: Embedding horizontal fiscal federalism within a framework of coalition stability analysis, such as in Lessmann et al. (2009), could yield new and valuable insights about how issue linkage might facilitate cooperation.[3]

Taking a joint perspective on the models developed in this thesis may provide fruitful new approaches to answering further research questions. For example, the analysis of Chapter 2 could be extended by disaggregating the firm level (energy intensive and other sectors), or the household level (heterogeneous households, overlapping generations). Thereby, the initial perspective that focused only on efficiency would be complemented to include equity aspects, but also factor mobility between sectors. In turn, the distributional analysis in Chapter 4 could be extended to an open economy. Such a model could help to shed light on the question of whether the forces of globalization have a bearing on wealth inequality, and how this limits a national government’s scope of action.

[3]However, in a recent working paper, Schmidt and Runkel (2015) present a rather pessimistic outlook for international climate negotiations by jointly considering tax competition and the free-rider problem.

6.4.2 Vertical fiscal and environmental federalism

In this section, I would like to point towards one important field that this thesis has not taken into consideration, but which can be expected to be of great importance for advancing public economics, as well as the economics and the politics of climate change. While horizontal fiscal externalities have been discussed extensively, in particular in Chapters 2 and 3, analyzing fiscal externalities along the *vertical* dimension must also be part of the effort to integrate public finance considerations into the economics of climate change.

According to Oates (1999), fiscal federalism is concerned with "understanding which functions and instruments are best centralized and which are best placed in the sphere of decentralized levels of government". Vertical fiscal externalities pertain to the transmission of incentives between different hierarchical levels of government: local, regional, and national – and in some cases, such as the European Union, also supra-national.

Due to the lack of an authority capable of enforcing policy on a worldwide scale, or a jointly agreed upon climate policy regime, there is no subject for empirical studies of vertical fiscal externalities on the global level, yet. However, applying vertical fiscal federalism to the global level could improve our understanding of the optimal policy design for a future global climate regime. So far, there has not been much research combining vertical fiscal externalities and climate policy on multiple governmental levels (Dalmazzone, 2006). One of the few exceptions is Williams (2012), who compares different environmental policy instruments in a formal model with one federal government on the upper level, and several state-level governments on the lower level of the political hierarchy. The author calculates different Nash equilibria, and concludes that carbon taxes are welfare superior to emissions trading schemes or command and control policies.[4]

Besides contributing to a hitherto underexplored research area, studying vertical fiscal externalities within the context of climate policy is an important step towards a more rigorous understanding of the idea of a 'polycentric climate regime' (Ostrom, 2010). Elinor Ostrom argues that international negotiations for a solution to climate change on the global level have to be backed by a variety of efforts at national, regional, and local levels. By discussing how such bottom-up efforts can arise, she challenges the conventional theory of collective action, which posits that in the absence of an external authority no one will reduce CO_2 emissions: "What we have

[4]While analytically rigorous applications to the global level are still rare, there is a strand of literature that discusses vertical fiscal externalities in the context of EU climate policy. Böhringer et al. (2008), for example, show how the overlaps of climate policies in the EU cause efficiency losses. Further, Edenhofer et al. (2015c) discuss a minimum price for the emissions allowances as a solution to the current ineffectiveness of the EU ETS. Their analysis is based on the seminal contribution by Chichilnisky and Heal (1994), who apply the concept of Lindahl equilibria to the public goods problem that climate change poses, and emphasize the crucial role of lump-sum transfers for efficiency.

learned from extensive research is that when individuals are well informed about the problem they face and about who else is involved, and can build settings where trust and reciprocity can emerge, grow, and be sustained over time, costly and positive actions are frequently taken without waiting for an external authority to impose rules, monitor compliance, and assess penalties." (Ostrom, 2010, p. 555) However, a rigorous formal analysis of such a polycentric climate regime has not yet been undertaken.

The comparably large literature on tax competition has provided a host of theoretical models of interregional factor mobility, and thus has successfully conceptualized horizontal fiscal externalities. These studies, and in particular the analyses of Chapters 2 and 3 supply one building block towards the formal analysis of a polycentric climate regime.

Combining vertical and horizontal fiscal federalism seems to be a promising avenue for future research. It could produce a more detailed and rigorous understanding of incentive structures and the optimal design of policy instrument portfolios in a vertically and horizontally decentralized world. Establishing formal quantitative models could help to express the concept of a polycentric climate regime.

The need for an international agreement on climate change mitigation is undisputed. Decentral bottom-up efforts cannot fully substitute for international cooperation. However, developing a formal framework that describes a polycentric climate regime is still highly relevant for global climate policy and the international negotiations. Edenhofer et al. (2013), for instance, expect that such a framework will indicate rationales and options that reduce the magnitude of the challenge for negotiations on the global level.

Urpelainen (2013), in a study complementary to Ostrom (2010), verbally describes a channel through which unilateral action, for instance in the form of carbon pricing, could promote collective action. Both authors base their argument on political economy considerations, and they outline how institutions could and should change. Edenhofer et al. (2015a) put this channel into perspective by mentioning three further channels through which bottom-up efforts lead to collective action: technology spill-overs, social learning and signaling, and reciprocity. Based on these, the authors argue that it is possible to establish a hybrid climate regime that combines bottom-up with top-down approaches, and in which bottom-up incentives are coordinated in an international framework.

With a rigorous understanding of polycentric climate regimes in terms of formal models, the endeavor to establish a new public economics of climate change could be fruitfully advanced. Including the combined conceptual approaches of horizontal and vertical fiscal federalism seems a valuable building block. Observing the political process makes it clear that it is about time to understand the complexities of how climate policy can successfully be implemented in a decentralized world with multiple layers of governance.

6.5 A cautiously optimistic outlook

This thesis provides three specific studies of policy instruments and how they enhance a government's scope of action. The specific studies are accompanied by an overview over further beneficial interactions of simultaneously addressing climate change mitigation and other policy objectives. Its tone is quite optimistic as it offers a variety of new solutions and suggests new perspectives.

I believe in the utility of my contributions both for science and politics. But how much optimism do these findings actually justify given that the Intended Nationally Determined Contributions (INDCs) that are on the table (as of December 2015) are not sufficient for achieving the 2°C target?[5] It is obvious that mitigation efforts must increase, and there must be a mechanism that ensures monitoring and enforcement of the individually pledged efforts. It is questionable whether this will be achieved.

The results of Chapter 2 clearly indicate a unilateral incentive to tax carbon. At least until the carbon price has stimulated a transition to a low-carbon economy, the additional tax revenues can help to finance investments in productive public capital. However, the carbon price that is optimal with respect to the objective of financing public capital is likely to lie below the environmentally optimal level to achieve the 2°C target. Nevertheless, the unilateral motivation to price emissions could pave the way towards a global climate agreement by closing part of the 'emissions price gap' (Edenhofer et al., 2015a).

Unilateral carbon pricing facilitates global cooperation for several reasons (Edenhofer et al., 2015a). First, the positive fiscal effects operate on much shorter timescales. Thereby, the adoption by policy makers, who are under short-term political constraints, is rendered more likely, and a lock-in of carbon intensive technologies can be avoided. Further, a decentralized system of coordinated unilateral policies provides more political flexibility than rigid targets and timetables, and could be scaled up gradually over time.

Moreover, unilateral motivations to price carbon are consistent with the suggestions made by Levin et al. (2012) of how to overcome the 'super wicked' problem[6] of climate change: First, the avoided carbon lock-in creates an environmentally beneficial path dependency. Further, visibly connecting additional carbon pricing revenues with improvements of public capital stocks could win popular support for climate policy. The path dependencies bear the potential to entrench and expand political support over time, which Levin et al. (2012) consider prerequisites for ad-

[5]The Climate Action Tracker calculates that these INDCs amount to an expected temperature increase of 2.7°C compared to pre-industrial levels – under the optimistic assumption that governments commit to their pledges. However, a projection based on policies currently in place yields a 3.6°C increase (Gütschow et al., 2015).

[6]Recall that Levin et al. (2012) characterize super wicked problems with four key properties: time is running out; those who cause the problem also seek to provide a solution; the central authority needed to address it is weak or non-existent; and policy responses discount the future irrationally.

dressing super wicked problems.

In sum, the inclusion of fiscal considerations in the design of climate policy may facilitate global cooperation on climate change. This view receives support both from the academic literature, as well as from the momentum towards hybrid approaches in the political arena and the growing number of unilateral carbon pricing initiatives. As of March 2015, 39 national and 23 subnational jurisdictions have implemented or are scheduled to implement carbon-pricing instruments (Fay et al., 2015, Box 4.3). The most recent example is the Canadian province Alberta, whose finance minister explicitly plans to use the additional revenues for infrastructure investments. Perhaps we can take it as an indication that the hopes this thesis has raised might not be in vain.

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List of Papers and Statement of Contribution

The four core chapters of this cumulative dissertation (Chapters 2 to 5) are based on individual research papers. They are the result of collaborations in this PhD project between the author of the dissertation, his advisor Ottmar Edenhofer, his Post-Doc advisor Kai Lessmann, and other colleagues as indicated. The author of the dissertation has made extensive contributions to the contents of all four papers, from conceptual design and technical development to writing. This section explains how the author contributed to the four papers and acknowledges the main contributions of others.

Chapter 2 *Why Finance Ministers Favor Carbon Taxes, Even If They Do Not Take Climate Change into Account.* The final publication is available at Springer via http://dx.doi.org/10.1007/s10640-015-9982-1

The author's contribution to this chapter is the development of the numerical model on which the study is based, as well as the analysis and processing of model results and their visualization in the graphs of the chapter. Discussions and conclusions from these results were written in close cooperation with Ottmar Edenhofer and Kai Lessmann. The text of the chapter was written by the author of this thesis. The definition of the research question is based on an idea by Ottmar Edenhofer, with further refinement by the author as well as Kai Lessmann. The concept of the solution algorithm was developed by Kai Lessmann.

Chapter 3 *Optimal environmental taxation with capital mobility.*

The author of this thesis developed the numerical model used to derive the results presented in the Chapter. The data analysis and visualization in graphs are due to the author. Gregor Schwerhoff designed research. The text of the chapter was written by Gregor Schwerhoff in close cooperation with the author.

Chapter 4 *Is capital back? The role of land ownership and savings behavior*

The conception of the research question and the method to address it are the result of a joint effort by the author, David Klenert, and Kai Lessmann, with additional support by Ottmar Edenhofer. All calculations, the model implementation, data analysis and visualization were conducted by the author of this thesis, with support by David Klenert and Anselm Schultes. Interpretation, discussion, and conclusions were done in close collaboration with David Klenert, Kai Lessmann, and Anselm Schultes. The text of the chapter was written by the author of this thesis, all co-authors contributed refinements.

Chapter 5 *The fiscal benefits of climate policy: an overview.*

Jan Siegmeier and Linus Mattauch designed research, with refinements from all authors. Specifically, the author of this thesis developed the argument on tax competition and David Klenert developed the argument on inequality reduction. Jan Siegmeier wrote the article with major contributions from all authors, specifically to Sections 3.1 and 3.3 by the author of this thesis, and to Sections 2.2 and 3.5 by David Klenert.

Tools and Resources

This dissertation relies in parts on numerical modeling. Software tools were used to create and run the models, and to process, analyze, and visualize the results. This section lists these tools.

Modeling All numerical model experiments performed by the author made use of the General Algebraic Modeling System (GAMS), version 23.7.3 (Brooke et al., 1988) and the CONOPT3 solver, version 3.14S, for non-linear programs (Drud, 1994).

Data Processing Model output was analyzed using perl 5, version 18, R, version 3.0.2 (R Development Core Team, 2008), and visualized using GnuPlot, version 4.6 (Williams et al., 2012)

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Furthermore, I thank my co-authors. It is on the basis of our collaborative effort that my thesis came into being. Our discussions, the insights shared, and the pleasant working atmosphere are valuable to me both professionally and personally.

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Over the course of my time at PIK, the PI Group has undergone quite a transformation. During all stages, though, I have enjoyed the privilege of great co-workers, who always took time to give advice, engage in discussions, and have a cup of coffee with me. I appreciated the pleasant working atmosphere at PIK, and in particular in RD 3. This is not least due to the efforts of Ina Baum, Dorothe Ilskens, Kristiyana Neumann, Nicole Reinhardt, and Susanne Stundner. Moreover, I would like to thank PIK's press team for teaching me how not to see journalists as enemies, and for promoting my research through their channels.

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*Linus Mattauch also called my attention to the two quotes from the COP21 I chose as epigraphs to this thesis.