RENT AND REDISTRIBUTION

THE WELFARE IMPLICATIONS OF FINANCING LOW-CARBON PUBLIC INVESTMENT

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Abstract

Climate policy is more than carbon pricing: successful decarbonization of a national economy creates new rents and affects existing ones, requires public investment, has distributional implications and changes preferences.

This thesis argues that economic theory would be better equipped for analyzing the macroeconomic trade-offs of climate change mitigation if it put greater emphasis on three principles: first, a distinction between rents, derived from fixed factors of production, and capital, that can be accumulated, is needed to understand the impact of climate policy on the wealth distribution. Second, for both rent taxation and financing low-carbon public investment, there is no standard equity-efficiency trade-off. Instead, both rent appropriation and public investment can enhance efficiency and reduce inequality at the same time, when designed appropriately. These first two points are substantiated by incorporating fixed factors of production and household heterogeneity in preferences and income sources into otherwise standard models of economic growth, both of the infinitely-lived agent and the overlapping-generations type. Third, to evaluate consumption decisions, a distinction between welfare as subjective well-being and welfare as the satisfaction of preferences is vital. This follows from applying the behavioral account of decision-making to consumer choices in carbon-intensive sectors such as transportation.

Specifically, the following results are shown: (1) It is proved that to reach socially optimal outcomes, if there are any rents from (quasi-)fixed factors such as land or the atmospheric sink, these should be taxed and the revenue should be invested into productive public capital or redistributed to poor, newborn generations. (2) Simulations indicate that the timing of public investment relative to the timing of an increase in the carbon price or in technology subsidies matters for avoiding a lock-in. (3) If there are two cohorts of wealth owners in the economy, those who save dynastically and those who save in a life-cycle manner, capital taxation has a special role for changing the wealth distribution provided the revenue is used for public investment. It is proved that capital taxation can be Pareto-improving and inequality-reducing. In contrast, consumption and labor taxation are more efficient, but do not reduce inequality. (4) Given that the transport infrastructure and other contextual factors largely influence actual mobility behavior, evaluating the welfare gain of low-carbon public investment needs to differentiate between subjective well-being and preference satisfaction as distinct welfare conceptions.

These results can be seen as steps towards evaluating the extent of the validity of the two major societal narratives about capitalism, which is considered to be either liberation or exploitation, for the transition to a low-carbon economy.

Zusammenfassung

Klimapolitik geht über die Bepreisung von Kohlenstoff hinaus: Eine erfolgreiche Dekarbonisierung einer Volkswirtschaft schafft neue und beeinflusst bestehende Renten, erfordert öffentliche Investitionen und verändert Präferenzen.

Die vorliegende Dissertation zeigt auf, dass volkswirtschaftliche Theorie die makroökonomischen Abwägungen, die bei der Bekämpfung des Klimawandels auftreten, besser untersuchen könnte, wenn die folgenden drei Gesichtspunkte größeres Gewicht bekämen: erstens bedarf es einer Unterscheidung zwischen akkumulierbarem Kapital und Renten, die auf fixe Produktionsfaktoren anfallen. Diese Unterscheidung erlaubt ein besseres Verständnis des Einflusses von Klimapolitik auf die Vermögensentwicklung. Zweitens gibt es für Rentenbesteuerung und die Finanzierung von kohlenstoffarmen Investitionen keine gewöhnliche Abwägung zwischen Gleichheit und Effizienz. Stattdessen können Rentenbesteuerung und öffentliche Investitionen gleichzeitig die Effizienz erhöhen und die Ungleichheit senken, sofern sie entsprechend ausgestaltet werden. Diese ersten beiden Aussagen werden dadurch belegt, dass fixe Produktionsfaktoren sowie Heterogenität in Präferenzen und Einkommensquellen der Haushalte in übliche Wachstumsmodelle integriert werden – sowohl in solche mit unendlich lange lebenden Agenten als auch in solche mit überlappenden Generationen. Drittens ist für die Bewertung von Konsumentscheidungen eine Unterscheidung zwischen den beiden Wohlfahrtskonzepten des subjektiven Wohlergehens und der Präferenzerfüllung unerlässlich. Dies folgt aus Ergebnissen der Verhaltensforschung über die Entscheidungsfindung von Konsumenten in karbonintensiven Wirtschaftssektoren wie dem Transportwesen.

Insbesondere werden die folgenden Resultate erzielt: (1) Für den Fall, dass Renten auf (quasi-)fixe Faktoren wie Land oder die Atmosphärensenke auftreten, wird bewiesen, dass es zum Erreichen des sozialen Optimums nötig ist, jene Renten zu besteuern und die Einnahmen in produktives öffentliches Kapital zu investieren oder an neugeborene Generationen zu verteilen. (2) Simulationen belegen, dass der Zeitpunkt von öffentlichen Investitionen, bezogen auf den Zeitpunkt einer Erhöhung des Kohlenstoffpreises oder von Technologiesubventionen, bedeutsam für die Vermeidung eines Lock-In-Effekts ist. (3) Wenn es in der Wirtschaft zwei Gruppen von Vermögensbesitzern gibt, solche, die dynastisch sparen, und solche, die über den Lebenszyklus sparen, kommt der Kapitalbesteuerung eine besondere Rolle dafür zu, die Vermögensverteilung zu verändern, wenn durch die Einnahmen öffentliches Kapital bereitgestellt wird. Es wird gezeigt, dass Kapitalbesteuerung Paretoverbessernd wirken und gleichzeitig die Ungleichheit senken kann. Demgegenüber sind eine Konsum- oder Arbeitsbesteuerung zwar effizienter, senken

aber die Ungleichheit nicht. (4) Da der Einfluss der Transportinfrastruktur und anderer kontextabhängiger Faktoren auf die Wahl von Verkehrsmitteln hoch ist, muss eine Bewertung der Wohlfahrtsgewinne durch öffentliche Verkehrsinvestitionen zwischen subjektivem Wohlergehen und Präferenzerfüllung als unterschiedlichen Wohlfahrtskonzepten differenzieren.

Für den Übergang zur kohlenstoffarmen Wirtschaft können diese Ergebnisse als Schritte hin zu einer Abgrenzung der jeweiligen Gültigkeitsbereiche der beiden großen gesellschaftlichen Auffassungen über den Kapitalismus dienen – der entweder als Befreiung oder als Ausbeutung betrachtet wird.

Erzbischof: Verzeih o Herr! Es ward dem sehr verrufnen Mann
Des Reiches Strand verliehn; doch diesen trifft der Bann,
Verleihst du reuig nicht der hohen Kirchenstelle,
Auch dort den Zehnten, Zins und Gaben und Gefälle.
Kaiser: Das Land ist noch nicht da, im Meere liegt es breit.
Erzbischof: Wer's Recht hat und Geduld für den kommt auch die Zeit.
Für uns mög euer Wort in seinen Kräften bleiben!
Kaiser: So könnt ich wohl zunächst das ganze Reich verschreiben.

Johann Wolfgang Goethe, *Faust. Der Tragödie zweiter Teil,* 1832

We think too much of production, and too little of consumption. One result is that we attach too little importance to enjoyment and simple happiness, and that we do not judge production by the pleasure that it gives to the consumer.

Bertrand Russell, *In Praise of Idleness*, 1932

Preface

"Die schärfsten Kritiker der Elche / waren früher selber welche."[1] is a German saying, not originating from *Faust*, but due to F. W. Bernstein. Before undertaking the research for this thesis, I was somewhat attracted to the idea of "degrowth" – that the solution to environmental and some social problems is a reduction of economic output. I was deeply convinced by environmentalism and horrified by the great threat of unmitigated climate change for the future of humankind. I was also eager to apply theory to understand what to do about it, but with no idea where the real problems with economics and its critics lie. Now I am a fierce, if sympathetic critic of the degrowth idea, accusing the movement of fallacious reasoning, despite having the right intuitions about what is inadequately conceptualized in current economics. An alternative title for this thesis (if its framing were changed) could thus be "What the growth critics would need to know to produce valid arguments". For this conversion, I am extremely grateful to Ottmar Edenhofer. Many of the ideas elaborated on in this thesis must have been implicit in his thinking for a long time, and certainly the better part of what follows.

However, being a 'growth critic critic' does not make me a supporter of the idea that growth is a panacea. It was once enlightening for me to learn that Wittgenstein's *Philosophical Investigations* can be read as rejecting *both* realism and anti-realism about meaning. I am greatly indebted to my undergraduate tutors for teaching me how to think – and I consider it fortunate that this happened on arcane topics with no ideological preconceptions, such as the philosophy of mathematics. By contrast, politics, but even discourse in the social sciences – as I painfully learned in the past years – seem all too often hampered by an implicit *tertium non datur:* who is not for something must be against it.

Without the support of many people this thesis would not exist.[2] First, I thank my advisor, Ottmar Edenhofer, for hiring yet another non-economics student to do research in economics with him. Over the years, he was a constant source of inspiration despite his gargantuan task of managing Working Group III of the IPCC. He splendidly succeeded in building an environment

[1] Roughly: "The fiercest critics of the moose / were formerly moose themselves." For a (probably fictitious) account of its genesis, see: `http://www.text42.de/elchkritik/die_kritiker_der_elche.shtml`.

[2] Scientification of the world seems akin to technological progress: it never stops. I recently learned that the subsequent acknowledgements strictly adhere to a "three-move structure subdivided into a number of steps realised by a relatively restricted range of lexico-grammatical patterns." (Hyland, K. and Tse, P. (2004). "I would like to thank my supervisor". Acknowledgements in graduate dissertations. *International Journal of Applied Linguistics,* 14(2):259-275.) Following this seminal work, a sizeable literature has discussed whether such a structure prevails in a variety of disciplinary and cultural contexts.

in which young researchers can grow. I am fortunate that he was very patient with me, giving me the chance to integrate our scattered research ideas into what I consider now a mostly coherent whole.

Next, I thank Georg Meran for acting as a second referee of my thesis and for further support. I also thank Volkmar Hartje for serving as chairman of the board of examiners.

I am very grateful to Felix Creutzig, who acted as a second advisor for part of the thesis. He often provided a perspective that was refreshingly complementary to Ottmar Edenhofer's and was an infinite supply of ideas and a great mentor. Most importantly, he taught me, more than anybody else, about the importance of writing. I am glad that he insisted that my contribution should lie in developing theory.

The research presented in this thesis is largely collaborative. I am extremely grateful to my close collaborators, Jan Siegmeier and David Klenert, for their efforts, loyalty, diligence, optimism and extensive discussions on a great variety of topics.

I was also very fortunate to work with Sophie Bénard and Monica Ridgway. I thank them for smoothly managing the transition from students to co-authors and their patience with me with regards to finishing our projects.

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Great support by the administrative teams of the three institutions, where I had the privilege to work, the chair "Economics of Climate Change" at the TU Berlin, the Potsdam-Institute of Climate Impact Research and the Mercator Research Institute on Global Commons and Climate Change is gratefully acknowledged.

I was also fortunate to obtain a graduate scholarship by the Studienstiftung des deutschen Volkes and am very grateful for the additional opportunities to learn, present work and connect with other students which this offered.

Despite all this assistance, any remaining errors are of course my own.

On a personal note, I thank my friends for emotional support in difficult times, inspiration and a constant willingness to listen to my ideas: my *old* friends David Heilmann, David Yadin and Simon Kempny, my *still young* friend Svenja Reith and my (not only geographically) *close* friends Alexandra Surdina, Cristin Lua, Damien Cornu, Janina Hesse, Judith Lehnert, Katharina Jochemko, Maëlle Salmon and Olga Heismann. Thank you for *making me feel understood* in so many different senses and contexts.

Finally, I thank my parents, Angela and Hans, for three decades of unconditional support. From an early age on, they brought me up in an attitude well described by the words of Amartya Sen, that to him, 'academic' means 'sound' instead of 'unpractical' or 'conjectural'. They made me disregard social conformity and equipped me with a diverse set of moral intuitions. Most importantly, they encouraged me to pursue whatever subject I found exciting, which may have taught me not to be intimidated by disciplinary boundaries – it is to them that this thesis is dedicated.

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Chapter 1

Introduction

Two narratives about capitalism dominate economic thinking: "capitalism is exploitation" and "capitalism is liberation" (Haidt, 2015). Recurring themes of the first narrative are that honest workers are abused by greedy capitalists, the destruction of nature, the impairment of social cohesion and the seduction of consumers by companies through advertisement. The second narrative, by contrast, glorifies entrepreneurship, poverty eradication, freedom of trade, technological progress and individual liberty.

Arguably, in the second half of the 20$^{\text{th}}$ century, economic theory has been dominated by the paradigm that capitalism is liberation.[1] For example, the glorification of entrepreneurship tends to result in ignoring unearned income: while there is overwhelming agreement that rent taxation is desirable (Friedman, 1978; Stiglitz, 2002; Mankiw, 2007), fixed factors, from which rents are typically derived, are largely absent from economic models (an exception is Feldstein (1977)). Redistribution is assumed to imply efficiency losses (Okun, 1975), while efficiency-enhancing policy measures are implicitly believed to be distributionally neutral, separating economics from justice. Moreover, welfare functions commonly employed in neoclassical economics contain a single argument, consumption, making it impossible to evaluate critiques of materialism.

A sad consequence of the preoccupation of 20$^{\text{th}}$ century neoclassical economics with the view that capitalism is liberation is that supporters of the exploitation view do not feel represented by economics as a discipline. It is sad for two reasons: first, because those disbelieving the benefits of capitalism point to relevant problems that those educated in a positive view of markets are too blind to see. Second, because this also means that analysis of the relevant problems of capitalism is seldom conducted with the sharp intellectual tools of economics such as microfounded modeling and welfare analysis. An example for this is the recent movement for "degrowth" (Martínez-Alier et al., 2010; Kallis, 2011), combining real shortages of economic theorizing regarding the major problems of environmental destruction, consumerism, inequality and economic instability into unjustifiably blaming economic growth as their root cause (for a prominent example, see Jackson, 2009).

In this thesis I do not wish to defend the view that capitalism is exploitation; I believe in capitalism's splendid success in improving living conditions and

[1] Notable exceptions include: Roemer (1982); Stiglitz (1994).

that markets are the right way to organize economic life. Instead, the main conclusions of this thesis suggest that an economic theory of climate change mitigation would benefit from paying greater attention to two crucial distinctions. These distinctions should matter to economic theory because, as I shall argue, they permit evaluation of the accuracy of the two narratives about capitalism in given circumstances.

The first distinction concerns ownership of production factors: their owners can be entrepreneurs or rentiers. Accumulation of productive capital by entrepreneurs is generally desirable as it increases the resources of a society, stimulates technological development and often also raises wages. But if 'capitalists' become rentiers, mostly owning production factors that are fixed, the rents they can earn on them bind resources that societies could use in a better way. I will argue later that blurring this distinction also distorts the relationship between efficiency and equality. Failure to distinguish between rentiers and entrepreneurs in neoclassical growth theory may be explained by historically low rents after the world wars and the great depression (Piketty, 2014), when neoclassical growth theory took off. The implication of this is to reinject a historically well-established differentiation between fixed factors, such as land, and capital, which can be accumulated, into neoclassical growth theory. (See Stiglitz (2015a,b,c) for a similar view.)

The second distinction concerns the normative evaluation of consumption – that happiness is something very different from preference satisfaction, and both can be legitimate representations of human welfare (Loewenstein and Ubel, 2008). Preferences of real human beings are all but well-ordered (Ariely, 2008) and people often choose the option that does not maximize their happiness (Hsee and Hastie, 2006; Kahneman, 2011). Failure to anchor this distinction in economic theory is due to the dominance of the outdated paradigms of first behaviorism and subsequently rationalist cognitivism in psychology at the time when microeconomic theory in its currently used form was developed (Layard, 2011). While proponents of the liberation narrative generally cherish the preference view as it implies that individuals always know best what is good for themselves, proponents of the exploitation narrative are more skeptical. To them, identifying social welfare with the satisfaction of preferences revealed in choices evokes the notion of human beings exploited by undesirable influences on the preferences. For instance, exploiters are believed to create desires in consumers by advertisement that these else would not have. Proponents of the exploitation view are hence at times sympathetic to happiness as a welfare criterion.

In his recent and extremely influential book, Piketty (2014) argues, based on an unprecedented multitude of data on wealth and income, that capitalism in the 21st century may resemble the "patrimonial capitalism" of the 19th century. This has put wealth inequality at the top of the research agenda in economics, while it has featured prominently on the political agenda already since at least the financial crisis of 2008. If growth rates in the decades to come are low, for instance because of slower increases in labor productivity (Demailly et al., 2013) or because high growth rates of the 20th century were a historical exception (Piketty, 2014, Ch. 2), the income share of capital may rise and at the same time, wealth will be more unequally distributed (Piketty, 2014). This raises the fear that social hierarchies will be dominated by inheritance and not by achievements that are remunerated through labor income, as in the 19th century. The solution, according to Piketty, lies in taxing wealth owners at very high rates. Yet he does not specify whether the wealth is embodied in capital or in fixed factors that yield rent. His empirical results and policy recommendations thus not only fuel the movement of the "99 percent", but also put pressure on the dominance of the liberation narrative in economic theory.

However, Piketty is unduly silent about another great challenge for capitalism in the 21st century: climate change mitigation and its ensuing complexities for managing global land-use. Unmitigated climate change would darken the prospect for a peaceful and prosperous future of humanity by the collapse of large ecosystems that are vital for subsistence needs (IPCC, 2014a) and could potentially result in violent large-scale migration (Adger et al., 2014). But sufficiently reducing greenhouse-gas emissions leads to further predicaments: if bioenergy, a crucial mitigation option for reaching ambitious climate targets (IPCC, 2014b), is managed badly, it could have disastrous consequences for food security, biodiversity and ecosystems services, such as the freshwater supply (Tilman et al., 2009; Rockström et al., 2009; Haberl et al., 2013; Creutzig et al., 2014). Further, with regards to wealth distribution, climate change mitigation will create new and change existing rents. Regulating the flow of emissions into the atmosphere by climate policy creates a scarce resource, atmospheric disposal space, while fossil reserves, of which only a small fraction can still be used, are devalued. Piketty's imagined rentiers of the 21st century may thus well derive some of their rent from their atmospheric property or their bioenergy estates.

Furthermore, the transition to the low-carbon economy is also a large-scale investment project: decarbonization necessitates adaptation of electricity grids to the particular requirements of renewable energy (Bruckner et al., 2014). The building stock will need to be overhauled (Lucon et al., 2014). Transport infrastructure will need to be modified, including changes required by the need for fuel switching (Sims et al., 2014). In particular, changes in the infrastructure are unlikely to be triggered by carbon pricing alone, but require additional policy instruments. Further, some existing emitting stocks will need to be phased out before the end of their natural lifetime (Davis et al., 2010; Guivarch and Hallegatte, 2011) in order to avoid a "carbon lock-in" (Unruh, 2000). Low-carbon infrastructure investment thus is, besides carbon pricing, needed to achieve a low-carbon economy. Throughout this thesis, I thus take such investment as the example that illustrates why the two distinctions introduced above, that between rentiers and entrepreneurs as well as that between happiness and preferences, matter for economic theory. For example, suppose the government decides to build a railway line in order to lower transport emissions. How should this project be financed? Is there a special role for rents? What are the implications of such a project for equity? When should it be built compared to the introduction of other climate policy measures? And how will it influence mobility behavior?

This thesis shows that the two distinctions introduced above matter as follows for answering such questions: regarding the first distinction, the best way to finance low-carbon public investment is by taxing (land or carbon) rents, which must be distinguished from capital. Remaining income from rent taxation should be redistributed to poor and newborn generations. This would enhance efficiency by boosting the accumulation of productive private capital, while also mitigating inequality. Beyond rent taxation, if wealthy dynastic households exert a special influence on capital accumulation, there is a trade-off between financing public investment through inequality-decreasing capital taxation and even more efficient, but inequality-increasing labor taxation. Different cohorts of savers then prefer different tax rates. The thesis thus also paints a different picture about trade-offs between equality and efficiency. Regarding the second distinction, evaluating the welfare gain of low-carbon public investment needs to distinguish between maximizing people's happiness and maximizing the satisfaction of their preferences, given actual behavior of users of infrastructure.

More specifically, in Part I of this thesis, I show that rent taxation can be used for financing the optimal level of public investment, if the rent from a fixed production factor is sufficiently high. If there is not enough productive private capital due to imperfect intergenerational altruism, the revenue from taxing the rents must also be redistributed to newborn generations to reach the socially optimal solution. This is both valid for land rents and the climate rent. Further, in the transition to the low-carbon economy, infrastructure investments can be understood as increasing the substitution possibilities between carbon-intensive and carbon-free production. Which paths of public investment are welfare-enhancing then depends on a possible lock-in generated by imperfect appropriation of learning spillovers in developing low-carbon technologies.

In Part II, I consider the distributional impact of financing low-carbon public investment and its impact on consumption choices. The latter is illustrated for the case of transportation. Regarding distributional effects at a macroeconomic scale, I assume that modeling household heterogeneity should match empirical results about saving behavior and income sources across the wealth distribution. I show that this reverses some results from the literature on households with heterogeneous initial endowments but homogeneous preferences. It is confirmed that when financing public investment by distortionary taxation, Pareto-improving public investment is possible, no matter how it is financed. However, when a capital tax is levied, inequality is also reduced. A labor or a consumption tax is more efficient, but would increase or stabilize inequality, respectively. Introducing heterogeneous cohorts in the wealth distribution – making "class distinctions" – thus questions the orthodox view about trading off efficiency for equity. Moreover, for the normative assessment of particular forms of public investment, the behavioral account of households' decisions must be considered. The transport infrastructure may shape agents' preferences and impacts their choices. This is potentially a problem for the normative view that defines welfare as the satisfaction of preferences: I argue that actual mobility behavior thus reinforces the need to distinguish between subjective well-being ("happiness") and (a revised form of standard) preference satisfaction as possible welfare criteria.

The remainder of this introductory chapter reviews the economic theory and the major empirical facts on which this thesis builds. It also motivates the modeling choices and the need to go beyond standard normative economics in the further chapters. In particular, in Section 1.1, I discuss evidence that production factors which cannot be accumulated may play a significant role in national economies in the 21st century. In Section 1.2, I review rent taxation and public investment as topics of public economics to argue that appropriating rents in order to use them for financing underprovided public capital can be an effective strategy for managing the global commons. In Section 1.3, I touch upon recent empirics of wealth inequality and its causes to highlight its significance for climate policy. In Section 1.4, I combine the insights of the three previous sections to explain the choice of models employed in this thesis. I also explain there why the models used lead to a number of non-standard normative problems. Finally, Section 1.5 derives specific research questions and presents a detailed outline of this thesis.

1.1 Fixed factors in the twenty-first century?

One of the main tenets of this thesis is that, by introducing production factors that are fixed into otherwise standard models of growth theory, some policy implications of those models change. To assess the importance of this claim, this section considers empirical evidence for the existence of fixed factors in the 21st century, that is, those factors that in some way cannot be accumulated or are not depletable. Three prominent candidates for fixed factors that may significantly impact economic outcomes in the future are discussed subsequently: the atmosphere as a carbon sink, global land and the biomass harvestable on it as well as urban land. Global land availability is the paradigm example of a biophysical boundary for the economy, whereas urban land is a socially constructed fixed factor. Although a limit on total global emissions would need to be imposed by *societies*, the atmospheric capacity for absorbing greenhouse gases (without emissions inducing large-scale global changes) *is* a biophysical limit. The available evidence suggests an important role for all three factors in the future, while at the same time making it understandable that 20th century economics needed not be concerned with fixed factors and their rents.

The atmosphere as a carbon sink

Humans cause climate change by emitting greenhouse gases into the atmosphere. A changing climate potentially leads to unmanageable large-scale risks for ecosystems and the economic systems depending on it (IPCC, 2014a). For example, unmitigated climate change could threaten food security, both by decreasing agricultural productivity and by adverse impacts of ocean acidification on fish stocks. It could lead to the collapse of large scale ecosystems, such as some rainforests and could accelerate biodiversity loss as climatic changes may proceed faster than the maximum speed at which species can migrate. Climate change could thus severely deteriorate the living conditions in many parts of the world, mostly indirectly, but sometimes also directly: for instance, some densely populated coastal regions may become uninhabitable through sea level rise. (Field et al., 2014)

Because the details of such changes are subject to large and deep uncertainties, climate change economics focuses on the costs and benefits of achieving different climate stabilization scenarios for the 21st century (IPCC, 2014b). It is known with comparatively high certainty how different amounts of cumulative emissions translate into changes in global mean temperature. For example, to reach the target of limiting the increase of the global mean temperature to 2° C in 2050 with 66 % probability, the total available disposal space in the atmosphere has been estimated to be 1010 Gt CO_2 for the period 2011–2050, accounting for non-CO_2 forcings accordingly (IPCC, 2013, Section E8). Climate stabilization at that level also necessitates that the economy operates essentially carbon neutral in the second half of the 21^{st} century (IPCC, 2014c). Even allowing for more global warming or a greater risk of missing the 2° target would still likely necessitate a carbon-free economy towards 2100 if the most severe climate change risks are to be avoided (IPCC, 2014c, Table SPM.1). Sufficiently addressing climate risks would thus make greenhouse gas emissions a very scare production factor, giving rise to numerous challenges surrounding the development and deployment of mitigation technologies (IPCC, 2011, 2014b). The most efficient economic solution to the climate problem is a uniform global price on emissions; a carbon price can also be motivated by a variety of fiscal considerations and ancillary benefits of mitigation (Edenhofer et al., 2015). Importantly, the disposal space in the atmosphere for carbon is much scarcer than the amount of known total fossil resources (IPCC, 2011, Figure 1.7).

This thesis assumes that future climate policy will define carbon budgets that are binding for the economy, whether at an international or at a national level. While there can be at best modest hope for an internationally binding ambitious climate agreement (for instance because setting a global carbon price is a collective action problem), many countries have enacted or are developing climate mitigation measures that effectively limit the emissions of their national economies (Somanathan et al., 2014): for example, Dubash et al. (2013) find that in 2012, 67 % of global greenhouse gas emissions were covered by national legislation, compared to 45 % in 2007. But does the assumption of (somehow) limited emissions, such as carbon budgets, for the economy make the atmosphere a fixed production factor? Of course, a carbon budget is only fixed intertemporally, not at every point in time, and thus is equivalent to a scarce exhaustible resource rather than to a fixed factor. In that sense, the climate rent would be equivalent to resource rents rather than to fixed factor rents. However, whether climate policy defines a production factor that is fixed at a certain time or fixed over time strongly depends on the choice of the policy instrument that implements the budget. For instance, if the carbon budget is implemented by an emission trading scheme in which permits have short lifetimes (say, a year), the total cumulative budget corresponds to a production factor that is fixed over those short time periods. (For further discussion of this see also Chapter 4 and for the magnitude of the rent derived from the factor atmosphere, see Section 1.2.1).

Global land and biomass

The land available to an economy is the paradigm example of a fixed production factor, widely discussed by the classical economists. Here I assess what is known about whether one should expect global (agricultural) land to be scarce in the future. In contrast to the scarcity of the atmosphere, which is well quantifiable, the scarcity of agricultural land in the 21^{st} century is subject to enormous uncertainties. While global land is a potential biophysical limit on economic activity, urban land is not primarily scarce because of this limit, but its scarcity and high value is socially constructed, see below.

Evidently, global available land is an economically-relevant quantity that is fixed, despite locally limited land reclamation projects. However, whether this matters much for economic outcomes depends on its potential scarcity in terms of its use for the economy and thus on whether there will be future technological change that is land-augmenting. Towards assessing its scarcity, very diverse sources of demand for land would need to be taken into account: food production, ecosystem services including biodiversity conservation and freshwater protection, bioenergy generation, soil carbon storage, reduced deforestation and degradation or afforestation as climate change mitigation options, as well as amenity use and wilderness conservation for non-anthropocentric reasons.

In particular, opinions differ markedly as to what the use of bioenergy as an option for mitigating climate change will mean for the pressure on global land in the 21st century (Creutzig, 2014). Estimates of global technical bioenergy potentials for 2050 differ between < 50 EJ/yr to > 1000 EJ/yr (Smith et al., 2014, Section 11.13, see also Creutzig et al., 2014). This enormous range is due to widely differing assumptions: optimistic estimates are derived from considering high yield growth of energy crops (Popp et al., 2014), partially justified by successful field trials (Creutzig, 2014). By comparison, current bioenergy use is at approximately 50 EJ/yr, of which around 80 % are for traditional biomass use (Chum et al., 2011). Biomass used for food, livestock feed and fiber is at approximately 180 EJ/yr (Haberl et al., 2013).

Pessimistic estimates, by contrast, start with the finding that net global primary production (NPP) of biomass has stayed constant over the last thirty years, despite all improvements in agricultural productivity (see Running, 2012 and Haberl et al., 2013). However human appropriation of NPP doubled in the 20th century (Krausmann et al., 2013) being at 30 % of total above-ground NPP. Similarly, whether high yield improvements in food crops would lead to a significant reduction in land used for food production (Hoogwijk, 2004; Hoogwijk et al., 2005) – or not (Bruinsma, 2009) – is also contested (Creutzig, 2014).

So how scarce will global agricultural land get? I subsequently elucidate a number of first-best and second-best considerations that feed into the disparate results about the future of land use to illustrate the immense uncertainties around its future scarcity.

The major first-best arguments for or against considering future global land as a scarce resource fall into three categories: yield potential, importance of other sustainability objectives and demand projections. First, high yield assumptions for some energy crops are justified as they have been demonstrated in field experiments. However the maximally observed yields are typically far higher than average yields (see Creutzig (2014) for an overview). Some also believe that yield improvements grow linearly, not exponentially (Fargione et al., 2010). Second, optimistic estimates about agriculture to deliver both food and bioenergy may neglect undesirable side effects of contested importance. High yields often require high fertilizer input and irrigation – and the detrimental effects of fertilization or the limited availability of water may not be taken into account enough or are not well understood. Moreover, greater emphasis on biodiversity conservation or wilderness protection may additionally limit bioenergy potentials. Third, global demand for food depends to some degree on the diet consumers choose. While the demand for meat is widely believed to be increasing (Tilman et al., 2011; Heinrich Boell Stiftung and Friends of the Earth Europe, 2014) significant climate policy might also induce dietary shifts (Stehfest et al., 2009; Popp et al., 2010) as well as improvements in management within existing livestock systems (Havlík et al., 2014) and thus reduce pressure on land availability from food production. Demand for bioenergy depends on the availability of other mitigation options and varies across mitigation scenarios according to the climate stabilization envisaged (Edenhofer et al., 2014). Nevertheless, there is converging evidence that ambitious mitigation requires significant bioenergy input including generating negative emissions by combining it with carbon capture and storage (BECCS, see Clarke et al., 2014 and Fuss et al., 2014).

Second-best arguments concern what can be realistically expected regarding the availability of policy instruments as well as the future development of institutions and practices: optimistic assumptions about bioenergy potentials by Integrated Assessment Models typically require globally uniform carbon pricing, including pricing of land-use emissions. A global enforcement for this seems particularly difficult for the case of emissions from agriculture and related land use changes. Further, about one third of food produced is wasted globally. While in rich countries a large amount of food is wasted by consumers, there are high productivity losses due to inadequate storage, transport and cooling of agricultural products in poor countries. Both could be significantly reduced by simple technical or behavioral measures, which seem difficult to introduce in practice, however. (FAO, 2011) Lastly, biomass potential could also be limited because some areas may be inaccessible due to political conditions: one may suppose that investment in energy crop plantations is only possible under relatively stable legal and political institutions so that it may be infeasible in "failed states" (Erb et al., 2012). (See Creutzig (2014) for a more elaborate discussion of most of these points.)

To sum up, while very little can be definitely concluded about the degree of scarcity of future global land, it may be safely assumed that the task of climate change mitigation, along with an increasing population with improving living standards, may make global land somewhat or even significantly scarcer. In fact, combating climate change by large-scale mitigation options that greatly impact global land use, such as BECCS and afforestation, could somewhat transfer environmental risks from the use of the atmosphere to global land use (Tavoni and Socolow, 2013). From a historical perspective, there is thus some reason to believe that macroeconomic models of the 21st century may be somewhat closer to the economic reasoning of the 19th century regarding the importance of fixed production factors. While the economic models of the 20th century could safely assume away any land-related scarcities due to the enormous productivity increases in agriculture, the above discussion may be seen as providing some rationale for the reintroduction of (globally fixed) land into growth theory.

Socially constructed fixed factors: urban land

Urban land is a significant component of societal wealth. This can be justified by looking at the macroeconomic significance of housing:[2] in Britain, France and Germany, for instance, half of total wealth is embodied in housing and increases in wealth since 1950 are largely due to housing as well (Piketty, 2014, Ch. 3 and 4). Importantly, Piketty and Zucman (2014) find that across major industrialized countries, at least 20–30 % of new wealth generated in 1970–2010 are due to price effects. This points to a potential role for rigidities in the supply of urban land in explaining the wealth share of housing (see also Rognlie (2014)). Others go further and claim that land prices, not construction costs, primarily explain surging house prices: Knoll et al. (2014) find that, across major advanced economies, 80 % of the increase in house prices between 1950 and 2012 can be attributed to increasing land prices. Stiglitz (2015a) recently demonstrated that the assumption that wealth consists entirely of capital cannot be reconciled with aggregate data about the U. S. economy.

Further, urbanization is projected to continue over the course of the 21st century, both in developed and developing economies, but to a much greater degree in developing economies. While currently around 50 % of the global population lives in cities, by 2050 this number is expected to increase to 66 % in 2050 (Seto et al., 2014). This would lead to an even larger influence of urban land in understanding wealth dynamics in the future. Climate policy may exacerbate the scarcity of urban land: high densities are necessary for low-carbon cities since they generate less transport demand, particularly when combined with mixed zoning (Seto et al., 2014). Currently, urban densities across the world are declining (Angel et al., 2010; Seto et al., 2014). However more compact cities are required for the decarbonization of the transport sector, which may potentially increase the scarcity of urban land.

The importance of urban land for economic outcomes is thus widely acknowledged. But why should urban land be considered a *fixed factor*? A straightforward justification would point to regulations and laws that limit the amount of land around cities on which property may be built, see for example Glaeser et al. (2005). Moreover, there may also be additional regulations limiting the height of buildings on existing urban land. The accurateness of this justification of course depends on how flexible such regulations are, in particular whether the policy-makers are ready to convert agricultural areas around cities into urban building sites in the face of growing demand. This may vary widely across situations: While Houston is famously the only major U.S. city without zoning policies, elsewhere urban growth is limited by green belts (see Masucci et al., 2013, for the case of London), for instance. In many locations, the respective laws may be assumed not to change in the medium term.

But a deeper justification would point out that the value of urban land is determined by its proximity to centers of social activity:[3] urban agglomera-

[2]Estimating the share of the value of unimproved land in total wealth is notoriously difficult due to high spatio-temporal variability and disparate potential methodologies (see, for instance, Özdilek (2011). Some claim that the land value is $1/3$ of the value of housing and hence $1/6$ of total wealth (Löhr, 2013, Part IV), but too little work in empirical macroeconomics exist on this to rely on such numbers definitively.

[3]This insight may be traced back to Adam Smith: "In country houses at a distance from any great town, where there is plenty of ground to choose upon, the ground-rent is scarce any

tions are the result of increasing returns to scale (Fujita et al., 2001) that may stem from the presence of industrial clusters, political institutions, universities, public amenities etc. Urban land is hence scarce because good access to a country's major economic, political or cultural centers is limited to a few cities per country, given the structure of growth processes and agglomeration dynamics (Gabaix, 1999; Brakman et al., 2009, Ch. 7). This justification for considering urban land as a fixed factor runs deeper then the one presented above because agglomeration dynamics are much harder to change by policy instruments. The fact that many urban centers in much of the world have not changed for centuries underlines this: it seems almost unimaginable that politics could succeed, to use a German example, in turning Fulda into a second Frankfurt, or Braunschweig into a second Berlin in order to alleviate the scarcity of urban land in those two major centers of social activity.

Thus, taking both explanations together, scarce urban land is largely a social construction, a result of economic agglomeration, and not a biophysical limit. Of course there are notable exceptions to this explanation for the value of urban land. In some global cities land *is* scarce for geographical reasons: land is there limited due to shores, rivers or mountains, as is for example the case in Barcelona, Hong Kong, San Francisco, Shanghai or Singapur.[4] But despite these cases, the majority of the wealth embodied in urban land is due to social construction, not to biophysical limits.

Beyond urban land, some other "assets" prominent in policy debates can be judged fixed in quantity due to social construction: Possessions that are *culturally* meaningful, but fixed for various reasons. Examples include, but are not limited to works of art, achievements in hierarchical education systems or even sport events which generate significant economic rents, such as the FIFA world cup or the Olympics. Capital with very high adjustment costs might also be well conceptualized as a fixed factor in the medium-term, an example for this may be nuclear power plants. For its empirical illustrations, this thesis focuses on the fixed factors relevant in the context of climate change mitigation; assessing the macroeconomic significance of such other fixed factors is beyond its scope.

In summary, this section identified production factors relevant at a global scale that are fixed. It provides a justification for exploring the consequences for optimal taxation of introducing fixed factors into growth models, the subject of Part I of this thesis. Two of these factors, the atmosphere and global land, are due to biophysical limits of the economy. A third, urban land, is relatively fixed over very long time horizons due to social construction. Policy response to the challenge of climate change mitigation *create* the rents associ-

thing, or no more than what the ground which the house stands upon would pay if employed in agriculture. In country villas in the neighborhood of some great town, it is sometimes a good deal higher, and the peculiar conveniency or beauty of situation is there frequently very well paid for. Ground-rents are generally highest in the capital, and in those particular parts of it where there happens to be the greatest demand for houses, whatever be the reason of that demand, whether for trade and business, for pleasure and society, or for mere vanity and fashion." (Smith, 1776/1904, Book V, Ch. 2, §68)

[4] There are similar examples of fixed *geographical* scarcities with considerable economic impact, not necessarily related to the urban context, when space is valued highly for another reason then proximity to centers of economic or social activity, namely due to aesthetic value: property at lakes, shores or cliff lines (Lake Geneva, Côte d'Azur, . . .) or even mooring areas (Monaco, Constance, . . .).

ated with the scarcity of atmospheric disposal space of carbon. Beyond that, they may also significantly increase the rents derived from global agricultural land and urban land, through the mitigation options of bioenergy deployment and inducing more compact cities. Climate policy thus leads to an increasing importance of fixed factors for future macroeconomic outcomes.

1.2 Fiscal policy for the commons: rent taxation and public investment

Some of the most challenging economic problems on the current political agenda are related to the mismanagement of global commons: While global environmental problems are a danger to millions of lives and future prosperity (IPCC, 2014a,b), another obstacle to improving human welfare stems from insufficient investments into the health sector, education and infrastructure (Estache and Fay, 2007; Jakob and Edenhofer, 2014).

Arguably, the problem of the global commons[5] is thus: natural resource stocks are overused due to missing cooperation, while some stocks that can be summarized as "public" capital, including health and education, are underprovided (Jakob and Edenhofer, 2014). A solution for this mismatch would be to limit the use of the former and appropriate the newly created rents, for instance through taxation, to use them for financing investments in the latter.[6]

In urban economics, such a paradigm for public good provision is well-established. The Henry George Theorem (or 'the golden rule of local public finance') holds that in a city, land rents equal the expenditure on a public good, provided the city's population is of optimal size (Arnott and Stiglitz, 1979; Arnott, 2004). The major consequence of the Henry George Theorem for local public finance is that a 100 % land rent tax is sufficient to finance the public good. This is independent of whether or not the public good is at its optimal level. It has been named after Henry George because of his claim that a single tax on land would be sufficient to finance public expenditure (see Subsection 1.2.1). The theorem has been widely applied to the actual financing of urban infrastructure projects across the world (Smith and Gihring, 2006; Medda, 2012; Walters, 2013). Stiglitz (2002, 2014) has also repeatedly pointed out the significance of the Henry George Theorem for the use of fossil resources – and thus on a macroeconomic scale – without ever formalizing this. Beyond the specific purpose of financing public goods, (land) rent taxation is widely believed to be a desirable form of generating government revenue. This is at least true if solutions for the practical difficulties associated with it, in par-

[5]In this context, I use the term "commons" in the sense of public economics, that is to denote "common goods", including mostly "common-pool resources" but also proper public goods, debates about terminology and alternative possible conceptualizations (Kaul and Mendoza, 2003; Helfrich, 2012) notwithstanding.

[6]This idea is different from the concept of a "double dividend" (Goulder, 1995; Bovenberg, 1999) of an environmental tax for two reasons. First, the focus here is on stocks, not flows, as is mostly the case in the double dividend literature. Second, and more importantly, no pre-existing distortions, such as distortionary labor taxation are involved in this case, but those are the reason for the existence of a "double dividend" in the original sense of the term. (See Siegmeier et al. (2015) for more on this.)

ticular separating the valuation of land from that of buildings, can be devised (Mirrlees et al., 2011, Ch. 16 and 20).

Part I of this thesis is concerned with translating the idea behind the Henry George Theorem to the level of the macroeconomy and examines its distributional consequences. Here, I summarize prior theoretical work on rent taxation as well as the optimal level and financing of public investment on which this thesis builds. I also consider empirical evidence for the underprovision of public investment and the potential revenue generated through appropriation of the climate rent.

1.2.1 Rent taxation

The previous section discussed evidence for the fact that fixed factors may play a larger role in determining economic outcomes in the future. Inevitably, fixed factors yield *rents*: A rent is a remuneration of a production factor that exceeds the cost of keeping it in its current use.[7] It represents a social value. For instance, a piece of land exists regardless of its owners' other economic decisions. He has no opportunity cost of providing it for production. This is not the case for capital, which the owner may decide to consume instead. The income generated from the flow of a natural resources is also a rent in this sense, although for the case of a fossil resource stock or an atmospheric carbon budget, the flow, in contrast to the stock, may be fixed intertemporally only. In this section, I clarify the implications of imposing taxes on rents.

A panacea?

Henry George initiated a movement that propounds the following recipe for government financing: tax land rents and abolish all other taxes (George, 1879/2006; Heavey, 2003). He wrote:

> I do not propose either to purchase or to confiscate private property in land. The first would be unjust; the second, needless. [...] It is not necessary to confiscate land; it is only necessary to confiscate rent. [...] Now, insomuch as the taxation of rent, or land values, must necessarily be increased just as we abolish other taxes, we may put the proposition into practical form by proposing *to abolish all taxation save that upon land values.* (George, 1879/2006, Bk. 8, Ch. 2)

George was not primarily concerned with public good provision. Instead, he argued that not taxing the rents would come at the cost of increasing poverty by depressing the share of national income accruing to labor.

> Poverty deepens as wealth increases, and wages are forced down while productive power grows, because land, which is the source of all wealth and the field of all labor, is monopolized. [...] This, then, is the remedy for the unjust and unequal distribution of wealth

[7] For a comprehensive discussion of this and alternative definitions of rent, see Dwyer (2014).

> apparent in modern civilization, and for all the evils which flow from it: *We must make land common property.* (George, 1879/2006, Bk. 8, Ch. 2)

Chapter 2 and 3 of this thesis examine a modernized version of this claim formally.

Yet George was by no means the only great economist to praise rent taxation as a means of generating fiscal revenue. However, the large agreement among economists that rent taxation is desirable does not result from a concern about poverty alleviation (which motivated George's work). Rather, there is a consensus that levying a tax on rent is non-distortionary[8] and thus the most efficient way of levying taxes, besides taxes correcting externalities (see Mankiw, 2007, Ch. 8, p. 169). Adam Smith already recommended rent taxation because it is non-distortionary:

> Ground-rents and the ordinary rent of land are [...] the species of revenue which can best bear to have a peculiar tax imposed upon them [because] [t]he annual produce of the land and labour of the society, the real wealth and revenue of the great body of the people, might be the same after such a tax as before. (Smith, 1776/1904, Book V, Ch. 2, §75)[9]

David Ricardo is usually even more associated with the study of rent. He stressed that land rent is *differential* in the sense that it depends on the fertility of the soil or the accessibility of urban land. Ricardo confirms that rent taxation is non-distortionary when writing: "A tax on rent would affect rent only; it would fall wholly on landlords, and could not be shifted to any class of consumers. The landlord could not raise his rent, because he would leave unaltered the difference between the produce obtained from the least productive land in cultivation, and that obtained from land of every quality." (Ricardo, 1817/1821, Chapter 10 §1)

Much later, even Milton Friedman granted that "the least bad tax is the property tax on the unimproved value of land, the Henry George argument of many, many years ago." (Friedman, 1978)

Yet today, rent taxation does not account for a large amount of fiscal revenues, with the exception of some states that are rich in fossil resources (see also Chapter 2, Figure 1). For example, in Germany, land taxes amount to 3 % of the total tax revenue, while fossil resource-related taxes amount to around

[8] Throughout this thesis, I take 'distortionary' to mean distorting private agents' decisions. This is not to be understood normatively. Whether a distortion raises or lowers welfare depends on the equilibrium which is distorted by the policy.

[9] Smith may even be said to have prefigured the method of land value capture embodied in the Henry George Theorem when writing: "Ground-rents, so far as they exceed the ordinary rent of land, are altogether owing to the good government of the sovereign, which, by protecting the industry either of the whole people, or of the inhabitants of some particular place, enables them to pay so much more than its real value for the ground which they build their houses upon; or to make to its owner so much more than compensation for the loss which he might sustain by this use of it. Nothing can be more reasonable than that a fund which owes its existence to the good government of the state should be taxed peculiarly, or should contribute something more than the greater part of other funds, towards the support of that government." (Smith, 1776/1904, Book V, Ch. 2, §76)

10 % (Bundeszentrale für Politische Bildung, 2014). One reason for the low share of land rent taxes, recognized by the classical economists already, is that, in practice, it is difficult to tax only the rent of raw land. One would need to avoid to also tax productive capital built on the land at the same time or distort improvements of land, such as clearing trees or providing infrastructure (Mankiw, 2007, Ch. 8, p. 169). Importantly a land rent tax on urban rent is likely to have adverse effects on the maintenance of the building stock. Another reason is that rents have been historically low after World War II (Piketty, 2014). Both reasons against rent taxation as a major part of fiscal revenue may apply less for the challenges of the 21^{st} century described above: For instance, the climate rent will be both a sizeable part of national output and easy to target. On the one hand, Metcalf (2007) notes that a universal carbon tax of 15 $ in the U.S. would yield 90 billion $ revenue (given that in 2005 total U.S. emissions were approximately $6\,\mathrm{Gt}\,CO_2$), not including equilibrium effects. (For more refined estimates of the climate rent, see Bauer et al. (2013) and Carbone et al. (2013).) On the other hand, pricing carbon *does* tax the resource rents only, without also taxing other production factors.

Is rent taxation distortionary? – An old question, a new answer and new reasons

In sum, economists ever since Adam Smith believed that rent taxation is non-distortionary. However, in 1977, Martin Feldstein showed that this thesis is of very limited applicability, in an article entitled "The surprising incidence of a tax on pure rent: a new answer to an old question". For Smith and Ricardo, the owners of the fixed factor, land, were rentiers doing nothing else but owning land and living only on the rent. Feldstein, by contrast, looked at land ownership as a part of the asset portfolio that constitutes the wealth of the average household.

Feldstein (1977) thus qualified the classical understanding of rent taxation as non-distortionary: of course, the tax will not diminish supply of the fixed factor, as it is fixed. But Feldstein explored three ways in which rent taxation can still be distortionary. First, there may be income effects: if landowners are not only rentiers, but also work, they may be induced to increase their labor supply by a rent tax. Second, in the short-term and with uncertainty, there may be price changes due to a rebalancing of a portfolio in case land and the other assets are subject to different risk. Third, and most importantly, even if there are no income effects, a rent tax can induce investment into other production factors, when households hold not only land but other assets which can be accumulated. (Feldstein, 1977)

Calvo et al. (1979) and Fane (1984) qualified Feldstein's findings. His last result does not hold if households are fully altruistic towards their descendants; see Calvo et al. (1979), who provide a "new (?) reason for an old answer:" the land rent tax is not shifted and is non-distortionary. The reason is that for dynastic households, (compensated) land rent taxes act as an intertemporal transfer, to which they will adjust their saving behavior. (The findings of Feldstein thus hold in an overlapping generations model, but not in a neoclassical growth model, see Section 1.4 below.) Fane (1984) clarifies the meaning of a 'compensated tax': in the present context, it does *not* consist in simple lump-sum revenue recycling, but in (a) issuing bonds to taxed landowners and remunerating those by the land tax revenue *and* (b) using the revenue from selling the bonds for a lump-sum payment to them.[10] Fane (1984) thus provides "the old reason for the old answer." Whether the redistribution scheme identified to be fully compensatory by Fane (1984) is feasible and hence the neutrality of rent taxation is relevant in practice, may however be doubted.

For the cases of the fixed factors important in the near future, the perspective of Feldstein seems generally more appropriate than that of the classical economists discussed above. Some fixed factors may indeed largely be owned by few rentiers only (say, oil barons or building tycoons) who have little other income. However, among the wealth of most households are investments into large funds, for instance their social security or insurance contributions, which get reinvested by pension funds or insurance companies in a wide set of assets, including fixed factors. In that sense the assets of their corporations will effectively be held by a large class of households (industries that obtain grandfathered permits may be another example for this). One may side with Ricardo when believing in the validity of full bequests: "[. . .] it is pleasing to conjure up the image of Ricardo defending his views on the land rent tax by pointing to his bequest model of savings" (Calvo et al., 1979). But at least for worlds in which households are not completely altruistic towards future generations, Feldstein (1977) has shown that beyond being a good way of raising money, rent taxation can have real effects on promoting capital accumulation. Taxing rentiers may not only be desirable if one is against rentiers (taking them to be exploiters of workers), but also because this may promote economic efficiency.

Part I of this thesis extends Feldstein's finding by considering distributional effects of various possible revenue recycling options, evaluates its normative significance (Chapter 3) and applies it to carbon pricing (Chapter 4).

1.2.2 Public investment

This subsection considers the second part of the global commons problem: some stocks which are typically publicly maintained are currently undersupplied (Bom and Ligthart, 2014; Calderón and Servén, 2014c). These stocks are *public capital* in the sense that government action is usually needed for their creation or maintenance and in the sense that they are in the common inter-

[10]Embedded in the analysis of the rent tax incidence is hence the scope of the validity of the celebrated *Ricardian equivalence*: financing government expenditure either by levying a tax now or by issuing debt now that is financed by raising taxes later does not change the path of aggregate consumption. That is, in their choices (forward-looking) households internalize the government's budget constraint. Equivalently, government bonds are not net wealth. Barro (1974) shows that this proposition is true in an overlapping generations-model with bequests (and thus also in the neoclassical growth model), but not true if there are no bequests. Buiter (1988) and Weil (1989) extend the finding that the Ricardian equivalence does not hold if there is no intergenerational altruism to the continuous Yaari-Blanchard overlapping generations model (Blanchard, 1985). Moreover, even without bequests, Ricardian equivalence holds in overlapping generations models for a tax on *land* because current generations will sell it to future generations (Buiter, 1989), the canonical tax for which it does not hold being a labor income tax. However, when households are time-inconsistent (which is now widely understood to be the general case, see Loewenstein and Prelec (1992); Frederick et al. (2002); Berns et al. (2007)), Ricardian equivalence does not hold (Laibson, 1997) regardless of the tax and the intergenerational structure. The subsequent chapters do not consider government debt and hence do not take up the interactions of the incidence of rent taxation with government bonds further.

est of the population by providing universally valued services. This notion of public capital goes beyond that of core physical infrastructure and is not exclusively motivated by the role of public capital in production. Gramlich (1994) notes that "[t]he definition that makes the most sense from an economics standpoint consists of large capital intensive natural monopolies, such as highways [. . .]." However, the concept of public capital used in this thesis is distinctively broader and includes education buildings, hospitals, public amenities such as parks, etc. It thus emphasizes, beyond the role of enhancing productivity, the nature of the commons problem of financing stocks that serve the public interest, although marginal productivity of public capital seems the only indicator for undersupply currently available.

I first review the evidence that the provision of public investment is suboptimally low. I then note that one can safely assume a unique function for governments to foster investment that is commonly understood to be public: this justifies the ad hoc role for productive or utility-enhancing public investment in much of growth theory. Further, I summarize the theoretical contributions analyzing the financing of public investment when both efficiency and equality can be objectives. Finally, I briefly point out some of the specific challenges for public investment during the transition to the low-carbon economy.

Is public investment undersupplied?

There is a consensus in academia and politics that public investment, notably in infrastructure, can enhance economic efficiency, but the optimal level of public investment remains disputed.

Aschauer (1989) first estimated a production function with public capital as input and found that it is very much undersupplied in the United States, resulting in an output elasticity of infrastructure investment of around 0.4. The research that followed Aschauer's seminal contribution, as reviewed by Gramlich (1994), qualified the putative enormous role for infrastructure in fostering growth, pointing to many flaws in the early macroeconometric studies arguing for a shortage of public investment. Later contributions have generally also found a weaker effect than Aschauer (1989), see Calderón and Servén (2014a) for an overview.

More recently, Bom and Ligthart (2014) conducted a meta-analysis over 68 empirical studies considering public investment in OECD countries. For the short-run effect of public capital broadly defined and at the national level, they find an output elasticity of public capital of 0.08. For the long-run effect and if only transport infrastructure and utilities at the regional level are included, this value raises to 0.19, still far below Aschauer's original estimate. Nevertheless their estimate still implies that public capital is undersupplied. On the one hand, when assuming an approximate ratio of public capital to GDP of 0.5 (Kamps, 2006), the marginal productivity of public capital is thus between 0.16 to 0.38. On the other hand, the marginal productivity of private capital can be inferred from computing the sum of the interest rate and the depreciation rate: with the later equal to 0.1 and the former equal to 0.04, public capital is generally undersupplied, with much larger efficiency gains when investing in regional and core infrastructure.

Is public investment really *public*?

In reality, the typical examples of what is understood as “public capital”, such as infrastructure and health and education facilities, are partly privately and partly publicly owned. For example, while education is largely organized publicly, at least in Europe, transport or energy infrastructure is both owned privately and publicly. Nevertheless, this thesis is based on the premise that these stocks are essentially “public”, that is determined by public investment. This premise seems credible for the following reason: In all the cases of “public” capital considered, it is the government that creates the stock (permits its constructions or regulates its characteristics) for *the common benefit.* This is not the case for private capital, such as machines and houses. For instance, tunnels and bridges may be privately built and financed, but the decision to build a tunnel or bridge at the specific location is public. Concerning the investment into the stock, it is thus equivalent whether the state invests itself or creates a concession for the private sector for the investment. There is, however, a difference in the financing of the stock. If it is privately owned, it will typically be financed by a user fee, whereas only governmental investment can be financed by more general means, for instance income or consumption taxes – and thus requires a contribution from all households, whether or not they benefit from the stock. It is for this last reason that this thesis focuses on ‘public’ capital as a case of true public investment.

Financing public investment optimally

In determining the optimal level of public investment, previous work has largely emphasized a trade-off. Public investment is efficiency-enhancing, but it must be financed by distortionary taxation, and so the welfare gain of the investment needs to be balanced with the welfare loss from taxation. This is the message of the seminal contribution of Barro (1990), introducing public capital into (endogenous) growth theory. It implies that the social optimum cannot be reached unless politically infeasible lump-sum taxes are employed to finance public investment (see also Turnovsky (1997)).

Further, when households are heterogeneous, it has been shown that when public investment increases growth or average welfare, it can increase wealth inequality or will be distributionally neutral in the long run, regardless of the financing mechanism (Glomm and Ravikumar, 1994; Chatterjee and Turnovsky, 2012). Public investment may reduce inequality – as the balance of the empirical evidence also suggests (Calderón and Servén, 2014b) – but this will always decrease efficiency (Alesina and Rodrik, 1994).

This thesis reconsiders both the efficiency and the distributional aspects of optimally financing public investment. More extensive reviews of previous work on the optimal financing of public investment in growth theory thus follow in Chapters 2, 6 and 7.

Carbon lock-in? Infrastructure investment during the transition to the low-carbon economy

Climate change mitigation is a dynamic problem: climate policy can induce a change in the size of stocks relevant for decarbonization, notably privately owned capital and infrastructure. Currently, around 75 % of all greenhouse gas emissions are related to capital stocks (IPCC, 2014c). In particular, public investment in infrastructure directly relating to carbon-intensive economic sectors, such as the electricity grid or the transport infrastructure, will need to be directed from perpetuating carbon-intensive production to facilitating low-carbon production to make ambitious mitigation feasible (Davis et al., 2010; Guivarch and Hallegatte, 2011; Waisman et al., 2012).

The dynamic nature of the problem of decarbonization has led some to conclude that one crucial obstacle in the transition to the low-carbon economy is the risk of a "carbon lock-in": the idea that "economies have been locked into fossil fuel-based energy systems through a process of technological and institutional co-evolution" (Unruh, 2000) due to path-dependency. Beyond pointing to the entanglement of the dominant energy system with political structures supporting it (Hughes, 1987), there may be at least three purely *economic* reasons that make a lock-in impairing the transition to the low-carbon economy likely: first, unappropriated learning spillovers (Kverndokk and Rosendahl, 2007; Kalkuhl et al., 2012) since learning-by-doing seems a credible explanation behind the rapid technical progress in developing more cost-effective renewable energy technologies (Fischedick et al., 2011).

Second, private capital may need to be abandoned before its natural lifetime: Davis et al. (2010) find that cumulative emissions from already existing infrastructure up to 2060 alone would lead to a rise of global mean temperature by $1.3°C$ above pre-industrial levels. Guivarch and Hallegatte (2011) extend their analysis to the case of inertia in asset location in the transport sector and non-CO_2 greenhouse gases. They highlight that under these additional constraints, reaching the 2° target without retrofitting capital or decommissioning it before the end of its natural lifetime would be extremely demanding, if not impossible. Carbon pricing alone may be an insufficient mitigation measure to change the composition of the relevant capital stocks sufficiently (Shalizi and Lecocq, 2010).

Third, a mismatch between mitigation efforts through carbon pricing and the composition of *public* infrastructure investment in carbon-intensive sectors may arise (Waisman et al., 2012; Siegmeier, 2015) – mitigation costs could be lower if appropriate low-carbon public investment was carried out (Avner et al., 2014). One may suppose that too little change in the composition happens in practice, for example, many European countries have not directed transport infrastructure spending away from aviation and road transport towards rail despite their long-term climate goals (ITF, 2014). (For a more detailed discussion of potentially inefficient infrastructure spending in view of decarbonization, see Siegmeier et al. (2015), Section 3.3.) In Chapter 5, this thesis takes up the first economic reason for a potential lock-in, but infuses it with the third.

While it is universally acknowledged that infrastructure impacts decentralized outcomes of production, the exact nature of the influence seems less clear, in particular for the context of distinguishing carbon-intensive and low-carbon economic activity. How can the impact of infrastructure be conceptualized? At least three possibilities of modeling the influence of public investment on private decisions are conceivable. First, the idea of infrastructure constituting an ad-hoc improvement of productivity or of utility (standard in growth theory) may be extended to infrastructure specifically enhancing low-carbon or carbon-intensive production or consumption. Second, one could assume that new infrastructure opens up previously unavailable options, importantly so for transport infrastructure (particularly regarding the (non-)availability of public transportation). This would need to be analyzed with models allowing for non-marginal improvements (Baumol, 2008). Third, it is possible that infrastructure investments enhance *substitution possibilities* between low-carbon and carbon-intensive production possibilities, which may be the case for integrating renewable energies into the electricity system. This may also be relevant when transport infrastructure is redesigned so as to allow for more intermodal mobility.

The thesis formally explores the last option and its influence on a lock-in generated by unappropriated technology spillovers in Chapter 5. By contrast, it does not model the impact of specific infrastructure on *preferences* (but see Sections 1.4.1, 9.1.4 and 9.2 for a brief discussion of the implication of this phenomenon for modeling mobility decisions.). Instead the thesis discusses the significance of empirical findings that confirm an impact on decisions (see Chapter 8).

1.3 Wealth inequality and distributional impacts of climate policy

Capitalism produces a very unequal wealth distribution. For example, in the United States, 5 % of the population own approximately 62 % of total wealth and the middle 55 % of the population own approximately 38 %, whereas the poorest 40 % of the population own virtually no wealth (Wolff, 2010). The wealth concentration at the top of the distribution is particularly striking: Saez and Zucman (2014) find that "[t]he rise of wealth inequality is almost entirely due to the rise of the top 0.1 % wealth share, from 7 % in 1979 to 22 % in 2012." Although the contemporary political climate in the U.S. may be particularly conducive to producing wealth inequalities (Krugman, 2014), high concentrations of wealth at the top of the distribution are, empirically speaking, a characteristic pattern of market economies (Davies et al., 2011; Piketty and Zucman, 2015; Piketty, 2014, Chapter 10).

Research of the last 15 years on wealth inequality has recently been synthesized by Piketty (2014). Three principal messages of his work are: (i) inequality (in wealth) is currently rising, after a historical low in the aftermath of World War II, when there were very high top tax rates for capital income in developed economies. (ii) Great wealth disparities are detrimental to society, as they might lead to "patrimonial capitalism" – marrying rich is a much safer way of acquiring a fortune than entrepreneurial ability. (iii) The key to avoiding that the 21st century will see the tremendous wealth inequality of the 18th and 19th century is a progressive wealth tax or a very high top capital income tax rate.

How does a greatly unequal wealth distribution arise within market economies? Two approaches exist to date. The first one, endorsed by Piketty (2014), focuses on the fact that the upper half of the wealth distribution is well approximated by a Pareto distribution[11] and considers stochastic explanations for this (Benhabib et al., 2011), such as exponential growth lasting for an exponentially distributed amount of time (see Jones (2015)). When the wealth accumulation process is governed by multiplicative random shocks, this generally leads to a Pareto distribution for the upper part (Piketty and Saez, 2014; Piketty and Zucman, 2015). Further, one can show that the thickness of the tail of the Pareto distribution of wealth increases with $r-g-\tau-\xi$, with r the interest rate, g the growth rate, τ the capital tax rate and ξ the share of consumption out of wealth (Piketty, 2014, Chapter 10 and Technical (online) appendix, p. 60 ff.; Piketty and Zucman, 2015; Jones, 2015). So one can conclude that $r > g$ – Piketty's celebrated "Central Contradiction of Capitalism" – leads to an increase in wealth inequality and that a tax on wealth or capital income can mitigate wealth concentrations at the top of the distribution.

The second – more microeconomic – strand of literature seeks to explain the great wealth disparities by focusing on heterogeneous income sources and saving motives. In particular, wealthy households have typically a dynastic saving motive, whereas middle-income households can be shown to rather follow a life-cycle pattern of saving – that is, they save when employed and dissave when retired (Attanasio, 1994; Browning and Lusardi, 1996; Dynan et al., 2004). The richer a household, the more of its income stems from capital income rather than from wage income (Diaz-Gimenez et al., 2011) and the wealthiest individuals work predominantly as self-employed entrepreneurs (Wolff, 1998). Further, time preference rates differ systematically across the population – the poor have a higher rate of time preference (Lawrance, 1991; Green et al., 1996).[12] Indeed, assuming some heterogeneity in time preferences is needed to reproduce the currently observed wealth distribution (Krusell and Smith, 1998). The introductions of Chapter 6 and 7 respectively and the next section discuss the consequences of these findings for modeling.

However, the "macroeconomics of Piketty" (Jones, 2014) has not addressed the impact of climate policy on the wealth distribution, of which this thesis seeks to clarify some aspects. For this, it considers the second approach to wealth inequality. In the first part of this thesis, it is shown that appropriating the (climate or land) rent can be used to subsidize wealth creation. The second part examines how the financing of public investment by various policy instruments can increase or decrease wealth inequality.

Previous work on the distributional effects of climate policy has focused solely on its effect on *income* inequality. Distributional considerations are widely acknowledged to matter for political feasibility of a higher carbon price,

[11] More precisely, it is assumed that the cumulative distribution function of the Pareto probability distribution well approximates the share of the population below a certain level of wealth or income, at least for high values. While Pareto noticed that income heterogeneity might follow this distribution, economic explanations for this hypothesis, although not canonical in economic theory, are discussed at least since Champernowne (1953) and were possibly even considered by Cantelli in 1921 (see Piketty (2014), Technical Appendix, and Jones (2015)).

[12] See also Haushofer and Fehr (2014) for a recent discussion in how far this is due to the fact that poverty *causes* higher discount rates, for instance through stress and negative affective states.

particularly as the poor may be significantly harmed by such a tax reform. In fact, carbon pricing is likely to be regressive (Bento, 2013),[13] but the regressivity of a carbon tax reform can be mitigated by appropriate revenue recycling (Metcalf, 1999; Bento et al., 2009). There is however disagreement on theoretical grounds whether such a reform can even be made progressive (Fullerton and Monti, 2013; Chiroleu-Assouline and Fodha, 2014). Arguably the most important, but not the only, reason for the regressivity of carbon pricing (without revenue recycling) is that poor households spend a larger fraction of their income on carbon-intensive products, in particular on electricity, heating and food, compared to the average household (Grainger and Kolstad, 2010; Fullerton, 2011).[14] When such carbon-intensive subsistence consumption is modeled explicitly, a carbon tax reform *can* be progressive when revenues are recycled as uniform lump-sum transfers (Klenert and Mattauch, 2015). This is for instance partially the current practice in Switzerland (Bundesamt fuer Umwelt. Schweizerische Eidgenossenschaft, 2014). Alternatively making existing distortionary taxes more progressive can also mitigate inequality in this context (Klenert et al., 2015). (See also Siegmeier et al., 2015, Section 3.5, for a more comprehensive overview of the distributional effects of carbon pricing.)

An exception to the focus on income effects is a recent contribution by Karp and Rezai (2014b). They clarify the role of a change in asset values induced by mitigation for the wealth distribution: avoided climate damages should raise the value of assets impacted by such damages. In an overlapping generations model, they find that all generations' welfare is increased by climate policy except that of the current young, if capital is a fixed production factor and mitigation necessitates some investments today. This insight can be generalized to the case of capital with adjustment costs for transforming consumption into investment goods (Karp and Rezai, 2014a).

Beyond the effect regarding avoided damages just described, there are at least two other channels for influencing the wealth distribution through climate policy: First, how does carbon pricing change the investment behavior of households and what are the distributional consequences of this? Second, how does the financing of large-scale low-carbon public investment influence the wealth distribution?

The present thesis provides some building blocks for addressing these two questions theoretically. Answers to both questions could potentially inform two recent policy debates: first, there is considerable uncertainty whether firms such as oil companies correctly estimate the value of their fossil reserves, given political commitments to achieve a virtually carbon free economy within the 21^{st} century. If they in fact overvalue the reserves they own (for example underestimating political commitment to mitigation), this would support the view that a "carbon bubble" (Carbon Tracker Initiative, 2013) exists – which may harmfully affect economic performance by leading to instability. Moreover, various capital-intensive enterprises could become "stranded assets" through carbon pricing. While these considerations are on the political agenda, impli-

[13]But see Rausch et al. (2010) for a different view on this, based on a large computable general equilibrium model: since poor households derive a large share of their income from government transfers, a price on carbon may be progressive because it only affects wage and capital income, but not transfers.

[14]This is true in high-income countries. In poor countries fuel taxes have been shown to be sometimes progressive (Sterner, 2012).

cations for the wealth distribution are not yet traced out. Second, the political feasibility of low-carbon infrastructure investment may depend on their underlying distributional consequences. Recent examples from real-world policy that may confirm this presumption include the construction of new electric power lines across Germany or the further development of the French high-speed rail system (Séguret, 2014). Further, carbon tax reforms in which revenues are recycled to finance local public investment may become more feasible due to greater efficiency or even enhanced visibility of the immediate benefits.

1.4 Appropriate models and their non-standard normative consequences

The two previous sections outlined the main ideas about economic policy that an assessment of the welfare implications of low-carbon public investment must consider. In this section, I consider appropriate models and welfare conceptions for this task. I begin by illustrating when the standard model of climate change economics, the neoclassical growth model, can meaningfully elucidate the welfare implications of financing low-carbon public investment and when it cannot. In the first subsection, I then outline three approaches that are more appropriate for the major part of this work, including overlapping generations models, heterogeneous saving behavior and the behavioral account of decision-making. I conclude that having identified these theories as more appropriate, they necessitate to go beyond the standard normative viewpoint of economics, which is that welfare is the discounted sum of the satisfaction of stable preferences of homogeneous agents about their own consumption. The second subsection then discusses extensions and modifications of the standard conception of welfare: the approach of Calvo and Obstfeld (1988) to aggregating the welfare of distinct cohorts, the difficulty of normative assessments with heterogeneous preferences and finally the distinction between subjective well-being and preference satisfaction accentuated by behavioral economics.

Consider three questions about the welfare effects of financing low-carbon infrastructure:

1) If taxing the rents from fixed factors (to use them for public investment) may be distortionary (see Section 1.2), can this distortion be beneficial and even socially optimal?

2) If preferences are heterogeneous across different groups of households (as is empirically documented, see Section 1.3), by what criterion can financing options for public investment be evaluated?

3) If infrastructure potentially influences the formation of preferences and decision-making (see below), how can its effect on individual welfare be evaluated?

These questions are at the heart of the agenda of this thesis (derived below, in Section 1.5), but cannot be answered, as this section will reveal, by the standard model of climate change economics: the “Ramsey model” of neoclassical growth theory (as developed by Ramsey (1928), Cass (1965) and Koopmans (1965), see Acemoglu (2009), Ch. 8, for an exposition). The features that make the model unsuitable for the questions above are that consumers (1) are modeled as infinitely-lived agents, who only accumulate one capital good; (2) have homogenous preferences; (3) have stable preferences (about their own consumption only). These shortcomings similarly apply to the two major extensions of the Ramsey model in environmental economics, the Dasgupta-Heal-Solow-Stiglitz model that adds an exhaustible resource to the Ramsey model (Dasgupta and Heal, 1974; Solow, 1974; Stiglitz, 1974) and the extension to endogenous technical change, "endogenous growth" (Romer, 1986; Acemoglu, 2009, Part IV). Further, the extensions proposed below are not included in many Integrated Assessment Models of climate change economics, such as DICE and REMIND (Nordhaus, 1994; Leimbach et al., 2010, see also Karp and Rezai, 2014a). I now discuss how each of the three drawbacks relates to the three questions above.

1) Rent taxation is non-distortionary in the Ramsey model (see Section 1.2.1 above and Chapter 2). The reason is that with homogeneous households who are fully altruistic to their descendants (as captured by infinitely-lived agents), a fixed factor will not be traded. However, when generations are explicitly distinguished by age, as is the case in an overlapping generations model, rent taxation acts as a forced government transfer from old to young, which is only neutral by the Ricardian Equivalence that holds in the Ramsey model and in overlapping generations models with full altruism (see Calvo et al. (1979) and Section 1.2.1). Thus the social optimality of redistribution when rent taxation is distortionary should be analyzed on the basis of an overlapping generations model (see below).

2) Heterogeneous preferences cannot in general be aggregated to a representative agent, in particular if agents live for varying periods of a model. Such heterogeneity could lead to different properties regarding aggregate saving: for instance, a standard result of the Ramsey model is that $r = \eta g + \rho$, with r the interest rate, g the growth rate of consumption, η the intertemporal substitution elasticity and ρ the time preference rate. However with heterogeneous agents that cannot be conflated into a single intertemporal representative agent, it is not clear how to meaningfully represent how agents' time preference rates ρ should determine the interest and the growth rate: in a Ramsey model with several agents, the agent with the lowest time preference rate ends up owning all capital in the steady state (Becker, 1980), thus making the model unsuitable.

3) The last criticism is directed at the standard use of a utility function that depends only on the agent's own consumption bundle (which may well include leisure, utility from public amenities, environmental quality etc.). When infrastructure and institutions have an influence on preference formation and decision-making, this must be reflected in the utility function employed. It is beyond the scope of this work to model such an effect formally (but see Section 9.2), instead the focus here is on reviewing behavioral findings about mobility decisions that confirm the hypothesis that the infrastrcuture shapes preferences and to assess the normative significance of this.

There are, however, some contexts that matter for the subject of this thesis, which the Ramsey model *can* elucidate: first, trade-offs between private and public capital can be successfully described in the standard infinitely-lived agent context. Second, for analyzing the timing of infrastructure investment relative to carbon pricing none of the drawbacks just highlighted is relevant either. Hence the analyses in Chapters 2 and 5 below *are* based on a Ramsey-type model.

1.4.1 Appropriate models

Here I describe existing approaches that are appropriate to provide answers to each of the questions 1)–3): overlapping generations models, a two-class model and selected choice-mechanisms from behavioral economics. Overlapping generations models are well established in public finance, but relatively rarely used in climate change economics. Two-class models, which have a classical flavor, are largely outside the focus of current economic research. Behavioral economics approaches abound in empirical environmental economics, but their normative implications are hardly ever considered for developing welfare theory in the context of climate change mitigation.

Overlapping generations models

Overlapping generations models (OLG) consider successive generations explicitly. The discrete or 'Diamond' OLG (Samuelson, 1958; Diamond, 1965) consists of agents living for two periods: they work in the first period and are retired in the second period. The continuous or "Blanchard-Yaari" OLG (Yaari, 1965; Blanchard, 1985) consists of cohorts of individuals born at each instant in time that face a probability of death. The Ramsey model can be obtained as a special case of the discrete model when there are operative bequests and of the continuous OLG model when the death probability is zero. Both OLG models are suitable for studying distributional conflict, both intragenerational (between younger and older agents at a point in time) and intergenerational (between different agents over time). In both models, the existence of disconnected generations gives rise to an externality: notably, saving is Pareto suboptimal. The relevant effect is a *pecuniary externality:* price-related effects of trading decisions impact utilities of unconnected households. The First Welfare Theorem ensures in *finite* economies only, that pecuniary externalities do not give rise to Pareto suboptimal allocations, but this need not be the case when there are infinitely many households (see Acemoglu, 2009, Ch. 9).[15] OLG models can hence be used to examine fiscal policy in a second-best setting. The canonical version of the discrete OLG yields overaccumulation of capital, while that of the continuous OLG features underaccumulation. In environmental economics, OLG models have been used to study questions of intergenerational conflict about the costs and benefits of environmental policy and their distribution (John and Pecchenino, 1994; Stephan et al., 1997; Bovenberg and Heijdra, 1998; Heijdra and Meijdam, 2002).

[15] At root of the usefulness of OLG models to generate second-best settings is thus actually the veridicial paradox of infinity of "Hilbert's Hotel" (Shell, 1971).

This thesis uses OLG models (in Chapters 3 and 4) for examining wealth effects in the context of climate policy when there are distinct assets: when capital and a fixed factor are separate stocks, rent taxation is distortionary in an overlapping generations model (see Feldstein (1977) and Section 1.2.1). The reason is that it harms the owners of the fixed factor and this ownership is distributed non-uniformly across generations. Assessing the welfare implications of this effect with a social planner solution that defines welfare as a function of the preferences of all agents requires to aggregate the distinct cohorts explicitly (see below).

A two-class model

Saving behavior varies widely across the wealth distribution (see Section 1.3). A representative agent model (or one with heterogeneous agents distinguished by initial endowments only) cannot reproduce the division of households into the wealthy, who save dynastically, the middle-class, who saves in a life-cycle fashion, and the poor households who do not save (see Section 1.3). An alternative approach should take into account this division explicitly. For instance, a model with two explicit groups of savers could well represent the actual saving behavior that determines capital accumulation of the economy (leaving aside the poor households as they do not save).

Such a two-class model with appropriate microeconomic foundations has been put forth by Michl (2009): high-income households ("capitalists") are modeled as infinitely-lived dynasties, while middle-income households ("workers") are represented by discrete overlapping generations that live for two periods. Their savings are determined by their life cycle: that is, they save in the first period, while employed, and dissave during their retirement, the second period. This approach builds explicitly on the two-class models of Kaldor (1955-1956) and Pasinetti (1962).[16]

In neoclassical economic theory, the distribution of wealth is generally of no particular relevance for aggregate effects. By contrast, using microfounded models with heterogeneous behavior allows to integrate into a neoclassical setting the tenet of *classical* economics that distribution specifically matters for understanding macroeconomic outcomes. In particular, classical economics holds that distinct behavior of various cohorts ("class structure") matters. While in the steady-state of the Ramsey model the interest rate equals the time preference rate of the representative agent, in models with several agents with different preferences, the question arises whether the interest rate reflects the saving propensity of only some or of all of the different households. The answer is contained in the "Pasinetti Paradox": in a two-class model, in which one class only has capital income, such "capitalists" will determine the steady-state interest rate, the savings behavior of the other class does not matter for this (Pasinetti, 1962; Samuelson and Modigliani, 1966). The two-class model by Michl (2009) exhibits a similar property (which does not hinge on

[16] Banzini (1991) was the first to provide microfoundations for such models; see also Stiglitz (2015b) for a two-class model with exogenous saving rates that is similar to the model used in Chapter 6.

the infinitely-lived agent having only capital income):[17] the infinitely-lived agent determines the interest rate, while the overlapping generations households determine the capital share of each group. In such a model, distributional properties thus matter for elucidating aggregate effects.

Chapter 6 and 7 explore aggregate and distributional effects of financing options for public investment with a modified (neoclassical) version of the two-class model of Michl (2009).

The behavioral account of decision-making

Traditional economics describes the choices of households by assuming that they maximize a utility function that represents their (stable) consumption preferences: choices *reveal* preferences. 'Utility' is thus conceived as a representation of preferences over the choice options. It is moreover assumed implicitly that consumers evaluate these options with correct beliefs about their likelihood (in the presence of uncertainty) and that their decisions are actually made by maximizing the utility function. The description of households' behavior in Ramsey and OLG models is based on these assumptions.

Behavioral economics has collected countless deviations from this "rational choice" approach. In particular, much empirical evidence points to an enormous impact of the context of a decision on its outcome (Tversky and Kahneman, 1981; Ariely et al., 2003; Thaler and Sunstein, 2008; Kahneman, 2011), which is difficult to reconcile with the above assumptions. Chapter 8 discusses this for the case of mobility behavior. The context of transportation choices impacts the decision-making process, for instance the framing of displaying environmental effects influences mode choice (Avineri and Waygood, 2013). Further, over long time-scales, the built environment one lives in impacts the *formation* of preferences (Weinberger and Goetzke, 2010). This means that for specific forms of climate policy measures, such as providing information about environmental impact and building low-carbon transport infrastructure, a model assuming that consumers maximize a utility function that represents preferences independent of the decision environment will not accurately describe their behavioral responses.[18] Thus the models of Chapters 2–7, which do not discard this assumption, are not suitable to formal modeling of the effect highlighted here. Instead, a formalization of both framing effects and a distinction between fundamental and specific preferences about mobility may be needed beyond the work presented below (see also Section 9.2).

A further important example in the context of low-carbon mobility is the finding that commuting causes unhappiness: not only is this the least desired activity in a daily routine (Kahneman et al., 2004), but also the longer people commute, the less satisfied are they with their lives. The reason is that in making employment and residential choices, financial and status aspects of

[17]In the models of this thesis, this is only true as long as growth is neoclassical and not endogenous, that is when there are diminishing and not constant returns to factors that can be accumulated (see also Chapter 7).

[18]See Chapter 8, Section 2 for a more general discussion of why "behavioral economics" (DellaVigna, 2009; Camerer et al., 2011) is an improvement over the orthodox approach to modeling consumer choice and Chapter 8, Section 3, for details that allow to evaluate how inaccurate the rational choice approach may be in describing actual mobility behavior. A short general discussion of these points is Shleifer (2012).

the decisions are much more salient than reduced time for social life through longer commutes (Stutzer and Frey, 2008). This may be due to the misprediction of adaptation to external rewards compared to reduced time for social life (Loewenstein and Schkade, 1999; Frey and Stutzer, 2014).

The findings about commuting build on developments in social psychology that allow for a reliable measurement of subjective well-being: self-reported experience of one's quality of life *does* characterize people's life satisfaction and present mood accurately.[19] This allows to study economic choices in a dimension separate of their outcomes: the impact of one's decisions on one's happiness.

Beyond the example of commuting, there is a consensus in the behavioral sciences that choices often do not promote happiness: on the one hand, inaccurate predictions about the hedonic value of a choice or failure to follow correct predictions in the decision-making process lead to a deviation between actual and happiness-maximizing choices (Hsee and Hastie, 2006). On the other hand, humans do not necessarily seek happiness – instead, much behavior is driven by the need for meaning, not by the desire to be happy (Baumeister et al., 2013). Nevertheless, the distinction between preference satisfaction and subjective well-being is often blurred, at least implicitly. Fleurbaey and Blanchet (2013) (p. 202) even claim that "[e]conomics has been constructed around the concept of utility, and it is apparently easy for economists to forget that when the economic model makes the individual maximize $u(x)$, this means that the individual cares about x, not $u(x)$."

This thesis discusses the consequences of the behavioral account of decision-making specifically for describing the impact of low-carbon investment in the transport sector. However, the implications of the case study about mobility behavior and transport policies (Chapter 8) may be more widely applicable for evaluating public policy and critiques of materialism (see Chapter 9).

1.4.2 Beyond standard normative theory

The standard normative viewpoint from which economics evaluates policy options is: welfare is the discounted intertemporal sum of the satisfaction of stable preferences of homogeneous agents about their own consumption. Policies should aim to maximize welfare thus defined. This viewpoint is a substantive normative position: it is not self-evident that the consequences of economic policy should be evaluated from this and not any other conceivable position (Hausman, 2012). The standard approach is of limited applicability to the questions and models introduced above. This subsection hence discusses more suitable extensions and an alternative viewpoints.

Heterogeneous cohorts

The least substantial modification to the standard approach needed in this thesis is the extension to the case of distinct generations. Welfare of each indi-

[19]For more on the definition of subjective well-being as well as discussions of the reliability and validity of the measures as standardly used in happiness economics and positive psychology, see (Kahneman and Krueger, 2006; Diener et al., 2009).

vidual cohort can still be defined as the discounted sum of the satisfaction of preferences, but in addition the welfare of such cohorts must be aggregated. A natural extension is to define again the discounted sum of the welfare of each cohort as total welfare. However, in this step the rate of time preference of the social planner need not equal the rate of time preference at which generations discount their future utility, even when one wishes to endorse the standard normative position that welfare is the satisfaction of individual (intertemporal) preferences. To illustrate the idea, suppose the size at time τ of a generation born at time v is $\phi e^{-\phi(\tau-v)}$, that is, the size of cohorts declines exponentially as in Blanchard (1985). Welfare at time t is then defined as the sum of the welfare of those already born but still alive and future generations:

$$W(t)=\int_{-\infty}^{t}\left\{\int_{t}^{\infty}u(c(v,\tau))e^{-\delta(\tau-v)}\phi e^{-\phi(\tau-v)}\mathrm{d}\tau\right\}e^{-\rho v}\mathrm{d}v + \int_{t}^{\infty}\left\{\int_{v}^{\infty}u(c(v,\tau))e^{-\delta(\tau-v)}\phi e^{-\phi(\tau-v)}\mathrm{d}\tau\right\}e^{-\rho v}\mathrm{d}v.$$

with δ denoting the generational and ρ the social rate of time preference, u representing generational utility and $c(v,\tau)$ consumption at time τ of the generation born at time v. Here, the utility of each cohort is discounted back to its date of birth.

This extension to the standard social welfare function of growth models has been developed by Calvo and Obstfeld (1988). In particular, they show that the approach outlined is time-consistent, whereas alternatives, such as giving the same weight to all generations alive at time t regardless of their date of birth is not (unless the social rate of time preference equals the private rate). Further, they show that the optimal static distribution at any point in time is independent of the intertemporally optimal *aggregate* solution.

This "Calvo-Obstfeld two step procedure" can be applied to determine the socially optimal solution in both continuous and discrete OLG models (Heijdra, 2009, p. 664-666). Chapters 3 and 4 use the extension of the standard approach sketched here to evaluate the social optimality of age-dependent revenue recycling of rent taxation.

Heterogeneous preferences

The standard approach can be less straightforwardly extended when preferences are heterogeneous in the sense that the economy is populated by both infinitely-lived and life-cycle households. The difficulty is not specifically such heterogeneity of the preferences because the standard social welfare functions of growth models are already cardinal and thus permit interpersonal comparisons (Fleurbaey, 2009): computing the discounted sum of utility at different points in time implicitly presupposes that utility is somehow cardinal. So if one is prepared to grant that some cardinality makes sense even for aggregating life-cycle with infinitely-lived utility for the two-class model introduced above and used in Chapters 6 and 7, aggregation of utilities would be permissible by defining a standard social welfare function. Instead the real additional difficulty here is with the discounting. How exactly should dynastic and life-cycle preferences be aggregated intertemporally? Notably, a solution would be more complicated than the Calvo-Obstfeld approach, but involve similar considerations regarding the use of the social and private time preference rates and potential time-inconsistency of the welfare function. Formally discussing the possibilities and their consequences for defining social welfare is beyond the scope of this thesis (but see also Chapter 6, Section 4).

Instead, the financing options of public investment in Chapter 6 and 7 are not evaluated by a social welfare function, but by considering both whether they constitute Pareto-improvements and their distributional effects.

Welfare as subjective well-being or as modified preference satisfaction?

As discussed above, the influence of the context of a decision on its outcome may be large. Moreover, humans often seek happiness by making choices that are inadequate for this goal (and sometimes explicitly do not seek it).

Both findings together put pressure on that part of the standard welfare conception that specifies welfare as the *satisfaction of given preferences*. After all, if preferences are influenced by the context of a decision, why should the current context be better than any other context? How are different contexts to be evaluated? When preferences about mobility are formed by the spatial surroundings, why should the nature of those surroundings matter normatively?

Going beyond transportation, the key example popularized by Thaler and Sunstein (2008) is that the order in which food options are presented in a cafeteria influences food choices. But why should the order of the options *determine* what is desirable? Similarly, given that people are known to make decisions under uncertainty according to Prospect Theory (Kahneman and Tversky, 1979), why should the dependence on the *status quo* matter normatively? But assigning a special normative weight to the status quo or the context is the direct implication of applying the welfare theory of rational choice to the behavioral account of decision-making. Using unmodified revealed preferences as a welfare criterion means that "whatever people choose makes them better off" (Loewenstein and Ubel, 2008).

However, many would agree that somehow *some* preferences cannot be part of welfare[20], for example preferences that are harmful to the individual in some way.[21] Beyond that, for the cases in which people seek happiness but fail to

[20] I find it a surprising feature of debates in welfare theory that there seems to be very little attention to the distinction between realism and anti-realism about morality (Mackie, 1977; Sayre-McCord, 2014). For instance, Loewenstein (2009) (see his Figure 2) is explicitly realist in his thinking that there must be 'true' welfare, "that which makes life worthwhile" and that identification of welfare with preference satisfaction or happiness captures 'true welfare' imperfectly. By contrast, many economists seem to be implicit anti-realists about welfare. They may wish to hold that 'welfare' is just a label that can be attached to some independently defined policy goals, for instance. So a realist version of the above should read "cannot be part of 'true' welfare, while an anti-realist version would read "welfare cannot be exclusively *defined* in terms of preferences. I do not take a position here, but believe that one's methaethical view might well impact one's normative view in the debate what welfare is (for reasons developed by Greene (2002)).

[21] Very liberal scholars would contradict this: For example, despite all evidence that people's intertemporal choices can be time-inconsistent (Berns et al., 2007), Becker (2005) argues that one reason "seldom mentioned as a general factor partly behind the rise in obesity is the expectation that new drugs will greatly reduce the adverse consequences of being obese. I am not claiming that many teenagers are conscious of this consideration. However, any one who

obtain it, either due to misprediction of the experiential value of the options or due to limited self-control (Hsee and Hastie, 2006), maximizing happiness and not satisfying revealed preferences may look attractive as a welfare criterion.

Two main approaches currently seek to revise the standard view (Loewenstein and Ubel, 2008): both agree with the diagnosis that the behavioral account of decision-making necessitates a revision of the orthodox view for the reasons just stated, but differ in how radical such a revision should be: The first endorses the idea that welfare is determined by the satisfaction of preferences, but concedes that preferences sometimes need to be "purified" (Hausman, 2012). The difficulty for this approach is to provide an account of how the purification of preferences should proceed and whether this is possible in practice (Bernheim and Rangel, 2007, 2009; Hausman, 2012; Sunstein, 2015). The second approach instead identifies welfare with subjective well-being (Layard, 2011; Greene, 2013) in view of the difficulties for the standard preference account outlined above. However, happiness may not be a good proxy for welfare because human beings desire much beyond positive mood and satisfaction with life (Baumeister et al., 2013; Fleurbaey and Blanchet, 2013).[22] For a brief review of the main arguments for and against each of the alternatives, see Chapter 8, Section 4.3.

Chapter 8 discusses how transport policy options can be justified explicitly on the ground of one of these two approaches to welfare. It considers key behavioral effects in mobility choices, including self-control problems about physical exercise, unhappiness stemming from commuting, status-seeking behavior in car purchases and the influence of the infrastructure on the formation of travel preferences. However, the lesson from introducing the distinction between (modified) preference satisfaction and subjective well-being can be broader. Critiques of consumerism – along the lines that firms exploit consumers by creating desires for new products (Jackson, 2009) that are not 'good for them' – cannot be evaluated under the orthodox welfare definition. But they can be assessed in terms of the two welfare conceptions discussed here (see also Section 9.1.4).

has observed the development of blood pressure and cholesterol lowering drugs during the past few decades can rationally believe that in twenty years or so still newer drugs that control diabetes and other diseases will be developed. Then for anyone who likes to eat sugary and fat foods, it does not seem so irrational to do so when the consequences will be much less harmful to health than they are at present." I take the fact that many find this reasoning absurd to be evidence for a widespread intuition that there are preferences of which the satisfaction is not welfare-enhancing.

[22] The preference satisfaction view might alternatively be modified in distinguishing "superficial" and "fundamental" preferences. Then one could acknowledge that the cases in which "superficial" preferences are formed by the choice environment are irrelevant to welfare analysis and at the same time hold that welfare is the satisfaction of fundamental preferences (see Decancq et al., 2015). There seems to be no empirical account currently available for fleshing out this distinction. (However, theoretically, Lancaster (1966) and more recently Dietrich and List (2015) build on the related idea that consumers care about (a subset of the) properties of goods, not the goods *per se* when making choices.) Nevertheless, one may speculate that such a view on welfare would give rise to roughly the same policy implications as a happiness maximization view that allows for exceptions to maximizing happiness when people *rationally* and strongly want something else, while accepting that they must sacrifice some happiness for it. I believe this points to a convergence of the two viewpoints, given what is currently known about human decision-making.

1.5 Objectives and outline

This thesis studies, at a theoretical level, some implications of the transition to a low-carbon economy which have not been sufficiently conceptualized in climate change economics. In particular, the field has neglected that mitigation implies wealth redistribution within countries, particularly as it creates new rents and shifts existing ones. There are also overlooked efficiency effects of appropriating rents through environmental policy when such policy causes changes in the wealth distribution. At the same time, the size of infrastructure investments (to be conceived as investments into a – mostly public – stock, see Section 1.2.2) and its funding options need to be designed carefully for minimizing welfare losses along the transition to a low-carbon economy. All this is the motivation for reconsidering the idea of rent taxation for public investment (see Section 1.2) and studying the ensuing distributional and normative complexities in the first part of this thesis. Moreover, financing public investment has the potential to address some of the equity concerns about the introduction of climate policy, independent of rent taxation. But the precise redistributive effects depend on the financing options available and heterogeneity in behavior across households. Further, given that consumption decisions are subject to many behavioral effects in some sectors to be decarbonized, such as transport and food, a rigorous normative assessment of low-carbon public investment also needs to consider welfare conceptions that modify the orthodox approach of the satisfaction of households' identical, stable preferences. Assessing the welfare and the distributional effects of public investment is the topic of the second part of this thesis.

The research presented in the following chapters can thus be divided along two separate sets of questions. The first set of research questions, covered in Part I, builds on the premise that there are fixed factors that yield substantial rents:

- Can the idea of using revenues from rent taxation for productive public investment be adapted to a macroeconomic scale?
- How can the efficiency aspects of (land) rent taxation be evaluated normatively? How can socially optimal outcomes be achieved when redistribution of revenues may be age-dependent?
- Is the distortion due to the appropriation of the climate rent beneficial?[23]
- How does the timing of infrastructure investment matter? How can socially optimal outcomes be achieved when infrastructure enhances substitution between carbon-intensive and low-carbon production?

The second set of research questions, addressed in Part II, does not assume that fixed factors matter, but looks at the welfare effects of low-carbon public investment, particularly analyzing the relationship between aggregate and distributional as well as the role of behavioral effects:

[23]Throughout this thesis, I take 'distortionary' to mean distorting private agents' decisions without any implied normative significance, see Footnote 8.

- Can productive public investment be financed in a way that at the same time reduces inequality? How does the heterogeneity in saving motives and income sources across households matter for this? What are the differences between capital, labor and income taxation as financing options in this context?

- When does the behavioral account of decision-making matter for climate policy? How does it explain mobility choices? What are implications for designing mitigation measures and more generally for welfare analysis of transport policies? What can be learned from the influence of the transport infrastructure, as an example of productive public investment, on mobility decisions?

These two sets of questions are addressed in seven manuscripts, reproduced as Chapters 2–8 of this thesis. Chapter 9 synthesizes the results and discusses its broader implications.

Chapter 2 examines when taxing the rents derived from a fixed factor, such as land, is sufficient to maintain a stock of productive public investment.[24] It shows, in a standard growth model, that this is the case when land is sufficiently productive relative to public capital. It thus establishes a macroeconomic analog of the Henry George Theorem of local public finance and shows that this new macroeconomic relationship is very robust.

Chapter 3 links land rent taxation to the goal of enhancing efficiency and equity at the same time.[25] It examines whether, in presence of rents derived from a fixed factor, there is a socially optimal policy for the case that private capital is underaccumulated due to imperfect intergenerational altruism. It employs a continuous overlapping generations model and the Calvo-Obstfeld (1988) approach to social optimality in such models. It is proved that recycling the revenue from land rent taxation in a way that is biased towards the young, poor generations reproduces the social optimum. The article thus is a normative generalization of Feldstein's (1977) insight that rent taxation can be distortionary, but beneficially so. It also provides an additional distributional motive for rent taxation.

Chapter 4 applies the insights of the previous chapter to the case of the climate rent.[26] Carbon pricing appropriates rents from an exhaustible resource. Depending on the type of carbon pricing that is implemented, this can either be the limited disposal space of greenhouse gases in the atmosphere, or the

[24] Chapter 2 will be resubmitted to the *Journal of Public Economic Theory* and a previous version was published as a CESifo Working Paper: Mattauch, L., J. Siegmeier, O. Edenhofer, O. and F. Creutzig (2013). Financing Public Capital through Land Rent Taxation: A Macroeconomic Henry George Theorem. *CESifo Working Paper* 4280.

[25] Chapter 3 is published in *Finanzarchiv/public finance analysis:* Edenhofer, O., L. Mattauch, and J. Siegmeier (2015). Hypergeorgism: When rent taxation is socially optimal. *Finanzarchiv/public finance analysis* 71(4). A previous version was published as a CESifo Working Paper: Edenhofer, O., L. Mattauch, and J. Siegmeier. Hypergeorgism: When is Rent Taxation as a Remedy for Insufficient Capital Accumulation Socially Optimal? (2013). *CESifo Working Paper* 4144.

[26] Chapter 4 is in preparation for submission to the *Journal of Environmental Economics and Management* and a previous version has been published as a CESifo Working Paper: Siegmeier, J., L. Mattauch and O. Edenhofer. Climate policy enhances efficiency: a macroeconomic portfolio effect. *CESifo Working Paper* 5161.

stock of fossil reserves. The chapter uses a variant of the continuous overlapping generations model of Chapter 3 in which declining availability of the exhaustible resource is offset by publicly-financed technical change. It proves that climate policy induces an efficiency-enhancing portfolio effect, because appropriating the climate rent, for instance by auctioning permits of an emission trading system, boosts investment in private capital. The social optimum is only reached when revenue recycling is biased towards the younger generations, as in Chapter 3. It is explored whether the beneficial portfolio effect occurs under various forms of climate policy and it is proved that it holds for an emission trading system (independent of the lifetime of permits), a constant carbon tax and privatization of the atmospheric stock.

Chapter 5 turns to the role of optimal timing of carbon pricing and low-carbon infrastructure provision.[27] It examines how the substitution elasticity between clean and dirty production influences the size of a carbon lock-in that is due to uninternalized technological spillovers. The main finding is that a high elasticity leads to a greater lock-in for laissez-faire, but requires less drastic policy interventions to reproduce the social optimum compared to a low elasticity. The chapter uses a standard Ramsey-type growth model, with a stylized representation of the atmospheric carbon sink, that is solved numerically. It shows that an exogenous change in infrastructure policy over time greatly influences the size of the lock-in.

While Part I is centered around revenue generation through taxing fixed factors or correcting externalities, Part II focuses on public spending and distribution:

Chapter 6 examines the welfare effects of capital taxation for financing productive public investment in a two-class model:[28] empirically, high-income and middle-income households differ markedly in their saving behavior. The former class saves dynastically, while the latter class mostly accumulates wealth in a life-cycle fashion. In this context, the chapter proves that capital taxation can be both Pareto-improving and reduce inequality. In the model employed, high-income households are represented as infinitely-lived and middle-income households are modeled as overlapping generations. It is shown that a version of the Pasinetti (1962) Paradox governs the formation of the interest rate.

Chapter 7 generalizes the model of the previous chapter to compare capital taxation to other financing options:[29] in order to study consumption and labor income taxation, the two-class model of the previous chapter is extended to include a labor-leisure choice, utility-enhancing public investment and en-

[27] Chapter 5 is published in *Economic Modelling:* Mattauch, L., F. Creutzig, O. Edenhofer (2015). Avoiding Carbon Lock-In: Evaluating Policy Options for Advancing Structural Change. *Economic Modelling* 50:49–63. A previous version has been circulated as a Climatecon Working Paper. Mattauch, L., F. Creutzig and O. Edenhofer. Avoiding Carbon Lock-In: Policy Options for Advancing Structural Change. *Climatecon Working Paper* 1-2012.

[28] Chapter 6 is under review at *Metroeconomica*. A previous version has been published as a CESifo Working Paper: Mattauch, L., O. Edenhofer, D. Klenert, S. Bénard (2014). Distributional effects of public investment when capital is Back. *CESifo Working Paper* 4714.

[29] This chapter is under review at *Macroeconomic Dynamics*. A previous version has been published as a CESifo Working Paper: Klenert, D., L. Mattauch, O. Edenhofer and K. Lessmann (2014). Infrastructure and Inequality: Insights from Incorporating Key Economic Facts about Household Heterogeneity. *CESifo Working Paper* 4972.

dogenous growth. It is solved numerically. The result about capital taxation of the previous chapter is confirmed in the more general setting. Further, it is found that consumption and labor income taxation yield higher welfare than capital taxation, but that consumption taxation is distributionally neutral, while labor income taxation increases inequality. The results of the chapter contrast with previous work, which claimed that public investment, regardless of how financed, either increases wealth inequality or is distributionally neutral, but show that the approach pursued here is more robust.

Chapter 8 looks at the behavioral response to public investment, considering mobility behavior and the transport infrastructure as an important special case.[30] It examines which transport policies are effective for decarbonizing mobility by inducing more non-motorized transport and discusses the welfare implications of behavioral mitigation options. It is argued that evaluating the ancillary benefits of mitigating climate change in transportation necessitates the distinction of subjective well-being from preference satisfaction as independent welfare conceptions. In particular, the transport infrastructure influences both decision-making and preference formation and thus requires a revision of the orthodox approach in welfare economics, that of maximizing the satisfaction of fixed preferences.

Chapter 9 summarizes the results of the previous chapters, explores options for further research and discusses the policy relevance of the findings of this thesis.

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[30] This chapter is published in *Transportation Research Part D: Transport and Environment:* Mattauch, Linus, Monica Ridgway, Felix Creutzig (2015). Happy or liberal? Making sense of behavior in transport policy design. *Transportation Research Part D: Transport and Environment,* Doi: 10.1016/j.trd.2015.08.006. It has also been circulated as an MCC Working Paper: Mattauch, L., M. Ridgway, F. Creutzig. Happy or Liberal? Making sense of behavior in transport policy design. *MCC Working Paper 5/2014*.

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Part I

Taxing rents to reach social optimality

Chapter 2

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

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

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Abstract

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

JEL classification: H21, H54, Q24 H40

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

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1 Introduction

Public capital is a key determinant of aggregate productivity (Romp and De Haan, 2007; Bom and Ligthart, 2014): productivity increases may stem from investments into physical infrastructure, but also into the health and the education system or into the stock of publicly available knowledge. However, collecting revenue for public investment through taxation usually creates inefficient allocations (Barro, 1990; Barro and Sala-I-Martin, 1992). Typically, a trade-off between productivity growth from public investment and efficiency loss from distortionary taxation is identified, which determines the best possible level of public investment. It is lower than the socially optimal level, which thus cannot be reached when lump-sum taxation is infeasible.

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

Our argument is based on two premises. First, we assume that public investment is productivity-enhancing[1], be it in the form of infrastructure (Barro, 1990; Gramlich, 1994), research and development (Romer, 1990) or investment into human capital via education or the health system (Glomm and Ravikumar, 1992; Bloom et al., 2004). The nature of the investment may differ according to the state of a country's economy: In developing countries, *building* new infrastructures and public capital stocks would enhance productivity (Agénor, 2013). In developed countries, *maintaining* the existing, but deteriorating infrastructures requires public investment. Moreover, *transforming* infrastructures is required for overcoming the lock-in into carbon-intensive production processes to mitigate global warming and its economic damages (Unruh, 2000; Davis et al., 2010; Lehmann et al., 2012; Mattauch et al., 2015).

Second, we assume that fixed factors are relevant for the production process: In fact the rents on non-reproducible factors such as land are a highly significant share of total economic output (Caselli and Feyrer, 2007). Furthermore, while our model assumes that taxing land rents is non-distortionary, our results translate to settings in which it *is* distortionary, but beneficial (as in Feldstein (1977) or Edenhofer et al. (2015); see Section 5.2).

The main result of this article is related to the Henry George Theorem,

[1] For a review of the theoretical literature of the link between government spending and growth, see Irmen and Kuehnel (2009). Empirical reviews of this premise are provided by Romp and De Haan (2007), Bom and Ligthart (2014), Zagler and Dürnecker (2003) and Creel and Poilon (2008).

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

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

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

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

2 Model

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

2.1 Socially optimal allocation

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

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

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

The production function has the conventional properties that $F_K, F_G, F_L\ F_S > 0$, but $F_{KK}, F_{GG}, F_{LL}, F_{SS} < 0$, where $F_S := \mathrm{d}F/\mathrm{d}S(K_t, G_t, L, \bar{S})$ etc. In Section 3, we distinguish two cases: the production function has (i) decreasing returns to scale in the accumulable factors private and public capital and (ii) constant returns in these factors. The two cases lead to steady-state convergence and long-run endogenous growth, respectively. Labour supply is constant. Total land $\bar{S}$ is also constant over time, so the social planner seeks the optimal distribution of private capital K and public capital G. Unless noted otherwise, it is additionally assumed that the production function is linearly homogenous in private capital, labour and land. Output is divided between consumption C_t and investment into the two capital stocks, which have depreciation rates δ_k and δ_g respectively. The social planner chooses consumption C_t and investment into public capital I_{gt} to maximize the welfare of an infinitely-lived representative household with instantaneous utility given by $U(C) = (C^{(1-\eta)} - 1)/(1-\eta)$.

The maximization problem of the social planner is thus

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

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

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

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

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

and similarly

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

which implies

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

2.2 Decentralized equilibrium

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

2.2.1 Households

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

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

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

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

[3]The appropriate transversality condition is:

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

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

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

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

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

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

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

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

2.2.2 Firms

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

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

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

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

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

and

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

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

2.2.3 Government

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

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

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

3 Main results

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

3.1 Land rent taxation reproduces the social optimum

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

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

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

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

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

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

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

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

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

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

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

and

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

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

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

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

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

□

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

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

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

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

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

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

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

3.2 A macroeconomic Henry George Formula

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

3.2.1 The case of the neoclassical growth model

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

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

$$F_K^* = F_K(K^*, G^*, L, \bar{S}) = \rho + \delta_k \tag{20}$$

$$F_G^* = F_G(K^*, G^*, L, \bar{S}) = \rho + \delta_g \tag{21}$$

$$F(K^*, G^*, L, \bar{S}) = C^* + I_g^* + \delta_k K^* \tag{22}$$

$$I_g^* = \delta_g G^*. \tag{23}$$

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

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

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

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

The land rent R is thus given by

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

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

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

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

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

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

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

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

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

Inserting Equation (26) yields the claimed formula. □

3.2.2 The case of endogenous growth

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

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

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

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

so that

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

Inserting this in Equation (4) yields

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Hence

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

□

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

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

5 Discussion

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

5.1 Alternative models of government spending

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

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

For the second case, it can be shown that the findings of this study are all valid regardless of whether the productive public good is formulated as a stock (to which the government expenditure continuously adds) or flow (equal to government expenditure). However, the stock formulation seems preferable as we are chiefly concerned with *productivity-enhancing* public expenditure such as infrastructure provision. Considering a public capital stock is also more convenient for further empirical analyses because of symmetry: for instance, depreciation parameters for public and private capital may be different. Moreover, it is plausible that in developed economies land rents are sufficient to finance what is generally defined as public investment up to the socially optimal level (see Section 5.4) – but it is doubtful that they can additionally cover the much broader category of government flow spending.

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

5.2 Stock markets and household heterogeneity

Analysing the dynamics of stock markets for fixed factors of production, such as land, with the neoclassical growth model has severe limitations. (This may have been first noted by Feldstein (1977); see Burgstaller (1994) for a comprehensive overview.) Although a price for land – the present value of all future land rent income – is formed, land will not be traded: the continuum of homogenous agents of this model own an equal share of land, but have neither an incentive nor a trade partner to buy or sell any of it. A neoclassical growth model with land, as introduced above, thus exhibits "partial equilibrium" properties concerning the factor land: for instance, land rent taxation is non-distortionary and the tax falls entirely on the owners of land, although this is not the case in more general circumstances (Feldstein, 1977). There is in particular no rebalancing of households' savings portfolios: households have no incentive to invest more in capital when a land rent tax is introduced. Edenhofer et al. (2015) explore, by means of a continuous overlapping generations model, the social optimality of land rent taxation when heterogeneous households acquire more land as they get older. In such a model, which exhibits suboptimal capital accumulation, when land is taxed, households invest into other assets, notably private capital. Thus land rent taxation is distortionary, but beneficial. The results of the present study can be reproduced in such a framework with some minor modifications due to the demographic structure.

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

5.3 Labour- and land-augmenting technological progress

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

The main results of this paper hold as long as the economy is on a balanced growth path. Such a path can exist if and only if productivity growth in land equals productivity growth in labor (including population growth). If the economy is not on the balanced growth path, factor shares may be different, depending on the production function. The feasibility of the social optimum depends on the factor shares according to Proposition 3: outside the balanced growth path an increasing factor share accruing to land makes reaching the social optimum more likely. For example, for the case of a CES production function with substitution elasticity σ, the factor share accruing from land grows faster than the factor share accruing from labour if and only if either $\sigma > 1$ and productivity growth in land is greater than that in labour or $\sigma < 1$ and labour productivity growth is greater than that in land.

Henry George claimed that the factor share accruing to land grows faster than that accruing to labour.[8] While this is not possible in the steady state

[8]"In identifying rent as the receiver of the increased production which material progress

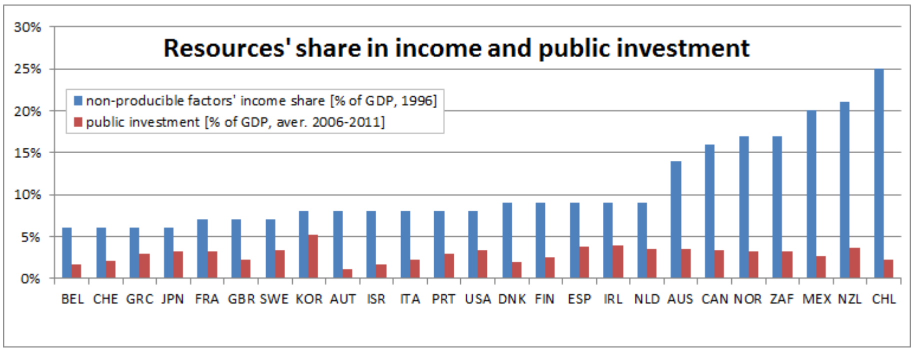

Figure 1: Income shares of non-producible factors (Caselli and Feyrer, 2007) and public investment (OECD, 2013), ISO3 country codes.

or under a Cobb-Douglas production function in general, outside a balanced growth path Henry George's claim about the role of the land rent may be true. In particular the condition that $\sigma < 1$ and productivity growth in labour was greater than in land seems to have some plausibility for economic development in the 19^{th} century. It is less plausible for current developed economies, for which it may be supposed that $\sigma > 1$, but still that labour productivity grows faster than land productivity.

5.4 Empirical relevance

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

Regarding the investment needs of industrialized countries, maintaining the infrastructure and adapting it to the challenges of climate change (Davis et al., 2010) translates into significant shares of government spending: The OECD reports public investment shares averaged over 2006 to 2011 for 34 countries that range between 1.1% (Austria) and 5.22% (South Korea) of GDP. The investment needs in poorer countries are highlighted by data from the World Bank (2009) showing that access to basic utility services such as water, sanitation and electricity in low-income countries was 65%, 36% and 23%, respectively, and still only 92%, 72% and 97% for upper-middle income countries. Estache and Fay (2007) estimated overall infrastructure investment and maintenance expenditure needs between 2005 and 2015 for low, lower-middle and upper-middle income countries to be 7.5, 6.3 and 3.1 percent of GDP, respectively, just to meet increasing demand due to projected growth. While these actual or projected spending figures may not be *optimal* by some welfare criteria, they show the order of magnitude and the larger public investment needs in poorer countries lacking the most basic infrastructure.

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

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

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

6 Conclusion

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

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Chapter 3

Hypergeorgism: when rent taxation is socially optimal[1]

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Hypergeorgism: when rent taxation is socially optimal

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Abstract

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

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

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

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1 Introduction

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

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

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

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

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

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

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

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

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

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

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

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

2 Model

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

2.1 Decentralised model

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\lim_{\tau\to\infty}[k(\nu,\tau)+p(\tau)s(\nu,\tau)]e^{-R(t,\tau)}=0 \quad (6)$$
$$\text{with} \quad R(t,\tau)\equiv\int_{t}^{\tau}(r(\tilde{t})+\phi)\mathrm{d}\tilde{t}.$$

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

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

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

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

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

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

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

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

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

The no-arbitrage condition is crucial for the main result below since it links the stock and flow markets for land by relating the unit value of land as an investment p to its after-tax rent, $(1-T)l$.

Using the instantaneous budget identity (3), transversality condition (6) and no-arbitrage condition (9), the lifetime budget constraint can be derived:[5]

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

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

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

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

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

$$C(t) = (\rho+\phi)[K(t) + p(t)S + \bar{W}(t) + \bar{Z}(t)], \tag{12}$$
$$\text{with} \quad \bar{W}(t) \equiv \int_{-\infty}^t \bar{w}(t)\phi e^{-\phi(t-\nu)}\mathrm{d}\nu = \bar{w}(t)$$
$$\text{and} \quad \bar{Z}(t) \equiv \int_{-\infty}^t \bar{z}(\nu,t)\phi e^{-\phi(t-\nu)}\mathrm{d}\nu,$$

where C and K denote total consumption and capital, and $\bar{W}$ and $\bar{Z}$ the total present values of labour income and transfers from the government to individuals. Therefore, aggregate consumption is the same constant fraction of total wealth as for each individual.

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

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

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

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

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

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

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

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

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

yielding the standard first-order conditions

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

where δ is the depreciation rate of private capital.

2.2 Social planner

The social planner solution is chosen as a normative benchmark to evaluate the tax policies examined below. We assume that social welfare consists of the

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

preference satisfaction of all heterogeneous individuals weighted by a utilitarian social welfare function. For simplicity, we assume that the socially optimal rate of pure time preference equals the private rate of pure time preference.[7]

Social welfare V at time t is defined as follows:

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

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

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

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

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

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

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

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

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

$$\max_{C(t)} \int_{t=0}^{\infty} U(C(t)) e^{-\rho t} dt \tag{19}$$
$$\text{with} \quad U(C) = \ln(C)$$
$$\text{s.t.} \quad \dot{K}(t) = F(K(t), L(t), S(t)) - C(t) - \delta K(t).$$

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

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

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

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

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

2.3 Steady states

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

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

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

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

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

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

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

A unique (non-trivial) steady state solution exists and the steady state is saddle-point stable. In the following the system is reduced to two dimensions by

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

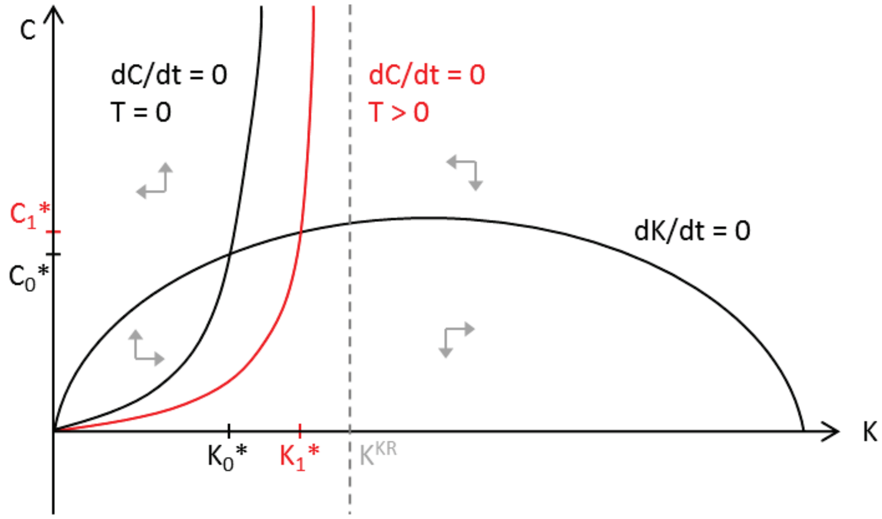

Figure 1: Phase diagram for redistributions with $\bar{Z}^{\dagger}(K) - \bar{z}^{N\dagger}(K) \geq 0$ for all $K \in [0, K^{kr}]$ and all $T \in [0;1]$

setting $\dot{p} = 0$. This projection captures all relevant dynamics.[9] We denote variables at the steady state (where all three of Equations (22–24) hold) by an asterisk *. In particular,

$$p^* = p(K^*) = \frac{(1-T)l(K^*)}{r(K^*)} \tag{25}$$
$$r^* = r(K^*) = F_K(K^*) - \delta$$
$$l^* = l(K^*) = F_S(K^*).$$

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

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

$$\phi \bar{z}^{N*} + r^* \bar{Z}^* = T l^* S. \tag{26}$$

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

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

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

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

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

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

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

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

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

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

2.4 Underaccumulation and redistributive effects

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

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

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

Without taxes and transfers ($T = z = 0$), there is suboptimal underaccumulation due to the generation replacement effect, as is standard in continuous OLG models: since newborns have a lower level of consumption than the average household, aggregate consumption growth is lower than individual consumption growth. Through general equilibrium effects, this leads to a suboptimally low level of aggregate capital. More precisely, using Equation (25), the numerator of the second term simplifies to $K^* + l^*S/r^*$ which is always positive. Thus, the interest rate of the decentralised case is higher than the implied price of capital in the social planner's steady state (compare Equation 21). It then follows from $F_{KK} < 0$ and Equation (16) that capital accumulation is lower, $K^* < K^{kr}$. As K^{kr} is to the left of the maximum of the parabola described by Equation (22), a lower capital stock implies suboptimal consumption, $C(K^*) < C(K^{kr})$ (see also Figure 1).

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

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

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

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

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

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

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

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

3.1 Non-optimal redistributions: uniform and compensatory

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

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

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

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

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

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

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

One can derive

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

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

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

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

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

From this result it also follows that a 'compensatory' redistribution cannot be socially optimal.[11] A simple compensation would be to continuously remunerate land owners for taxes they paid, as considered for example by Calvo et al. (1979). This is important to analyse because isolating the effect of the tax as a shift in relative prices requires compensating the tax payers.

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

[11] A sketch proof of its non-optimality is as follows: starting from a uniform redistribution, some of the transfers from selected young generations are shifted to selected older generations, which have more land and thus a higher tax burden. At time $\tilde{t}$, the shift of *contemporaneous* transfers does not affect C since any cohort consumes the same fraction of their wealth (Equation 11). However, the expectation of similar *future* transfers does have an effect, since the expected increased transfers towards today's youngest generations will be at the cost of unborn generations ($\nu > \tilde{t}$), whose future loss finances today's consumption. Technically, $\bar{Z}(\tilde{t})$ is higher than without the shift. By itself, this effect increases C at any given K – the hyperbola of Equation (23) with shifted transfers is above the original hyperbola for all K. (Additionally, $\bar{z}^N$ is lower when transfers are shifted, since increased transfers in the far future are discounted more than losses in the nearer future. This strengthens the overall effect of the shift of transfers, $(\bar{Z}^* - \bar{z}^{N*})$ in Equation (23).) However, since higher C implies foregone investment and thus a lower K^*, the overall effect on C^* is negative.

3.2 Optimal redistributions: 'newborns only' and exponential

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

which yields

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.3 Hypergeorgism: general result

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

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

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

The proposition is proved in Appendix A.5. An intuition why the result is true has already been developed in Section 2.4. The idea of proof is to trace the price effect and the redistribution effect of taxing land in the general equilibrium setting. The second half of the statement follows by showing that the two effects cannot lead to overaccumulation given the upper bound on the tax rate.

The proposition is very general regarding the redistribution scheme, but the generality implies two disadvantages: First, only a comparison between the unregulated market outcome and a policy case is possible. One may also

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

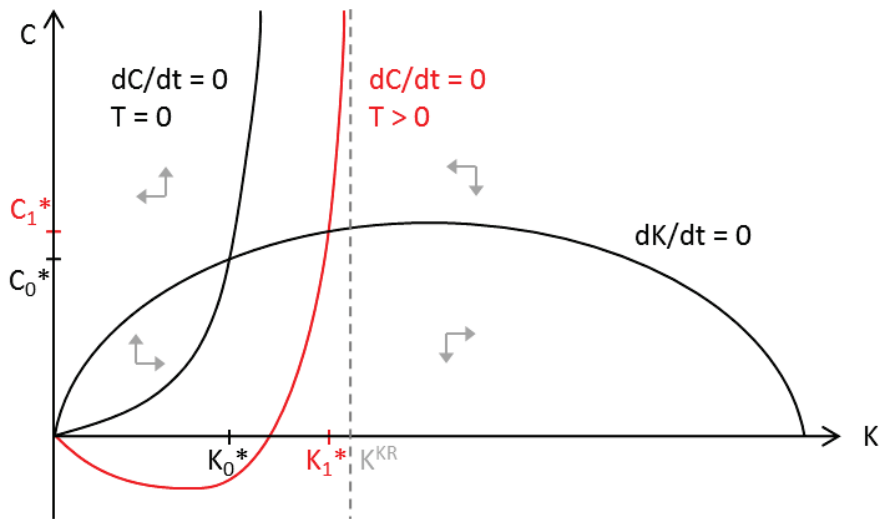

Figure 2: Phase diagram for redistributions with $\bar{Z}^{\dagger}(K) - \bar{z}^{N\dagger}(K) < 0$ for some $K \in [0, K^{kr}]$ and $T < T^{opt}$

want to know whether a higher tax implies higher welfare in general. Given the uniform redistribution, a higher tax rate does in fact imply higher welfare, but this is not necessarily true for all other redistributions. Second, the proposition considers a welfare improvement only and is not informative about the achievability of the social optimum. But a general optimality condition for arbitrary tax rates and redistribution schemes can be obtained from Equation (28) if we use Equation (26) to replace $\bar{Z}^*$:

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

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

3.4 Capital subsidy

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

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

so restoring the Keynes-Ramsey case requires

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

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

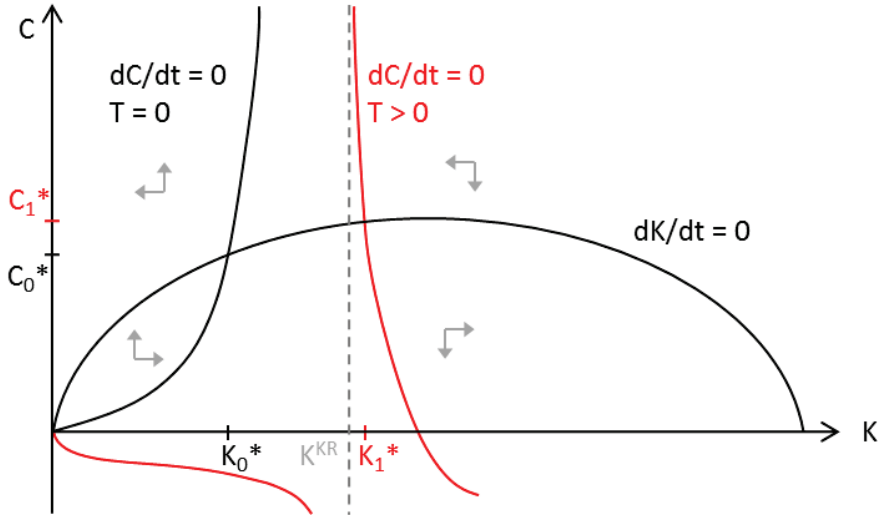

Figure 3: Phase diagram for redistributions with $\bar{Z}^{\dagger}(K) - \bar{z}^{N\dagger}(K) < 0$ for some $K \in [0, K^{kr}]$ and $T > T^{opt}$

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

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

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

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

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

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

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

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

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

4 Extensions

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

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

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

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

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

Third, welfare effects during the transition to a new steady-state differ from those of the above analysis. Recall that above we compare an existing steady-state without policy to a new steady-state with policies in place. This means that our policies are no Pareto-improvements as some generations might be worse off during the transition from a steady-state without policies to one with a policy in place. Here we consider the case that the introduction of a land rent tax together with one of the redistribution schemes is unanticipated by households. For this, one can conjecture that (i) generations born after the tax reform will always be better off (at least under the additional assumption that $F_{KL} > 0$). (ii) For existing generations, there is a threshold in age determining whether the tax reform will make them better off. If agents are older than this threshold they will lose. The threshold depends on the redistribution scheme and the tax rate. A brief justification for this conjecture is as follows: agents born after the tax reform have no non-human wealth and their human wealth increases by the tax reform, because they now receive transfers. Moreover, their wage rate increases. The reason for this is that aggregate capital increases during the transition, although aggregate consumption first declines before it increases to a new, higher level. Agents born before the tax reform loose in proportion to the wealth they own, while all face the same probability of dying before the new steady-state level has been reached. The transitional welfare effects thus leave scope for a welfare improvement through a bond path that uses some of the efficiency gains when close to the new steady-state to partially compensate the losers at the time of enactment of the tax. One might prove these conjectures by applying methods similar to those used in Heijdra and Meijdram (2002) if these can be adapted to the closed-economy setting.

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

5 Conclusion

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

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

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A Appendix

A.1 Derivation of the Keynes-Ramsey rule and the no-arbitrage condition

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

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

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

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

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

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

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

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

Inserting the time derivative of (62) into Equation (64) yields the Keynes-Ramsey rule (8). Using Equation (63) and its time derivative to replace μ and $\dot{\mu}$ in Equation (65) and applying Equation (64) gives the no-arbitrage condition for investing in land or capital (9).

A.2 Individual lifetime budget constraint and consumption level

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

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

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

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

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

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

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

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

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

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

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

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

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

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

A.3 Aggregate solution

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

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

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

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

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

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

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

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

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

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

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

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

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

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

is

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

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

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

and thus finds the first-order conditions:

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

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

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

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

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

A.5 Proof of Proposition 5

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

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

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

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

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

$$C_H^1(K) = \phi \frac{\rho+\phi}{r(K)-\rho} \left\{ K + \frac{l(K)S}{r(K)} - \frac{T\,l(K)S}{r(K)} + \bar{Z}^{\dagger}(K) - \bar{z}^{N\dagger}(K) \right\}, \tag{72}$$

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

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

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

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

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

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

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

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

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

To this end, it is sufficient to show

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

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

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

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

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

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

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Chapter 4

Climate policy enhances efficiency: A macroeconomic portfolio effect[1]

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Climate policy enhances efficiency: a macroeconomic portfolio effect

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Abstract

Carbon pricing not only regulates the flow of emissions, but also collects rents from underlying fossil resource stocks. Assuming that these stocks are tradable, carbon pricing shifts aggregate investment towards alternative assets. If capital is underaccumulated, this implies lower gross costs of climate policy and a welfare improvement. We prove that under an emission trading scheme, such a beneficial macroeconomic portfolio effect between fossil fuel stocks and capital is induced if not all permits are allocated for free. We also analyze the impact of alternative policy instruments: first, a carbon tax also induces a portfolio effect, but cannot simultaneously implement a given mitigation path and collect an arbitrary share of the rent. Second, the right to recurrently receive a share of total emission permits could be treated as a tradable asset. This yields the same results as a conventional emission trading scheme, but improves the robustness of the macroeconomic portfolio effect of climate policy in real-world settings.

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

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

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1 Introduction

A lack of political effort to implement ambitious climate change mitigation has frequently been justified by pointing out that other objectives, such as promoting economic growth, creating jobs or reducing inequality, take priority in *national* economic policy. Yet, most studies of the impacts of climate policy on growth and distribution have been conducted either on a sectorally resolved, technologically detailed level, analyzing effects on and between specific industries and households, or on an international level, considering the feasibility of agreements between nation states. However, the efficiency and the distributional effects of climate policy are neither confined to directly regulated sectors and technologies, nor to the international level: on a national scale, there are complex interactions with non-climate inefficiencies and policy goals, and appropriately designed climate policy instruments can improve overall efficiency and welfare.[1]

Specifically, this paper shows that pricing the flow of carbon emissions, and thus appropriating rents from fossil resource stocks interpretable as 'climate rents', induces a macroeconomic distortion by directing investment towards producible capital as the alternative asset. If capital was previously underaccumulated, this 'macroeconomic portfolio effect' constitutes a welfare improvement and lowers the gross costs of climate policy.

This result has three major policy implications: First, and most importantly, there is generally an *efficiency* reason for the appropriation of climate rents for the public, rather than only a distributional motive - it may be *necessary* to collect the rents if the socially optimal allocation is to be implemented. Second, dynamic effects on stocks matter for the efficiency of flow-oriented climate policy instruments. Third, specifically for climate policy implemented as a permit scheme, the previous points imply an additional reason why permits should not be allocated for free.

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

We use a specific formal model and policy instrument, namely a two-asset overlapping-generations (OLG) model and three forms of carbon pricing, to prove the main result of this article. However, this specific model should be interpreted as an illustration of the more general idea of a beneficial macroeconomic portfolio effect due to rent collection via resource- and climate policy. This general idea is based on three major assumptions:

First, we assume that capital is suboptimally underaccumulated. This seems generally plausible if capital is broadly defined to include physical as well as human capital.

Second, the investment choice between capital and fossil resource stocks requires that both are available as privately owned, tradable assets in the econ-

[1] As a binding and sufficiently ambitious international agreement seems currently unlikely, independent national efforts come into focus - and with them, the effects of climate change and climate policy on national economies that may motivate such efforts (Edenhofer et al., 2015a; Siegmeier et al., 2015).

omy under consideration. This may be the case either for a national economy that has both substantial fossil resources and capital goods, or for the world economy (interpreting rent collection as a global carbon pricing scheme). The liquidity of markets for emission-related assets also depends on the climate policy instrument chosen; for example, if the right to perpetually obtain a certain share of annual (national or global) emission rights was a tradable asset, the distribution of property rights to fossil resources would be less important for the portfolio effect to occur (see Section 4.3).

Third, we consider a situation where long-term climate policy has already been imposed - that is, the government has introduced an emission permit scheme, credibly committed to a path for the issuance of these permits *and* the degree to which they will be auctioned, and the economy has already adapted to each of these measures. We thus neglect the anticipation and transitional effects of the tax reform and only compare economic aggregates on balanced paths with limited emissions, but with or without rent collection.[2]

We relate our main result to four fields of research: We highlight its differences to literature on optimal climate policy and its international feasibility, and to literature on the existence of a 'double dividend' of environmental taxation. We then point to its similarity to previous findings about rent taxation in public finance. Finally, important complementary results concern resource taxation under endogenous growth and asset price changes under avoided climate damages.

First, the bulk of literature on climate policy on the one hand uses relatively disaggregated models with high detail for emission-intensive sectors to identify optimal paths for greenhouse-gas (GHG) emission abatement and their costs (Clarke et al., 2014) and to compare different implementations of policy options in terms of efficiency and distribution (Fischer and Newell, 2008; Aldy et al., 2010; Asheim, 2012; Kalkuhl and Brecha, 2013). On the other hand, game-theoretical models with highly abstract nation states as players are used to analyze the political economy and thus feasibility of international climate policy (Finus, 2008; Stavins et al., 2014). Neither focuses on the 'intermediate' level of national economies and issues of public finance.

Second, the 'double dividend' literature does address some of this gap: Given that an externality will be internalized by an environmental tax, *using the revenues* to cut pre-existing distortionary taxes is preferable to *lump-sum redistribution* by the very definition of a distortionary tax (Goulder, 1995). This constitutes a second dividend besides the environmental benefit. However, this positive revenue-recycling effect is counteracted by a 'tax-interaction effect' (Bovenberg and De Mooij, 1994): the environmental tax increases the price of dirty goods, thus substituting a narrow-based implicit tax for a broad-based explicit tax, e.g. on labor. Thus, it is unlikely that the gross costs of an environmental tax swap are negative unless the initial tax system is inefficient (Goulder, 1995; Bovenberg, 1999). One potential source of inefficiency is inadequate taxation of rents from a fixed factor used in the production of a polluting good (Bento and Jacobsen, 2007): then, an environmental tax swap

[2] This is relevant for cases such as the European Emissions Trading System (EU ETS), where permits were initially allocated for free, and auctioning was introduced gradually and without full prior anticipation. This option improves the political feasibility of introducing such a scheme, which may be an advantage over a carbon tax. See Koethenbuerger and Poutvaara (2009) and Heijdra et al. (2006) for a theoretical analysis of transition effects of introducing a tax on a fixed factor or pollution, respectively.

shifts some of the burden of taxation from labor to the fixed factor, and the price of the polluting good does not increase by the full amount of the environmental tax. Thus, the tax-interaction effect may be reduced and negative gross policy costs become more likely. While the effect presented here also stems from the collection of rents from a fixed factor, it is independent of a pre-existing distortionary tax system. Instead, increasing welfare in the economy is possible by addressing a dynamic inefficiency in savings behavior: Given that GHG emissions will be reduced, *using a policy instrument that collects the rents* from the emissions-related fixed factor (here, fossil resource stocks) to finance a given public revenue requirement *is preferable to lump-sum taxation* because it stimulates alternative, productive investments, i.e. capital accumulation. The effect is unambiguously welfare-enhancing if capital is otherwise underaccumulated. Moreover, it is independent of the recycling of the policy's revenues: In our specific model described below, we use climate policy revenues to finance public investment in resource efficiency improvements for analytical tractability, but in principle they could be used otherwise, e.g. for measures with a redistribution effect.[3]

Third, our contribution is related to results on non-environmental optimal taxation. The basic insight that a tax on rents from a fixed factor such as land generally is distortionary, since it directs investment away from land and towards capital, goes back to Feldstein (1977). Petrucci (2006) and Koethenbuerger and Poutvaara (2009) noted that this distortion is beneficial if capital was previously underaccumulated, e.g. due to imperfect intergenerational altruism. Edenhofer et al. (2015b) provided a formal proof and found that some forms of revenue recycling can establish the social optimum. Although Feldstein already suggested that his findings would apply to resource rent taxation, we are not aware of any work on this in the pertinent literature, nor related to environmental policy. Nevertheless, rents in the context of climate policy did recently receive some attention: Fullerton and Metcalf (2001) highlighted the creation of rents by different environmental policy instruments, and how their appropriation by the public sector affects the instruments' relative efficiency. Bauer et al. (2013) estimate the size of both the remaining resource rents and policy revenues (carbon rent) under climate policy regimes of different stringency; and Carbone et al. (2012) consider the potential of harnessing climate policy revenues for public debt reduction. However, the focus of these studies is on the size of and spending options for revenues of climate policy, while the macroeconomic effects of raising such revenues have been neglected. A potential reason for this is that collecting rents is still often presented as a non-distortionary source of public revenue (Stiglitz, 2014; Segal, 2011; Mankiw, 2008, Chapter 8), despite Feldstein's findings.

Finally, the contributions closest to the present paper are Groth and Schou (2007) and Karp and Rezai (2014b). The latter demonstrates, using a discrete OLG model, that climate policy can have aggregate beneficial effects due to a change in asset values. If capital is a fixed production factor, a Pareto-improving transfer is possible: If the mitigation necessitates some investments today, all generations welfare is increased except that of the current young.

[3]Regarding redistribution, we formally show that the social optimum as defined by Calvo and Obstfeld (1988) can be reached if rent taxation is sufficient to finance both technical progress offsetting resource depletion and a redistribution scheme that addresses imperfect altruism between generations, the root cause of underaccumulation in our model.

However, their effect is due to reducing overuse of a productive renewable resource and not to wealth effects due to the mitigation policy. (Karp and Rezai, 2014a) generalize the insight to the case of accumulable capital with adjustment costs for transforming consumption into investment goods and a climate damage function. Here we abstract from climate damages and focus on the wealth effects of the instruments that correct the externality. By contrast, Groth and Schou (2007) also consider taxation in general equilibrium with capital and non-renewable resources as alternative assets, but focus on its effects on long-run endogenous growth in a dynamically efficient setting with infinitely-lived agents. They show that taxation of a non-renewable resource that enters the 'growth engine' of an economy affects long-run growth, while capital taxation does not.

The remainder of this article is structured as follows. Section 2 lays out the formal model, in which households own both capital and fossil resource stocks and are confronted with climate policy as a permit scheme. Section 3 presents the main result that such a climate policy induces a macro-economic portfolio effect: the higher the share of permits that is auctioned, the more investment is shifted away from fossil resource stocks and towards undersupplied capital, and the higher is social welfare. Section 4 discusses some of the model's assumptions and the effects of alternative policy instruments, such as a carbon tax. It also introduces a 'stock instrument' related to personal carbon trading schemes, and discusses its potential advantages over regulating the flow of emissions. Section 5 concludes.

2 Model

In this section, we set up a continuous overlapping generations (OLG) model (Yaari, 1965; Blanchard, 1985) to study whether climate policy induces a beneficial portfolio effect. There are two assets, capital and an exhaustible resource, no bequests (which leads to capital underaccumulation), and we assume technological progress in resource efficiency which is publicly financed. We keep brief our description of standard elements that have been developed in more detail elsewhere (Edenhofer et al., 2015b). Climate policy is implemented here as a short-term, upstream emission trading scheme, i.e. permits have short lifetimes and regulate fossil resource extraction. This simplifies the exposition, since the path of resource extraction and emissions is exogenous. The next section analyzes the dependency of the balanced path on the share of permits that are auctioned to obtain the main result. The discussion section extends this result to policy instruments that keep resource extraction endogenous, such as a long-term permit scheme or a carbon tax.

On the supply side, assume a single final good produced from aggregate capital $K(t)$, labor $L(t)$ and fossil resource extractions $E(t)$ augmented by publicly provided technology $A(t)$. The production function has constant returns to scale, diminishing marginal productivity in individual inputs and satisfies the Inada conditions in all arguments. The representative firm's problem is

$$\max_{K(t),L(t),E(t)} F(K(t),L(t),A(t)E(t)) - [r(t)+\delta]K(t) - w(t)L(t) - b(t)E(t) \quad (1)$$

yielding the standard first-order conditions

$$r(t)+\delta = F_K(\cdot), \quad w(t) = F_L(\cdot), \quad b(t) = F_E(\cdot), \quad (2)$$

where δ is the depreciation rate of private capital.

On the demand side, let ϕ be the birth rate, equal to each individual's instantaneous probability of death. Thus ϕ is also the death rate in the entire population (population size is constant and normalized to one) and individuals' lifetimes are exponentially distributed. If for individuals born at time ν, some age-dependent variable at time t has a value $x(\nu,t)$, its aggregate (population) value is denoted by the capital letter, and

$$X(t) = \int_{-\infty}^{t} x(\nu,t)\phi e^{-\phi(t-\nu)}\mathrm{d}\nu. \tag{3}$$

At time t, an individual born at $\nu \leq t$ has expected lifetime utility

$$u(\nu,t) = \int_{t}^{\infty} \ln c(\nu,\tau) e^{-(\phi+\rho)(\tau-t)}\mathrm{d}\tau \tag{4}$$

with consumption $c(\nu,t)$ and rate of pure time preference ρ. Individuals' budget identity is

$$\begin{aligned}\dot{k}(\nu,t) + p(t)\dot{s}(\nu,t) + c(\nu,t) = r(t)k(\nu,t) + [(1-T(t))b(t) - p(t)]e(\nu,t) + \\ + w(t) - z(t) + \phi[k(\nu,t) + p(t)s(\nu,t)]\end{aligned} \tag{5}$$

with $\dot{k}(\nu,t) = \mathrm{d}k(\nu,t)/\mathrm{d}t$, etc.[4] Individuals own capital k, on which they earn interest at rate r, and a share s of the total (exhaustible) fossil resource stock S, which they can sell or buy at a price p. Alternatively, they can extract an amount e at zero cost and sell it at price b, but have to surrender a share T of the revenue to the regulator. We assume that the resource stock is homogeneous and that all resource deposits are known (and fully owned), thus abstracting from new discoveries and (uncertain) technological change. Each individual receives the same wage w and potentially pays a lump-sum tax z (in Section 3.3, we discuss the consequences of age-dependent transfers $z(\nu,t) < 0$ for social welfare). There are no bequest motives, but a competitive, no-cost life insurance sector to close the model, which pays an annuity $\phi(k+ps)$ in return for obtaining the individuals' assets in case of death. Thus, the changes in resource ownership of all *living* generations after accounting for extractions do not sum to zero:

$$\int_{-\infty}^{t} \dot{s}(\nu,t)\phi e^{-\phi(t-\nu)}\mathrm{d}\nu + E(t) = \phi S(t). \tag{6}$$

Finally, the individual also respects a solvency condition:

$$\lim_{\tau\to\infty}[k(\nu,\tau) + p(\tau)s(\nu,\tau)]e^{-R(t,\tau)} = 0 \tag{7}$$
$$\text{with} \quad R(t,\tau) \equiv \int_{t}^{\tau} (r(\tilde{t}) + \phi)\mathrm{d}\tilde{t}.$$

The government implements an upstream climate policy that limits GHG emissions by limiting fossil resource extraction, and uses revenues from climate policy (and, for later comparison, lump-sum taxation) to finance technological progress offsetting the decreasing supply of fossil fuels. These policies do not result from endogenous maximization of a welfare criterion, but are

[4]See Edenhofer et al. (2015b) on the equivalence to a notation in terms of nonhuman assets $a = k + ps$. We separate the two assets here to make the portfolio effect more transparent.

exogenously given (see Section 4.1 for a discussion). More precisely, the government continuously limits aggregate resource extraction by issuing an exponentially decreasing amount of short-term extraction permits[5] $\bar{E}(t)$, so that

$$E(t) \leq \bar{E}(t) = E_0 e^{-\sigma t}. \tag{8}$$

We assume that this constraint is binding at all times, i.e. that unregulated extraction rates would exceed the maximum permissible extraction rate σ. The total resource stock S evolves according to

$$\dot{S}(t) = -\bar{E}(t). \tag{9}$$

Using Equation (8) and setting $\lim_{t\to\infty} S(t) = 0$ for simplicity (implying full extraction of the initial quantity S_0), we thus obtain $\bar{E}(t) = \sigma S(t)$ and $E_0 = \sigma S_0$. A similar relationship holds for individuals, who do not choose s and e separately: even if there are several different resource stocks, their combination in individuals' portfolios is identical across homogeneous households. Thus individual resource owners will extract an amount $\bar{e}(\nu,t)$ in the same proportion to the aggregate admissible extraction as their individual resource share in the total resource stock, so $\bar{e} = \bar{E}s/S = \sigma s$. Suppressing time dependencies, we can then rewrite the budget constraint as

$$\dot{k} + p\dot{s} + c = w + rk + [(1-T)b - p]\sigma s - z + \phi(k + ps). \tag{10}$$

The share T of rents from resource extraction can be interpreted as an initial auctioning of a share T of permits and free allocation of the remaining permits, or equivalently, as initial free allocation of all permits followed by a tax on revenues from resource extraction. Total revenues from this resource rent collection and lump-sum taxes z are instantaneously invested into technological progress I_A. The government's budget identity thus is

$$T(t)b(t)\bar{E}(t) + Z(t) = I_A(t). \tag{11}$$

Assume that the change in technological progress is linear in public investment into resource productivity improvements,

$$\dot{A}(t) = \theta I_A(t) A(t), \tag{12}$$

with R&D investment efficiency θ. This assumption greatly simplifies the subsequent analysis, since the research investment required to exactly offset the regulated resource depletion at rate σ, which we denote by I_A^*, is then constant:

$$I_A^* = \sigma/\theta \tag{13}$$

By Equation (12), this implies $A(t) = A_0 e^{\sigma t}$, and thus by Equation (8), we have $A(t)\bar{E}(t) = const. = A_0 E_0$: The 'effective supply' of the fossil resource remains stable.

Individuals maximize utility (4) by choosing paths for c and s, subject to budget identity (10) and solvency condition (7). From the first-order conditions

[5] Extraction permits are equivalent to issuing permits for the amount of CO_2 emissions that the use of the extracted resource will cause, but simplifies exposition here. Moreover, note that non-exponential mitigation paths can also be accommodated: the crucial assumption for reaching an analytical solution is that technological progress can keep effective resource supply constant. See Section 4.2 for a discussion.

of this optimization problem, one obtains the usual Keynes-Ramsey rule for the dynamics of individual consumption

$$\frac{\dot{c}(\nu,t)}{c(\nu,t)} = r(t) - \rho \tag{14}$$

and a no-arbitrage condition between the resource stock and capital (Appendix A.1):

$$\frac{\dot{p}(t)}{p(t)} = r(t) + \frac{p(t) - [1 - T(t)]b(t)}{p(t)}\sigma. \tag{15}$$

The last term reflects the effect of exogenously imposing the resource extraction path.

From the instantaneous budget identity (10), transversality condition (7) and no-arbitrage condition (15), we also obtain a lifetime budget constraint (Appendix A.2):

$$\int_t^\infty c(\nu,\tau)e^{-R(t,\tau)}\mathrm{d}\tau = k(\nu,t) + p(t)s(\nu,t) + h(\nu,t), \tag{16}$$

$$\text{with} \quad h(\nu,t) = \int_t^\infty [w(\tau) - z(\nu,\tau)]e^{-R(t,\tau)}\mathrm{d}\tau.$$

Thus the present value of the consumption plan at time t of individuals born at ν equals their total wealth of capital, fossil resources and the present values of lifetime labor income and (potentially age-dependent) taxes/transfers.

Solving the Keynes-Ramsey rule (14) for c and substituting this in Equation (16) shows that each individual consumes the same fixed fraction of her total wealth (Appendix A.2):

$$c(\nu,t) = (\rho + \phi)[k(\nu,t) + p(t)s(\nu,t) + h(\nu,t)]. \tag{17}$$

We can now derive the remaining aggregate demand-side quantities according to (3) (see Appendix A.3). Using Equation (6), aggregation of Equation (17) yields

$$C(t) = (\rho + \phi)[K(t) + p(t)S(t) + H(t)]. \tag{18}$$

Aggregate consumption is the same constant fraction of total capital, resource, labor income and transfer wealth as for each individual. For the dynamics of the total capital stock, apply the definition of K, Leibniz' rule and the individual budget constraint (10) to get

$$\dot{K}(t) = w(t) + r(t)K(t) + b(t)\bar{E}(t) - I_A - C(t). \tag{19}$$

The growth rate of aggregate consumption can be derived from the definition of C, using Leibniz' rule and Equations (14) and (17):

$$\frac{\dot{C}(t)}{C(t)} = r(t) - \rho - \phi(\rho + \phi)\frac{K(t) + p(t)S(t)}{C(t)}. \tag{20}$$

The last term is due to the 'generation replacement effect': A share ϕ of the population, owning capital K and resource wealth pS, dies and is 'replaced' by newborns without assets. This continuous turnover of generations of different wealth also affects aggregate consumption growth, since consumption is a fixed fraction $(\rho + \phi)$ of wealth. The effect of newborns' lack of capital and fossil resources is always negative. Note that the dynamics of aggregate quantities are independent of lump-sum taxes Z.[6]

3 Results

In this section, we prove that climate policy may induce a beneficial portfolio effect (Theorem 1): The idea of the proof is to compare two ways of financing a given public revenue requirement (here, for R&D directed at resource efficiency improvements), either by a lump-sum tax or by auctioning some or all permits as a means to collect rents. Lump-sum taxation does not affect capital underaccumulation (which is a feature of the OLG model), while collecting scarcity rents from resource stocks makes investing in capital relatively more attractive, which enhances efficiency and welfare.

First, we characterize balanced paths on which capital and consumption stay constant while regulated resource depletion and R&D offset each other (Section 3.1).

Then, we compare pure lump-sum R&D funding to an auctioning of permits (or a tax on extraction revenues) on balanced paths. In the former case, there is underaccumulation, which is mitigated in the latter case, leading to higher aggregate consumption (Section 3.2).

The social optimum is defined as in Calvo and Obstfeld (1988), which implies that the Keynes-Ramsey levels of capital and consumption are socially optimal given the assumptions of our model (see Appendix A.4). It cannot be achieved, unless permit auctioning yields sufficient revenues in excess of technology investment which are redistributed to the benefit of the young rather than lump-sum (Section 3.3).

3.1 Balanced paths

The differential equations for the aggregate resource stock S, technology A, the resource stock price p, aggregate capital K and aggregate consumption C describe the dynamics of the economy (Equations (9), (12), (15), (19) and (20), respectively). The price of the extracted resource b and capital interest r depend on K, A and S via the production function, so they do not add extra dimensions.

For simplicity, we will contrast below two polar cases of financing R&D, either by permit auction revenues only, or purely by lump-sum taxation. For this reason, we assume that permit auction revenues are by themselves sufficient to finance the research investment level (13) chosen by the government to offset regulated resource depletion (8):

$$\text{There exists a } T^* \in [0;1] \text{ such that } I_A^* \leq T^* b(t)\bar{E}(t) \quad \text{for all } t. \tag{21}$$

[6] For age-dependent *transfers* $-z(\nu,t)$, there is a second 'redistribution' effect: The aggregate population expects lifetime transfers of $-\bar{Z}(t)$, while newborns expect $-\bar{z}(t,t)$. The difference is an additional term in the numerator of the last fraction, the impact of which depends on how transfers redistribute wealth among generations. It *only* disappears for age-independent transfers, $\bar{Z}(t) = \bar{z}(t,t)$ (see also Section 3.3, Appendix A.3 and Edenhofer et al. (2015b) for details).

See 4.1 for further discussion of this assumption[7]. The inequality of course also implies that the alternative lump-sum financing of R&D is feasible in terms of potential revenues, too, since resource rents are part of each individual's lifetime income. If lump-sum taxes are politically infeasible, the consequence is a trade-off between the beneficial effect described below and distortions from other taxes, which is beyond the scope of the analysis presented here.

Then, with exogenously given depletion (8) and research (13) fixing the evolution of S and A, balanced paths are described by

$$\left\{K(t) = K^*, C(t) = C^*, S(t) = S_0 e^{-\sigma t}, A(t) = A_0 e^{\sigma t}, p(t) = p_0^* e^{\sigma t}\right\},$$

where A_0, S_0 are given and K^*, C^*, p_0^* denote the solution to the following system of equations (using Equations (2))

$$\dot{K} = 0 \to \quad C_P(K) = F(K) - \delta K - I_A^*, \tag{22}$$

$$\dot{C} = 0 \to \quad C_H(K) = \phi(\rho + \phi)\frac{K + p_0(K)S_0}{r(K) - \rho}, \tag{23}$$

$$\text{Eq.(15)} \to \quad p_0(K) = (1 - T^*)\sigma\frac{b_0(K)}{r(K)}, \tag{24}$$

written here with K as the independent variable for convenience in the subsequent analysis. For the last equation, we substituted $\dot{p}/p = \sigma$ in the no-arbitrage condition, and used that

$$b = F_E = F_{AE}(K, L, AE)A = F_{AE}(K, L, A_0 E_0) A_0 e^{\sigma t} \equiv b_0(K) e^{\sigma t}.$$

The crucial policy parameter determining the values of K^*, C^* and p^* is the auctioned share of permits T, since the optimal choice of the extraction rate σ or of the total amount of permits (represented here by the total available resource stock S_0) are assumed to be given.

Equation (22) defines a parabola-shaped curve in the C-K-plane and Equation (23) a hyperbola. The $\dot{K} = 0$ locus is shifted downwards relative to the origin by I_A^*. We assume that I_A^* is sufficiently small so that two intersections of the parabola and hyperbola exist (for empirical plausibility see Footnote 7). While the lower is unstable, the upper is saddle-point stable. In the following, the system is reduced to two dimensions by maintaining $d(pS)/dt = 0$. This projection captures all relevant dynamics.[8] We denote variables on the

[7]Empirically, I_A^* can be assumed to be significantly smaller than the mitigation costs of climate change, because these also comprise forgone consumption due to costly transformation of the capital stock (e.g. different power plants). However, the costs of climate change are very small compared to aggregate output or capital (in the order of 0.04 to 0.14 percentage points of reduction of annual consumption growth (IPCC, 2014)). Conceptually, our assumptions about the size of I_A are distinctively un-Malthusian, because they insure that the transformation of the economy to a low-carbon state is possible at little cost and without disturbing stability .

[8]This can be shown in the three-dimensional system: Linearizing around the steady states shows that the lower is unstable, while the upper is a saddle point with one stable arm. Since C is a jump variable which instantaneously adjusts such that the optimality and transversality conditions are observed, the system is on the stable path, see Edenhofer et al. (2015b) and appendices of Petrucci (2006). We merely subtract here a constant to one of the differential equations of the dynamical system examined previously. The above assumption about I_A^* ensures that this does not change the topology of the phase space and thus also not its stability properties.

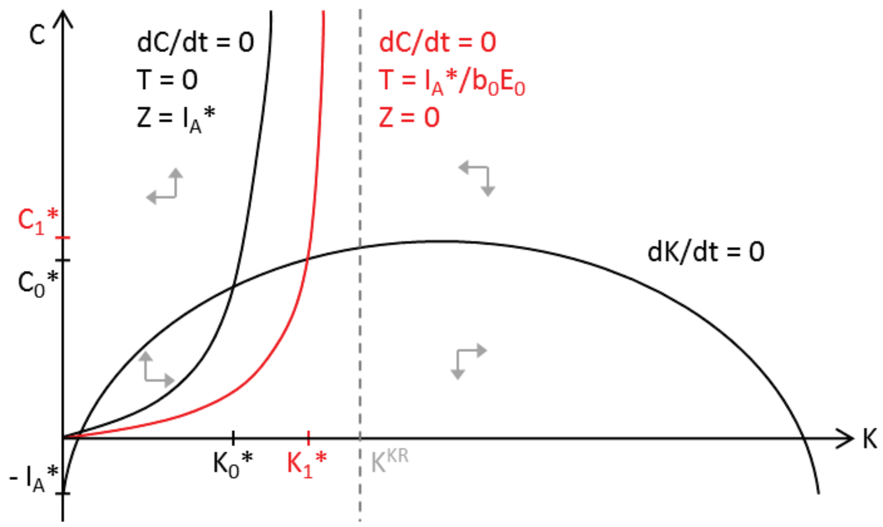

Figure 1: Phase diagram for aggregate consumption C and capital K. K^{kr} denotes the Keynes-Ramsey capital level, given by $F_K(K^{kr}) - \delta = \rho$.

balanced path (where all three of Equations (22–24) hold) by an asterisk *. In particular,

$$r^* = F_K(K^*) - \delta, \quad b_0^* = F_E(K^*)A_0, \quad p_0^* = (1-T)\sigma b_0^*/r^*. \tag{25}$$

Finally, on the balanced path the growth factor $R(t,\tau)$ simplifies to

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

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

3.2 The macroeconomic portfolio effect of climate policy

We now show that underaccumulation of capital due to the generation replacement effect can be mitigated by resource rent collection, which directs investment towards capital, but not by lump-sum taxation.

We first discuss why aggregate capital and consumption are suboptimally low. The reference point for social optimality are the Keynes-Ramsey steady-state levels of consumption $C^{kr}$and capital K^{kr}, which satisfy

$$C^{kr} = F(K^{kr}) - \delta K^{kr} - I_A^* \tag{26}$$

$$\text{and} \quad F_K(K^{kr}) - \delta = \rho. \tag{27}$$

This is derived using the approach of Calvo and Obstfeld (1988), see Appendix A.4.

Equation (23) is essential for analyzing the welfare effects of rent collection, since the position of the parabola (Equation 22) does not change. Solving for the steady state interest rate and using Equations (25) yields

$$r^* = \rho + \phi(\rho+\phi)\frac{K^* + p_0^* S_0}{C^*} = \rho + \phi(\rho+\phi)\frac{K^* + (1-T)\sigma S_0 b_0^*/r^*}{C^*}. \tag{28}$$

Thus, the interest rate of the decentralized case is higher than the implied price of capital in the socially optimal steady state (Equation 27). From $F_{KK} < 0$ and Equation (2) follows a lower level of capital, $K^* < K^{kr}$. Since K^{kr} is left of the maximum of the parabola (22), a lower capital stock implies that consumption is suboptimal, $C(K^*) < C(K^{kr})$.

We now discuss the two policy cases, corresponding to the two hyperbolas in Figure 1. First, assume that there is no auction or tax on fossil resource extraction ($T = 0$) and that technological progress is financed by lump-sum taxation (the government's budget identity (11) becomes $Z^* = I_A^*$, which does not change the aggregate dynamics). Then, the second term in Equation (28) has its maximal value, and capital accumulation and aggregate consumption attain their lowest values (since the intersection of the hyperbola and the parabola is always to the left of the maximum of the parabola).

At the other extreme, with only the collected resource rents to finance technological progress ($\hat{T}b\bar{E} = I_A^*$ and $Z = 0$), underaccumulation is reduced relative to the lump-sum tax case, since the tax lowers $p_0 S_0$, so *ceteris paribus* the second term in Equation (28) is smaller. The intuition is that the lower rent earnings make investing in the resource stock less attractive than capital investment, as reflected in the no-arbitrage condition (15), and thus causes a rebalancing of the asset portfolio. Also, a lower resource stock price means less 'missing wealth' for the newborns, and thus a smaller generation replacement effect (but the effect is still non-zero for all T, so the social optimum cannot be reached without additional policies, see next subsection). These effects are of course not isolated, but interact via general equilibrium effects. We thus formalize and prove the effect, also allowing for combinations of both financing options.

Theorem 1. *Suppose that the economy is on a balanced path on which publicly financed technological progress exactly offsets decreasing availability of short-term (extraction) permits, that any share of these permits may be auctioned or allocated for free, and that lump-sum payments are available. Then, the higher the share of permits that is auctioned, the higher is social welfare.*

This result is proved in Appendix A.5 by showing that the higher the auctioned share of permits T, the higher are aggregate capital and consumption. The basic message is that it is welfare-enhancing to fulfill the revenue requirement for R&D investment by distortionary auctioning of permits instead of fulfilling it by non-distortionary lump-sum taxation (which should only close a potential gap if revenues from full auctioning are insufficient). However, the theorem is stronger: It implies that *even if* the revenue requirement can be fulfilled without auctioning all permits, it is still desirable to auction permits to the largest degree possible for efficiency reasons. Revenues in excess of R&D investment needs are redistributed here by a lump-sum transfer that is uniform across all generations; other transfer schemes are explored in the next subsection.

As a direct consequence of Theorem 1, the gross costs of climate policy are reduced if permits are auctioned because the costs of introducing a climate policy regime relative to scenarios in which there is no mitigation (not modeled here) is reduced by the efficiency gain described in our model.

3.3 Non-uniform revenue redistribution and social optimality

As an extension to the basic model above, we now show that if climate policy revenues exceed R&D financing requirements, they can be used for age-dependent transfers that may establish the social optimum.

If resource revenues exceed required R&D investments ($T^* < 1$), it can be seen from Equations (23), (24) and (28) that raising the auctioned share above T^* further reduces the value of the fossil resource and the interest rate, and increases the capital stock and consumption. But due to the missing capital wealth ϕK of the newborns, the generation replacement effect never fully disappears by this price effect alone (the second term in Equation (28) remains positive). It only disappears if the revenues in excess of required R&D investments are used for age-dependent transfers to the newborns. This is proved by Edenhofer et al. (2015b), whose results apply directly to our case as well, only accounting for the need to finance R&D along with transfers:

If lump-sum payments z that enter individuals' budget constraint (5) are potentially *age-dependent* ($z = z(\nu,t)$, instead of $z(t)$), we obtain a more general expression for aggregate consumption growth (while all other equations for aggregate dynamics remain unchanged; see Appendix A.3):

$$\frac{\dot{C}(t)}{C(t)} = r(t) - \rho - \phi(\rho+\phi)\frac{K(t) + p(t)S(t) - \bar{Z}(t) + \bar{z}(t,t)}{C(t)}. \qquad (20')$$

Thus, for rent collection financing age-dependent transfers (negative z, which were defined as taxes), there is a 'redistribution effect' additional to the price effect discussed above: The difference between the expected transfers to the aggregate population $\bar{Z}(t)$ and to newborns $\bar{z}(t,t)$ reflects how transfers redistribute wealth among generations, and thus affects the size of the generation replacement effect. Only if transfers are age-independent ($\bar{Z}(t) = \bar{z}(t,t)$), the difference is zero and the redistribution affect disappears.[9] If, on the contrary, transfers are biased towards newborns, the social optimum may be established. For the case where only newborns receive any transfers, we have

$$\bar{z}_n(t,t) = -\frac{Tb(t)\bar{E}(t) - I_A(t)}{\phi}, \qquad (29)$$

$$\bar{z}_n(\nu,t) = 0 \quad \text{for } \nu > t \quad \text{and} \qquad (30)$$

$$\bar{Z}_n(t) = 0. \qquad (31)$$

The auctioning (or extraction tax) rate that reproduces the social optimum on the balanced path, for which the generation replacement effect disappears, is

$$T^{opt} = \frac{\phi(K^* + p_0S_0) + I_A^*}{b_0\sigma S_0} = \frac{\phi(r^*K^* + b_0\sigma S_0) + r^*I_A^*}{(r^*+\phi)b_0\sigma S_0}. \qquad (32)$$

For age-independent transfers, underaccumulation is mitigated by the price effect, but cannot be fully cured even for $T = 1$. For transfers to newborns only, the additional redistribution effect can compensate newborns' 'missing capital' and establish the social optimum. Both effects together may even lead to overaccumulation, so the optimal auctioning share may be smaller than one. See Edenhofer et al. (2015b) for further details and other redistribution schemes.

[9] Thus, the expressions (20) above and $\dot{H} = (r+\phi)H - w + Z$ (with Z defined as a tax), often considered standard results in the literature (Petrucci, 2006; Marini and van der Ploeg, 1988), are in fact a special case.

4 Extensions: further policy instruments

The main result of the present article builds on the assumption that climate policy consists of an emission trading scheme with permits with a short lifetime. This section explores alternative climate policy instruments: emission trading with long permit lifetime, a carbon tax and a hitherto unexamined instrument that limits availability of the atmospheric *stock* directly rather than the annual flow of emissions. Comparing these instruments to the case of short-term permits highlights the robustness of our result and further develops the intuition of our argument.

The first subsection discusses the sensitivity of the portfolio effect on the main modeling choices concerning resource availability. We conclude that the essential assumption for our analysis above is the short lifetime of the permits, which fixes the extraction (emission) path exogenously.

Consequently, the second subsection discusses alternative instruments for which extraction is endogenous. A long-term permit scheme and a constant carbon tax can be shown (for a Cobb-Douglas production function) to induce the same macroeconomic portfolio effect as a short-term permit scheme; for a time-dependent carbon tax, this seems probable but formally remains a conjecture. Additionally, while total emissions and rent collection can be chosen separately for permit schemes, there is a trade-off under a carbon tax: a high constant tax maximizes the portfolio effect, but a time-varying tax is needed for effective emission reduction.

The third subsection describes the ‘stock instrument’: households hold tradable ownership certificates to the stock of the atmosphere rather than permits to a flow of emissions. This instrument is equivalent to a conventional permit scheme under the assumptions employed here. However it may be more effective in more realistic settings in which fossil resources are not perfectly tradable and households are motivated to protect the environment.

4.1 Premises of the short-term permit scheme model

The above model of an emission trading scheme has been easily tractable (despite the OLG structure) for two reasons: Short permit lifetimes allow for a direct control of the extraction path. Additionally, we exploited the fact that the degree of rent extraction can be chosen independently from the extraction path: by requiring that the revenues equal the investments into resource productivity improvements that are necessary to exactly offset declining resource supply, a balanced path is established.

We now discuss the restrictiveness of the underlying assumptions:

First, we chose a specific shape of the permissible extraction path, and resource efficiency improvements: for simplicity, we chose an exponentially declining extraction path ($E(t) = E_0 e^{-\sigma t}$), and accordingly assumed that R&D investment translate into resource efficiency improvements as $\dot{A} = \theta I_A A$, so that $I_A = \sigma/\theta$ leads to $A(t)E(t) = \text{const}$. An exponential extraction path is analytically convenient, but the exact shape of the path is irrelevant for our results as long as technological progress is such that spending no more than a certain fraction of output on R&D can offset the decreasing resource supply. This optimistic assumption about technology is a mere artifice to obtain an analytical solution.

Second, we require public financing of resource efficiency improvements: An alternative would be to assume exogenous technological progress. We use publicly-financed R&D to underline (1) the necessity of R&D to counter mitigation-induced scarcity, and (2) that even if the mitigation path is given, the government still has a choice regarding R&D investment. The government's optimization problem that should determine this choice is not modeled here. Completely offsetting resource scarcity and maintaining a steady state via R&D is chosen merely for simplicity. Furthermore, public investment in resource efficiency improvements could be interpreted to also include investment in infrastructure that matches resource-efficient technologies, such as railways, public transport and bike lanes, charging infrastructure for electric vehicles, or electricity grids and system services necessary for integration of fluctuating renewable sources of energy.

Third, related to the second point, we assume that public financing of R&D is feasible – technologically, as ensured by assumptions on the production function, and in terms of available fiscal instruments, since if climate policy revenues are insufficient, lump-sum taxes are available in our model to top them up.

Fourth, we assume short lifetimes of permits to fix the extraction path: due to inertia of the climate system, what matters are the cumulative GHG emissions over longer periods (several decades), not their short-term path (Meinshausen et al., 2009; Ciais et al., 2013). However, practical implementations of climate policy via emission trading schemes, such as the EU ETS and the California Cap-and-Trade scheme, operate on shorter time scales, with emission budgeted over trading periods of eight and three years, respectively. Forward 'banking' of unused permits is generally allowed, but can be neglected if we assume that emission budgets are a binding constraint. More importantly, 'borrowing' of permits to delay mitigation is not possible in California, and restricted to within a trading period in the EU, so the endogeneous exhaustion of the short-term budget can be approximated well by a fixed path. The fixing of such a long-term mitigation path by the government is not necessarily less efficient than a decentralized solution, depending e.g. on whether individual agents or the government are more forward-looking.

This supports our modeling of a short-term permit scheme above. Yet it remains to be shown if our hypothesis also holds for other policy instruments, to which we turn next.

4.2 Carbon tax and long-term permit scheme

The main difference of a carbon tax compared to a short-term permit scheme is that the last of the assumptions above is relaxed, i.e. the extraction path is determined endogenously, and it may be affected by the path of the tax. Extraction is also endogenous under permit schemes with unrestricted banking and borrowing between periods or long permit lifetime (once the permits are auctioned). In this sense, they resemble a carbon tax rather than a short-term permit scheme, so the conclusions drawn in the following for a carbon tax similarly apply.

We start by modifying the resource extraction part of our continuous OLG model for a carbon tax instead of a short-term permit scheme. We then show that a government aiming to establish a balanced path with constant aggregate capital and consumption not only needs to invest into technological progress to offset resource scarcity as before, but also has to keep the carbon tax constant. In such a setting, the full dynamical system resembles the short-term permit case, so Theorem 1 can be extended: a higher constant carbon tax level (higher constant permit auctioning rate) leads to higher social welfare. Thus, there is some climate change mitigation even under a constant carbon tax: Although it does not *directly* affect the path of resource extraction and GHG emissions (Dasgupta and Heal, 1979), the portfolio effect leads to a higher capital stock and lower interest rate, so extraction is slower. This also holds for a long-term permit scheme with constant auctioning - but here, the total amount of emissions can additionally be limited to any desired level by capping the total amount of available resources on its introduction: In the case of the carbon tax, S stands for the fossil reserves, in the case of a permit scheme it is the remaining carbon budget. Finally, we briefly consider scenarios where the system is not on a balanced path, because effective climate policy is imposed by a non-constant carbon tax (which implies different growth rates of the resource stock and the resource stock price, so that the OLG-specific generation replacement effect is non-constant). Even then, a macroeconomic portfolio effect can be conjectured to occur; but the carbon tax remains less flexible than a short-term permit scheme, independent of assumptions about technological progress, since choosing a mitigation path fixes the path of revenues from rent collection.

Assume an OLG model with two assets, capital and an exhaustible resource, as above, but endogenous extraction under a (potentially time-dependent) carbon tax instead of an exogenously given extraction path implemented by a short-term permit scheme. The carbon tax is interpreted as an ad-valorem tax on resource extraction and may be used to finance resource efficiency improvements.

The firms' problem remains unchanged. On the demand side, with individual resource extraction e as an independent control variable, the individual budget identity (5) does not simplify to (10), and the path of aggregate resource stock is endogenous (we suppress time dependencies in the following):

$$\dot{S} = -E. \tag{9'}$$

Individual optimization yields a simpler no-arbitrage condition than before, identical to the well-known Hotelling rule, and an additional condition on resource prices:

$$\dot{p}/p = r, \tag{15'a}$$

$$p = (1-T)b. \tag{15'b}$$

Thus, while resource extraction e and resource stock ownership s can be chosen separately, their prices are not independent. However, they may grow at different rates: Combining the two conditions gives

$$\dot{b}/b = r + \psi \quad \text{with} \quad \psi := \dot{T}/(1-T), \tag{15'c}$$

so a decreasing tax ($\psi < 0$) implies that p grows faster than b. From the firms' first-order conditions (2), we have

$$\frac{\dot{b}}{b} = \frac{\dot{F}_E(K,L,A,E)}{F_E(K,L,A,E)} = \frac{\dot{A}}{A} + \frac{\dot{K}F_{EK}}{F_E} + \frac{(\dot{A}E + A\dot{E})F_{EE}}{AF_E}. \tag{33}$$

Substituting this into ($15'c$) and solving for $\dot{E}$ shows that *ceteris paribus* (in particular for constant K), the resource extraction rate depends on the change rate of the tax, but not on its level.

The dynamics of aggregate capital and aggregate consumption remain unchanged:

$$\dot{K} = w + rK + bE - I_A - C, \tag{19}$$

$$\frac{\dot{C}}{C} = r - \rho - \phi(\rho + \phi)\frac{K + pS}{C}. \tag{20}$$

For the government, we have

$$TbE + Z = I_A, \tag{11'c}$$

$$\dot{A} = \theta I_A A. \tag{12}$$

Compared to the short-term permit case, government-controlled extraction $\bar{E}(t)$ has been replaced by $E(t)$, which is determined endogenously from the households' problem above. The government takes into account the firms' and households' first-order conditions (thus being the leader in a Stackelberg game) when it chooses the carbon tax T and public investment in resource efficiency improvements I_A. These are balanced in the government's budget by lump-sum taxes or transfers Z, if necessary.

Assume that the government seeks to establish a balanced path with $K(t) = K^*, C(t) = C^*$. From Equation (19) follows that this requires the marginal resource productivity to grow as fast as resource supply declines (otherwise output is not constant), while for the generation-replacement effect in Equation (20) to stay constant, the resource stock price has to grow as fast the resource stock declines, so we have

$$\frac{d}{dt}(AE) = 0, \tag{34}$$

$$\frac{d}{dt}(pS) = 0. \tag{35}$$

Appendix A.6 shows that these conditions can be satisfied on a balanced path by choosing

$$I_A = 1/\theta(-\dot{E}/E), \tag{36}$$

$$\psi = 0, \tag{37}$$

so a balanced path only exists under a carbon tax if the tax is constant. On such a balanced path, we have

$$\dot{b}/b = \dot{p}/p = \dot{A}/A = -\dot{E}/E = -\dot{S}/S = r(K^*), \tag{38}$$

since as long as the carbon tax and R&D investment are constant, the resource stock and resource extraction change at the same rate, so the price for the extracted resource and the stock also need to evolve at the same rate. A non-constant carbon tax would drive a wedge between them ($\dot{p}/p = r = \dot{b}/b - \psi$).

Nevertheless, a balanced path is consistent with a *constant* carbon tax of any level (except $T = 1$, for which the resource stock market would collapse). On such a path, the contribution of resource wealth to the generation replacement effect is constant, but smaller for a higher carbon tax ($pS = (1-T)b_0(K^*)S_0$). Thus, the following result holds (proved in Appendix A.6):

Corollary 2. *Assume that production can be described by a Cobb-Douglas function. Suppose the decreasing availability of fossil resources is exactly offset by technological progress, which is publicly financed by the revenues of a constant carbon tax and, if necessary, lump-sum taxes. Then, the higher the absolute level of the constant carbon tax, the higher is social welfare.*

As indicated above, this result is similarly applicable to the case of an emission trading scheme with long permit lifetimes or unlimited banking and borrowing between periods: On a balanced path, a long-term permit scheme that leaves the determination of the extraction path to the market, but collects fossil resource rents by perpetually auctioning (a share of) permits and financing resource efficiency improvements, does also induce a macroeconomic portfolio effect. Again, higher auctioning rates unambiguously imply higher consumption and thus higher welfare. However, unlike a constant carbon tax, it can additionally implement the most important aspect of climate policy by directly restricting cumulative emissions to any desired extent (by interpreting S_0 as a carbon budget and setting it to a fraction of fossil resource reserves). A constant carbon tax only changes the extraction path indirectly via the portfolio effect, because a higher capital stock and lower interest rate leads to slower extraction.

Finally, consider a *non-constant* carbon tax that affects the endogenous extraction path (Dasgupta and Heal, 1979). The tax will need to decrease to provide an incentive for resource conservation and thus mitigation (Sinclair, 1994). As we saw above, this does not result in a balanced path in a continuous OLG setting (so we cannot apply the same analytical method as above). Nevertheless, *some* part of the fossil resource rent still is extracted by the carbon tax, the value of the fossil stock is reduced and saving in producible capital becomes more attractive, so the basic effect can be expected to hold for a non-constant carbon tax as well:

Conjecture 3. *The macroeconomic portfolio effect still holds under a time-dependent carbon tax.*

Even a time-dependent carbon tax is still less flexible than a permit scheme: If the extraction path is fixed by the carbon tax, the path of tax revenues is also fixed - in contrast to a short-term permit scheme, in which the amounts available for extraction can be chosen independently from the auctioning rates (which may be constant, as above, or vary over time). Without this additional flexibility, it is not possible to implement a given mitigation path *and* arbitrary rent collection simultaneously. Instead, there is a trade-off: the macroeconomic portfolio effect induced by a time-dependent carbon tax is weaker than under a permit scheme to the extent that the mitigation incentive of a falling tax rate is given priority.

4.3 Owning the atmosphere: a 'stock instrument'

The stock-flow structure of our model also suggests an alternative instrument: Instead of regulating the flow of emissions, one could limit the availability of the stock and make claims on it tradable: Households obtain property rights for the atmosphere and the government regulates to how much annual emissions this entitles them. We first describe what the instrument consists in and subsequently show that it is equivalent to the model presented earlier in this article. We then consider two arguments why the stock instrument may be preferable to a short-term permit scheme: fossil resources may be less tradable than atmospheric property rights, and a stock instrument may lead to enhanced environmental awareness compared to conventional emission trading.

We suggest a stock instrument for climate policy with the following structure: Assume that households own shares s_a of the atmosphere (instead of shares of fossil resource stocks). Ownership of such shares entitles them to annually obtain emission rights, the amount of which decreases at rate σ. Households can sell these emission rights to firms at a price l and pay taxes on the revenues (they 'rent out' their share of the atmosphere to the firms). They can also trade the shares among each other. Our suggestion is related to the 'long-term permit' component of the McKibbin-Wilcoxen hybrid climate policy (McKibbin and Wilcoxen, 2002), which those authors also allow to embody declining annual emission rights (McKibbin and Wilcoxen, 2007; McKibbin, 2012).[10] However, this type of permit system has not been considered in an analytical model before the present article. It is also related to the case of 'exogenously shrinking' land considered by Buiter (1989) in the context of debt neutrality of taxation of fixed factors.

For this alternative instrument, the model presented in Section 2 is modified as follows: The individual budget becomes

$$\dot{k} + p\dot{s}_a + c = w + rk + [(1-T)l - p\sigma]s_a - z + \phi(k + ps_a). \tag{5''}$$

Here the contribution $-p\sigma s_a$ comes from the annual decrease in emission rights attached to the ownership of an atmospheric stock. The dynamics of the atmospheric stock are controlled by the government and, as above, taken to be

$$\frac{\dot{S}_a}{S_a} = -\sigma. \tag{9''}$$

Its decreasing availability reflects the limited disposal space for emissions. Still $\dot{S}_a = -E$, so that $E = \sigma S_a$. So σ is both the rate of decline of the atmospheric stock as well as the ratio between emissions used and total available space in the atmosphere. In particular, while households rent out their share of the atmosphere to the firm for one year, E denotes the emissions permitted in production, which are proportional to the current given size of S_a. Hence

$$l = F_{S_a}(K,L,AE(S_a)) = F_E(K,L,AE(S_a))\sigma. \tag{39}$$

The remaining modification to the previous model is Equation (6), which has to be changed to

$$\int_{-\infty}^{t} \dot{s}(\nu,t)\phi e^{-\phi(t-\nu)}\mathrm{d}\nu - \sigma S(t) = \phi S(t), \tag{6''}$$

as the atmospheric stock shrinks without being used. The remaining defining equations of the model are identical. The only change to the dynamics of the

[10] The nature of the 'long-term permits' is not central to the major advantages of the hybrid climate policy propounded by McKibbin and Wilcoxen (2002). In McKibbin and Wilcoxen (2007), the authors attribute the suggestion of embodying declining emission rights into a long-term permit to Rob Stavins, while in McKibbin (2012) some advantages to this specific design are briefly mentioned, see also below.

model is a no-arbitrage condition between the atmospheric stock and capital:

$$\frac{(1-T)l}{p} + \frac{\dot{p}}{p} = r + \sigma. \qquad (15'')$$

As the remaining equations describing the dynamics of the economy are unchanged, the stock instrument will be equivalent to the short-term permit scheme, if $l = b\sigma$. This holds by Equation (39). The equation between prices l and b is true because renting the stock of the atmosphere S_a at rate l, or buying a flow of resources $\bar{E} = \sigma S$ at price b, must have the same value to firms. Thus, the original and modified budget equations are the same. The deeper reason for this equivalence is that the short-term permit scheme already contains the core of the stock instrument, which is to treat e as proportional to s and thus to prevent endogenous extraction dynamics.

While the stock- and flow instruments are formally equivalent in our model of a closed, competitive economy, where everyone owns resources (or parts of the atmosphere), differences may arise in more realistic settings. The two instruments seem to imply different distributions: While considering the fossil resource stocks underlying an emission trading scheme evokes that ‘only resource owners’ possess such assets, introducing a new property structure is associated with the idea that ‘everyone gets permits’. However, an initial or perpetual reallocation of shares of the stock is in principle possible for *both* instruments, so differences between the two instruments do not arise primarily from different distributions. Instead, we discuss two genuine distinctions:

First, the models of this article rest on the assumption that the fossil resource or atmospheric stocks are fully tradable. Yet in economic reality, there may be several classes of agents, or heterogeneous countries which mostly hold either capital assets or fossil resources. If there are investors that specialize on one class of assets only, or are barred from investing in the alternative class of assets, a portfolio effect may not occur, as fossil resources are not fully traded. A stock instrument, in contrast, creates assets that are (designed to be) fully tradable, overcoming a possible ‘separation’ of assets that could weaken the portfolio effect if climate policy was introduced as a conventional short-term permit scheme.

Second, a standard argument against implementing climate policy by an emission trading system is that it crowds out social preferences, namely personal motivation to behave in an environmentally-friendly way (Frey, 1999; Bowles and Polania-Reyes, 2012). An alternative climate policy could attempt to make the scarcity of carbon sinks more tangible to individuals, and provide them with an opportunity to express social preferences directly and visibly for others. A consequence of such a policy may be greater political support for introducing or tightening a cap on emissions (see also McKibbin, 2012). This has been the chief motivation behind the idea of personal carbon trading (PCT) schemes (Hillman, 1998; Fleming, 1997) to which our suggestion of a ‘stock instrument’ is related. They have been discussed in some theoretical detail (Starkey, 2012a,b) and also received considerable interest from policy makers (Fawcett, 2010). The schemes closest to our model are the Ayres scheme (Ayres, 1997) and the Cap&Share scheme (as described in Starkey, 2012a), where every year, a decreasing amount of tradable emission rights is initially allocated to individuals on an equal per capita basis, and can then be sold on to emitting firms. In addition to this flow market, our suggested instrument involves a 'secondary' stock market where rights to the flow of individuals' future allocations of permits are traded as an asset. Thus, while PCT only differs from conventional emission trading systems by regulating emissions directly at the level of the households, our proposed stock instrument would additionally give households some 'property rights to the atmosphere', with ensuing investment decisions. Whether such a policy may enhance environmental awareness and may be more socially acceptable than conventional emissions trading is a question for future research.

5 Conclusion

In his seminal contribution on rent taxation Feldstein (1977, p.356) wrote that *"[i]ncreasing the effective rate of tax on natural resources creates a capital loss for the current owners and thus induces additional capital accumulation"*. For the case of climate policy, this effect has so far been unexamined. The present article therefore has studied the impact of climate policy on aggregate investment behavior. For an emission trading system in which permits have short life times, auctioning of permits was proved to induce a shift of investment away from fossil resource stocks towards producible capital. If capital is underaccumulated – a plausible assumption if capital is broadly conceived and includes human capital – this 'macroeconomic portfolio effect' increases efficiency and thus social welfare. The effect also implies that the gross costs of climate policy are lower compared to cases in which rent extraction is allocation-neutral. If imperfect intergenerational altruism is the source of capital underaccumulation, using the revenues from rent-extracting policies to the benefit of the young may even establish the social optimum.

A similar effect occurs for the case of a carbon tax (or a permit scheme with long permit lifetimes), which is however not equivalent to a short-term permit scheme: the tax rate (or auctioning share) is the only policy variable and the resource extraction path is endogenous, while under a short-term permit scheme the share of permits to be auctioned and the resource extraction path can be chosen separately.

The portfolio effect relies on the assumption that the resource stocks affected by the conventional,'flow-based', permit scheme are tradable assets directly competing with capital goods. If this is not the case, and in particular in settings with several countries or classes of agents with different resource endowments, a 'stock-based' scheme that introduces ownership of a share of perpetually renewed emission rights may offer a remedy: while being formally equivalent to the conventional permit scheme, the new asset may be more liquid and more widely available. Furthermore, environmental awareness and political feasibility of stringent climate policy could be enhanced by distributing atmospheric property rights instead of implementing an upstream emissions trading system.

We conclude that extracting resource rents (e.g. by climate policy) is efficient due to dynamic investment effects, and not only desirable for distributional reasons. Furthermore, if climate policy is implemented as a permit scheme, investment dynamics provide a new reason for the old conclusion that permits should not be allocated for free.

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A Appendix

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

The budget constraint (10) can be split into a constraint in monetary terms and another in terms of the fossil resource by defining $d(\nu,t) = \phi s(\nu,t) - \dot{s}(\nu,t) - \bar{e}$, where $\bar{e} = \bar{E}/Ss = \sigma s$. Dropping the time arguments, we obtain:

$$\dot{k} = w + [r+\phi]k + (1-T)\sigma bs + pd - z - c \tag{40}$$

$$\dot{s} = \phi s - d - \sigma s. \tag{41}$$

Individuals maximise utility given by Equation (4) by choosing $c(\nu,t)$ and $d(\nu,t)$, subject to Equations (40), (41) and the transversality condition (7). Writing λ and μ for the multipliers of (40) and (41) in the current value Hamiltonian H_c, we obtain the following first order conditions:

$$\frac{\partial H_c}{\partial c} = \frac{1}{c} - \lambda = 0 \tag{42}$$

$$\frac{\partial H_c}{\partial d} = \lambda p - \mu = 0 \tag{43}$$

$$\frac{\partial H_c}{\partial k} = (\rho+\phi)\lambda - \dot{\lambda} \quad \Rightarrow \quad \lambda(r+\phi) = (\rho+\phi)\lambda - \dot{\lambda} \tag{44}$$

$$\frac{\partial H_c}{\partial s} = (\rho+\phi)\mu - \dot{\mu} \quad \Rightarrow \quad \lambda(1-T)\sigma b + \mu(\phi-\sigma) = (\rho+\phi)\mu - \dot{\mu}. \tag{45}$$

Inserting the time derivative of (42) into Equation (44) yields the Keynes-Ramsey rule (14). Using Equation (43) and its time derivative to replace μ and $\dot{\mu}$ in Equation (45) and applying Equation (44) gives the arbitrage condition for investing in fossil resources or capital (15).

A.2 Individual lifetime budget constraint and consumption level

First, to derive the lifetime budget constraint (16), regrouping terms in (10) and adding $\dot{p}s - (r+\phi)ps$ on both sides gives:

$$\dot{k} + p\dot{s} + \dot{p}s - (r+\phi)(k+ps) = w + (1-T)\sigma bs - p\sigma s + \dot{p}s - rps - z - c = \\ = w - z - c.$$

The last equality follows from (15). This leads to

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

which is the lifetime budget constraint (16), written here in the more general form with age-dependent transfers/taxes $z(\nu,t)$. For the integration of the left-hand side in the last step, we used $\exp(-R(t,t)) = 1$ and Equation (7).

Then, the individual consumption level follows from solving the Keynes-Ramsey rule for c, which gives

$$c(\nu,\tau) = c(\nu,t)\exp\left(\int_t^\tau (r(\tau)-\rho)\mathrm{d}\tau\right),$$

and substituting this into the lifetime budget equation,

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

Hence, individual consumption is a fixed fraction of wealth.

A.3 Aggregate solution

We derive the aggregate quantities for general age-dependent transfers $z(\nu,t)$, and then simplify them for uniform transfers to obtain the relations given in the main text.

The aggregate consumption level $C(t)$ for general transfers is obtained directly from aggregation of Equation (17), as given by Equation (18) in the main text.

The dynamics of the total capital stock (19) are obtained by applying Leibniz' rule to

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

replacing $\dot{k}$ by its expression from the individual budget constraint (10), and using Equation (6) for aggregate changes in resource ownership:

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

The government budget constraint (11) was used in the last step, to the effect that the aggregate result does not directly depend on the transfer scheme $z(\nu,t)$. However, it may have an indirect effect via prices, stock levels and consumption.

Similarly, we derive the dynamics of aggregate consumption, first for the case of general, age-dependent transfers $z(\nu,t)$:

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

The first equality follows from Leibniz' rule. For the second, $c(t,t) = (\rho+\phi)[k(t,t)+p(t)s(t,t)+h(t,t)] = (\rho+\phi)[h(t,t)]$ is used. In the third step, $\phi C(t)$ is replaced using Equation (18). Alternatively, we could have directly differentiated Equation (18) and used that, by Leibniz' rule, $\dot{H} = (r+\phi)H - w + Z + \phi(\bar{Z} - \bar{z}(t,t))$. We thus obtain

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

This is the general result (20′) used in Section 3.3. For the special case of uniform, age-independent transfers,

$$z(\nu,t) = z_u(t), \tag{46}$$

we have $\bar{Z}(t) = \bar{z}(t,t) = \bar{z}_u(t)$ and Equation (20′) simplifies to Equation (20) in the main section.

A.4 Socially optimal solution

The social planner solution represents a normative benchmark to evaluate the adequacy of the climate policies discussed in the article. The application of the approach of Calvo and Obstfeld (1988) to the social planner problem is as in Edenhofer et al. (2015b), we restate it here to make this article self-contained.

We here define social welfare as the (discounted) preference satisfaction of the heterogeneous households. The socially optimal rate of pure time preference is assumed to equal the private rate of pure time preference for simplicity.

Social welfare V at time t is defined as follows:

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

which is the social welfare function considered by Calvo and Obstfeld (1988) when the private equals the social rate of pure time preference.

We now apply the two-step procedure of Calvo and Obstfeld (1988) for social planner problems with overlapping generations to determine the socially optimal level of aggregate capital and consumption: (i) the optimal static distribution is derived for every point in time, (ii) the intertemporally optimal solution is chosen independently.

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

$$U(C(t)) = \max_{\{c(\nu,t)\}_{\nu=-\infty}^{t}} \int_{-\infty}^{t} \ln c(\nu,t)\phi e^{-\phi(t-\nu)} \mathrm{d}\nu \tag{47}$$

$$\text{subject to:} \quad C(t) = \int_{-\infty}^{t} c(\nu,t)\phi e^{-\phi(t-\nu)} \mathrm{d}\nu. \tag{48}$$

The solution to this problem is:

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

The result is true since all agents have the same utility function. Intuitively, distributing the fixed amount $C(t)$ among all living agents at time t thus makes giving an equal share to each of them optimal. As population is normalized to 1, the share given to the individual equals the total amount of consumption, $C(t)$, so that total utility is $\ln(C(t))$.

Proof. Solving the maximization problem (47) with integral constraint (48) and writing λ as multiplier to that constraint, one obtains the current-value Hamiltonian

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

and thus finds the first-order conditions:

$$\frac{\partial H_c}{\partial c} = \frac{\phi}{c(\nu,t)} + \lambda \phi = 0 \tag{49}$$

$$(t-\nu)\lambda = (t-\nu)\lambda - \dot{\lambda}. \tag{50}$$

The last equation implies that λ is constant, so from Equation (49) it follows that the optimal $c(\nu,t)$ is constant for all ν, too. Setting $c(\nu,t) = c'(t)$ in Equation (48) implies

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

Inserting this in Equation (47) gives the result. □

(ii) The *intertemporal maximization problem* of the social planner is then the following problem:

$$\max_{C(t)} \int_{t=0}^{\infty} U(C(t))e^{-\rho t} dt \tag{51}$$

$$\text{with} \quad U(C) = \ln(C)$$

$$\text{s.t.} \quad \dot{K}(t) = F(K(t), L(t), A_0 E_0) - \delta K(t) - I_A^* - C(t).$$

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

$$\frac{\dot{C}(t)}{C(t)} = F_K(K(t), L(t), A(t)\bar{E}(t)) - \delta - \rho. \tag{52}$$

We therefore take the Keynes-Ramsey level of consumption and capital as the reference point for social optimality in the main part of the paper.

A.5 Formal proof of the portfolio effect

Proof of Theorem 1. The idea of the proof is to compare the steady state of the decentralized equilibrium for two different auctioned shares of permits (or tax rates on resource extraction revenues): It will be shown that although for a *fixed* capital stock, consumption, and thus social welfare, is lower with a higher auctioned share, both the consumption and the capital stock are higher in the steady state, the higher the auctioned share is. This is illustrated in Figure 1.

Consider two auctioning shares, $0 \leq T_1 < T_2 \leq 1$. Let the steady state defined by Equations (22) and (23) for the two shares be denoted by (K^{1*}, C^{1*}) and (K^{2*}, C^{2*}). The superscripts 1 and 2 also indicate the respective cases for the parabola and the hyperbola. From the definition of social welfare given in Section 3, it is sufficient to prove that

$$C^{1*} < C^{2*}.$$

The parabola (22) (defined by $\dot{K} = 0$) is not affected by the auctioned share. However the hyperbola (23) (defined by $\dot{C} = 0$) changes: It is equivalent to the following expression

$$C_H^i(K) = \phi \frac{\rho + \phi}{r(K) - \rho} \left\{ K + \frac{\sigma b_0(K) S_0}{r(K)} - T_i \frac{\sigma b_0(K) S_0}{r(K)} \right\} \tag{53}$$

for $i = 1, 2$. As the last term in the curly bracket is negative, it follows that $C_H^2(K) < C_H^1(K)$ for all $K \in [0, K^{kr}]$. In Figure 1, the hyperbola for T_2 is below that for T_1.

For any $K < K^{1*}$, we also have $C_H^1(K) < C_P^1(K)$ and $C_P^1(K) = C_P^2(K)$ since the parabola is independent of T. Hence $C_H^2(K) < C_P^2(K)$ for $K < K^{0*}$. Moreover, $C_H^i(K)$ is positive for all $K \leq K^{kr}$, and thus tends to $+\infty$ as K approaches K^{kr}. Thus the (non-trivial) intersection of parabola and hyperbola for T_2 must occur at a capital stock K^{2*} with $K^{1*} \leq K^{2*} < K^{kr}$. In this interval, $C_P(K)$ is increasing in K, thus $K^{1*} < K^{2*}$ and also $C^{1*} < C^{2*}$, as required. □

A.6 Dynamical system and portfolio effect for constant carbon tax

We first show that a carbon tax needs to be constant for a balanced path to exist. From Equations (19) and (20), we saw that $K(t) = K^*, C(t) = C^*$ requires $d/dt(AE) = 0$ and $d/dt(pS) = 0$. From the first condition and Equation (12) follows that the government needs to set $I_A = 1/\theta(-\dot{E}/E)$ on a balanced path. The second condition can be rewritten with the help of Equation ($15'b$) as $d/dt[(1-T)bS] = 0$. So the government needs to choose $\psi(t)$ such that the following system of differential equations is solved:

$$\begin{aligned} \dot{S}/S &= -E/S, \\ \dot{b}/b &= \psi - \dot{S}/S \quad (\text{for } (1-T)bS \neq 0), \\ \dot{b}/b &= \psi + r. \end{aligned}$$

The last two conditions are only both satisfied if $\dot{S}/S = -r$, which is constant on the balanced path. From the first equation then follows that

$$\dot{E}/E = \dot{S}/S = -r.$$

Furthermore, using the balanced-path conditions $d/dt(AE) = 0$ and $\dot{K} = 0$ in (33), and again $\dot{E}/E = -r$, we have

$$\dot{b}/b = \dot{A}/A = -\dot{E}/E = r.$$

This can only hold simultaneously with the fifth equation above if

$$\psi = 0.$$

We now show that Theorem 1 extends to the case of a constant carbon tax (or long-term permit scheme). For the aggregate dynamics under a general carbon tax, we obtained in Section 4.2:

$$\dot{S} = -E, \tag{9'}$$
$$\dot{p}/p = r \quad \text{and} \quad p = (1-T)b, \tag{15'a}$$
$$\dot{b}/b = r + \psi \quad \text{with} \quad \psi := \dot{T}/(1-T), \tag{15'c}$$
$$\dot{K} = F(K,L,AE) - \delta K - I_A - C, \tag{19}$$
$$\dot{C}/C = r - \rho - \phi(\rho+\phi)(K+pS)/C, \tag{20}$$
$$\dot{A} = \theta I_A A. \tag{12}$$

The first five equations represent the behavior of the private agents, the last equation the government's resource efficiency investment. Assume that the government implements a tax which is constant ($\psi = 0$), implying that $\dot{p}/p = \dot{b}/b = r$. Furthermore, assume that it uses the revenues for R&D investment that exactly offsets resource extraction, $I_A = 1/\theta(-\dot{E}/E)$, so that $AE = const.$ and $\dot{A}/A = -\dot{E}/E$. Then, the essential dynamics of the system are captured by just four differential equations (without the second and the last equation above).

Finally, for simplicity we assume that production can be described by a Cobb-Douglas function, $Y = F(K,L,AE) = K^{\alpha}(AE)^{\beta}L^{(1-\alpha-\beta)}$. Using Equation (33), we then have

$$\frac{\dot{b}}{b} = \frac{d/dt F_E(\cdot)}{F_E(\cdot)} = \frac{\dot{A}}{A} + \alpha\frac{\dot{K}}{K}.$$

The essential dynamical system can now be written as

$$\dot{S}/S = -E/S, \tag{54}$$
$$\dot{E}/E = \alpha\dot{K}/K - r(K), \tag{55}$$
$$\dot{K}/K = \left[F(K) - \delta K - C + \dot{E}/(\theta E)\right]/K, \tag{56}$$
$$\dot{C}/C = r(K) - \rho - \phi(\rho+\phi)\left[K + (1-T)\beta F(K)S/E\right]/C. \tag{57}$$

Substituting (55) into (56) and defining $\varepsilon := E/S$, we obtain

$$\dot{S}/S = -\varepsilon, \tag{58}$$
$$\dot{\varepsilon}/\varepsilon = \varepsilon + \alpha\dot{K}/K - r(K), \tag{59}$$
$$\dot{K}/K = \left[F(K) - \delta K - C - r(K)/\theta\right]\theta/(\theta K - \alpha), \tag{60}$$
$$\dot{C}/C = r(K) - \rho - \phi(\rho+\phi)\left[K + (1-T)\beta F(K)/\varepsilon\right]/C. \tag{61}$$

The last three equations are a dynamical system in ε, C and K. Its fixed point satisfies

$$\varepsilon = r(K), \tag{62}$$
$$C = F(K) - \delta K - r(K)/\theta, \tag{63}$$
$$C = \phi(\rho+\phi)\,[K + (1-T)\beta F(K)/r(K)]\,/\,[r(K)-\rho]\,. \tag{64}$$

In the C-K-plane, the last two equations describe a parabola and hyperbola as before (cf. Equations (22) and (23)). The fixed point is stable, since the same argument as in Footnote 8 applies (in this case with two jump variables, C_0 and $\varepsilon_0 = E_0/S_0$ chosen such that the transversality conditions are met). Thus, the occurence of a macroeconomic portfolio effect under a carbon tax can be proved in a similar way as for the short-term permit case:

Proof of Corollary 2. Similar to the proof of Theorem 1 with Equation (53) modified to

$$C_H^i(K) = \phi \frac{\rho+\phi}{r(K)-\rho}\left\{K + \frac{\beta F(K)}{r(K)} - T_i \frac{\beta F(K)}{r(K)}\right\}.$$

□

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Chapter 5

Avoiding Carbon Lock-In: Policy Options for Advancing Structural Change[1]

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Avoiding Carbon Lock-In: Policy Options for Advancing Structural Change

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Abstract

An obstacle for the transformation to a low-carbon economy is the carbon lock-in: fossil fuel-based ("dirty") technologies dominate the market although their carbon-free ("clean") alternatives are dynamically more efficient. We study the interaction of learning-by-doing spillovers with the substitution elasticity between a clean and a dirty sector to evaluate the robustness of policies averting the carbon lock-in. We find that the substitution possibilities between the two sectors have an ambivalent effect: although a high substitution elasticity requires less aggressive mitigation policies than a low one, it creates a greater welfare loss through the lock-in in the absence of regulation. The socially optimal policy response consists of a permanent carbon tax as well as a learning subsidy for clean technologies. We thus indicate that the policy implications of (Acemoglu, D., Aghion, P., Bursztyn, L., Hemous, D., 2012. The Environment and Directed Technical Change. American Economic Review 120 (1): 131-166), calling for merely temporary interventions based on the mechanism of directed technical change in the same setting, are limited in scope. Our results also highlight that infrastructure provision is crucial to facilitate the low-carbon transformation.

JEL classification: O30, O38, Q54, Q55
Keywords: structural change, low-carbon economy, carbon lock-in, mitigation policies, learning-by-doing

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1 Introduction

Climate change mitigation requires drastic cuts in emissions in the 21^{st} century and necessitates a transformation from a fossil-fuel based to a decarbonised economy. Both empirical evidence and theoretical argument suggest that an obstacle to this transformation is the possibility of a carbon lock-in [Unruh 2000, Schmidt and Marschinski 2009, Davis and Caldeira 2010, Lehmann et al. 2012]: the economy remains in an equilibrium in which carbon-intensive (“dirty”) technologies dominate the market although they are intertemporally inferior to low-carbon (“clean”) alternatives. The size of such a market failure and the appropriate policy responses to it crucially depend on the substitution possibilities between such sectors, which are influenced by infrastructures, yet sometimes also by behavioural and institutional factors. They also depend on the mechanism underlying the development of clean production technologies. Which policy options best advance structural change towards the low-carbon economy is less clear: few studies have examined policy responses that are sufficient to avoid a carbon lock-in [Fisher and Newell 2008, Gerlagh et al. 2009].

The purpose of this study is twofold: first, we contribute to quantifying the size of a lock-in by studying the impact of the substitution elasticity between a dirty and a clean sector. We find an ambivalent effect: a high elasticity creates a greater lock-in in the absence of regulation, but also requires less drastic policy intervention. This has implications for the effectiveness of second-best policy. Second, our article is a sensitivity study of [Acemoglu et al. 2012] (henceforth: AABH), who analyse the impact of directed technical change in the framework of the present article: our results show that with learning-by-doing behaviour of clean technologies instead of directed technical change, effective mitigation policies need to be permanent, not temporary, regardless of the value of the substitution elasticity because demand for intermediate dirty production never becomes zero.

We use a two-sector intertemporal general equilibrium model and solve it numerically to identify policy options that are sufficient to avoid high welfare losses. A common stylized setting is employed to depict structural change to a low-carbon economy: there is one clean sector, without emissions, and one dirty, emitting greenhouse gases. This approach has been adopted by AABH and, for instance, also by [Gerlagh and Hofkes 2002] and [Cassou and Hamilton 2004]. Our model set-up, including the representation of global warming, is nearly identical to that of AABH in order to be comparable in terms of policy implications: we respect all parameter choices and functional forms of AABH except those concerning the nature of technological progress. While AABH focuses on the effects of directed technical change for the transformation to a low-carbon economy, our work relies on the assumption of learning through spillover effects in the clean sector as its capacity is built up.

Such a learning-by-doing approach [Arrow 1962] is well-established within energy economics [Kverndokk and Rosendahl 2007]: the cost of renewable technologies decreases with cumulative installed capacity at a stable rate [Fischedick et al. 2011, ch. 10.5.2]. No comparable effect exists for dirty, mature technologies [MacDonald and Schrattenholzer 2001]. It has moreover been demonstrated theoretically that – in presence of learning-by-doing externalities – optimal carbon pricing is insufficient to overcome a lock-in into mature low-carbon technologies in the energy market [Kalkuhl et al. 2012]. We further discuss the differences between the assumptions of learning through increased capacity and directed technological change and their empirical plausibility in Section 2.1.3.

The carbon lock-in was originally examined from a systemic perspective highlighting the co-evolution of technology and institutions [Unruh 2000]: the technologically caused lock-in is exacerbated by institutional and policy failures. Our analysis focuses exclusively on the lock-in as a phenomenon of market failure and leaves aside institutional failures. In our model the lock-in arises through the combination of two externalities: first, learning spillovers that arise from building up capacities in the clean sector are unappropriated and are a stylized representation of positive externalities in the development of low-carbon technologies. Second, the negative impact of carbon-intensive production on utility through climate damages are ignored in the unregulated market outcome. The combination of the externalities can prevent the market from building-up the carbon-free sector and cause a delayed transition to the low-carbon economy. Different interpretations of the concept of a carbon lock-in are frequent [Lehmann et al. 2012, Page 2006], with some focussing on the non-malleability of capital, for instance by irreversible investment in coal power plants, as an additional cause of the suboptimal share of clean production. Instead we focus here on the interplay between *one* cause inhibiting the development of the clean sector and the substitution possibilities: as the latter represent infrastructural and institutional limitations to produce clean instead of dirty goods, it is the interplay of both factors that captures the co-evolution of technology and institutions. Since the specific model setup matters for analysing the carbon lock-in, we rely on numerical solutions instead of using an even more stylised model that would be more amenable to analytical treatment. The model is described in Section 2.

The principal message of our study is that although a higher substitution elasticity requires less aggressive optimal mitigation policies, it creates higher welfare losses from a lock-in. The optimal policy response requires both a carbon tax and a learning subsidy. The ambivalent role of the substitution possibility suggests to also examine second-best policy responses: we show that even if the only policy option available is a carbon tax, it can correct most of the welfare loss from the lock-in if the tax is set much higher. Furthermore, regarding the sensitivity of the results of AABH with respect to their conception of technological progress, we find that whether climate change mitigation requires a permanent or a merely temporary policy intervention depends primarily on the mechanism governing technological progress in the clean sector and not on the value of the substitution elasticity. We show that the optimal policy suggested by AABH, which is temporary and triggers a rapid switch from the carbon-intensive to the low-carbon sector, does not reproduce the socially optimal outcome in our model, which differs only by the assumptions about the technologies. Instead, effective mitigation policies need to be permanent, regardless of the value of the substitution elasticity. This is because with a somewhat more gradual development of clean technologies, there will be permanent demand for dirty production that decreases but is never strictly zero. Further, substitution possibilities crucially influence the feasibility of different climate policy options: we find that more stringent mitigation targets require a (much) higher carbon tax if the elasticity is low. They also determine the timing of the optimal subsidy to the clean sector.

The topic of this article is thus related to, but independent of, discussions about adverse effects of green subsidies on climate change mitigation along the lines of a "Green Paradox" [Sinn 2008, Sinn 2012]. The idea of the Green Paradox (in the present context) is that green subsidies may provide an incentive for resource owners to extract a part of their fossil reserves earlier because the subsidies may devalue their assets. Whether this effect matters for climate change mitigation has been debated [van der Ploeg 2013, Edenhofer and Kalkuhl 2011]: climate change mitigation in this century depends crucially on achieving a limit on cumulative emissions much lower than the total emissions that would be generated from burning all fossil resources. Green subsidies, in particular, may lead to a temporarily higher extraction of fossil resources, but will also decrease future resource extraction. They thus lead to more resources being left underground and the latter effect is likely to dominate the former [van der Ploeg 2013]. To focus exclusively on the specific lock-in effects due to the substitution elasticity and for comparison to the study by AABH, we abstract from these effects by not explicitly considering resource owners in our model, which would be necessary to generate effects similar to the Green Paradox. The reason is that effects related to the substitution elasticity and learning behaviour of clean energy are independent of the timing effects of resource extraction due to anticipation of policy changes by resources owners that give rise to the Green Paradox. In contrast, recent research explicitly takes into account fossil fuel extraction to also consider the optimal policy mix of carbon taxation and subsidising renewables [Rezai and van der Ploeg 2013] or the second-best case of subsidising renewables when carbon pricing is infeasible [van der Ploeg and Withagen 2014]. However these articles do not adopt a two-sector structure.

A substitution elasticity is not a natural constant, but an artefact of economic theory: the ease of using one technology or product instead of another one. In particular, substitution possibilities are influenced by infrastructure in relevant sectors of the economy, although behavioural and institutional effects are also important, for instance, in the transport sector, too. In the electricity sector, in which the division between carbon-free and fossil-fuel based technologies is clear-cut, the use as opposed to the generation of renewable energy is not straightforward and requires appropriate infrastructure since renewable energy production misaligns with electricity demand in time and space. Infrastructure investments can enable renewable energy use so that the misalignment across space and time is compensated for: grid extensions allow large scale transfers of electricity from generation sites to load sites. In the transport sector, substitution possibilities can also be mostly understood in terms of technology and infrastructure [Schaefer et al. 2009]. However, consumer preferences are also important to determine the elasticity between carbon-intensive and low-carbon modes in the case of transportation, since mode choice also involves important trade-offs in terms of security, privacy, comfort and health as well as being driven by habituation to a single mode. Both examples highlight the need for additional policy that increases the elasticity, for example financing appropriate energy infrastructure or fostering institutional changes towards intermodal transport. Thus a scenario of an *increasing* substitution elasticity is the most plausible one for the coming decades, particularly in the light of estimates that current substitution possibilities between clean and dirty sectors are very low [Pelli 2011, Pottier et al. 2014].

2 Model

We use a discrete-time intertemporal general equilibrium model that is similar to that of AABH except for the different conception of technological progress and the different role of government policy options. There are two sectors, one emission-intensive ("dirty") and one carbon-free ("clean"). Those sectors manufacture inputs used in the production of a final good that can be freely used for investment in each sector or for consumption. Households ignore the effect of global warming, which is described by the heuristic approximation chosen in AABH. Technological progress in the clean sector is subject to a learning-by-doing effect based on its cumulative capacity, technological progress in the dirty sector is exogenously given.

The decentralized equilibrium contains two market failures: first, the environmental externality – dirty production decreases utility through damages of global warming – is not taken into account by the decentralized agents. Second, firms in the clean sector do not appropriate the intertemporal learning spillover resulting from their production.

2.1 The decentralized economy

We present the maximization problems of the agents in the economy and how policy instruments enter their choices. The derivations of the first-order conditions are given in A.

2.1.1 Demand

The representative household derives utility U_t from consumption C_t and the environmental quality, represented as the size of the carbon sink S_t :

$$U(C_t, S_t) = \frac{(\phi(S_t)C_t)^{1-\eta} - 1}{1-\eta} \tag{1}$$

with $\eta \neq 1$. The function $\phi(S_t)$ represents the impact of climate damages on utility including the possibility of an environmental catastrophe and is specified in Section 2.1.4. The household maximizes intertemporal utility, which is given by:

$$\max_{C_t, K_{i,t}} \sum_{t=0}^{T} U(C_t, S_t) \frac{1}{(1+\rho)^t}. \tag{2}$$

It is assumed that the effect of the investment decisions on S_t is ignored, thus representing climate change as an externality. The household owns labour L_t and capital K_t and faces the budget constraint

$$C_t + I_t = r_{1,t}K_{1,t} + r_{2,t}K_{2,t} + w_{1,t}L_{1,t} + w_{2,t}L_{2,t} + \Gamma_t, \tag{3}$$

with I_t denoting investment, $r_{i,t}$ the interest rate, $w_{i,t}$ the wage in sector $i = 1, 2$ and Γ_t the lump-sum transfer from the government budget to the household. The price of consumption is set to one as the final good is chosen as numeraire. The maximization is also subject to the dynamic constraint on the capital stock

$$K_{t+1} = I_t + (1-\delta)K_t \tag{4}$$

with depreciation rate δ. The household can distribute labour and capital arbitrarily between the sectors:

$$\bar{L} = 1 = L_{1,t} + L_{2,t} \tag{5}$$

$$K_t = K_{1,t} + K_{2,t} \tag{6}$$

Labour is normalized to 1 for simplicity.

2.1.2 Supply

The economy produces a single good Y, which is composed of a carbon intensive intermediate good Y_1 and a low-carbon intermediate good Y_2. It is assumed that this final production is given by a CES function

$$Y(Y_1, Y_2) = A_t(Y_1^{\frac{\epsilon_t-1}{\epsilon_t}} + Y_2^{\frac{\epsilon_t-1}{\epsilon_t}})^{\frac{\epsilon_t}{\epsilon_t-1}} \tag{7}$$

in which $\epsilon_t > 0$ represents the elasticity of substitution between the clean and dirty goods. The higher the elasticity ϵ_t, the better substitutable are the clean and the dirty good. It may change with time exogenously. This seems plausible over long time horizons as substitution possibilities are driven by appropriate infrastructure, so that they can be changed by suitable policies. For instance, these may include to give other urban transport modes priority over cars or to adapt national power grids to the requirements of a high share of renewable energy generation.

General technological progress A_t evolves exogenously, reflecting an exogenous growth rate or total factor productivity g_e :

$$A_t = A_0 \exp(g_e t) \tag{8}$$

Intermediate good Y_i is produced from capital K_i and labour L_i according to a Cobb-Douglas production function:

$$Y_1 = F_1(K_1, L_1) = K_1^{\theta}(L_1)^{1-\theta} \tag{9}$$

$$Y_2 = F_2(A_2, K_2, L_2) = K_2^{\theta}(A_2 L_2)^{1-\theta} \tag{10}$$

Final-good Producer The final good producer maximizes profits Π :

$$\max_{Y_1, Y_2} \quad \Pi = Y - (p_1 + \tau_1)Y_1 - p_2 Y_2$$

where p_1, p_2 are the prices of the clean and dirty goods and τ_1 is a tax on emission-intensive products (*carbon tax).* The carbon tax is levied on the final good producer to reflect the fact that in principle any product could generate emissions, although levying it on the producer in the dirty sector would of course be equivalent.

Dirty sector The dirty firm maximizes profits Π_1 :

$$\max_{K_1, L_1} \quad \Pi_1 = p_1 Y_1 - r_1 K_1 - w_1 L_1$$

Clean sector In the clean sector, there is additional endogenous technological progress that depends on the cumulative output of that sector through learning-by-doing [Arrow 1962]. The cumulative output represents the stock of experiences made and is thus formalised as:

$$H_{t+1} = (Y_{2,t} - Y_{2,t-1}) + H_t \tag{11}$$

H_0 denotes the initial stock of knowledge. The technology of the sector is given by

$$A_{2,t} = \frac{\beta}{1 + (\frac{\omega}{H_t})^{\gamma}}. \tag{12}$$

so that $A_{2,t} \rightarrow \beta$ as $H_t \rightarrow \infty$. The choice of making learning-by-doing dependent on output and not capital changes has also been adopted by [Kalkuhl et al. 2012]: learning rates are standardly estimated given changes in cumulative installed capacity, which is related to physical output. It is matched closer by output in monetary units rather than capital in monetary units for two reasons: first, in the highly stylized setting of two sectors, capital will need to be broadly interpreted and include other things besides installed capacity, for instance the machines needed to produce and install it. Second, because more output can be produced for an additional unit of capital investment through the learning, capital invested later (after learning) is more productive than older capital, necessitating more complicated functional forms.

Further, the functional form in Equation (12) is justified as follows: β, γ and ω determine the shape of the learning curve for the clean technology. The level the clean technology converges to when it reaches maturity is given by β, thus determining the maximum productivity. The speed of the convergence to that level is determined by ω and γ. The three parameters together determine the learning rate of the technology. It is additionally assumed that H_0 is small, so that technology in the dirty sector is initially much more advanced. Moreover, we assume $\beta > A_{1,0}$ in accordance with expectations on efficiency of renewable technologies in the future [Breyer 2013, Kost and Schlegel 2012]. Clean technology thus lags behind and takes more time to develop, but will eventually be more advanced than dirty technology. On this high level of generality the chosen learning curve of the clean technology in the model cannot correspond to actual data of the learning behaviour of renewable energies. Yet the functional form employed is commonly used for the learning behaviour of carbon-free technologies [Kalkuhl et al. 2012] and similar modelling of learning-by-doing is very common in energy economics [Kverndokk and Rosendahl 2007, Edenhofer et al. 2005].

It is assumed for simplicity that spillovers in the clean sector are totally unappropriated by firms: individual firms are small enough not to take into account their individual contribution to the stock of global knowledge. (See [Romer 1986] and [Fisher and Newell 2008] for a more sophisticated treatment.)

The clean firm maximizes profits Π_2 :

$$\Pi_2 = (p_2 + \tau_2)Y_2 - r_2K_2 - w_2L_2.$$

Here τ_2 is a *subsidy* on clean output.

No capital inertia in investments is assumed: in equilibrium, wages and interest rates are equalized across sectors because production factors are perfectly mobile. Thus

$$w_1 = w_2 \tag{13}$$

and

$$r_1 = r_2. \tag{14}$$

These conditions hold as production is never zero in these sectors, which is the case because intermediate inputs are imperfectly substitutable. Next, the development of the clean and dirty technology chosen here is compared to the mechanism propounded by AABH.

2.1.3 Two conceptions of technological progress: learning-by-doing vs. directed technical change

Technological progress that differs between the two sectors of an economy leads to different sectoral growth rates [Baumol 1967]. For the case of structural change towards the low-carbon economy AABH focus on endogenously determined sector-biased technological progress – *directed technical change* (DTC) [Acemoglu 2002]. Our approach is to assume a sector-biased technological change that is exogenously given, but inspired by empirical findings on the learning of low-carbon technologies. Here we compare the two approaches and discuss their relevance.

In the model of AABH, profit-incentives of workers in research and development ("scientists") determine whether technological progress proceeds in the clean or dirty sector. However, the model has the feature that innovation occurs in one sector only, unless a knife-edge condition (Lemma 1 of AABH) is fulfilled: as a consequence, if the clean sector is significantly more productive than the dirty sector, no dirty output will be produced and the whole workforce will work in the clean sector and vice versa. This is due to the specific calibration of the direction of technical change: from Equation (11) and the specified calibration ($\gamma = 1; \eta_d = \eta_c = 0.02$) in Section V of that study, one can deduce that if all innovation improves the technology of the dirty sector A_1 and none that of the clean sector A_2 :

$$A_{1,t} = 1.02 A_{1,t-1} \text{ and } A_{2,t} = A_{2,t-1} \quad (15)$$

If instead all innovation benefits the clean sector A_2 :

$$A_{1,t} = A_{1,t-1} \text{ and } A_{2,t} = 1.02 A_{2,t-1}. \quad (16)$$

The former is the case if the dirty sector is much more advanced than the clean sector. The latter happens if there are sufficiently high subsidies for the clean sector. The switch between these two possibilities – the time that passes while all scientists "migrate" from one to the other sector – is either immediate or happens within a time span of 15 years (3 periods) in AABHs numerical simulation, depending on different parameter combinations.

By contrast, we examine the impact of a well-documented stylized empirical fact about low-carbon technologies on policies for advancing structural change: a decline in cost per unit output through learning effects due to increased experience [Fischedick et al. 2011, Ch. 10.5.2.] [Kost and Schlegel 2012]. No learning effect, at least not on a similar scale, is known for mature, dirty technologies
[MacDonald and Schrattenholzer 2001, Breyer 2013], in particular as in this model, A_1 also reflects the cost of fossil fuel. While in our model there is an overall increase in total factor productivity that affects both sectors equally, technology in the clean sector $A_{2,t}$ depends positively on cumulative capacity H_t that represents the stock of experiences made with the low-carbon technology. (See Equation (12) in Section 2.1.2 for a detailed explanation.) Examining the impact of learning-by-doing mechanisms in the structural change

framework adopted by AABH has already been called for [Pottier et al. 2014].

Which conception of technological progress is more plausible for modelling structural change at this abstract level? While there is some evidence for the concept of DTC [Popp 2002], the decisive factor for understanding the risk of intertemporal lock-ins during the transition to the low-carbon economy is the learning behaviour of renewable energies [Edenhofer et al. 2011]. Learning-by-doing is also the more comprehensive concept: it includes the migration of scientists and engineers to other sectors. Scientists and engineers need experiments to learn and need to build up capacities and equipment – this cannot be steered by huge research subsidy over a short time period as a suddendly much larger output of the clean technologies might not be profitable in a very short time span. The learning-by-doing approach thus stresses that the redirection of R&D-efforts is subject to path-dependencies in the careers of individuals, in the technological regulations and in the design and management of research institutions.

Our aim in this study is not to doubt the importance of DTC for understanding economic growth and structural change. We argue instead that the particular mechanism of DTC in the model of AABH represents a special case in the space of possible structural transformations towards the low-carbon economy, conflicting with empirical studies of the learning behaviour of technologies. We identify an immediate switch between sectors as produced by AABHs model as corresponding to a very high learning curve in our model (see Section 3.4). Our study hence shows that focusing on the learning behaviour of low-carbon technologies changes the picture of sensible policy responses to the carbon lock-in.

2.1.4 Climate damages

The climate externality caused by the production of the dirty sector and its negative impact on utility are modelled as in AABH[1], see p. 135 and 155 f. therein. In particular there is the possibility of an "environmental disaster" (zero utility) at very high temperatures.

Let S_t denote the size of the carbon sink (or the "quality of the environment" (AABH)) and assume that its range is between 0 and the 'pre-industrial' level $\bar{S}$. Denote the emission intensity by ξ and the regeneration rate by ζ and recall that $Y_{1,t}$ is dirty intermediate output. The size of the carbon sink evolves as follows:

$$S_{t+1} = -\xi Y_{1,t} + (1 + \zeta) S_t, \tag{17}$$

[1]It has been argued that AABH's policy implications are also not robust when a different climate module is used that represents the carbon cycle better [Pottier et al. 2014]. Nevertheless, we adopt here AABH's representation of the climate module in order to show that when *only* the nature of the technical change is varied, the policy implications of their study do not hold. (See [Greaker and Heggedal 2012] for a similar strategy on the duration of patents.)

if the right-hand side is between 0 and the pre-industrial level $\bar{S}$. Alternatively, $S_{t+1} = 0$ if the right-hand side is negative, and $S_{t+1} = \bar{S}$ if the right-hand side is greater than $\bar{S}$.

S is subsequently related to global mean temperature. Assume the standard approximation that if Δ is global mean temperature and C_{CO2} is carbon concentration in the atmosphere, then

$$\Delta = 3 \log_2 \left(\frac{C_{\text{CO2}}}{280} \right), \tag{18}$$

which, for instance, implies that a doubling of CO_2 concentration leads to a temperature increase of 3° C. From this equation we build a functional relationship between S_t and Δ in two steps: First, calibrate the range of S :

$$S = 280 \cdot 2^{\frac{\Delta_{\text{dis}}}{3}} - \max\{C_{\text{CO2}}, 280\}. \tag{19}$$

S is zero (using Equation (18)) at the temperature level of an "environmental disaster", which is here given by Δ_{dis}. So if $\Delta = \Delta_{\text{dis}}$, utility is zero (see Equation (22)). Further, S reaches its maximum value for the pre-industrial value of C_{CO2}. Second Δ can then be expressed as a smooth function of S if $C_{CO2} \geq 280$: from Equation (19), it follows for this case that

$$C_{\text{CO2}} = 280 \cdot 2^{\frac{\Delta_{\text{dis}}}{3}} - S \tag{20}$$

and thus using Equation (18) that

$$\Delta(S) = 3 \log_2 \left(2^{\frac{\Delta_{\text{dis}}}{3}} - \frac{S}{280} \right). \tag{21}$$

Finally, define a damage function $\phi(S_t)$ (introduced above as the argument of the utility function) that gives utility the desired property of a possible environmental disaster and follows appropriate standard assumptions about climate damages for a moderate temperature increase. The function employed by AABH that has these properties is

$$\phi(S) = \varphi(\Delta(S)) = \frac{(\Delta_{dis} - \Delta(S))^{\lambda} - \lambda \Delta_{dis}^{\lambda-1} (\Delta_{dis} - \Delta(S))}{(1-\lambda)\Delta_{\text{dis}}^{\lambda}}. \tag{22}$$

This function ensures that the marginal utility of the carbon sink tends to ∞ and utility tends to $-\infty$ as S goes to zero. The parameters are chosen to match the standard damage function of the DICE model [Nordhaus 1994] for the medium range of possible temperature increases (for details see AABH, Sections I. and V A. and its FEEM working paper version (Nota di Lavoro 93.2010), Section 4). In particular, $\phi = 1$ if S is at its pre-industrial level $\bar{S}$, so that ϕ represents damages in percent of remaining consumption.

2.2 Social optimum and deriving optimal policy: analytic results

We distinguish two types of equilibria: the social optimum and the decentralized equilibrium with government intervention introduced in the previous subsection (which includes the laissez-faire case if there is no policy in place). We obtain our results by comparing different policy choices of the government with the social optimum. Here we derive expressions for the socially optimal policy instruments in terms of the shadow prices of the socially optimal solution. In the next subsection, we discuss a different approach for numerical implementation, which allows to calculate second-best scenarios and which is used for the numerical results in Section 3. (See [van der Ploeg and Withagen 2014] and [Kalkuhl et al. 2012] for similar recent treatments of the two approaches.)

Determining the social optimum provides a benchmark for evaluating the effectiveness of policy options. The social planner determines the optimal allocation in the economy by maximizing intertemporal utility of the representative agent subject to the constraints on factors of production, the production technologies, the influence of environmental quality and the macroeconomic budget constraint. The social planner problem is thus

$$\max_{C_t, K_{i,t}} \sum_{t=0}^{T} U(C_t, S_t) \frac{1}{(1+\rho)^t} \tag{23}$$

subject to Equations (4) – (12), (17) – (22) and the macroeconomic budget constraint $Y_t = C_t + I_t$.

The social planner hence recognizes both the negative impact of the carbon-intensive production on the household's utility through decreasing environmental quality as well as the productivity gains through learning-by-doing in the clean sector. The full optimization problem and the optimality conditions are presented in B.

Here we derive expressions for the socially optimal levels of the tax and the subsidy in terms of the shadow prices associated with the social planner problem by calculating the social value of clean and dirty production in terms of the co-states and marginal productivities. (The optimality conditions are however not employed in deriving the numerical results below (see Subsection 2.3).)

The optimality conditions can be interpreted as follows: λ_t, μ_t and κ_t are the shadow prices for additional units of total capital, environmental quality and knowledge, respectively. This means that λ_t stands for the social cost of carbon (in utils), μ_t for the social benefit of capital and κ_t for the social benefit of knowledge, meaning that marginal cost or benefit of increasing the respective flow quantities by one unit, as usual. ν_t and ψ_t are shadow prices corresponding to the constraints given by the production functions of the intermediate goods, representing the social benefits that would result from relaxing the respective production functions.

Equation (49) shows that the social cost of consumption μ_t is equal to the discounted marginal utility of consumption, as usual. Equation (50) provides a difference equation for the social cost of carbon λ_t and shows that its change depends on the discounted marginal utility of the atmosphere and its regeneration rate. Equation (52) similarly gives the change of the social cost of consumption μ_t : the difference to its decentralized version (see Equation 32) is that it specifically depends on the value marginal productivity of capital in the second sector (instead of the interest rate), due to the way the interdependencies that only the social planner takes into account are represented in the optimization.

Equation (52) can be rewritten as follows

$$\frac{\nu_t}{\mu_t} = \frac{\partial Y}{\partial Y_{1,t}} - \xi \frac{\lambda_t}{\mu_t} \tag{24}$$

and thus provides an expression for the socially optimal pricing of the dirty intermediate good. When normalized with respect to the social cost of consumption, ν_t gives the social value of an additional unit of the dirty intermediate good (in monetary units), which is the difference of its marginal productivity in final production and the social value of the emission associated with it. One can thus determine the optimal carbon tax level in terms of the respective shadow price. By comparing Equations (24) and (34) one obtains:

$$p_{1,t} = \frac{\nu_t}{\mu_t} \text{ and } \tau_{1,t} = \xi \frac{\lambda_t}{\mu_t} \tag{25}$$

Similarly, to obtain an expression for the optimal subsidy and the price of the clean good, rewriting Equation (53) yields

$$\frac{\psi_t}{\mu_t} = \frac{\partial Y}{\partial Y_{2,t}} + \frac{\kappa_t}{\mu_t} - \frac{\kappa_{t+1}}{\mu_t}. \tag{26}$$

Inserting Equation (56) one obtains an expression for the socially optimal pricing of the clean intermediate good:

$$\frac{\psi_t}{\mu_t} = \frac{\partial Y}{\partial Y_{2,t}} + \frac{1}{\mu_t}(\psi_{t+1} \frac{F_2}{\partial g} \frac{\mathrm{d}g}{\mathrm{d}H_t}) \tag{27}$$

Thus, ψ_t, when normalized, indicates the social value of an additional unit of clean intermediate output, which is the sum of its marginal productivity in final production and the value of the additional stock of knowledge generated by it which is productive in the next period. One can thus determine the optimal level of the subsidy and the price of the clean good in terms of the shadow prices, by comparing Equations (27), (35), (38) and (39):

$$p_{2,t} = \frac{\psi_t}{\mu_t} \text{ and } \tau_{2,t} = \frac{1}{\mu_t}(\psi_{t+1} \frac{F_2}{\partial g} \frac{\mathrm{d}g}{\mathrm{d}H_t}) \tag{28}$$

Finally, by comparing Equations (54) and (55) with Equations (36) – (39), one recovers the relationship between the prices that govern the distribution of capital and labour in terms of the appropriate shadow prices.

2.3 Model implementation and calibration

The optimisation problem of the social planner (Equation (23)) and the government (Equation (30)) form non-linear programs. These are solved numerically with GAMS [GAMS Development Corporation 2008], using its solver CONOPT: for the case of the social planner, GAMS solves the optimisation problem given by Equations (4) – (12), (17) – (22) and (23) directly, without the need for considering its first-order conditions.

The decentralized equilibrium is treated differently: the laissez-faire equilibrium is completely described by the first-order conditions of household and firms as well as the constraints on technologies, production and budgets: (3) – (22), (29) and (32) – (39). This set of difference equations can be solved in GAMS by optimizing with respect to a dummy variable. For the cases of government intervention, GAMS optimizes the household's welfare (see Equation (30)) with respect to all the equations of the decentralized equilibrium and with the policy instruments as decision variables.

In more detail, this means that the government anticipates the agents choices and sets the policy variables – the carbon tax and the learning subsidy – with the aim of maximizing social welfare. It redistributes taxes and subsidies lump-sum to the representative agent:

$$\Gamma_t = \tau_{1,t} Y_{1,t} - \tau_{2,t} Y_{2,t} \tag{29}$$

The maximization problem of the government is thus

$$\max_{\tau_1, \tau_2} \sum_{t=0}^{T} U(C_t, S_t) \frac{1}{(1+\rho)^t} \tag{30}$$

subject to the the first-order conditions of the agents, the household's budget constraint, the technology constraints and the state of the carbon sink, that is, subject to Equations (3)–(14),(17)–(22), (29) and (32)–(39). This approach means that the first-order conditions of households and firms serve as a reaction function for the governmentŠs optimization problem, which optimizes welfare. In contrast, the social planner solution only serves as a benchmark to assess the goodness of policy options.

Finally, second-best analyses are then conducted by limiting the government's possibilities for intervention to one variable only. The approach just detailed is essential beyond the method employed in Subsection 2.2 for computing the second-best scenarios below.

The model is calibrated to be comparable with AABH. The time period of the numerical simulation corresponds to five years, intertemporal parameters are hence chosen with respect to that interval. The time horizon is T=175 years.[2] Those parameters with values identical to the calibration of the model of AABH are displayed in Table 2 in C. Since the technological progress and

[2]The model is solved with a time horizon of T=250 years, but since towards the end of that time horizon the deinvestment dynamics dominate economic behavior, we do not show the last 75 years in the illustrations below, as is standard.

capital dynamics are conceptualised differently from AABH in the present model, a standard rate of capital depreciation (0.03% per year, that is $\delta = 0.141$) is selected and the rate of exogenous technological progress is chosen to obtain a long-run growth rate of consumption of 1.8% per year. The remaining parameters for the technological progress in the clean sector are chosen such that the clean sector initially lags behind and eventually is more efficient than the dirty sector, so that technological progress reproduces the stylized facts about future learning of renewable technologies [Fischedick et al. 2011, Ch. 10.5.2.].

3 Numerical results

In this section the results of the numerical simulations of our model are reported. As the model has two externalities – pollution and information spillovers – two policy instruments are needed to reach the social optimum (first-best). A policy with just one instrument cannot achieve the first-best, and so is a second-best policy. First the size of the lock-in is quantified (3.1), subsequently the optimal policy intervention is calculated as the welfare-maximizing tax paths (3.2). High welfare losses can be avoided even if only a single instrument is available to the government (3.3). The impact of a higher learning curve on the duration of the structural change is examined (3.4). Finally, the optimal policy is characterized when the social optimum is constrained by a two degree target (3.5).

Throughout, three cases for the substitution possibilities for clean and dirty production are considered and represented by values of the substitution elasticity ϵ. Two cases, $\epsilon = 3$ and $\epsilon = 10$, are equal to those in AABH's numerical simulation to make our findings comparable to that study. In addition a third case is examined in which ϵ increases linearly over time from initially $\epsilon = 3$ up to $\epsilon = 10$ eventually, the computationally simplest case of an increasing elasticity. This case represents future infrastructure developments designed to facilitate the use of clean instead of dirty goods. The three cases are labelled the "low", "high" and "increasing" scenario below. Welfare losses resulting from sub-optimal or missing policy intervention are quantified in balanced-growth equivalents (BGE) [Mirrlees and Stern 1972, Anthoff and Tol 2009] as environmental quality enters utility directly in our model. A balanced-growth equivalent for policy P is the level of initial consumption that, if that consumption grows with a constant rate, produces the same welfare as does P. We follow the computations in [Anthoff and Tol 2009, Section 2.1.] in our numerical implementation to calculate BGEs for the policy scenarios below.

The subsequent numerical results should be understood as indicative of the modeled dynamics only. The results remain limited in so far as the model remains a crude representation of the real world dynamics of a carbon lock-in. In particular, optimal warming levels are to be understood in this way – for making points about qualitative differences between scenarios, not about exact implications of potentials goals of climate policy. For the purpose of this article, the impact of a combination of assumptions about technological progress and substitution elasticities on the lock-in, a close calibration to real-world data thus is inessential.

3.1 Lock-In

In the unregulated decentralized equilibrium the economy produces too much of the dirty good compared to the social optimum: the intertemporally inferior carbon-intensive technology dominates the market and a transition to the low-carbon economy occurs later than would be socially optimal. For a high substitution elasticity the lock-in is generally more severe than for a low one: with a high elasticity there is less demand for clean production so the learning in that sector takes longer and aggravates the market failure. The lock-in into the dirty sector is quantified in three respects: (a) the aggregate discounted welfare losses over time are measured in balanced-growth equivalents, (b) the delay of the structural transformation is given as the difference between the socially optimal and actual time of reaching a 50 % share of the clean sector and (c) the total and the additional amount of global warming compared to the social optimum is calculated. For the different substitution scenarios the simulations can be summarized as follows: the "high" scenario leads to a much greater lock-in compared to the "low" scenario on all scales, whereas the "increasing" scenario represents an intermediate case, see Figure 1. Figure 2 compares the socially optimal time paths with those of the unregulated market outcome for the share of the clean and the dirty sector and the state of the atmosphere. (The time paths of further variables are presented in D.) There are significant differences in the deviations of the decentralized paths from the socially optimal outcome: in the "low" case a share of the clean sector is missing that is approximately constant over time, while in the "high" case the switch from the dirty to the clean sector is delayed, the "increasing" scenario representing a middle case. The socially optimal amount of global warming is below 2°C for the "high" and "increasing" case and $2.9°C$ for the "low" case: due to the difficulty in substituting away from low-carbon production, it is socially optimal to accept more global warming in order to have more consumption. However, the better the substitution possibilities, the higher is the additional amount of global warming produced by the externality. The sectoral shares in the "increasing" case are, moreover, non-monotonic because the changing substitutability influences the demand for the intermediate goods: as long as the clean technology is not yet mature, an increasing substitution elasticity leads to *less* demand for the clean good, while the opposite is true when the clean technology is more competitive then the clean good.

3.2 First-best Policy Response

In the absence of policy intervention, severe welfare losses occur due to the combination of market failures that creates the lock-in. This motivates the subsequent analysis of policy responses that avoid it. To correct the externalities, a carbon tax and a learning subsidy are feasible policy instruments. The welfare-maximizing time paths of the policy instruments are computed for the

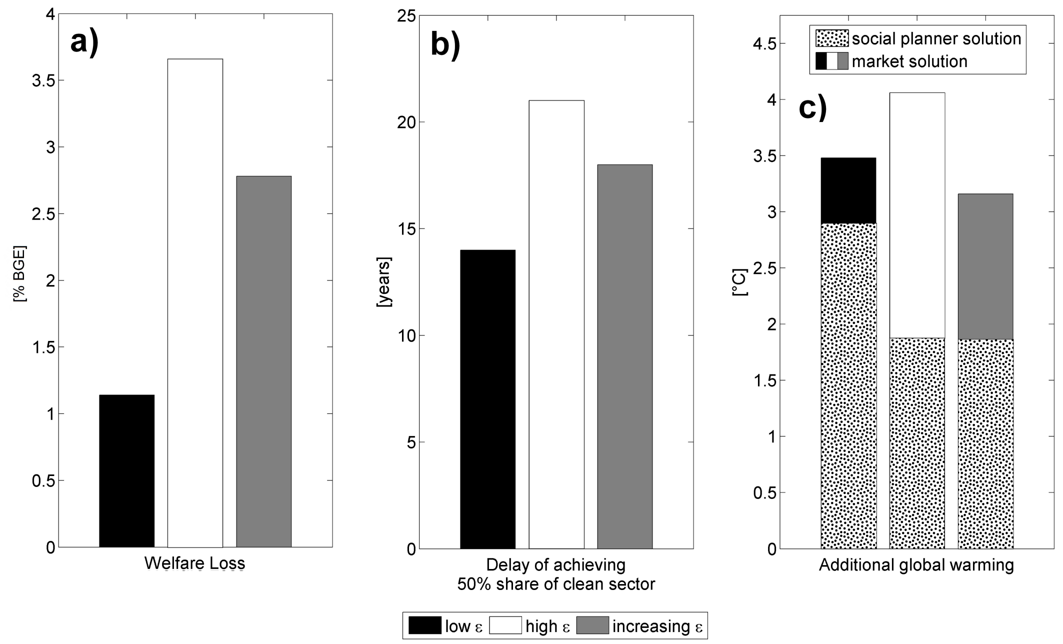

Figure 1: The lock-in of the unregulated market outcome for different substitution elasticities: comparison to the socially optimal outcome in terms of (a) welfare (in % BGE consumption loss), (b) delay of clean sector and (c) (additional) global warming.

three different substitution possibilities (Figure 3). In all cases, carbon prices are increasing with time, and, with the exception of the "high" case of $\epsilon = 10$, subsidies are decreasing. Carbon prices increase because of general productivity growth and higher damages. The share of the dirty sector (strongly) decreases in all scenarios, while its absolute volume (moderately) increases only in some. The subsidy for the case of $\epsilon = 10$ is non-monotonic for the following reason: initially, subsidising the clean sector is not necessary because the benefit of this would be too low (the sector being too unproductive to warrant a subsidy). It is sufficient if the subsidy starts later for the clean sector to dominate later on – which indicates that for such substitution possibilities the switch from one dominating technology to the other can be very fast. For this case the subsidy strongly increases once the government starts to use it and peaks around two decades after its introduction. By comparison, the optimal policy in the "low" case of $\epsilon = 3$ involves a substantially higher carbon price and a moderately higher learning subsidy (at least after the sudden initial increase and peak of the subsidy in the "low" case) than in the other cases. Except for an initially high learning subsidy, the "increasing" case requires policy instruments much more in the order of the "high" case than the "low" case.

The optimal policy intervention for the structural change to avoid the lock-in is permanent for all scenarios. This is in particular true for the carbon tax: carbon pricing needs to be permanent because the clean sector will never be so much more productive as to make demand for dirty intermediate production negligible. The learning subsidy, although it is decreasing, must last until no

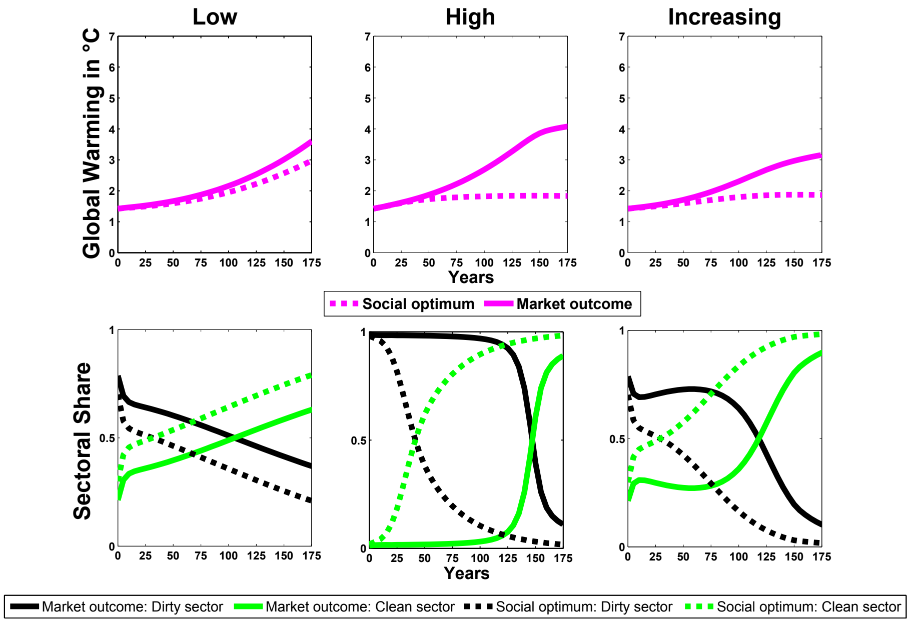

Figure 2: Comparison of the (unregulated) market and the social planner solution: the time paths of global warming and the share of the clean and dirty sector for the different cases of the substitution elasticity.

more learning can occur because the maximum productivity is reached (see Equation 12). In our numerical implementation, the convergence of the clean technology towards its maximum productivity is slow, so that the subsidy stays in place for the time horizon considered.[3]

3.3 The size of the carbon lock-in as additional intervention: second-best policy with a single instrument

In a second-best policy scenario the government has only a single instrument available to maximize welfare. Even in this case it can significantly improve the market outcome. This second-best intervention requires that the single instrument is set significantly higher compared to the optimal intervention. Results are close to the social optimum: numerical solutions show that for the different cases of elasticities the second-best optimum does not produce losses

[3]This is not to say that the optimal policy response must be permanent under any conceivable parametrisation of the model. An exception is for example the case of a very high regeneration rate, so that atmospheric quality can reach its pre-industrial level very rapidly: no carbon tax is needed from then on. But this case is not relevant for physical reality as the regeneration of the atmosphere and associated natural systems in the carbon cycle will in physical reality not occur in the next centuries [IPCC 2013]. Similarly, as an addition to the model presented, one could include rising extraction costs for fossil resources into the model that would slow down productivity in the dirty sector so much as to make it uncompetitive with the clean sector. This scenario is however unlikely due to the enormous and easily accessible amount of cheap coal, which needs to be left under ground for any serious efforts to limit global warming (see [Allen et al. 2009, Edenhofer et al. 2011, IPCC 2014b]).

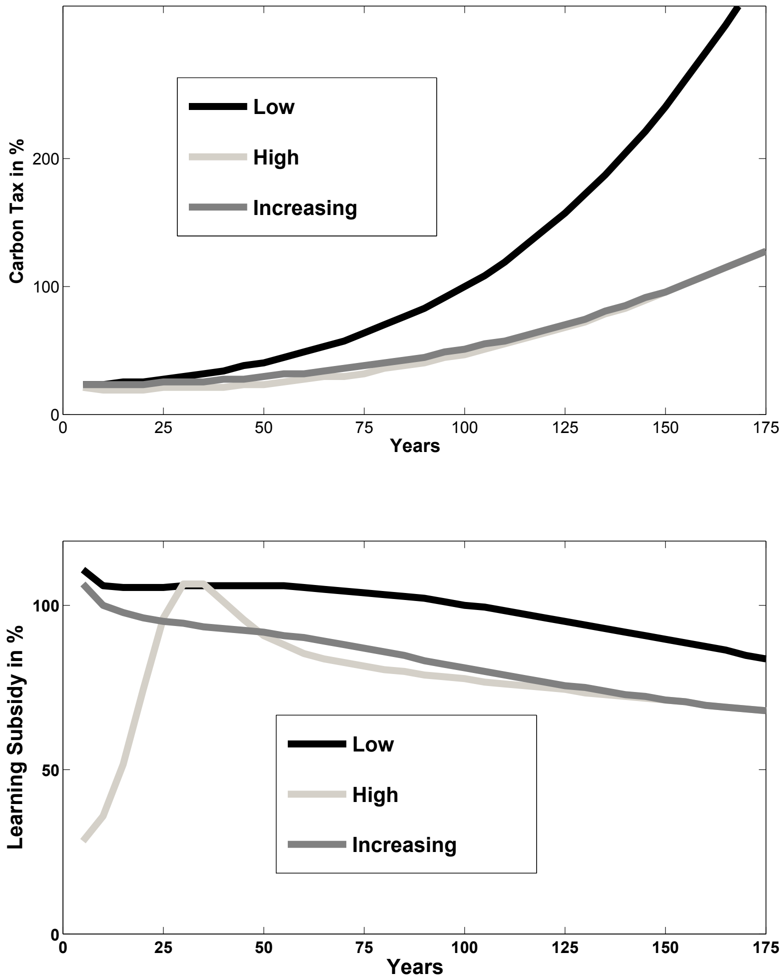

Figure 3: The optimal policy mix required to reproduce the social optimum. Prices are given in % of the reference case of the value at $t = 100$ for $\epsilon = 3$.

greater than 0.2 % BGE (for the case of only a carbon tax, the losses for only a subsidy being an order of magnitude lower), even if the first-best production and consumption paths differ markedly. This is an unsurprising result: both the climate and the learning externality impact the distribution of inputs to the dirty and clean sector. So one instrument set significantly higher than in the first-best optimum can correct much of the second externality.

This result is illustrated for the case that the *carbon tax* is the single instrument available to the government: Figure 4 displays the first-best (=Pigouvian) carbon tax $\tau_{1,t}$ compared to the single instrument carbon tax $\tau'_{1,t}$ for the three cases of the substitution possibility. Again, if substitution possibilities are poor, socially optimal mitigation is more difficult to achieve by policy intervention: the lower the substitution possibilities, the higher the carbon tax thus has to be set when used to overcome the lock-in even beyond simply correcting the climate externality.

This finding completes our thesis that substitution possibilities play an ambivalent role: while in Subsection 3.1 it was shown that in the unregulated outcome good substitution possibilities cause the highest welfare losses, the numerical results of Subsections 3.2 and 3.3 demonstrate that poor substitution possibilities require the highest policy intervention.

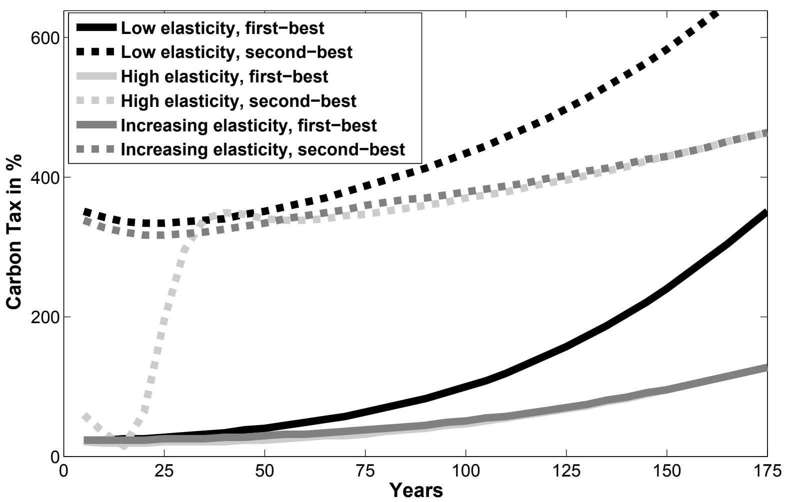

Figure 4: The second-best carbon tax $\tau'_{1,t}$ compared to the first-best tax $\tau_{1,t}$ for different substitution elasticities in % of the reference value at $t = 100$ for $\epsilon = 3$

3.4 The impact of a high learning curve on the transition

This subsection provides an elementary consideration about the dependence of the structural change on the learning curve. "Transition time" denotes the time taken in the social planner solution to reach a share of 80 % of the clean sector

	$\epsilon = 3$	ϵ linearly increasing from 3 to 10	$\epsilon = 10$
$\gamma = 0.27$	190	100	50
$\gamma = 0.2$	180	65	15
AABH [a].	70	–	15

[a]Own estimations from results given in [Acemoglu et al. 2012]

Table 1: Transition time as a function of the learning rate and the substitution elasticity.

from at least a 20 % share of that sector. The transition time is calculated for two different learning curves for the clean technology. Besides the standard parametrisation of $\gamma = 0.27$ a low value of $\gamma = 0.2$ is considered that results in a higher learning curve (see Figure 6 in C).

Table 1 presents the values of the transition time for two different learning curves and three cases of the substitution elasticity. This measure characterizes the transition from the fossil-fuel based to the low-carbon economy as a gradual adjustment or an immediate switch: the higher the substitution elasticity, the shorter the transition time.

By comparison, the numerical solution to AABH's model contains a rather abrupt switch (see Figure 1 D of AABH) due to their knife-edge condition for innovation to happen in both sectors (see Lemma 1 and Figure 1 B of AABH): in that model the transition time is 15 years for $\epsilon = 10$ and 70 years for $\epsilon = 3$ for the discount value of $\rho = 0.001$ (per year). Although the two conceptions of technological progress are very different, our analysis indicates that the outcome of ABBH's directed technical change corresponds to a learning curve of sudden extremely high competitiveness. Such an outcome is implausible due to path-dependencies in technological development, as discussed in Subsection 2.1.3.

3.5 Implications of a two degree target

Due to high uncertainties about economic damages and losses of human lives, standard cost-benefit-analysis is of limited normative cogency for evaluating policy responses to climate change. A more promising normative approach will seek to evaluate pathways of decarbonisation taking a guardrail on climate damages as given. Limiting the most severe impacts from climate change requires keeping global mean temperature below 2°C [IPCC 2014a, Lenton et al. 2008]. This two degree target has become the focus of many political efforts to limit global warming and economic studies have demonstrated its feasibility [IPCC 2014b].

Under the unconstrained cost-benefit analysis of climate damages, the socially optimal amount of global warming is significantly above 2°C for low values of the substitution elasticity (see Figure 2) in our model: for $\epsilon = 3$ it is 2.9°C at t=175. For this case we compute the additional policy intervention necessary to comply with a two degree target. We find that the carbon tax for the two degree target is significantly – eventually about ten times – higher than the carbon tax from the first-best optimum of an unconstrained cost-benefit analysis (see Figure 5). Low substitution possibilities hence make ambitious mitigation very expensive and difficult to implement politically as they require aggressive carbon pricing towards the end of the decarbonisation. This again motivates to treat substitution possibilities as non-constant over time and potentially subject to further policy intervention.

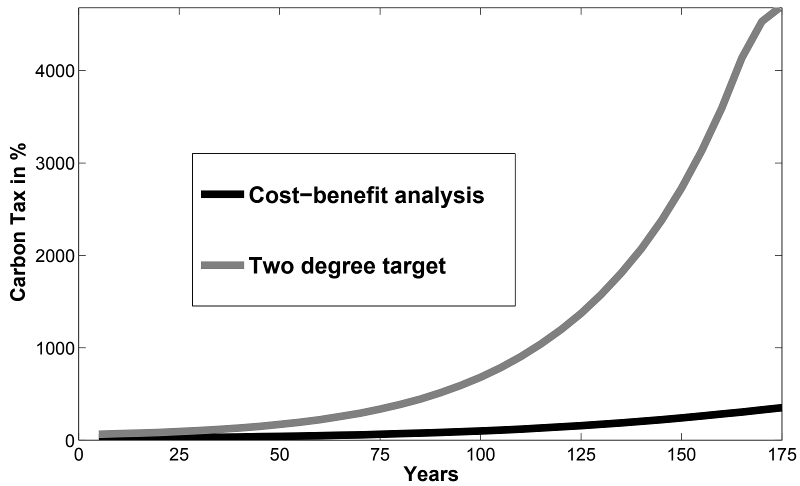

Figure 5: Comparison between the optimal carbon tax paths resulting from a cost-benefit analysis and the two degree target given a low substitution elasticity $\epsilon = 3$ (in % of the reference value at $t = 100$ for $\epsilon = 3$)

3.6 Comparison to the findings of AABH

AABH argue that a high substitution elasticity between the carbon-intensive and the carbon-free sector of the economy facilitates the structural change from a carbon-intensive to a low-carbon economy as it requires an immediate, but less comprehensive and merely temporary policy intervention. We confirm this result with our model, but highlight that a high substitution elasticity also creates greater risks of a welfare loss from a lock-in. We disagree with AABH that an immediate, but temporary policy intervention is optimal: a permanent intervention is required if a more empirically plausible conception of advancing renewables is assumed[4]. This is immediate from comparing Figure 1 A

[4]Another difference between AABH and the present model is that only in the former the unregulated outcome leads to an "environmental disaster" (AABH p. 141). Although this could in principle happen in the present model, it does not for the entire parameter range examined. This difference is once more due to the different conceptions of technological progress: in

and C of AABH with Figure 3 above. Our study can thus be seen as indicating that ABBH's policy advice for fostering low-carbon structural change is limited in scope: it depends on a particular calibration of technological progress in the framework of directed technical change, the normative assumption of an unconstrained cost-benefit-analysis, the restriction to finding the optimal policy response and an elasticity of substitution between sectors that is constant over time. The lesson for giving policy advice is that there is a high variability of trajectories for structural change according to particular assumptions – for which often no well-established empirical estimates exist; no clear-cut policy message based on one set of assumptions is hence legitimate.

3.7 The role of a changing substitution elasticity

Policies changing relevant infrastructure may increase substitutabililty. Our modelling results in Subsections 3.1 to 3.5 demonstrate that the *timing* of such policy measures and their combination with taxes and subsidies matters. Enhancing the substitution possibilities at the right time during the phase of structural change may help the decarbonisation and avoid a severe lock-in. According to our results, if infrastructure measures are taken up too late, mitigation requires high carbon pricing. If they are taken up too early, they may aggravate welfare losses from a lock-in if the other policy measures are insufficient.

The last point indicates a limitation of our interpretation of substitution possibilities in terms of infrastructures: these do not always influence the substitutability in both directions. In case substitutability is increased and the carbon-intensive technology is significantly more competitive, it will receive a larger share of production – implying high welfare losses if no tax against global warming is in place. However, some infrastructure measures do not act on substitutability in this way: for instance, tailoring urban transport infrastructure towards public and non-motorized modes facilitates substituting *away* from car transportation, but will not increase the share of the carbon-intensive mode if no other policy is in place.

4 Conclusion

This paper discusses how substitution possibilities between carbon-intensive and low-carbon production influence which policy interventions are appropriate for avoiding a carbon lock-in. An ambivalent role for such substitution possibilities is identified: high substitutability increases the risk of a lock-in, but requires less drastic policy interventions to trigger structural change towards the low-carbon economy. A learning-by-doing approach for mod-

the present model, the fact that clean and dirty consumption are imperfect substitutes always generates some demand for clean production, which causes learning effects of this sector (and which is not the case in AABH). These learning effects lead to a greater competitivity of clean over dirty production before global warming reaches the scale of an environmental disaster for any scenario examined in this study.

elling technological progress in the clean sector with a conventional learning curve implies that a permanent intervention is necessary for structural change towards the low-carbon economy. The policy recommendation of AABH – based on directed technical change – that triggering the structural change requires a merely temporary intervention, is a special case in the parameter space of substitutability and modes of technological development.

The substitution elasticity between carbon-intensive and low-carbon production cannot be assumed to be constant over the next decades. We identify infrastructures as the main factor determining the substitutability and conclude that infrastructure investments can hence influence the substitution elasticity and be part of the policy response to the carbon lock-in. Disentangling different determinants of substitution possibilities in the major economic sectors that face decarbonisation as well as studying the policy options influencing substitutability are promising topics for future work.

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Vitae

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A First-order conditions of decentralized agents

Household The Lagrangian corresponding to the household's maximization problem is:

$$\mathcal{L}(C_0, \ldots, C_T, K_0, \ldots, K_T, \mu_0, \ldots, \mu_T) = \sum_{t=0}^{T} (U(\phi(S_t)C_t)) \frac{1}{(1+\rho)^t} + \mu_t (r_t K_t + w_t L_t + \Gamma_t - C_t - K_{t+1} + (1-\delta)K_t)) \quad (31)$$

The optimal choice for the household is thus characterized by the following first-order conditions:

$$\frac{\partial \mathcal{L}}{\partial C_t} = \frac{\partial U}{\partial C_t}(C_t)\frac{1}{(1+\rho)^t} - \mu_t = 0 \quad (32)$$

and

$$\frac{\partial \mathcal{L}}{\partial K_t} = \mu_t (r_t + (1-\delta)) - \mu_{t-1} = 0. \quad (33)$$

Final-good Producer The usual equilibrium price conditions apply including the carbon tax:

$$p_1 + \tau_1 = \frac{\partial Y}{\partial Y_1}, \quad (34)$$

$$p_2 = \frac{\partial Y}{\partial Y_2}. \quad (35)$$

Dirty Firm The usual static equilibrium conditions for the interest rate and the wage apply:

$$r = p_1 \frac{\partial Y_1}{\partial K_1}, \quad (36)$$

$$w = p_1 \frac{\partial Y_1}{\partial L_1}. \quad (37)$$

Clean Firm The standard static equilibrium conditions apply including the learning subsidy:

$$r = (p_2 + \tau_2) \frac{\partial Y_2}{\partial K_2} \quad (38)$$

$$w = (p_2 + \tau_2) \frac{\partial Y_2}{\partial L_2}. \quad (39)$$

Prices are then determined by the general equilibrium, that is by inserting Equations (34-39) into the Equation (3) and solving the optimality conditions of the household subject to (3).

B Optimisation Problem of the Social Planner

The social planner problem given by Equations (4) – (12), (17) – (22) and the macroeconomic budget constraint $Y_t = C_t + I_t$ can be simplified to the following system of equations:

$$\max_{C_t, K_t, K_{1,t}} \sum_{t=0}^{T} U(C_t, \phi(S_t)) \frac{1}{(1+\rho)^t} \tag{40}$$

$$0 = -S_{t+1} - \xi Y_{1,t} + (1+\zeta) S_t \tag{41}$$

$$0 = -K_{t+1} + Y(Y_{1,t}, Y_{2,t}) - C_t + (1-\delta) K_t \tag{42}$$

$$0 = -Y_{1,t} + F_1(K_1, L_1) \tag{43}$$

$$0 = -Y_{2,t} + F_2(g(H_t), K_t - K_{1,t}, \bar{L} - L_{1,t}) \tag{44}$$

$$0 = -H_{t+1} + (Y_{2,t} - Y_{2,t-1}) + H_t \tag{45}$$

Here, we have abbreviated

$$Y(Y_{1,t}, Y_{2,t}) = A_t (Y_{1,t}^{\frac{\epsilon_t - 1}{\epsilon_t}} + Y_{2,t}^{\frac{\epsilon_t - 1}{\epsilon_t}})^{\frac{\epsilon_t}{\epsilon_t - 1}} \tag{46}$$

and

$$g(H_t) = A_{2,t} = \frac{\beta}{1 + (\frac{\omega}{H_t})^\gamma}. \tag{47}$$

The Lagrangian corresponding to the social planner's maximisation problem then is:

$$\begin{aligned}
&\mathcal{L}(C_0, K_0, S_0, K_{1,0}, L_{1,0}, Y_{1,0}, Y_{2,0}, H_0, \lambda_0, \mu_0, \nu_0, \psi_0, \kappa_0, \dots, \\
&\quad C_T, K_T, S_T, K_{1,T}, L_{1,T}, Y_{1,T}, Y_{2,T}, H_T, \lambda_T, \mu_T, \nu_T, \psi_T, \kappa_T) = \\
&\quad \sum_{t=0}^{T} U(C_t, \phi(S_t)) \frac{1}{(1+\rho)^t} + \lambda_t(-S_{t+1} - \xi Y_{1,t} + (1+\zeta) S_t) + \\
&\quad \mu_t(-K_{t+1} + Y(Y_{1,t}, Y_{2,t}) - C_t + (1-\delta) K_t) + \\
&\quad \nu_t(-Y_{1,t} + F_1(K_1, L_1)) + \psi_t(-Y_{2,t} + F_2(g(H_t), K - K_1, \bar{L} - L_1)) + \\
&\quad \kappa_t(-H_{t+1} + (Y_{2,t} - Y_{2,t-1}) + H_t)
\end{aligned} \tag{48}$$

The social optimum is thus characterised by the following conditions:

$$\frac{\partial \mathcal{L}}{\partial C_t} = \frac{\partial U}{\partial C_t} \frac{1}{(1+\rho)^t} - \mu_t = 0 \tag{49}$$

$$\frac{\partial \mathcal{L}}{\partial S_t} = \frac{\partial U}{\partial \phi}\frac{\partial \phi}{\partial S}\frac{1}{(1+\rho)^t} - \lambda_{t-1} + \lambda_t(1-\zeta) = 0 \tag{50}$$

$$\frac{\partial \mathcal{L}}{\partial K_t} = -\mu_{t-1} + \mu_t(1-\delta) + \psi_t\frac{\partial F_2}{\partial K_t} = 0 \tag{51}$$

$$\frac{\partial \mathcal{L}}{\partial Y_{1,t}} = -\xi\lambda_t + \mu_t\frac{\partial Y}{\partial Y_{1,t}} - \nu_t = 0 \tag{52}$$

$$\frac{\partial \mathcal{L}}{\partial Y_{2,t}} = \mu_t\frac{\partial Y}{\partial Y_{2,t}} - \psi_t + \kappa_t - \kappa_{t+1} = 0 \tag{53}$$

$$\frac{\partial \mathcal{L}}{\partial K_{1,t}} = \nu_t\frac{\partial F_1}{\partial K_{1,t}} - \psi_t\frac{\partial F_2}{\partial K_{1,t}} = 0 \tag{54}$$

$$\frac{\partial \mathcal{L}}{\partial L_{1,t}} = \nu_t\frac{\partial F_1}{\partial L_{1,t}} - \psi_t\frac{\partial F_2}{\partial L_{1,t}} = 0 \tag{55}$$

$$\frac{\partial \mathcal{L}}{\partial H_t} = \psi_t\frac{F_2}{\partial g}\frac{\mathrm{d}g}{\mathrm{d}H_t} - \kappa_{t-1} + \kappa_t = 0 \tag{56}$$

C Parameter choices for numerical solution

Table 2 and 3 detail all parameters for simulation. Since AABH do not state precisely their employed values for the emission intensity ξ and regeneration rate ζ of the atmosphere, we compute our own emission intensity and regeneration rate with the values for current CO_2 increase and dissipation given in [Rezai et al. 2012]. Figure 6 illustrates the role of the learning parameter γ for generating a higher learning curve as used for the analysis in Subsection 3.4.

Parameter	Significance
$\eta = 2$	intertemporal elasticity of substitution
$\epsilon = 3, 10$	elasticity of substitution between clean and dirty sector
$\rho = 0.00501$	discount rate
$\theta = 0.3$	factor intensity in production
$\bar{S} = 280 \cdot (2^{\frac{\Delta_{dis}}{3}} - 1) \approx 1098,9$	pre-industrial CO_2-concentration: 280 ppm
$S_0 = 280 \cdot 2^{\frac{\Delta_{dis}}{3}} - 389 \approx 989,9$	current CO_2-concentration: 389 ppm
$\Delta_{dis} = 6.9$ř	disaster temperature
$\lambda = 0.3492$	damage scale parameter

Table 2: Parameters as assumed by AABH (see also their working paper version Fondazione Eni Enrico Mattei. Nota di Lavoro 93.2010.

Parameter	Significance
$\delta = 0.141$	depreciation of capital
$g_e = 0.049$	general productivity growth
$\beta = 8$	maximum productivity
$\omega = 300$	scaling parameter
$\gamma = 0.27$	curvature of learning curve
$\xi = 1.7$	emission intensity
$\zeta = 0.00137$	regeneration capacity of atmosphere
$K(0) = 5$	initial value of capital stock
$H(0) = 0.3$	initial value of knowledge
$L(t) = 1$	normalized size of labour force over all time periods

Table 3: Additional parameters calibrated to match stylized facts

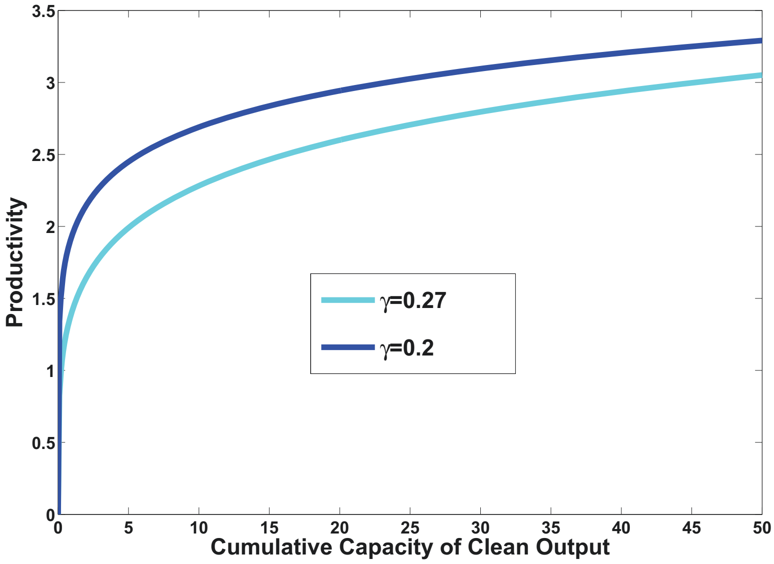

Figure 6: Two learning curves differing by the learning parameter γ for the clean technology.

D Additional figures representing the lock-in

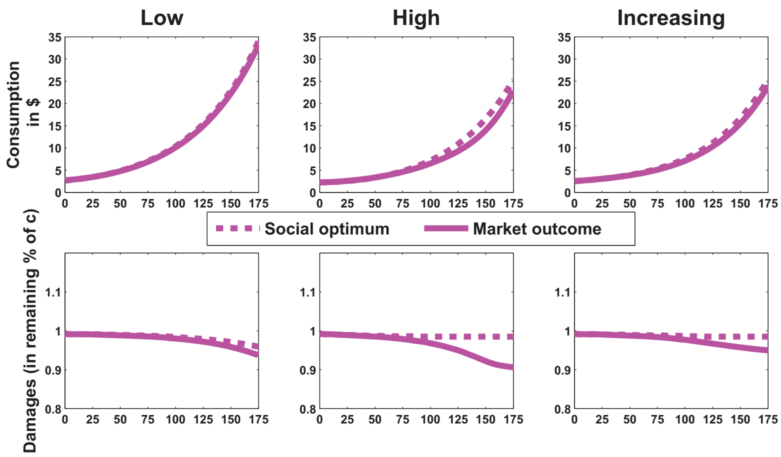

Figure 7: Comparison of the (unregulated) market and social planner solution: the time paths of consumption (in monetary units, given initial value for capital) and damages (share of remaining consumption relative to pre-industrial environmental quality)

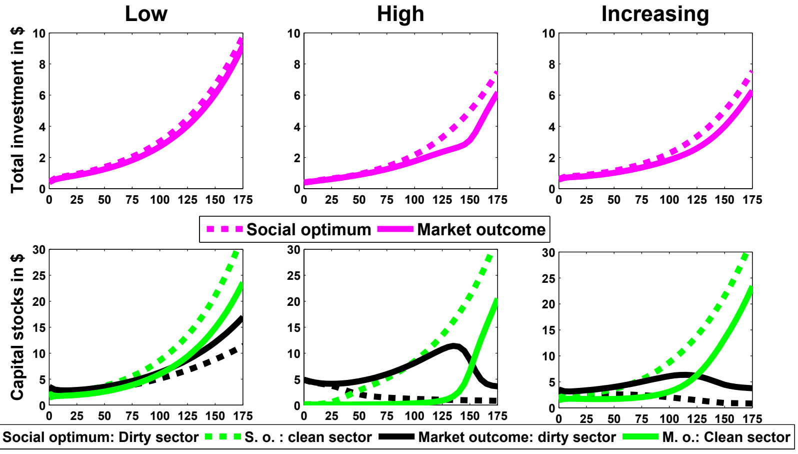

Figure 8: Comparison of the (unregulated) market and social planner solution: the time paths of total investment and capital stocks in both sectors (in monetary units, given initial value for capital)

E Sensitivity analysis

We first check for robustness of the main results across variations of the crucial parameter for this study, the substitution elasticity ϵ. We then provide a general sensitivity analysis and find that our main results are robust for all parameter variations displayed in Table 5. Results of extensive further sensitivity checks are available as a Supplementary Information from the corresponding author by request.

Value of ϵ	Welfare loss in % BGE
2	0.74
3	1.14
4	1.59
5	2.07
6	2.53
7	2.89
8	3.13
9	3.36
10	3.66
11	3.90
12	3.91

Table 4: The lock-in of the unregulated market outcome for further substitution elasticities: comparison to the socially optimal outcome in terms of welfare given in % BGE.

With regards to robustness with respect to variations of the substitution elasticity, Figures 9 and 10 present the differences in the time-paths of the socially optimal and the unregulated market outcome for further values. Moreover, Table 4 quantifies the welfare loss through the lock-in for a broader range of values. The analysis confirms that the "low" and "high" case considered in the main part of the article capture all relevant differences. For the limiting cases, one observes the following outcome: as ϵ approaches 0, the sectoral share of clean and dirty sectors approach 0.5 in both decentralized version and socially optimal allocation, in accordance with the limiting case of a Leontief production function. For $\epsilon > 11$ and the case of the unregulated market outcome, no transformation towards the clean sector occurs within the considered time frame anymore.

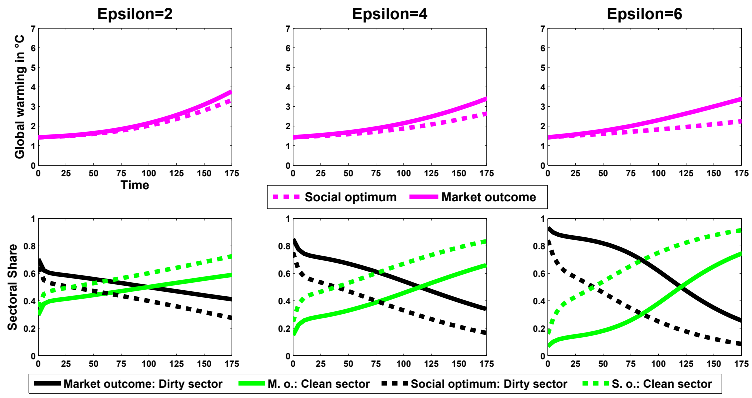

Figure 9: Sensitivity of the comparison of the (unregulated) market and the social planner solution: the time paths of global warming and the share of the clean and dirty sector for the further cases of the substitution elasticity.

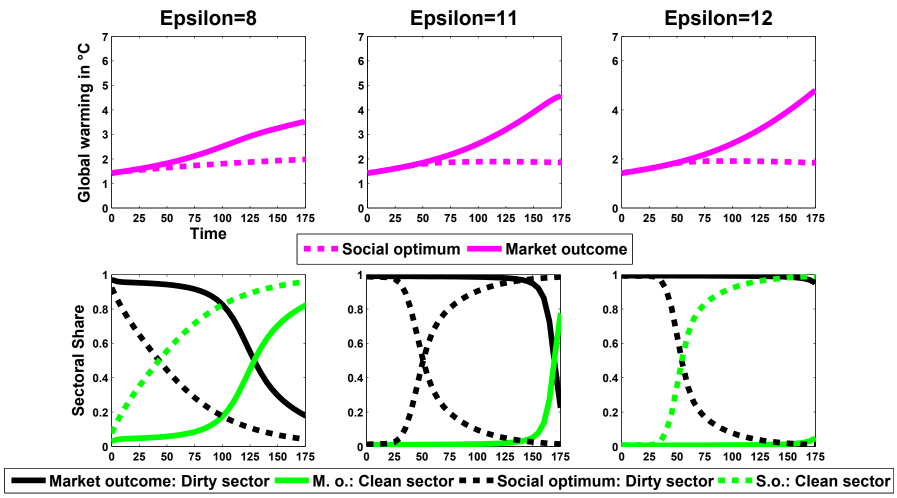

Figure 10: Sensitivity of the comparison of the (unregulated) market and the social planner solution: the time paths of global warming and the share of the clean and dirty sector for the further cases of the substitution elasticity.

Parameter	Low Value		Stand. value		High value
Elasticity of intertemp. subst. η	1.1	1.5	2	2.5	3
Welfare loss in % BGE	1.22	2.02	2.53	2.74	2.83
Pure rate of time preference ρ	0.01	0.03	0.00501	0.01	0.1
Welfare loss in % BGE	2.58	2.56	2.53	2.45	1.34
Factor intensity in intermediate production (capital share) θ	0.1	0.2	0.3	0.4	0.45
Welfare loss in % BGE	2.73	2.65	2.53	2.17	1.95
Disaster temperature Δ_{dis}	6	6.5	6.9	7.5	7.8
Corresponding initial value of environmental quality S_0	731	868.2	989.9	1194.9	1308.6
Welfare loss in % BGE	2.76	2.60	2.53	2.43	2.38
Damage scale parameter λ	0.1	0.3	0.3492	0.5	0.7
Welfare loss in % BGE	2.19	2.45	2.53	2.71	2.98
Depreciation of capital δ	0.05	0.1	0.141	0.25	0.4
Welfare loss in % BGE	2.49	2.52	2.53	2.41	2.17
General productivity growth g_e	0.021	0.035	0.049	0.063	0.077
Welfare loss in % BGE	2.22	2.50	2.53	2.46	2.35
Maximum clean productivity β	6.5	7	8	9	10
Welfare loss in % BGE	1.08	1.60	2.53	2.83	2.57
Scaling Parameter ω	200	250	300	350	400
Welfare loss in % BGE	2.65	2.63	2.53	2.36	2.20
Curvature of learning curve γ	0.2	0.24	0.27	0.3	0.35
Welfare loss in % BGE	1.04	1.99	2.53	2.26	1.04
Emission intensity ξ	1	1.4	1.7	1.8	1.9
Welfare loss in % BGE	2.27	2.41	2.53	2.56	2.60
Regeneration rate ζ	0.0005	0.001	0.00137	0.003	0.006
Welfare loss in % BGE	2.55	2.54	2.53	2.49	2.32

Table 5: Welfare losses in the unregulated market outcome for parameter variations around the standard parametrization (with $\epsilon = 6$): comparison to the socially optimal outcome in terms of welfare given in % BGE.

We now provide a sensitivity analysis for all parameters (see C) for this study. We check the robustness of our main results by giving the welfare loss in the unregulated outcome across parameter values in Table 5. Moreover, we checked whether, for the parameter combinations tested, a change in the time-paths of the socially optimal and the unregulated market outcome occurs (in comparison to Figure 2, more in this in the Supplementary Information). We find that for the ranges shown, results do not change qualitatively, ensuring that the policy implications also do not change.

We subsequently explain the changes in welfare losses in the unregulated outcome with respect to varying parameters displayed in Table 5. Welfare losses as functions of a single parameter are either monotonically increasing, monotonically decreasing or inverted U-shaped. They remain in the range of 1Ű3 % BGE.

For the elasticity of intertemporal substitution η, welfare losses are monotonically increasing. A higher η means that an unequal distribution of consumption over time lowers welfare. This is true in this model as consumption losses due to the lock-in occur early on in the model while the economy is growing, so that a higher η produces high welfare losses. A higher rate of pure time preference ρ lowers welfare losses, as expected. Later consumption losses are more discounted and also much less investment and growth occurs, so that damages are lower. A higher capital intensity in production θ leads to results similar to a lower substitution elasticity: a more capital-intensive economy has higher socially optimal levels of warming and the lock-in occurs earlier and is smaller, which leads to decreasing welfare losses.

With a higher disaster temperature parameter [5]) warming levels translate into lower utility losses. Thus welfare losses are lower for a higher disaster temperature parameter. Similarly, with higher λ, damages have a greater weight in the utility function, so welfare losses increase.

Welfare losses are highest for the standard depreciation rate δ, they are slightly lower for low rates and much lower for high depreciation rates. For low depreciation rates, the delay of the transition for the decentralized case is lower, leading to slightly reduced welfare losses. For high depreciation rates, although the delay is greater, welfare losses are lower due to much lower climate damages, because the size of the economy is much smaller.

Lower values for general productivity growth g_e lead to lower damages as the economy is smaller, and hence to lower welfare losses. Higher rates also lead to *lower* welfare losses because much less of a lock-in occurs. This is because if the economy is much more productive, learning happens much quicker in the decentralized equilibrium by comparison to the socially optimal case.

The key parameters governing the learning of the clean sector β and γ both yield an inverted U-shape curve in terms of welfare losses. For β, the maximum productivity of the learning technology, high rates mean that learning happens fast both in the social planner and the decentralized version, so there is little lock-in and hence little welfare losses. On the other hand, low rates mean that the transition happens slowly for the social planner solution, so that welfare losses are also lower compared to the standard case. The lock-in is hence greatest for a medium maximum productivity of the learning technology. The same is true for varying γ, the *curvature* of the learning curve. Low values of γ lead to high learning rates, while high values mean that learning happens slowly (see C). The results for varying γ are thus similar to β, but reversed. A lower scaling parameter ω makes the social planner solution switch more rapidly than the decentralized version, whence welfare losses are higher.

[5]This parameter must be varied with the resulting initial level of environmental quality in order to leave current CO_2-concentrations fixed, see Subsection 2.1.4.

As the behavior with respect to varying depreciation, productivity growth and learning seems most important and relevant to the main conclusions of the study, the Supplementary Information (available upon request) contains further Figures (akin to Figure 2 above) illustrating the behavior described here.

Finally, the higher the emission intensity ζ and the lower the regeneration rate ξ, the greater are the welfare losses: although socially optimal damages are somewhat higher in these cases, the unregulated damages are more than proportionally higher.

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Part II

Welfare effects of public investment: heterogeneous classes and behavioral transport choices

Chapter 6

Distributional effects of public investment when wealth and classes are back[1]

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Distributional effects of public investment when wealth and classes are back

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Abstract

In developed economies, wealth inequality is high, while public capital is underprovided. Here, we study the impact of heterogeneity in saving behavior and income sources on the distributional effects of public investment. A capital tax is levied to finance productive public capital in an economy with two types of households: high income households who save dynastically and middle income households who save for retirement. We find that inequality is reduced the higher the capital tax rate is and that low tax rates are Pareto-improving. There is no clear-cut trade-off between efficiency and equality: middle income households' consumption is maximal at a higher capital tax rate than high income households' consumption.

JEL classification: E6, H23, H31, H40, H54

Keywords: Public capital, wealth disparity, inequality, household heterogeneity, Pasinetti Theorem, saving behavior

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1 Introduction

Capital taxation has for a long time not been favored by economists as a revenue-raising option, but has recently received much attention as a means of mitigating inequality in wealth (Piketty, 2014). “Capital is back” (Piketty and Zucman, 2014) as a factor to be taxed for financing public investment in industrialized countries: on the one hand, the capital-output ratio increases (Piketty, 2014) which in part explains great wealth disparities (Wolff, 2010). On the other hand, public investment may significantly enhance aggregate productivity (Romp and De Haan, 2007; Bom and Ligthart, 2014). Research on the distributional consequences of public investment has rarely analyzed the impact of distinct financing options. Further, realistic concepts of household heterogeneity in saving motives (Attanasio, 1994; Browning and Lusardi, 1996; Dynan et al., 2004), income sources (Wolff, 1998; Quadrini, 1997; Diaz-Gimenez et al., 2011) and time preference (Lawrance, 1991; Green et al., 1996) should crucially influence the outcome of different financing options for public investment, but previous analyses have neglected such heterogeneity.

This article introduces a model of two stylized types of households to study the effect of financing productive public investment by a capital tax. It answers the following question: is it possible to invest in public capital in a way that all households benefit while the financing mechanism mitigates wealth inequality? The answer is yes when there is significant underprovision of public capital and public investment is financed by a capital tax. We also prove that for each household type a different rate of capital taxation is optimal. These results hold for moderate to high values of the substitution elasticity between capital and labor.

Previous theoretical work on the provision of public capital has focused on homogenous households, neglecting systematic differences across income groups. It has emphasized that a trade-off exists between investment into productive public capital and efficiency losses from taxes financing these investments. This trade-off determines an optimal tax rate (Barro, 1990). When household heterogeneity is taken into account to study the effects of public investment on *inequality*, all agents are typically assumed to have identical preferences, while the heterogeneity stems from different initial endowments. For example, Alesina and Rodrik (1994) show that when households differ by the division of their endowment in wealth and (inelastic) labor supply, households with higher labor to capital ratio prefer higher capital taxes. Their model implies that growth is always reduced when the preferred tax rate of all households but those who only hold capital is implemented. When public investment also affects the labor-leisure decision of households, Chatterjee and Turnovsky (2012) find that investing in public capital increases inequality in wealth (and welfare) in the long run, but also growth and average welfare, independent of the financing mechanism.

Here we introduce a model of productive public capital and wealth inequality in which the heterogeneity stems from different saving motives, income sources and time preference rates. There are two different types of households: dynastically-saving high income households, whose only source of income is the interest from their capital stock and middle income households who live for two periods and save out of a life-cycle motive. A capital tax is levied by the government to finance productive public investment. The effect of other revenue sources, such as labor or consumption taxation, and the comparison with capital taxation is treated in our companion paper, Klenert et al. (2014), that extends the present analysis to less stylized functional forms. Our main point in the present article is to prove that capital taxation can both reduce inequality and be Pareto-improving.

Baranzini (1991) was the first to introduce two-class models in which there are capitalists, who leave bequests to their offspring, and workers who save over the life cycle only, thus providing earlier work by (Kaldor, 1955-1956) and Pasinetti (1962) with micro-foundations. Michl (2009) presents a version of a two-class model with a dynastically saving capitalist and workers living for two periods, on which our model builds by modeling saving behavior across classes similarly.[1] We focus on financing public investment, whereas Michl (2009) instead employs a non-marginalist approach to production in order to assess different social security schemes. Recently, Stiglitz (2015a,b) also considers a similar set-up with exogenously given saving propensities.

Our model contains a version of the 'Pasinetti Theorem': In the steady-state the capitalists' propensity to save determines the interest rate (Pasinetti, 1962). We focus on the realistic case of the economy being populated by two classes, neglecting the "dual-Pasinetti equilibrium" of middle income households owning all capital (Samuelson and Modigliani, 1966), which is widely considered irrelevant (Pasinetti, 1966, 1974).[2] In view of the empirical evidence summarized by Piketty (2014), one may rather wonder whether the 'anti-dual outcome', that high income households own all capital, is a real possibility (Taylor, 2014; Zamparelli, 2015).

To the best of our knowledge, Steedman (1972) was the first to examine how government activity influences the Pasinetti result, while La Marca (2005) more recently provided a synthesis of how government activity leads to the different possible equilibria. The case of the government providing productive public investment has, however, not been considered in the Post Keynesian strand of literature, but is otherwise standard (Barro, 1990; Futagami et al., 1993; Turnovsky, 1997). Recently, Tavani and Zamparelli (2014) study productive public capital also in a *classical* setting with a division between workers, who own no capital, and capital holders. They find that government action should differ according to the different growth model closures of elastic labor supply at a given wage share or fixed labor supply with adjusting real wage. Depending on the different closures, the government may be able to alleviate distributional conflicts by taxing profits to finance public investment.

[1]Michl and Foley (2004) and Michl (2009) label the two classes 'capitalists' and 'workers' respectively. We prefer to label these classes 'high income households' and 'middle income households' instead, because recent data Wolff (2010) suggests the existence of a third class, which hardly saves anything in some countries, see below. We believe that the term 'worker' is rather associated with such a third class.

[2]See Pasinetti (2012) for reflections from a contemporary perspective and implications for the current economic situation.

In this article, we prove the following results: first, the higher the capital tax, the higher the share of capital owned by the middle income households, thus mitigating inequality in wealth. This result is due to the different saving motives of the two household types and hence the Pasinetti property of our model. Second, there is not one optimal level of capital taxation, but each type of household desires a different level. Middle income households are more favorable to the investment in public capital and desire a higher capital tax rate than high income households. The reason is that middle income households' savings depend only on their labor income. These first two results are reversed for low values of the substitution elasticity between capital and labor. Third, a Pareto-improving capital tax rate exists nevertheless: it can be proved that if public capital is underprovided, both classes are made better off as long as public capital is not unreasonably productive. The results together imply that there is no clear trade-off between equity and efficiency.

The division of households into two types with respect to their saving behavior is highlighted by recent data on wealth ownership. For example Wolff (2010) finds for the U.S. that the wealthiest 5 % of the population own roughly 62 % of total wealth, the next 55 % of the population own close to the remaining 38 %, while the rest of the population owns virtually no wealth. What distinguishes these cohorts? An analysis of the literature yields three major characteristics. First, the saving motive: The wealthiest cohort has been found to save dynastically, while the middle part of the wealth distribution is known to save in a life-cycle fashion (Attanasio, 1994; Browning and Lusardi, 1996; Dynan et al., 2004). Second, the income source: the wealthiest individuals are more likely to be self-employed entrepreneurs and to receive a higher share of capital income (Wolff, 1998; Quadrini, 1997; Diaz-Gimenez et al., 2011; Wolff and Zacharias, 2013).[3] Third, lower income households have higher time preference rates, as shown by Lawrance (1991) and Green et al. (1996). These empirical findings suggest dividing households into three groups with distinctly different saving motives: The wealthiest income cohorts are mainly self-employed and save dynastically, which suggests that they should be modeled as infinitely-lived households who only receive capital income. The cohorts in the middle of the wealth distribution save mainly for their retirement and are thus best represented as overlapping generation agents that have income from both labor and capital. The poorest households do not save, although, depending on the country, they may benefit significantly from public pensions that can be considered to be life-cycle savings (unless in a "pay as you go" system). Depending on this, they may be seen as part of the second group if their public pension claims count as life-cycle savings. If this is not the case, they are excluded from our analysis as the benefits they may derive from public investment are unlikely to affect their saving behavior.

Finally, evidence indicates that public investment is indeed suboptimally low in OECD countries. Building on Aschauer (1989) and Gramlich (1994), Bom and Ligthart (2014) recently conducted a meta-analysis: the output elas-

[3] According to Wolff (1998) 72 percent of the richest 1% were self-employed entrepreneurs for data on U.S. households for 1995.

ticity of public capital is estimated to be between 0.08 and 0.19, with short-run effects and a broad definition of public capital giving the lower bound. The higher estimate is reached for the long run and particularly for transport infrastructure and utilities at the regional level. It is found that public capital is underprovided because its corresponding marginal productivity is (significantly) lower than that of private capital.

The remainder of this article is structured as follows: Section 2 sets out the model. Section 3 first presents its steady-state properties and then contains the proofs of the main results. Further subsections subsequently elucidate the role of the elasticity of substitution between labor and capital as well as the robustness of modeling assumptions about public capital, partially by means of numerical solutions. Section 4 summarizes the results and considers possible extensions.

2 Model

We model a one-good economy in which the government can finance public capital that enhances productivity. The population consists of two classes, high income households and middle income households. The representative middle income household provides labor when its members are young and they save for retirement; the household leaves no bequests. Middle income households are modeled as members of overlapping generations. The representative high income household holds capital and interest is its sole source of income. It has a dynastic saving motive and is thus modeled as an infinitely-lived agent. Both types of agents derive utility from consumption only. Factor markets clear and on the capital market, the supply consists of both high income households' investment and middle income households' savings. There are decreasing returns to scale in private and public capital, but constant returns to scale in private capital and labor. We first describe the household's behavior before detailing the role of the firms and the government.

High income household The high income household owns a capital stock K_t^c and maximizes intertemporal utility given by

$$\sum_{t=0}^{\infty} \frac{1}{(1+\rho_c)^t} \ln(C_t^c), \tag{1}$$

with consumption C_t^c and time preference rate ρ_c. Its budget constraint is

$$K_{t+1}^c - K_t^c = (1-\tau) r_t K_t^c - C_t^c, \tag{2}$$

where r_t is the interest rate and τ is the capital tax.

The initial capital stock is given as $K_1^c = K_0^c$. The high income household respects a transversality condition: $\lim_{t\to\infty}\left(K_t^c \prod_{s=1}^{t-1} \frac{1}{1+r_s}\right) \geq 0$.

Solving the maximization problem yields an Euler equation for this household:

$$\frac{C_{t+1}^c}{C_t^c} = \frac{1+(1-\tau) r_{t+1}}{1+\rho_c}. \tag{3}$$

Middle income household The middle income household lives for two periods, a 'young' (y) and an 'old' (o) stage. It maximizes its lifetime utility, where utility from consumption in the second period is discounted by the time preference rate ρ_w:

$$\ln(C_t^y) + \frac{1}{1+\rho_w}\ln(C_{t+1}^o). \tag{4}$$

In the first period, the middle income household rents its fixed labor to the producing firm, which in turn pays a wage rate w_t. Labor income can either be consumed or saved for the old age:

$$w_t L = S_t + C_t^y. \tag{5}$$

In the second period the middle income household consumes its savings and the interest on them:

$$C_{t+1}^o = (1+(1-\tau)r_{t+1})S_t. \tag{6}$$

Solving the optimization problem subject to the budget constraints leads to an Euler equation for this household:

$$\frac{C_{t+1}^o}{C_t^y} = \frac{1+(1-\tau)\cdot r_{t+1}}{1+\rho_w}. \tag{7}$$

From Equations (5-7) explicit expressions for saving and consumption in the two periods can be derived:

$$S_t = \frac{1}{2+\rho_w} w_t L \tag{8}$$

$$C_t^y = \left(\frac{1+\rho_w}{2+\rho_w}\right) w_t L \tag{9}$$

$$C_{t+1}^o = \left(\frac{1+(1-\tau)r_{t+1}}{2+\rho_w}\right) w_t L. \tag{10}$$

The savings rate is constant, as is standard in discrete OLG models when the utility function is logarithmic. The same is true for the consumption of the young agent, while C_{t+1}^o is still dependent on the interest rate r. Moreover, combining Equations (8-10) implies that C_t^y and C_{t+1}^o depend linearly on savings S.

Production The firm produces output according to a Cobb-Douglas production function. Public capital enhances productivity of both factors:

$$F(K_t, L) = A_t K_t^{\alpha} L^{1-\alpha} \tag{11}$$

with $A_t = P_t^{\beta}$ and $0 < \alpha, \beta < 1$. Throughout we assume $\alpha + \beta < 1$ to exclude the case of long-run or explosive growth.

K_t denotes the sum of the individual capital stocks

$$K_t = K_t^c + S_{t-1} \tag{12}$$

and β is the efficiency factor of public capital P_t. Profit maximization yields the standard rates of return for capital and labor (with δ_K denoting depreciation of private capital):

$$r_t + \delta_K = \frac{\partial F(K_t, L)}{\partial K_t} = \alpha \frac{F(K_t, L)}{K_t} \tag{13}$$

$$w_t = \frac{\partial F(K_t, L)}{\partial L} = (1-\alpha)\frac{F(K_t, L)}{L}. \tag{14}$$

Government The sole function of the government in this model is the provision of public capital. It finances its investments by the capital tax, thus influencing the interest rate. Hence the government's activity is summarized as the change in the stock of public capital (with δ_P denoting its depreciation):

$$P_{t+1} = P_M + (1-\delta_P)P_t + \tau r_t K_t. \tag{15}$$

For the following analytical results, we assume that for non-governmental provision of public capital P_M,

$$P_M = 0. \tag{16}$$

One could object to such a stylized role for public capital in our model that the finding of Pareto-improving public investment relies on very high marginal returns to public capital if public investment approaches zero. We address this concern by confirming numerically (in Subsection 3.3) that even if a minimal provision of public good $P_M > 0$ is present without government intervention our qualitative results do not change.

3 Results

In this section we show that inequality in wealth is mitigated by a capital tax levied for public investment in our model. We also characterize the optimal tax rate for each household type: the middle income household is more favorable to capital taxation and higher public investment than high income household. We point out that low capital tax rates lead to a Pareto improvement, even for the case in which the economy is functioning without any public investment. Figures 1 and 2 below illustrate the main findings. First, we characterize the steady-state and the validity range of the model. We then prove the results just stated for the case of a Cobb-Douglas production function. Further, the model is calibrated and analyzed numerically to determine the optimal tax rates, which cannot be calculated explicitly and to examine the role of potential non-publicly provided existing infrastructure. The numerical analysis also ensures that all critical values for the tax rate are within the validity limit of the two-class model for a wide range of parameters. Finally, we generalize the analysis to a wider range of elasticities of substitution between capital and labor.

3.1 Steady state and validity range

In our model, a version of the Pasinetti Theorem holds. In a model with two types of households, in which one household only receives income from capital – the capitalists –, the Pasinetti Theorem (Pasinetti, 1962) states that the capitalists will determine the steady state interest rate independently of the saving rate of the other household type or the production technology. This is true unless workers saving propensity is so high that the capitalist class ceases to exist (Samuelson and Modigliani, 1966).

In the steady-state of our model we find a similar duality although the saving behavior of our household types is derived from their intertemporal preferences: Either (i) the high income household determines the steady-state interest rate *or* (ii) its capital stock and consumption is zero and the economy is populated only by middle income households. Which regime holds in the steady-state of our model depends on its parameters. In the following analysis, we are exclusively concerned with (the applicable) case (i) (Pasinetti, 1966, 2012). We study the effect of the capital tax on the wealth distribution and call the tax rate at which the high income household's share of capital approaches zero, the limit of case (i), the model's validity limit.

The (unique, non-trivial) steady-state is saddle-point stable and the economy converges to it on a stable path because the high-income household's behavior determines the overall dynamics.[4] The Pasinetti-type behavior of the model in the steady-state can be explained as follows: The high income household's saving behavior determines the interest rate because reducing or increasing its investment is its only means of obtaining its desired long-term distribution of consumption to capital, as is also true in a standard Ramsey model. Any attempt of the middle income household to obtain a different interest rate would thus be balanced by the high income household adjusting its saving rate. Thus the middle income household accepts the interest rate as given. However, its propensity to save (which is independent of the interest rate) influences the amount the high income household saves, who is bound to own the share of total capital net of what the middle-income household saves. Thus the high income household determines the interest rate and with it the total capital stock, but the middle income households determine the capital share owned by the high income household.

[4]A heuristic argument for saddle-point stability is as follows: The dynamics of the model are captured by four Equations for the variables K^c, C^c, P and K, namely Equations (2), (3), (15) and substituting Equation (8) into Equation (12). If it were the case that $K^c = K$, then the model would be a neoclassical growth model with public capital in discrete time. The dynamics of public capital is such that the required stability properties carry over from the neoclassical growth model, where C^c is a "jump variable". What does Equation (12) add to the dynamics of the case $K^c = K$? The only modification is that in Equations (2) and (3) the interest rate is lower than if K^c was the only capital input (the revenue in Equation (8) stays a constant fraction of total output). This implies that there are no qualitative differences in the dynamics, only the steady-state value of K^c is smaller than the Keynes-Ramsey level of capital K by exactly S. This can be shown by transforming the original system by dividing all variables through Y, and noting that $\frac{K}{Y} = \frac{K^c}{Y} - \frac{1-\alpha}{1+\rho_c}$, which reduces the transformed system to three dimensions.

Steady-state values of variables are denoted by a tilde. We first assume that $\widetilde{C^c} > 0$ and then derive its validity range.

It follows from the high income household's Euler Equation (3) that

$$\widetilde{r} = \frac{\rho_c}{(1-\tau)} \tag{17}$$

and from its budget constraint (2) that

$$\widetilde{C^c} = \rho_c \widetilde{K^c}. \tag{18}$$

The steady-state level of public capital is given by:

$$\widetilde{P} = \frac{1}{\delta_P} \tau \widetilde{r} \widetilde{K}. \tag{19}$$

For later reference only, we note that in the steady-state an explicit expression for $\widetilde{K}$ can be obtained. From Equation (13) a steady-state relationship for the production factors $\widetilde{P}$ and $\widetilde{K}$ can be derived:

$$\alpha \widetilde{P}^{\beta} \widetilde{K}^{\alpha-1} L^{1-\alpha} = \frac{\rho_c}{1-\tau} + \delta_k. \tag{20}$$

Rearranging and inserting Equation (19) into Equation (20) gives an explicit expression for $\widetilde{K}$:

$$\widetilde{K}^{(1-\left(\frac{\beta}{1-\alpha}\right))} = L \left(\tau \frac{\rho_c}{\delta_P (1-\tau)} \right)^{\left(\frac{\beta}{1-\alpha}\right)} \left(\frac{\frac{\rho_c}{(1-\tau)} + \delta_k}{\alpha} \right)^{\left(-\frac{1}{1-\alpha}\right)} . \tag{21}$$

The equation shows that K as a function of τ is inverted U-shaped (recalling from above that we exclude the case $\beta > 1 - \alpha$). This is because of two counteracting effects: as τ increases, K initially increases due to the productivity-enhancing effect of public capital (given by the first term of the product). However, it eventually decreases because of the distortionary effect of capital taxation that discourages capital accumulation (represented by the second term above).

Validity limit The above equations are only valid if both agents have positive capital and consumption (see the discussion at the beginning of this section). This is ensured as long as the middle income household's savings are smaller than the total capital, that is

$$\frac{\widetilde{S}}{\widetilde{K}} = \frac{L\widetilde{w}}{(2+\rho_w)\widetilde{K}} = \frac{(1-\alpha)}{\alpha(2+\rho_w)} \left(\frac{\rho_c}{1-\tau} + \delta_k \right) < 1, \tag{22}$$

where Equations (8) , (14) and (20) were used to obtain an expression in terms of parameters only. We use the ratio $\frac{\widetilde{S}}{\widetilde{K}}$ as an indicator for wealth inequality below.

From Equation (22), one can derive that there exists a constant $\tau_{lim} < 1$ for which the steady-state characterization of the agents' behavior is valid in exactly the interval $(0; \tau_{lim})$. The expression of τ_{lim} is:

$$\tau_{lim} = 1 - \rho_c \left(\frac{1-\alpha}{\alpha(2+\rho_w) - \delta_k(1-\alpha)} \right). \tag{23}$$

For the remainder of the analysis, we assume that all critical values of τ are within the interval on which the analysis is valid. We check numerically in Section 3.3 that this assumption holds for a wide range of parameters, including those that best represent developed economies in a stylized way.

We next describe the impact of the capital tax rate on the steady-state behavior.

3.2 The effects of policy

The three main results on the role of fiscal policy in our model are stated as three propositions below: a capital tax levied for public investment decreases inequality in wealth (Proposition 1), middle income households prefer a higher capital tax rate than high income households (Proposition 2) and there exists a Pareto-improving range of capital tax rates (Proposition 3).

Below, inequality and optimality for the two household types are exclusively discussed in terms of their *wealth*: This is sufficient as the *consumption* of the high income household and the old and young middle income household are linear functions of their wealth. For the case of the high income household this is due to Equation (18), for middle income household's consumption it is an immediate consequence of Equations (8-10).

The economic intuition behind the three propositions can be developed as follows: The first result is a consequence of the Pasinetti Theorem. The middle income household's savings are proportional to its wage income, which is proportional to total output. So the share of the middle income household's savings to total capital – the indicator for inequality – depends linearly on the ratio of total output to total capital. By the properties of the neoclassical production function, the output-capital ratio depends positively on the marginal productivity of capital. However, the marginal productivity of capital increases for higher capital taxes, even independently of how the tax revenue is used. This follows from the Pasinetti-behavior of the model – as the interest rate is fixed by the high income household's behavior to be an increasing function of the tax rate (see Equation (17)).

The second result is derived from the fact that total capital depends in a convex way on the capital tax. The relationship is determined by the counteracting effects of the distortion through the capital tax and the beneficial effect of spending it on public investment that also impacts the productivity of private capital positively.[5] The maximal wealth of the middle income household then occurs for a higher capital tax value because his savings depend *only* on his labor income. His labor income depends monotonically on accumulated total private capital, but also on public capital, and the impact of the latter is always positive. The maximal wealth of the high income household occurs for lower capital values as a consequence of the first result: The share of total capital belonging to the middle income household increases faster than total capital the higher the capital tax. Hence the maximal share of the high income house-

[5]This is the same trade-off between efficiency-enhancing public investment and the distortionary capital taxation study by Barro (1990) for a single infinitely-lived agent.

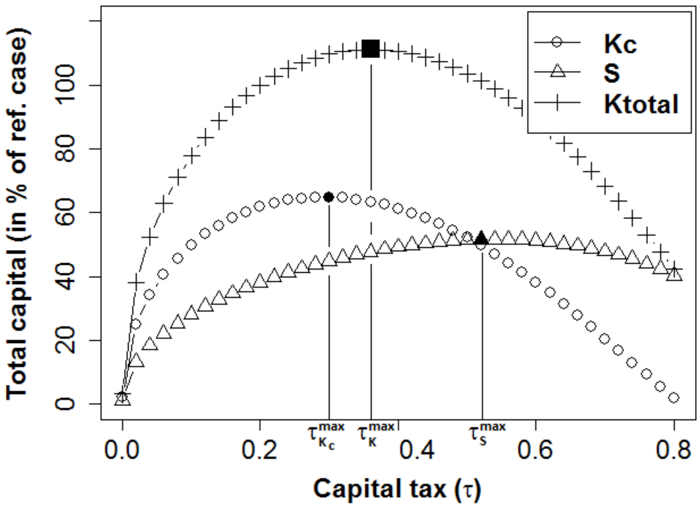

Figure 1: The graph shows the size of the different private capital stocks for capital taxes between 0 and τ_{lim} = 81%. Each capital stock has its maximum for a different value of the capital tax τ. The high income household prefers a lower tax rate than the middle income household, with the capital tax rate that maximizes total capital in between (i.e. $\tau_{K_c}^{max} < \tau_K^{max} < \tau_S^{max}$). Units of capital are normalized to 100% at the reference case of τ = 21%.

hold, must be reached for lower values of the capital tax than the maximal total capital.

The third result is due to the fact that the marginal productivity of public capital is higher than the efficiency loss from distortionary capital taxation, if little public capital is provided. Section 3.3 provides a numerical analysis of the size of this effect: The possibility that some public capital may exist even if there is no government intervention is considered there, but it is found that the level of non-government financed public capital would need to be very high to rule out the possibility of a Pareto improvement.

Figures 1 and 2 summarize the analytic results.

Proposition 1. *Capital taxation (used for public investment) decreases inequality in wealth:* $\frac{\mathrm{d}(\frac{\widetilde{S}}{\widetilde{K}})}{\mathrm{d}\tau} > 0$ *for* $0 < \tau < 1$.

Proof. By Equation (22),

$$\frac{\widetilde{S}}{\widetilde{K}} = \frac{(1-\alpha)}{\alpha(2+\rho_w)}\Big(\frac{\rho_c}{1-\tau} + \delta_k\Big), \tag{24}$$

which is increasing in τ. □

Proposition 2. *Middle income households prefer a higher capital tax rate than high income households: for some threshold rate* τ^*, $\frac{\mathrm{d}\widetilde{S}(\tau)}{\mathrm{d}\tau} > 0$ *for* $0 < \tau < \tau^* + \varepsilon$ *and* $\frac{\mathrm{d}\widetilde{K}^C(\tau)}{\mathrm{d}\tau} < 0$ *for* $1 > \tau > \tau^* - \varepsilon$ *for some* $\varepsilon > 0$.

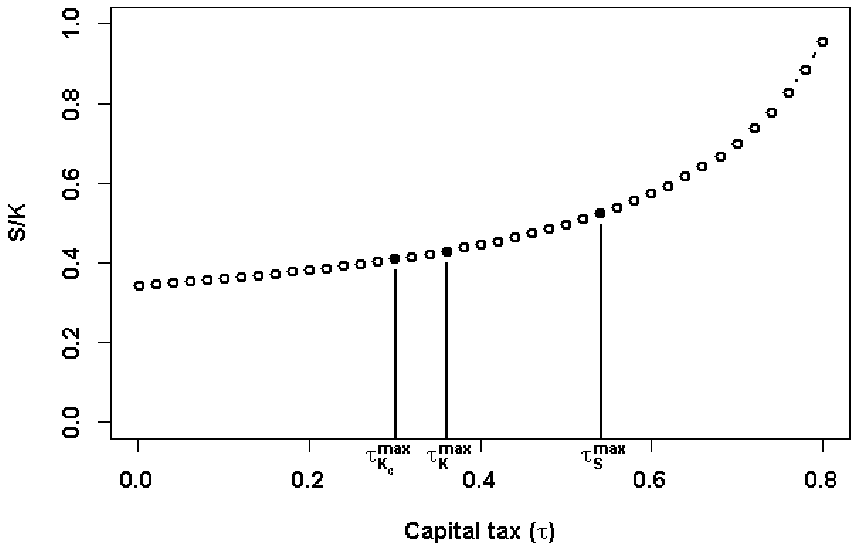

Figure 2: This graph illustrates Proposition 1: the middle income household's share of total capital increases within the validity range of capital taxes between 0 and $\tau_{lim} = 81\%$.

Proof. Let τ^* be the value of τ that maximizes $\widetilde{K}$ as a function of τ on $(0,1)$: it can be calculated that for $\tau^* = \frac{\beta(\rho_c+\delta_k)}{\beta\delta_k+\rho_c}$, $\frac{\mathrm{d}\widetilde{K}(\tau^*)}{\mathrm{d}\tau} = 0$ and shown that $\frac{\mathrm{d}\widetilde{K}(\tau)}{\mathrm{d}\tau} > 0$ for $\tau < \tau^*$ and $\frac{\mathrm{d}\widetilde{K}(\tau)}{\mathrm{d}\tau} < 0$ for $\tau > \tau^*$ (see Supplementary Material, available from the authors upon request).

By combining Equations (8), (14) and (19), we obtain:

$$\widetilde{S} = \frac{1-\alpha}{2+\rho_w} L^{(1-\alpha)} (\frac{\rho_c}{\delta_P})^\beta \left(\frac{\tau}{(1-\tau)}\right)^\beta \widetilde{K}^{\alpha+\beta}.$$

Let $\vartheta = \frac{1-\alpha}{2+\rho_w} L^{(1-\alpha)} (\frac{\rho_c}{\delta_P})^\beta$. Then:

$$\frac{\partial \widetilde{S}}{\partial \tau} = \vartheta \left(\frac{\tau}{1-\tau}\right)^\beta \left[\frac{\beta}{\tau(1-\tau)} + \frac{\alpha+\beta}{\widetilde{K}} \frac{\partial \widetilde{K}}{\partial \tau}\right] \widetilde{K}^{\alpha+\beta}. \quad (25)$$

Hence $\frac{\mathrm{d}S(\tau)}{\mathrm{d}\tau} > 0$ for $0 < \tau < \tau^*$. Also $\frac{\mathrm{d}S(\tau)}{\mathrm{d}\tau}$ is continuous and strictly positive at τ^*, thus positive on $[\tau^*, \tau^* + \varepsilon]$ for some ε.

For a similar argument for $\widetilde{K}^C$, use that

$$\widetilde{K}^C = \widetilde{K}(1 - \frac{\widetilde{S}}{\widetilde{K}}).$$

For $1 > \tau > \tau^*$, $\widetilde{K}^C$ is thus the product of two positive decreasing functions and hence $\frac{\mathrm{d}\widetilde{K}^C(\tau)}{\mathrm{d}\tau} < 0$ there. At τ^*, $\frac{\mathrm{d}\widetilde{K}^C(\tau)}{\mathrm{d}\tau}$ is strictly negative and continuous, hence it is also negative on $[\tau^* - \varepsilon, \tau^*]$. □

Proposition 3. *If* $2\beta < 1-\alpha$, *there exists a Pareto-improving range of capital tax rates* $\frac{\mathrm{d}\widetilde{S}(\tau)}{\mathrm{d}\tau} > 0$, $\frac{\mathrm{d}\widetilde{K}^C(\tau)}{\mathrm{d}\tau} > 0$ *for small* $\tau > 0$.

Proof. From Equation (25), $\frac{\mathrm{d}\widetilde{S}(\tau)}{\mathrm{d}\tau} > 0$ is positive, if $\frac{\mathrm{d}\widetilde{K}(\tau)}{\mathrm{d}\tau} > 0$ is, which is true for all $0 < \tau < \tau^*$.

For $\widetilde{K}^C = \widetilde{K}(1-\frac{\widetilde{S}}{\widetilde{K}})$, it is sufficient to prove that $\lim_{\tau\to 0}\frac{\mathrm{d}\widetilde{K}(\tau)}{\mathrm{d}\tau} > 0$, because

$$\frac{\mathrm{d}\widetilde{K}^C(\tau)}{\mathrm{d}\tau} = \frac{\mathrm{d}\widetilde{K}(\tau)}{\mathrm{d}\tau}(1-\frac{\widetilde{S}}{\widetilde{K}}) + \widetilde{K}\frac{\mathrm{d}}{\mathrm{d}\tau}(1-\frac{S}{K}) \tag{26}$$

and the second summand goes to zero by Equation (24) as well as noting $\lim_{\tau\to 0}\widetilde{K}(\tau)$. It can be shown that

$$\lim_{\tau\to 0}\frac{\mathrm{d}\widetilde{K}(\tau)}{\mathrm{d}\tau} = \begin{cases} \infty & \text{if } 2\beta < 1-\alpha, \\ 0 & \text{if } 2\beta > 1-\alpha. \end{cases} \tag{27}$$

(See the Supplementary Material for the derivation of this claim). □

In the subsequent subsection we verify numerically that the proposition also holds for $\beta > \frac{1}{2}(1-\alpha)$. Empirically, with current estimates of $\beta = 0.2$ and $\alpha = 0.38$ (see page 14 below), the parameter restriction needed here to obtain the analytical result is rather harmless.

3.3 Calibration and robustness with respect to modeling public capital

In the derivation of the three propositions above, we assumed that there is no public capital when there are no taxes levied to finance it ($P_M = 0$). This implies a very high, potentially implausible, marginal productivity of public capital when very little of it is provided. To relax this assumption (needed for analytical tractability above), we present results from a numerical simulation as a robustness check, in which it is assumed that some public capital is provided even without government intervention. We also determine the tax values which cannot be calculated analytically, such as $\tau_{k_c}^{max}$ and τ_s^{max} and list the corresponding values for the distribution of capital between the agents $\frac{S}{K}$. We finally determine the range of each input parameter, within which the validity condition (23) from Section 3.1 holds: outside the validity range, the model is not meaningful because only one class would exist. Table 2 gives the broad range of parameters in which the model is within the validity limit.

The simulation yields that the results of Propositions 1–3 also hold for low to moderate base levels of the public capital stock and illustrates the dependency of optimal tax rates on different public capital productivities β. The results are summed up in Table 1. The corresponding figures show the trajectories of capital K, K^C and S and consumption C (Figure 1) and of capital ownership $\frac{S}{K}$ (Figure 2) for tax rates between 0 and $\tau_{lim} = 0.81$. Values of the stocks displayed are steady-state values without indicating this by a tilde in this subsection.

Parameter	$\tau_{k_c}^{max}$	τ_{k}^{max}	τ_{s}^{max}	$\frac{S}{K}\|\tau_{k_c}^{max}$	$\frac{S}{K}\|\tau_{k}^{max}$	$\frac{S}{K}\|\tau_{S}^{max}$
$\beta^1 = 0$	0	0	0	0.34	0.34	0.34
$\beta^2 = 0.1$	0.16	0.2	0.37	0.37	0.38	0.43
$\beta^3 = 0.2$	0.29	0.36	0.54	0.41	0.43	0.53
$\beta^4 = 0.3$	0.41	0.49	0.64	0.45	0.49	0.62
$\beta^5 = 0.4$	0.52	0.60	0.70	0.51	0.57	0.71
$\beta^6 = 0.5$	0.63	0.69	0.75	0.60	0.68	0.80
$P_M^1 = 0$	0.29	0.36	0.54	0.41	0.43	0.53
$P_M^2 = 4$	0.14	0.24	0.48	0.37	0.39	0.48
$P_M^3 = 8$	0	0.12	0.44	0.34	0.36	0.46
$P_M^4 = 12$	0	0	0.40	0.34	0.34	0.45

Table 1: Numerical results for varied public capital parameters β and P_M. The table displays the capital tax values which maximize the different capital stocks and the ratio of middle income household's savings to total capital for these tax rates. The highlighted rows correspond to the standard calibration, see Table (2) for the other parameter values. Units of P_0 can be converted to units of the private capital stock K as follows: $P_M = 4$ corresponds to $P_M \approx 21\%$ of the steady-state value of K in the baseline calibration.

The non-highlighted rows in Table (1) show the results for varied public capital productivity (β), and varied initial public capital stock (P_M), displaying the change in the numerical values for τ and $\frac{S}{K}$. The main results remain true up to a base level of public capital of $P_M < 8$ (corresponding to $\approx 21\%$ of the steady-state value of K in the baseline calibration). For values $P_M \geq 8$, no Pareto improving policy is possible anymore as further public investment is of no value to the high income household, who prefers a tax rate of 0. For the case of totally unproductive public capital ($\beta = 0$) each agent prefers a tax rate of 0.

A more extensive sensitivity analysis of all parameters of the model shows that for the ranges given in Table (2), the results obtained with the standard calibration are robust. In particular all capital stocks as functions of the capital tax rate reach their maximum within the model's validity limit for a large parameter range.

We calibrated the model so that for a capital tax of 21 %, which is the average capital tax rate in OECD countries between the years 1970 and 2000 (Carey and Rabesona, 2002), the distribution of wealth is as in Wolff (2010): in the U.S. in 2007, 62 % of net worth are held by the top 5 % of the population and almost 38 % of net worth by the next 55 % (while the bottom 40 % hardly possess any net worth). In accordance with findings on significant differences in intertemporal behavior of different income cohorts, the time preference rate of high income households is chosen lower than that of middle income households (Lawrance, 1991; Green et al., 1996).

The capital's share of income α in the production function was chosen to be 0.38. This is in accordance with observations by the OECD, that in 26

OECD countries with reliable data available, the labor share of income was dropping from 66.1 % to 61.7 % from 1990 to 2009 (OECD, 2012). The productivity of public capital β, which is varied above to highlight the robustness of the result, has been estimated to be between 0.08 and 0.19 (Bom and Ligthart, 2014), downwardly correcting higher estimates from earlier studies (Aschauer, 1989; Gramlich, 1994). Labor L, the total working hours, is a fixed factor in our model. Its value scales all variables.[6] We normalize labor $L = 100$ and measure the other variables in this unit to obtain values in a convenient range. Time is measured in steps of 30 years, as middle income households are assumed to live for two periods.

Parameter	Range	Standard value	Corresponding annual value
ρ_c	0.2 – 1.6	0.56	1.5%
ρ_w	3.0 – 8.0	3.98	5.5%
δ_k	0.3 – 1.7	0.7	4%
δ_P	0.3 – 3.1	0.7	4%
β	0.0 – 0.5	0.2	–
P_M	0.0 – 5.0	0.0	–

Table 2: For values inside the range given in column two, the results of the model are economically meaningful: that is, the functions $K(\tau)$ and $S(\tau)$ reach their maximum within the validity range ($0 < \tau < \tau^{lim}$). In the third and fourth column the standard values used in the simulation and the corresponding yearly values are given.

3.4 The role of the elasticity of substitution between capital and labor

The above results are proved for the case of a Cobb-Douglas production function (see Equation 11), implying an elasticity of substitution of capital and labor $\sigma = 1$. In this subsection we relax this assumption to show that the first two results of the article depend on the value of σ. Its empirical value has recently been debated: For instance, a meta-study finds that "the weight of the evidence suggests a value of σ in the range of 0.40 to 0.60" (Chirinko, 2008) with 26 out of 31 studies finding an elasticity below 1 (see also Rognlie, 2014). This would imply that a Cobb-Douglas production function is not a good approximation to reality. In contrast and more recently, Piketty and Saez (2014) and Piketty and Zucman (2015) argue, based on the data on changes in the capital-output ratio collected in Piketty and Zucman (2014), that the elasticity must be higher than 1, however. It is thus vital to understand how the above results change if an elasticity unequal to 1 is considered.

We show below that for elasticities significantly lower than 1, there is an additional effect that determines the level of inequality when public capital

[6]This can be seen from Equations (8), (9) and (10) for the overlapping generations household, from Equation (18) and (21) for the infinitely-lived household and Equation (19) for the public good.

is financed by a capital tax: wealth inequality can also be rising because, for fairly inelastic production factors, a capital tax harms wages more than capital. Below, we first prove that wealth inequality could also *increase* for low elasticities and high capital tax rates or for all capital tax rates and very low elasticities. We subsequently determine numerically for which values this happens: under our standard parametrization (see Subsection 3.3) we find that: (i) inequality is unambiguously decreasing for all values of $\sigma > 0.82$, (ii) it is declining for low tax values and then rising for high tax values for $0.61 < \sigma \leq 0.82$. and (iii) inequality is rising for $\sigma \leq 0.61$.

To obtain these results, let production be given by

$$F(K_t, L) = \left(\alpha K^{\gamma} + (1-\alpha)(AL)^{\gamma}\right)^{\frac{1}{\gamma}} \tag{28}$$

with $A = P^{\beta}, P_M = 0, \gamma < 1, \gamma \neq 0$.

This implies that the elasticity of substitution between capital and labor σ is given by $\sigma = \frac{1}{1-\gamma}$. For this particular CES-production function, an explicit expression for the steady-state capital share of middle-income households $\frac{\widetilde{S}}{\widetilde{K}}$ can still be derived (derivation in the Supplementary Material):

$$\frac{\widetilde{S}}{\widetilde{K}} = \frac{(1-\alpha)}{\alpha(2+\rho_w)}\Big(\frac{\rho_c}{1-\tau} + \delta_k\Big) \times \Big(\frac{1}{(1-\alpha)}\big((\frac{1}{\alpha}(\frac{\rho_c}{1-\tau} + \delta_k))^{\frac{\gamma}{(1-\gamma)}} - \alpha\big)\Big). \tag{29}$$

It can further be shown that the function $\frac{\widetilde{S}}{\widetilde{K}}(\tau)$ has a maximum at:

$$\tau_z = 1 - \frac{\rho_c}{\alpha(\alpha(1-\gamma))^{\frac{1-\gamma}{\gamma}} - \delta_K}. \tag{30}$$

as, for the relevant parameter range, the derivative is positive for $\tau < \tau_z$ and negative for $\tau > \tau_z$ (see Supplementary Material): $\frac{\widetilde{S}}{\widetilde{K}}(\tau)$ has exactly one maximum at τ_z, which is in the economically relevant range of $\tau \in (0,1)$ for specific values of γ only.

This finding gives rise to different cases: If $\tau_z < 0$, or $\tau_z > 1$, wealth inequality will increase or decrease monotonically, respectively. Further, the maximum of the function $\frac{\widetilde{S}}{\widetilde{K}}(\tau)$ matters only for the economic outcome if it is within the validity limit of the model, which is now dependent on γ, as it is determined by $\frac{\widetilde{S}}{\widetilde{K}}(\gamma) < 1$. If the maximum occurs within this range, inequality will decrease for tax values lower than this maximum and increase for tax values higher than it. If instead the maximum occurs for $\tau_z \in (0,1)$ but yields $\frac{\widetilde{S}}{\widetilde{K}}(\tau_z) > 1$, inequality is decreasing for all (meaningful) tax rates. We verify numerically below that all these cases occur and that they monotonically depend on γ.

We next determine the specific cases for γ for which the limiting cases (that is, $\frac{\widetilde{S}}{\widetilde{K}}(\tau_z)$=0 and $\frac{\widetilde{S}}{\widetilde{K}}(\tau_z)$=1) occur. First, set $\tau = 0$ in Equation (30) and solve for γ. This yields:

$$(\frac{1}{\alpha}(\rho_c + \delta_K)) = (\alpha(1-\gamma_0))^{\frac{1-\gamma_0}{\gamma_0}} \tag{31}$$

Second, to find out for which γ, $\frac{\widetilde{S}}{\widetilde{K}}(\tau_z) = 1$, it can be verified that

$$\frac{\widetilde{S}}{\widetilde{K}}(\tau_z) = -\frac{\alpha\gamma_1}{(2+\rho_w)}\big(\alpha(1-\gamma_1)\big)^{\frac{1-\gamma_1}{\gamma_1}}. \tag{32}$$

Setting this equal to 1 leads to:

$$(-\frac{2+\rho_w}{\alpha\gamma_1})^{\frac{\gamma}{1-\gamma_1}} = \alpha(1-\gamma_1). \tag{33}$$

Equations (31) and (33) are not generally solvable analytically for γ. We instead solve these equations numerically: solutions for γ_0 and γ_1 and the corresponding elasticities σ_0 and σ_1, depending on α for robustness, are given in Table 3. Further, Figure 3 illustrates the behavior of $\frac{\widetilde{S}}{\widetilde{K}}(\tau)$ for key values of the elasticity. Table 4 then presents how the preferred tax rates of the two cohorts depend on it. It illustrates that public investment is still Pareto-improving for any elasticity, but that middle income households may prefer lower capital taxes for low elasticities.

α	γ_0	σ_0	γ_1	σ_1
0.2	-1	0.5	- 0.42	0.7
0.3	-0.78	0.56	-0.29	0.78
0.38	-0.645	0.61	-0.22	0.82
0.5	-0.48	0.68	-0.15	0.87
0.6	-0.37	0.73	-0.1	0.91

Table 3: Threshold values of the elasticity given for various values of α. At σ_0 the highest share of middle income households' capital $\widetilde{S}/\widetilde{K}$ occurs for $\tau = 0$ and thus wealth inequality is continuously increasing. At σ_1, $(\widetilde{S}/\widetilde{K})(\tau_z) = 1$ and thus wealth inequality is continuously decreasing over the range of all meaningful tax rates. The highlighted row is the standard calibration.

The numerical results on the role of the elasticity of substitution can thus be summarized as follows: Propositions 1 and 2 above are reversed for elasticities of substitution between capital and labor significantly lower than 1, while Proposition 3 still holds. That is, while financing public investment by capital taxation is still Pareto-improving, inequality may be rising and the middle-income households may be the class which prefers comparatively lower tax rates. There are critical values of the elasticity of substitution σ at which the effects are reversed: For $\sigma > 0.82$ all of the results obtained for the Cobb-Douglas case $\sigma = 1$ still hold. For $\sigma \leq 0.61$, inequality is rising for all tax rates and middle income households prefer a lower capital tax rate than high income households. In between these values, inequality will first decrease for lower tax rates and then increase for higher values. Also in this range, there is a reversal of the class which prefers the higher tax rate. To sum up, in the set-up of the present article, the traditional conclusion that capital taxation is bad for middle and lower classes even if it is spent productively thus holds for low elasticities, despite the Pasinetti property of the model.

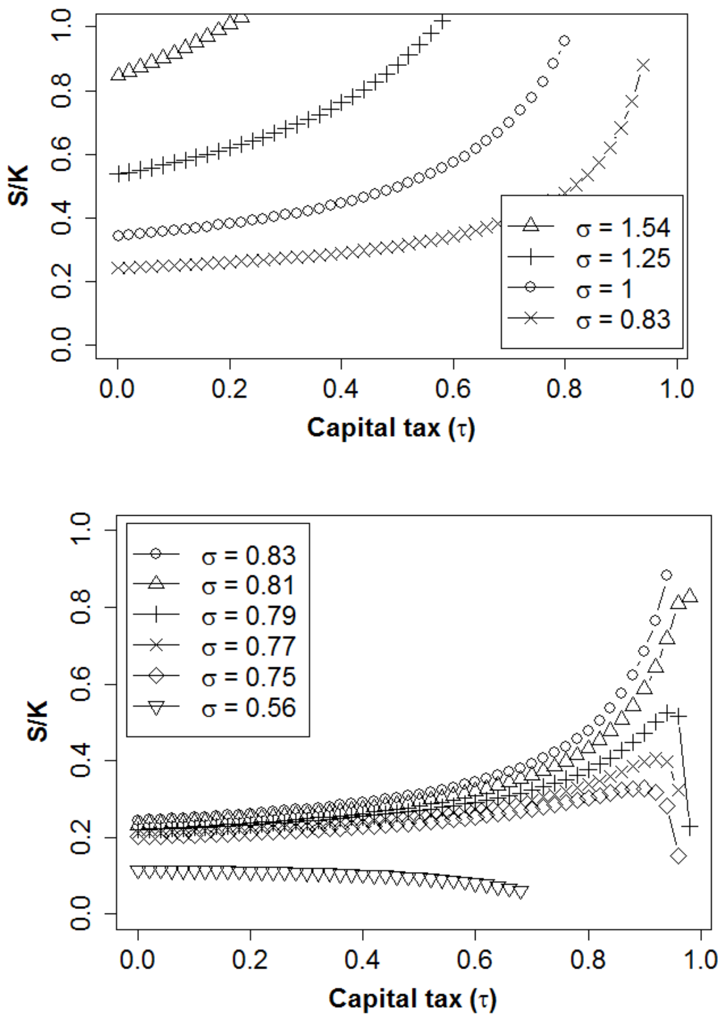

Figure 3: Wealth inequality as a function of the capital tax rate for various elasticties. The upper panel shows selected cases of high elasticities that reproduce the behavior of the Cobb-Douglas function, the lower panel shows cases of low elasticities that illustrate the deviating cases. The middle income households' share of total capital increases monotonically only with high elasticities and decreases monotonically with low elasticites. For middle cases, it increases for low tax rates, but then decreases for high tax rates.

4 Conclusion and outlook

This paper shows that under stylized assumptions about heterogeneous saving behavior of households there is no simple equity-efficiency trade-off. We assume that the heterogeneity in saving behavior can be captured in two types of households: High income households save dynastically and their only source of income is capital interest. Middle income households save a portion of their

γ	σ	$\tau_{k_c}^{max}$	τ_k^{max}	τ_s^{max}	$\frac{S}{K}\vert\tau_{k_c}^{max}$	$\frac{S}{K}\vert\tau_k^{max}$	$\frac{S}{K}\vert\tau_S^{max}$
0.3	1.43	0.08	0.22	N/A	0.76	0.86	N/A
0	1	0.29	0.36	0.54	0.41	0.43	0.53
-0.2	0.83	0.22	0.24	0.34	0.26	0.27	0.28
-0.3	0.77	0.22	0.24	0.32	0.22	0.23	0.23
-0.5	0.67	0.24	0.24	0.26	0.156	0.156	0.166
-0.8	0.56	0.22	0.22	0.20	0.110	0.110	0.111
-3	0.25	0.08	0.08	0.04	0.009	0.009	0.012

Table 4: The table displays the capital tax values which maximize the different capital stocks and the ratio of middle income household's savings to total capital for these tax rates. It extends Table 1 to varied elasticities between capital and labor. The highlighted row corresponds to the original case of a Cobb-Douglas production function. In the first row, middle income households own all capital for $\tau = 0.35$, which is lower than the value at which $\widetilde{S}$ reaches its maximum.

wages for retirement.[7] Under this assumption about households we prove that public investment financed by capital taxation decreases inequality in wealth for any capital tax rate. Middle income households are in favor of a higher capital tax rate than high income households. These results are reversed if the elasticity of substitution between labor and capital is significantly lower than 1. Low capital tax rates constitute a Pareto improvement over the unregulated outcome for any elasticity, however. The results establish that for the assumed type of heterogeneity and a high substitution elasticity, balancing the goals of equity and efficiency is not a single trade-off, but is rather characterized by three stages. While the higher the tax, the more equal the wealth distribution, there are three distinct stages regarding efficiency: (i) Low capital taxes (up to 29 % in our model) increase consumption for both classes, there is no trade-off; (ii) higher capital taxes (up to 54 %) still increase *aggregate* output, but decrease consumption of high income households[8]; (iii) all even higher capital taxes decrease both household types' consumption.

There are two ways in which the analysis of this article could be extended: First, we only characterized potential policy interventions by their effect on inequality and consumption of the two types of households, eschewing the question which outcome is *socially optimal*. While the question of social optimality in overlapping generation models has been widely discussed (Calvo and Obstfeld, 1988; Heijdra, 2009), we do not know of any treatment of the role of a social planner in models with heterogeneous agents in which some households evolve as overlapping generations and some are infinitely-lived.

[7] Depending on the economy the model represents, low income households can be either assumed to behave similarly or it can be assumed that they do not save and are irrelevant to the present analysis of wealth inequality.

[8] One might expect yet another stage: some range in which there is an increase in the income of the middle income households, but a decrease in aggregate output – which would represent the conventional view on equity and efficiency as conflicting goals. Such a stage does not exist in this model because there is no direct transfer to middle income households: When output decreases, both their capital and labor income also decrease.

Several reasonable normative viewpoints are conceivable in such a context. Defending one particular of them will need to answer the following question: With two household types having different time preference rates, does the time preference rate of the social planner only apply to the birth date of subsequent overlapping generations or should the utility of one or both household types also be discounted by this rate?

Second, the model employed in the present analysis relies on a set of very specific assumptions, introduced for isolating the effect of heterogeneous saving behavior and tractability. The results of this article also hold for more general production and utility functions (resulting in non-constant savings rate) and can be extended to other forms of generating fiscal revenue: labor taxation under non-fixed labor supply and consumption taxation. Our companion article confirms numerically that the results of this study hold under these more general assumptions (Klenert et al., 2014).

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Chapter 7

Infrastructure and Inequality: Insights from Incorporating Key Economic Facts about Household Heterogeneity[1]

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Infrastructure and Inequality: Insights from Incorporating Key Economic Facts about Household Heterogeneity

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Abstract

We study the impacts of investment in public capital on equity and efficiency. Taking into account stylized facts on wealth accumulation, we model agent heterogeneity through differences in saving behavior, income source and time preference. We find that in the long run, public investment is Pareto-improving and that it reduces inequality in wealth, welfare and income at the same time, if it is financed by a capital tax. Consumption tax financing is also Pareto-improving but distribution-neutral. Only for labor tax financing, a trade-off between equity and efficiency occurs. Additionally we find that agents differ in their preferred tax rates. The results for capital and labor tax financing are valid for both, the case of decreasing and constant returns to accumulable factors.

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1 Introduction

Public investment in infrastructure has recently received much attention as an attractive option for accomplishing two main objectives of economic policy: Promoting efficiency and growth as well as reducing inequality in wealth. Evidence from the empirical literature suggests that investment in infrastructure can have a decreasing effect on inequality (Calderón and Servén, 2014b), while enhancing growth at the same time (Calderón and Servén, 2014a). The authors admit that for both relationships, little is known about the magnitude of the effects and the underlying mechanisms.

In this article, we confirm that public investment can enhance equality, but show that, in the long run, this depends strongly on the financing mechanism: Capital tax financing can both promote inequality reduction in wealth, welfare and income, and enhance the total level of these variables, when its revenue is spent on public investment. Financing public capital with a consumption tax enhances the efficiency but leaves the level of inequality virtually unchanged. The result on consumption tax financing is, to our knowledge, novel in the literature, as is the result that inequality in wealth and welfare is reduced if public investment is financed by a capital tax. In our analysis, the frequently discussed trade-off between equity and efficiency only occurs for the case of labor tax-financed public investment, which indeed increases inequality in all indicators.

Additionally, the optimal tax level for each household is determined and it is shown that agents differ in their preferred tax rates. This is an extension for the case of heterogeneous households of the trade-off identified by Barro (1990) between providing productive public investment and its distortionary financing. Nevertheless, up to a certain rate of all taxes, total levels of wealth, welfare and income are always enhanced, making all agents better off, and thus constituting a Pareto improvement. Our results rest on an approach of modeling household heterogeneity that is based on stylized facts about income sources, saving behavior and time preferences.

Previous theoretical work comes to ambiguous conclusions on the distributional effects of infrastructure investment: Alesina and Rodrik (1994) show that inequality-reducing public investment always decreases the efficiency. In Glomm and Ravikumar (1994) it is found that in the long run, the impact of public investment in a productivity-enhancing knowledge stock is neutral on the distribution. The authors consequently argue that there is no equity-efficiency trade-off in the long run when it comes to public investment. Chatterjee and Turnovsky (2012) find that labor and consumption tax financing increase income inequality in the long run, while capital tax financing can decrease income inequality. Regarding inequality in wealth and welfare, they show that public investment always enhances inequality in the long run.

We attribute these results to the way heterogeneity is introduced: In the aforementioned studies, agents differ only in their initial capital endowments. Only Alesina and Rodrik (1994) additionally account for differences in income sources.

A model with these types of heterogeneity assumptions however is not able to reproduce the observed wealth distribution (De Nardi, 2004; De Nardi and Yang, 2014). "[F]or many purposes, the representative-consumer model should be abandoned in favor of a model that matches key microeconomic facts" (Carroll, 2000a). Here we comply with this request: By departing from the standard assumptions on heterogeneity our results on consumption tax financing of infrastructure differ from previous studies, as well as the results on capital tax financing, when inequality in wealth and welfare is considered.

In our model we account for the following economic facts:[1] Rich households have been shown to save in a dynastic fashion, while households in the middle-income cohorts exhibit more of a life-cycle saving behavior (Attanasio, 1994; Dynan et al., 2004; Browning and Lusardi, 1996). Neither motive in isolation can reproduce the observed wealth distribution (Carroll, 2000b). The wealthier a household is, the more his income sources shift away from wage income towards business and capital income and the more likely it is that he is self-employed (Quadrini, 1997; Diaz-Gimenez et al., 2011; Wolff, 1998). Lawrance (1991) and Green et al. (1996) demonstrate that wealthier households have lower rates of time preference. Krusell and Smith (1998) show that allowing for different time preference rates is a key factor in reproducing the observed wealth distribution.

We develop a general equilibrium model in which high-income households are characterized by having a dynastic saving behavior and capital income as their only income source. Middle-income households are life-cycle savers, which split their labor income between current consumption and savings for retirement. Low-income households do not save or even dissave and are thus omitted.[2] Our model is related to the model developed in Michl (2009) and can also be seen as an extension of the models described in Stiglitz (1969, 2015) that incorporates optimizing agents. High-income households are modeled as a representative infinitely-lived agent, and the middle-income households are modeled as a representative overlapping-generations agent.[3] The model also allows for agents to differ in their time preference rate. We then calibrate the model to closely match stylized facts of the U.S. economy. In Mattauch et al. (2014) we show analytically, for a basic version of the model, that under these heterogeneity assumptions, capital tax-financed public investment can enhance productivity while reducing inequality. Here we generalize the basic model, in order to assess more channels through which public investment affects the distribution of wealth, welfare and income. We include consumption and labor taxation as revenue-raising mechanisms[4], introduce a labor-leisure choice and model public capital as affecting both production, and utility.[5] Due to our choice of two optimizing agents with distinct saving behavior, our model does not nest the other approaches mentioned before, but instead complements them by accounting for stylized facts on heterogeneous saving behavior.

[1]There are other factors which also influence the wealth distribution but go beyond the scope of this work: For instance the transmission of human capital within families and the existence of public insurance systems (De Nardi and Yang, 2014) as well as differences in rates of return (Guvenen, 2006).

[2]A stylized way to include the low-income households in our model is to include them in the middle-income group. We explore this approach in Appendix E and demonstrate that it does not change our main results significantly.

[3]In order to highlight the underlying mechanisms we choose to only look at two extreme cases of saving behavior: completely altruistic in the case of the infinitely-lived agent, and pure life-cycle in the case of the overlapping generations agent.

[4]We also discuss lump-sum tax and debt-financed public investment in Section 4.1.

[5]Since most public goods such as for example infrastructure and health care affect productivity and utility at the same time, it is crucial to account for both channels to avoid incorrect conclusions. See Chatterjee and Ghosh (2011) for more details.

Our article makes two main contributions. First, we demonstrate that introducing heterogeneity based on empirically observed household behavior has far-reaching consequences: Depending on its financing mechanism (capital, consumption or labor taxation), public investment can either have a decreasing, neutral or increasing impact on inequality. Our second contribution is that our modeling approach yields meaningful results for both endogenous growth and steady-state convergence and our results do not depend on the assumption of homogeneous time preference rates across all agents.

Our concept of heterogeneity, the first contribution, allows us to draw the following conclusions: (i) Higher levels of wealth, welfare and income and a reduced dispersion of these economic variables across households in the long run can be achieved by a policy of capital tax-financed public investment. Regarding income inequality, this result confirms the study by Chatterjee and Turnovsky (2012). It differs from their findings when inequality in wealth or welfare is considered and from the results derived in Alesina and Rodrik (1994) and Glomm and Ravikumar (1994). (ii) Financing public capital through a consumption tax has virtually no effect on the distribution of these variables in the long run.[6] (iii) By determining the tax level that maximizes each household's steady-state utility, we find that households differ in their preferred tax level. As a consequence of this result, there is no single optimal tax rate when financing public investment.

Our second contribution is that our results are very robust with regard to the modeling strategy (see Section 4.2): The results for labor and capital tax financing remain qualitatively the same for endogenous growth as well as for steady-state convergence of the model. All results hold for a wide range of heterogeneous time preference rates across households and the model behavior does not change for homogeneous time preference rates. Furthermore the results remain qualitatively the same if only public capital (as in Barro 1990), or only private capital (as in Romer 1986), is productivity-enhancing.

The remainder of this article is organized as follows: Section 2 outlines the model and its calibration. In Section 3 we characterize the model results for convergence to the steady state. In Section 4.1 we present extensions to the model such as additional financing mechanisms for public investment and the endogenous growth version of the model. In Section 4.2 we analyze the model's robustness to variations in the model assumptions and in parameter values. Section 5 concludes the article.

2 Model

The three most important features of the model are that (i) household heterogeneity is modeled through different saving behavior and different income sources. High-income households whose bequest motive is perfectly altruistic and who rely only on capital income are modeled as a representative infinitely-lived agent. Middle-income households who save according to a life-cycle motive are modeled as a representative overlapping-generations agent with labor and capital income. The households can also differ in their time preference rate. (ii) Public and private capital are combined in a weighted product, the composite externality. By varying the weight parameter we can vary the

[6]Other studies do not consider consumption taxes or find a strong negative effect of consumption tax financing on the distribution in the long run.

role capital plays in production: When the weight parameter of private capital equals 1 the role of private capital is analogous to the case examined by Romer (1986). For a weight parameter of private capital equal to 0, public capital plays the same role as in the model by Barro (1990). (iii) Public capital plays a dual role in our model, enhancing both the value of leisure in the utility function, and total productivity. Since it would not provide us with additional insights we neglect population growth and assume that the size of the representative households does not change. Still we account for the fact that the households are different in size in the calibration of the model (see Section 2.7).

2.1 The firm

The production sector is modeled as a single representative firm. Labor is provided by the middle-income household only, while both households supply capital. Production occurs with a Cobb-Douglas production function:

$$F(K_t, h_t) = \widehat{A} K_t^{\alpha} h_t^{1-\alpha}, \qquad \widehat{A} = A X_{p,t}^{\beta}, \qquad 0 < \alpha, \beta < 1 \tag{1}$$

with $h_t = 1 - l_t$ being the portion of the total time endowment that middle-income households dedicate to work. The remainder of their time is used for leisure l_t.

$X_{p,t} = K_t^{\varepsilon} K_{G,t}^{1-\varepsilon}$, with $0 < \varepsilon < 1$, represents a composite production externality, modeled as a weighted product of private and public capital. The capital entering the production function is the sum of the middle-income households' savings from the last period S_{t-1} and the high-income households' capital $K_{h,t}$:

$$K_t = S_{t-1} + K_{h,t}. \tag{2}$$

Note that for $\alpha + \beta < 1$ the economy converges to a steady state. But if $\alpha + \beta = 1$ and if the ratio of public to private capital remains constant, the model will display endogenous growth behavior. This can be deduced by an equivalent of Equation (1):

$$F(K_t, h_t) = A K_t^{\alpha+\beta} (h_t)^{1-\alpha} \left(\frac{K_{G,t}}{K_t} \right)^{(1-\varepsilon)\beta}.$$

A representative firm maximizes its profit:

$$\Pi_t = F(K_t, h_t) - (r_t + \delta_K) K_t - w_t h_t$$

where r_t and w_t represent the rental rates the firms have to pay to the households for capital and labor and δ_k is the depreciation rate of private capital. The following first-order conditions are obtained:

$$r_t + \delta_K = \frac{\partial F(K_t, h_t)}{\partial K_t} = \alpha A \left(\frac{h_t}{K_t} \right)^{1-\alpha} X_{p,t}^{\beta}, \tag{3}$$

$$w_t = \frac{\partial F(K_t, h_t)}{\partial h_t} = (1-\alpha) A \left(\frac{K_t}{h_t} \right)^{\alpha} X_{p,t}^{\beta}. \tag{4}$$

2.2 The high-income households

The high-income households are modeled as a representative infinitely-lived agent, to which we will also refer as "ILA". She derives utility from either consumption C_t or leisure l_h, which is fixed for this agent. We later show in Section 4.2.2 that the results of this paper are independent from the level of leisure the high-income households receive as long as it remains in a plausible range (see Table 7). Future utility is discounted by the time preference rate ρ_h. Her lifetime utility is given by

$$U = \sum_{t=0}^{t_{\text{final}}} u_t^{\text{ILA}} \cdot \frac{1}{(1+\rho_h)^t}, \tag{5}$$

with

$$u_t^{\text{ILA}} = \left(\frac{1}{b}\right)\left(C_t^a + \theta(X_{u,t} l_h)^a\right)^{\left(\frac{b}{a}\right)},$$

where $a = 1 - \frac{1}{\sigma_{\text{Intra}}}$, with σ_{Intra} being the intratemporal elasticity of substitution between consumption and leisure and $b = 1 - \frac{1}{\sigma_{\text{Inter}}}$, with σ_{Inter} being the intertemporal elasticity of substitution. θ is a weight factor for the leisure term and $X_{u,t} = K_t^{\varphi} K_{G,t}^{1-\varphi}$, with $0 < \varphi < 1$, is the composite externality as in the production sector, but with a different exponent φ.

The ILA chooses her levels of consumption C_t and capital accumulation $K_{h,t}$ to maximize Equation (5) according to her budget constraint:

$$K_{h,t+1} - K_{h,t} = (1-\tau_K) r_t K_{h,t} - (1+\tau_c) C_t, \tag{6}$$

where τ_c represents a consumption and τ_k a capital income tax. The agent takes the returns to capital, r_t, as well as all taxes as given by the firm and the government, respectively. Solving the optimization problem yields the following intertemporal decision equation (details on the derivation can be found in the Appendix B):

$$\frac{\left(\frac{\partial u^{\text{ILA}}}{\partial C_{t-1}}\right)}{\left(\frac{\partial u^{\text{ILA}}}{\partial C_t}\right)} = \frac{1 + (1-\tau_K) r_t}{1+\rho_h}. \tag{7}$$

2.3 The middle-income households

The middle-income households are modeled as a representative Diamond-type overlapping-generations agent, to whom we will also refer as an "OLG" agent and who lives for just two periods. The duration of each period is thirty years. In the first period the agent decides how to divide her fixed time endowment (which is normalized to 1) between work ($h_t = 1 - l_{y,t}$) and leisure ($l_{y,t}$) and how much of her labor income (w_t) she saves for the second period (Equation 9). In the second period, the savings plus the interests are consumed (see Equation 10). We use the subscript "y" to denote the young agent, and "o" to denote the old agent.

The lifetime utility of the OLG agent is given by:

$$u_t^{\text{OLG}} = \frac{1}{b}\left(C_{y,t}^a + \theta(X_{u,t} l_{y,t})^a\right)^{\frac{b}{a}} + \frac{1}{(1+\rho_m)}\frac{1}{b}\left(C_{o,t+1}^a + \theta(X_{u,t+1} l_o)^a\right)^{\frac{b}{a}}, \tag{8}$$

where l_o is the fixed leisure endowment of the old agent. We show in Section 4.2.2 that the level of this parameter does not change the character of the results as long as it remains in a plausible range. The young agent discounts her own old age by a factor ρ_m. The agent chooses $l_{y,t}$ and S_t to maximize her lifetime utility subject to the two budget constraints:

$$(1+\tau_c)C_{y,t} = (1-\tau_w)w_t(1-l_t) - S_t \tag{9}$$

$$(1+\tau_c)C_{o,t+1} = (1+(1-\tau_K)r_{t+1})S_t, \tag{10}$$

where τ_w is a tax on labor. Solving the optimization problem yields the equations of the inter- and intratemporal decision problem (details on the derivation can be found in the Appendix C):

$$\frac{\left(\frac{\partial u_t^{\text{OLG}}}{\partial C_{y,t}}\right)}{\left(\frac{\partial u_t^{\text{OLG}}}{\partial C_{o,t+1}}\right)} = (1+(1-\tau_K)r_{t+1}), \tag{11}$$

$$\frac{\left(\frac{\partial u_t^{\text{OLG}}}{\partial C_{y,t}}\right)}{\left(\frac{\partial u_t^{\text{OLG}}}{\partial l_{y,t}}\right)} = \frac{(1+\tau_c)}{(1-\tau_w)\cdot w_t}. \tag{12}$$

2.4 The government

The government levies taxes to finance investment in a public capital stock K_G. Public capital depreciates at the rate δ_G. The tax level is set exogenously, which means that the government does not optimize. We nevertheless can find the preferred tax rates of each agent by comparing their utilities in different steady states. The government's budget equation is thus

$$K_{G,t+1} - K_{G,t} = \tau_K \cdot r_t \cdot K_t + \tau_w \cdot h_t \cdot w_t + \tau_c \cdot (C_t + C_{y,t} + C_{o,t}) - \delta_G K_{G,t}. \tag{13}$$

Subsequently, the relative merit of financing public investment by the three distinct taxes will be compared.

2.5 Equilibrium and the Pasinetti Paradox

For $\alpha+\beta < 1$ the system converges to a steady state for all parameter combinations evaluated numerically (see Table 1 for the standard calibration and Table 7 for the parameter ranges evaluated in the sensitivity analysis). In the following, variables at their steady-state levels are denoted by a tilde. We see from Equation (7) that at this steady state, the high-income households' rate of pure time preference determines the steady-state interest rate of the aggregate economy $\widetilde{r}$:

$$\frac{1+(1-\tau_K)\widetilde{r}}{1+\rho_h} = 1 \Rightarrow \widetilde{r} = \frac{\rho_h}{(1-\tau_K)}. \tag{14}$$

This entails that in our model a form of the Pasinetti (1962) Paradox occurs. In its original formulation the paradox states that in a Solow model with two types of households, one of them only receiving income through capital interests – the "capitalists" – the steady-state interest rate is solely determined by the "capitalists" savings rate. Similarly, in our framework the long-run interest rate is only determined by the high-income households' time preference rate (and the capital tax rate), independent of the high-income households' income sources. The paradox furthermore implies that when middle-income households increase their saving, the high-income households' saving will be relatively lower. For more details on the Pasinetti Paradox in the context of a simpler version of this model see Mattauch et al. (2014). Note that the Pasinetti Paradox does not occur for endogenous growth, since in that case the interest rate no longer depends only on the time preference rate of the high-income household. The remaining equations that characterize the steady state can be found in Appendix D.

2.6 Measure of distribution

We take the coefficient of variation σ_j with $j \in [\mathrm{K}, \mathrm{U}, \mathrm{Inc}]$ as a measure of dispersion in wealth, welfare and income (see e.g. Ray 1997 for details on inequality measures). The cohorts represented by the two agents are of unequal size (see Chapter 2.7 on calibration), which has to be reflected in the calculation of the coefficient. In the following N is the total size of the households, while N_{m} and N_{h} stand for the size of the middle- and high-income household. The index "*pc*" marks a per capita variable:

$$\sigma_K = \frac{\sqrt{\frac{1}{N}\left(N_{\mathrm{m}}(S_{\mathrm{pc}} - \mu_K)^2 + N_{\mathrm{h}}(K_{h,\mathrm{pc}} - \mu_K)^2\right)}}{\mu_K},$$

with μ_K being the mean:

$$\mu_K = \frac{N_{\mathrm{h}} K_{h,\mathrm{pc}} + N_{\mathrm{m}} S_{\mathrm{pc}}}{N}.$$

2.7 Calibration

We calibrate the model such that in the baseline scenario the high-income households make up five percent of the population, while owning 62 % of total wealth and the middle-income households make up the next 55 % of the population while owning the remaining 38 % of total wealth. These numbers are chosen to match a study on the wealth distribution in the U.S. (Wolff, 2010). The model also roughly complies with the fact that 50–60 % of U.S. net worth accumulation is due to wealth transfers from one generation to another (Gale and Scholz, 1994). In the baseline scenario a minimal stock of public capital is already provided through a consumption tax, which is the least distorting of the three types of taxes.

The above results use the parameterization displayed in Table 1. All values are chosen for timesteps of thirty years.

We use the study by Chatterjee and Turnovsky (2012) as a benchmark for our calibration. Whenever we deviate from their calibration the reason lies in the different type of household heterogeneity used in our model: We model the households such that high-income households have a lower time preference rate than middle-income households, in accordance with Lawrance (1991), Dynan et al. (2004) and Green et al. (1996). Leisure is constant for agents receiving only capital income, which is true for the old middle-income household and the high-income household. These assumptions are analyzed for their robustness in Section 4.2.2. The parameter ranges in which our results remain qualitatively the same is given in Table 7.

Symbol	Parameter	Value	Value (p.a.)
α	Elasticity of capital in production	0.4	–
β	Exponent of public capital in production	0.2	–
δ_G	Depreciation of public capital	0.7	4%
δ_k	Depreciation of private capital	0.7	4%
ε	Private capital share in $X_{p,t}$	0.6	–
φ	Private capital share in $X_{u,t}$	0.6	–
l_h, l_o	Leisure of agents with only capital income	0.71	–
ρ_h	High-inc. households' time preference rate	0.45	1.2%
ρ_m	Middle-inc. households' time preference rate	6	6.7%
σ_{Inter}	Intertemporal elasticity of substitution	0.4	–
σ_{Intra}	Intratemporal elasticity of substitution	0.76	–
θ	Share of leisure in utility function	1.75	–

Table 1: Standard calibration of the model

3 Results

In this section we present the results for the case of decreasing returns to accumulable factors and thus of convergence to the steady state.[7] We assess the impact of our assumption of household heterogeneity on the performance of three revenue-raising mechanisms for public investment: capital income taxation, labor income taxation and consumption taxation. We analyze the impact of these policies on wealth, welfare, income, the distribution of these variables between different households, and on aggregate output. The various policies are evaluated relative to a scenario in which a basic level of public capital is supplied by a 2 % consumption tax.

In the long run, investment in public capital can be inequality-decreasing, distribution-neutral or inequality-increasing, depending on the financing mechanism: Capital taxation as a financing option reduces inequality, while a labor tax increases inequality and consumption taxation has a neutral effect on the distribution.[8] All three financing mechanisms promote efficiency up to a certain tax level.

Furthermore, by comparing the steady-state utility levels for varied tax values, we determine the tax level that maximizes each household's welfare for each financing mechanism.

The short-run effects can, for some financing mechanisms, be adverse: for instance, a labor tax can decrease short-run wealth inequality. A consumption tax is almost distribution-neutral in the long run, but has strong distributional impacts in the short run.

This section is structured as follows: In the first part, Section 3.1, we describe the effect of each financing mechanism for public capital for the case of convergence to a steady state. We discuss the effects of the policy on welfare, capital and income of each agent, as well as on aggregate output and on the dispersion of wealth, welfare and income. Furthermore, each household's

[7]In Section 4.1.1 we also determine the model's behavior for constant returns to accumulable factors and find that most of the results for capital and labor tax financing obtained in the steady state analysis also hold for endogenous growth.

[8]In Section 4.1 we also consider financing of public capital through government bonds and lump-sum taxes.

welfare-maximizing tax level is determined for each financing mechanism. In Section 3.1.4 the different financing mechanisms are compared in terms of their efficiency and equity implications. Finally, in Section 3.2, we describe the effects of the policies on the transitional dynamics.

3.1 Long-run results

In this section we investigate the long-run effects of increased public investment for a broad range of exogenously given capital, labor and consumption tax rates. We write dX to denote the percentage change of the variable X with respect to the baseline scenario of a 2 % consumption tax.

To avoid a discussion on how to compare aggregate utilities of short-lived OLG agents to that of infinitely-lived agents, in this section we only consider steady-state utility levels, to which we will refer as welfare. We denote the tax levels that maximize output and each agent's welfare level as $\tau_Y^{\max}$, $\tau_{u,\mathrm{ILA}}^{\max}$ and $\tau_{u,\mathrm{OLG}}^{\max}$.

3.1.1 Capital tax

When financing an increase in public capital with a tax on capital income, we find the following four effects:

1. Dispersion in wealth, welfare and income decreases for rising τ_k (see Figure 1 on the left).

2. Output is maximized for a 30 % capital tax.

3. For tax rates up to 64 % the policy is Pareto-improving (see Figure 1 on the right).

4. Middle-income households prefer a higher capital tax rate (40%) than high-income households (30%) (see Figure 1 on the right).

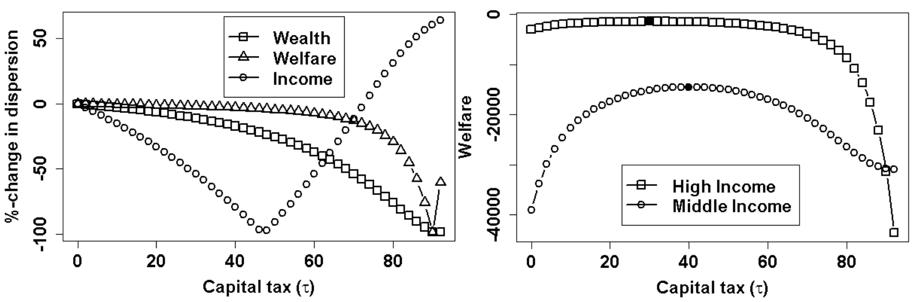

Figure 1: Effects of capital tax-financed public investment on the dispersion of wealth, welfare and income (left side) and on the welfare of both agents (right side). The downward spikes in the left figure reflect the points where middle-income households are equal in a certain variable to high-income households. For even higher tax rates the dispersion increases again, but this time the middle-income households are comparatively better off.

These results are explained as follows: Since the model has the Pasinetti property (see also Section 2.5), a capital tax increases the interest rate in the long run (see Equation 14), high-income households reduce their savings and

	dY(%)	du_{ILA}(%)	du_{OLG} (%)	$d\sigma_K$ (%)	$d\sigma_u$ (%)	$d\sigma_{\text{Inc}}$ (%)
$\tau_Y^{max} = 0.3$	31.5	53.6	61.5	−10.8	−1.8	−54.2
$\tau_{u,\text{ILA}}^{max} = 0.3$	31.5	53.6	61.5	−10.8	−1.8	−54.2
$\tau_{u,\text{OLG}}^{max} = 0.4$	29.1	51.3	63.2	−16.9	−2.9	−79.1

Table 2: Steady-state effects of a capital tax-financed increase in public spending. In the column on the left, the levels of capital tax rates which maximize output and utility of the different agents are given. In the remaining columns the changes in output, welfare and dispersion are given in percent, as compared to the baseline.

thus the income and wealth dispersion decreases. For low capital taxes the public capital stock and with it the composite externality increases, which increases the returns to labor (see Equation 4) and thus further decreases the dispersion in income.[9] These effects combined lead to a larger reduction in consumption and thus in welfare for high-income households than for middle-income households. Thus dispersion in all three variables decreases.[10]

A Pareto improvement exists because of the positive effect of the composite externality on utility and production. Whenever the positive effect of public investment outweighs the negative effect of taxation Pareto improvements are possible.

3.1.2 Labor tax

A labor tax affects only the middle-income households, since the high-income households do not receive any labor income. The effects of labor tax-financed public capital are displayed in Figure 2. Our main findings are:

1. Dispersion in all three variables increases (see Figure 2 on the left).
2. Output is maximized for a labor tax bigger than 92 %.
3. The policy is Pareto-improving up to more than 92% (see Figure 2 on the right).
4. Middle-income households prefer a lower income tax rate (68%) than high-income households (> 92 %) (see Figure 2 on the right).

The intuition behind these results is as follows: A labor tax solely affects the middle-income households' income, which increases the income dispersion strongly. Since the middle-income households' saving decision depends on the level of the wage income, their savings decrease, which causes the wealth dispersion to increase. Labor taxation increases the leisure consumption ratio, which can be seen in Equation (C.5). The increasing composite externality has an opposing effect on the leisure consumption ratio (since $a < 0$, for $\sigma_{Intra} < 1$), which dominates with the current parameterization (specified in Section 2.7), so leisure decreases. The high-income household experiences

[9]Some parts of the tax incidence also fall on the middle-income households through the depressing effect a capital tax can have on the wage rate. In our model this effect is offset by the positive effect of public investment on both factors.

[10]In the case of a capital tax the labor-leisure decision plays only a minor role: Total leisure for the middle-income households is slightly decreased since the value of leisure increases due to an increase in the composite externality. The composite externality increases as long as the increase in public capital offsets the decrease in private capital.

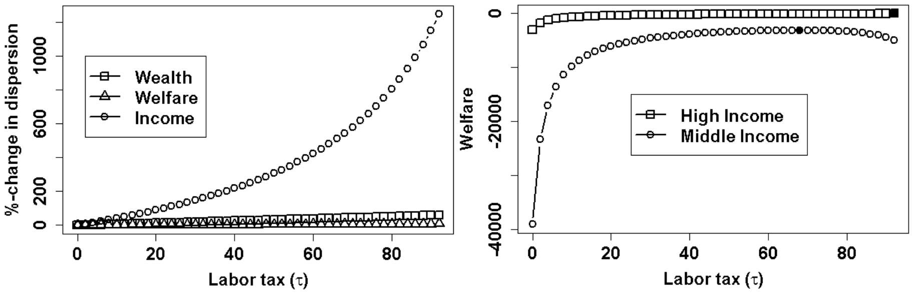

Figure 2: Effects of labor tax-financed public capital on the dispersion of wealth, welfare and income (left graph) and on the welfare of both agents (right graph). The high-income households prefer the maximum wage tax rate, since they do not receive wage income but benefit from public investment. The tax rate preferred by the middle-income households is quite high, which is a consequence of the current calibration, where the benefits of public investment outweigh the negative effects of a labor tax up to a tax rate of 68%.

	dY(%)	du_{ILA}(%)	du_{OLG} (%)	$d\sigma_K$ (%)	$d\sigma_u$ (%)	$d\sigma_{Inc}$ (%)
$\tau_Y^{\max} > 0.92$	443.2	98.4	87.8	59.4	7.9	1245
$\tau_{u,\text{ILA}}^{\max} > 0.92$	443.2	98.4	87.8	59.4	7.9	1245
$\tau_{u,\text{OLG}}^{\max} = 0.68$	276.9	96.7	92.2	43.9	5.3	539.6

Table 3: Steady-state effects of a labor tax-financed increase in public spending. In the column on the left, the levels of labor tax rates which maximize output and utility of the different agents are given. In the remaining columns the changes in output, welfare and dispersion are given in percent, as compared to the baseline. Some values are outside the feasible range of taxes in our model and are thus marked with a "$>$" sign.

a stronger increase in welfare due to its non-taxed income and the leisure-enhancing effect of the composite externality, while the middle-income household has reduced consumption through labor income taxation and reduced leisure, which causes inequality in welfare also to increase. The mechanism for the Pareto improvement described for the capital tax also applies here, it is even stronger since labor taxation decreases the private capital stock less than capital taxation.

3.1.3 Consumption tax

The consumption tax has the broadest tax base of the three taxes, since all agents, the infinitely-lived, the young and the old overlapping-generations agents are taxed. Financing public capital with a consumption tax has the following effects:

1. Output is maximized for a tax rate of $>$ 90 %.

2. The policy is Pareto-improving for consumption taxes up to more than 90 % (see Figure 3 on the right).

3. Both households prefer a consumption tax $>$ 90 % (see Figure 3 on the right).

4. Dispersion in all three variables changes only slightly (see Figure 3 on the left).

	dY(%)	du_{ILA}(%)	du_{OLG} (%)	$d\sigma_K$ (%)	$d\sigma_u$ (%)	$d\sigma_{Inc}$ (%)
$\tau_Y^{\max} > 0.9$	221.3	91.4	92.6	−0.3	−1.4	−0.7
$\tau_{u,\text{ILA}}^{\max} > 0.9$	221.3	91.4	92.6	−0.3	−1.4	−0.7
$\tau_{u,\text{OLG}}^{\max} > 0.9$	221.3	91.4	92.6	−0.3	−1.4	−0.7

Table 4: Steady-state effects of a consumption tax-financed increase in public spending. In the column on the left, the levels of consumption tax rates which maximize output and utility of the different agents are given. In the remaining columns the changes in output, welfare and dispersion are given in percent, as compared to the baseline. Some values are outside the feasible range of taxes in our model and are thus marked with a “>” sign.

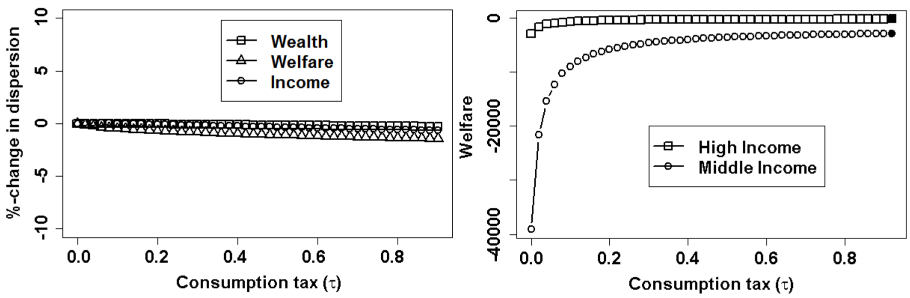

Figure 3: Effects of consumption tax-financed public capital on the dispersion of wealth, welfare and income (left side) and on the welfare of both agents (right side).

Consumption tax-financed public capital acts on the distribution in three ways: (i) The burden of the consumption tax itself falls on all agents (young/old OLG agent and ILA). However, the young OLG agent can react to the tax by reducing its labor supply. For the other agents, leisure is assumed to be constant. A reduction in leisure reduces the leisure component in the utility function but potentially increases income due to more hours worked. (ii) Public capital entering the production affects all agents via increased factor prices (in the short run). In order to maintain the interest rate at its Pasinetti level, the high-income household has to decrease its savings rate relative to that of the middle-income household. The long-run wage rate remains at increased levels in the steady state, which leads to an increased steady-state income and increased saving for the middle-income household. (iii) Public capital entering the utility function increases both agents' utility obtained through leisure. Only the young OLG agent has an endogenous labor-leisure choice and can react to increased public spending. For the standard calibration, an increase in public capital leads to a decrease in leisure (see also equation C.5), which leads to an increased income.

In sum these effects lead to the following outcome: The leisure-reducing effect of public capital (iii) outweighs the direct effect of the consumption tax (i) by far, so the leisure of the young OLG agent decreases. For the standard calibration and the parameter variations given in Table 7, the increase in the high- and the middle-income households' income is almost of the same size, so the resulting difference in the income, wealth and welfare distribution are very small and this policy appears almost distribution-neutral.[11]

Consumption tax financing always increases efficiency up to very high tax rates, since the Pasinetti property of the model ensures high capital accumulation, which has a positive effect on wages. Both agents steady-state income is then increased. Even though the agents' consumption decreases at some point, the utility-enhancing effect of public capital more than compensates for this loss. For that reason all agents prefer consumption tax levels up to 90 %.

3.1.4 Summary: Comparing the different taxes

In our model tax-financed public capital acts on the distribution in three different ways: First, through a change in the policy, the aggregate level of capital changes. Second, agents are affected differently by different tax instruments and finally, agents react to policies by changing their leisure level and their saving behavior. Since all taxes differ in their impact on aggregate capital, in their differential impact on the households and on the labor-leisure choice, each tax has different effects on equity and efficiency.

When comparing the results from Tables 2, 3 and 4, two main differences become apparent:

(i) The dispersion in all variables is strongly reduced by capital tax financing of public spending, while labor tax financing increases it. A consumption tax hardly changes the dispersion in all variables.

(ii) A consumption tax enhances the economy's output the most for a tax rate up to 20 %. Above that threshold a labor tax outperforms the consumption tax, while a capital tax performs worst. We attribute this to the disincentive to accumulate capital caused by the capital tax. For higher tax levels aggregate efficiency is highest for labor taxation, since labor taxation in this setup reduces leisure time thus causing middle-income households to work more and thereby increasing the public capital stock.

(i) and (ii) together suggest an equity-efficiency trade-off between inequality-reducing capital tax financing and efficiency-enhancing consumption tax financing.

By contrast all taxes constitute a Pareto improvement up to a certain tax rate. This result depends crucially on the base level of public capital. When the public capital stock is already at its optimal level, further investment does not enhance both agents' welfare and thus will not lead to a Pareto improvement.

The fact that the optimal tax rates (and with it the optimal levels of infrastructure provision) differ between the households has an important consequence for an optimizing government: Providing infrastructure beyond the optimum of one of the two classes, always involves a trade-off between the welfare of the different classes, at least for capital and labor tax financing. For

[11] Consumption tax financing can be slightly regressive or progressive, conditional on the role leisure plays in the utility function: Depending on the leisure endowment of old middle-income households l_o and the intratemporal elasticity of substitution σ_{Intra}, the change in dispersion varies between $[-4.7\%, 2.3\%]$ for the parameter ranges of these variables examined in the sensitivity analysis (see Table 7). Nevertheless these distributional effects are still more than an order of magnitude smaller when compared to the other financing mechanisms. See Section 4.2.2 for details on the sensitivity analysis.

those financing instruments, further normative assumptions would be necessary to determine the optimal tax level. Those normative assumptions can be avoided, however, if infrastructure is financed via consumption taxes: For this case the trade-off between the middle- and the high-income household disappears since both agents prefer the same tax rate.

3.2 Transitional dynamics

In addition to the steady state analysis we also analyze the transitory dynamics of the system, since it cannot be excluded that short-run distributional effects go into opposite directions compared to long-run effects. We examine the impact of an unanticipated policy shock: When the system is in a steady state, public spending is increased from the baseline level to a level which increases output by 30 %.

We find two main results: (i) Short-term effects opposite to the long-run outcome are found only in the case of labor taxation. Wealth inequality is decreased in the short run, but then converges to a steady state with increased wealth inequality (see Figure 9 in Appendix A). (ii) A consumption tax has almost no long-run effects on the distribution, but strong short-run effects. Wealth inequality is decreased while income inequality is strongly increased in the short run (see Figure 4). The dynamics for a capital tax are displayed in Figure 10, which can be found in Appendix A.

Short-term effects for both labor and consumption can be explained as follows. The slight initial decrease in the wealth distribution can be attributed to the Pasinetti property of the system: A sudden increase in public spending increases both factor prices, thus saving of both agents increases. Since the high-income household wants to force the interest rate back to her time preference rate, she decreases her saving, thus wealth inequality is reduced until the interest rate converges to the high-income household's time preference rate. The strong reaction of the income distribution for a labor and a consumption tax can also be explained by the Pasinetti Paradox: A sudden increase in public spending increases both factor prices. Since the interest rate before the shock is already at its Pasinetti level, the productivity-enhancing shock causes the interest rate to converge to its steady-state levels from above, while the wage rate converges to its steady-state levels from below. This leads to higher capital income than wage income in the short run and thus to increased income inequality. This effect is not visible at the moment of the shock, $t = 0$, since the savings level of the middle-income household has already been determined in the time step preceding the shock.

In the case of capital taxation (see Figure 10, Appendix A) dispersion in all variables converges to its steady-state value without noteworthy short-run effects except for the strong initial decrease in the income dispersion which accrues to the fact that middle-income households determine their savings in the period before the shock.

4 Extensions and robustness

This section consists of two main parts. In Subsection 4.1, we present three extensions to the model: We consider the case of endogenous growth and analyze

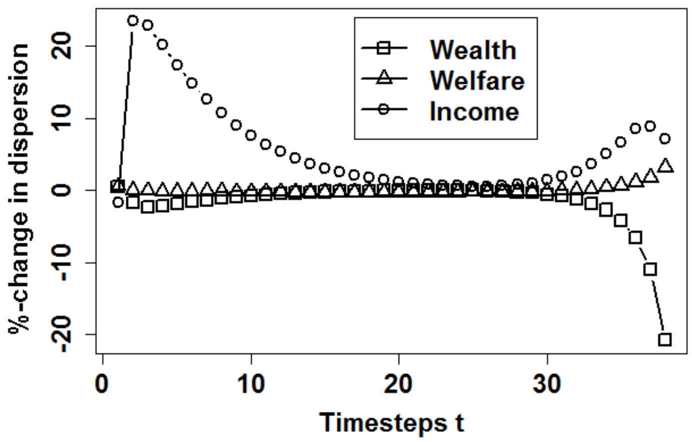

Figure 4: Transitory effects of an unanticipated increase of the consumption tax from the baseline steady state to a new steady state. The new steady state has a 30 % higher output level than the baseline. Even though the long-run effects of consumption tax-financed public investment are almost distribution-neutral, there are strong short-run effects.

the distributional implications when public spending is financed via lump-sum taxes or government debt.

An extensive discussion of the robustness of our findings is presented in Subsection 4.2. We focus on both, the robustness across theories and assumptions (Subsection 4.2.1), as well as on the robustness across parameter values (Subsection 4.2.2).

4.1 Extensions

4.1.1 Endogenous growth analysis

This section summarizes our findings from the endogenous growth version of the model. It can be seen as the analogue to Section 3.1 for the case of endogenous growth. In order to obtain constant instead of diminishing returns in accumulable factors, we set $\beta = 1 - \alpha$ (see Section 2.1). For this parameter choice the economy converges to a steady growth path on which consumption and capital for both agents, as well as output, public capital and the composite externality grow at the same rate g.

The differences to the steady state analysis are mainly driven by the fact that the Pasinetti Paradox does not occur in the case of endogenous growth (for more details on the Pasinetti Paradox see Section 2.5). Along the growth path we consider changes in the growth rate rather than in output as an indicator of efficiency.

We obtain three main results: (i) Similar to the steady state analysis, consumption tax-financed public investment is the most efficient policy, at least up to 20%, followed by a labor tax financing. Capital tax financing is the least growth-enhancing policy (see Figure 5). (ii) Capital and labor taxation yield results very similar to the steady state analysis, except for slight variations in the case of low tax rates, which are explained below. (iii) The results for a consumption tax deviate from the steady-state results (Figure 6 c). This behavior is analyzed in detail below.

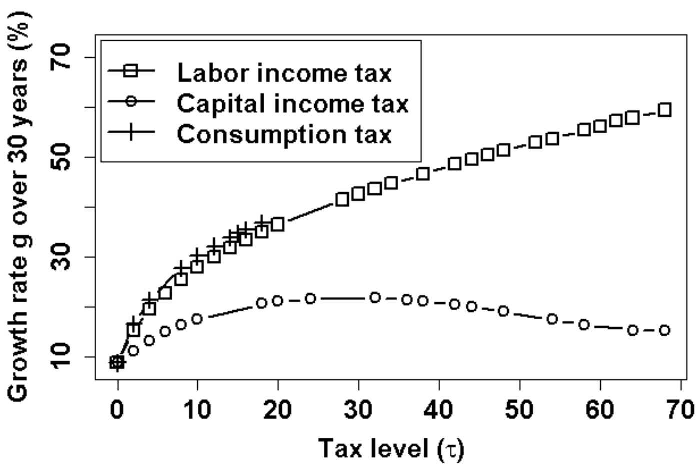

Figure 5: Effects of public investment on the steady-state growth rate: A consumption tax is the most growth-enhancing way to finance infrastructure investment, directly followed by a labor tax. A capital-tax is the least growth-enhancing policy instrument. Growth reaches its maximum already at a 30 % capital tax, while the other taxes enhance growth up to their maximum levels.

For labor tax rates up to 20 %, income and welfare dispersion increase as in the steady state analysis (see Figure 6 b). But wealth dispersion slightly decreases, an effect which we only obtain because public capital is very productive in the case of endogenous growth. This outcome can be explained by examining the effects of an increase in labor tax-financed infrastructure spending:

(1) Leisure (l_t) decreases because the quality of public capital is enhanced, while total capital increases. This leads to a decreased interest rate and an increased wage rate (see Equations 3 and 4).

(2) Public capital and thus the composite externality is increased, which enhances both the interest and the wage rate.[12]

(3) Combining both (1) and (2) leads to increases in both factor prices since effect (2) outweighs effect (1) for the interest rate. However it also leads to an increased ratio of wage rate to interest rate due to effect (1).

For small tax rates the productivity-enhancing effect of public capital more than offsets the negative effect of taxation and due to (3), the middle-income households' savings are affected more strongly by labor tax-financed public spending than the high-income households' savings.[13]

[12]An effect unobserved in the case without endogenous growth, in which the interest rate always stays at the level determined by the high-income households' time preference rate due to Pasinetti's Paradox.

[13]This effect is not visible in the income dispersion since the labor component of the middle-income households' income benefits less from labor tax-financed infrastructure spending than

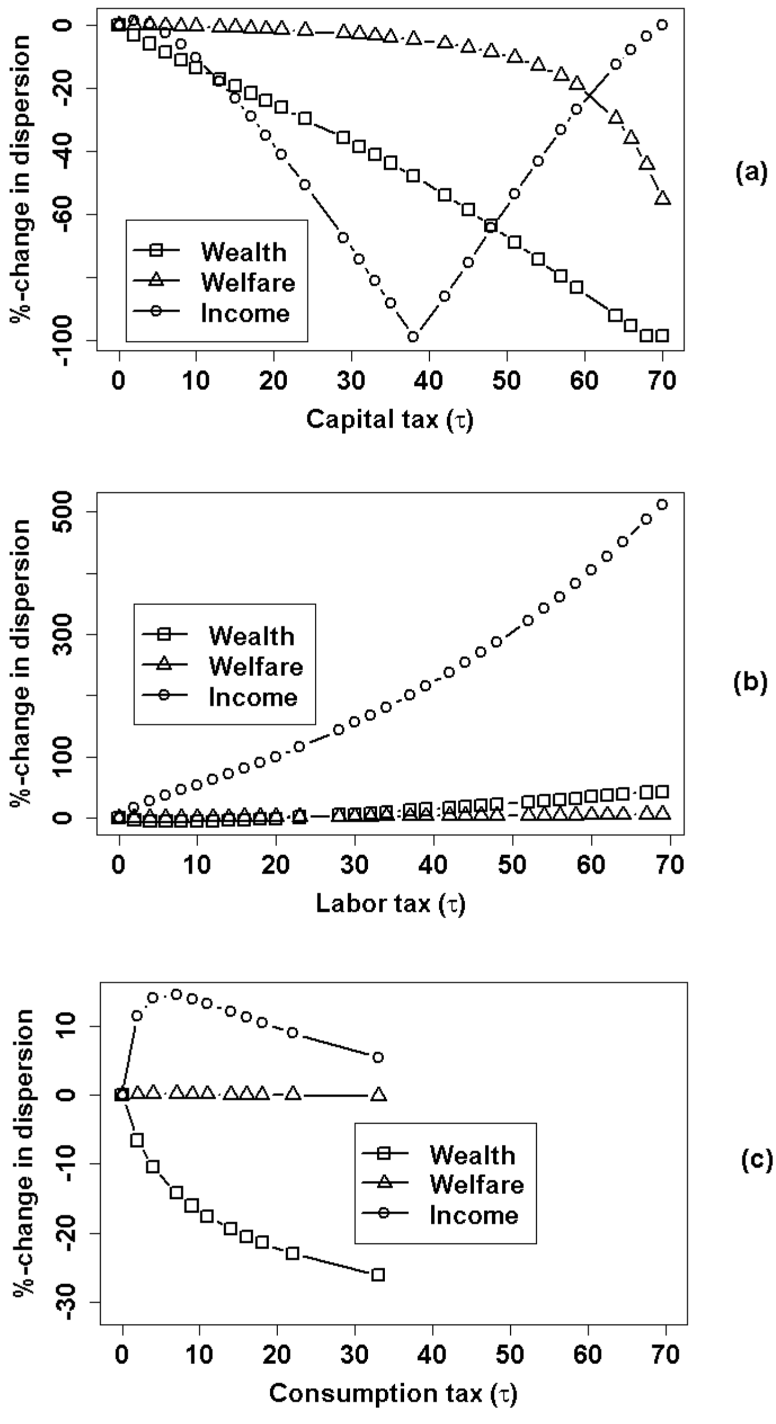

Figure 6: Effects of infrastructure financing through (a) capital, (b) labor and (c) consumption taxation on the dispersion of wealth, welfare and income for the case of endogenous growth. The downward spikes in Figure (a) reflect the points where middle-income households are equal in a certain variable to high-income households. For even higher tax rates the dispersion increases again, but this time the middle-income households are better off.

For tax rates below 8 %, effect (2) is also at work in the case of a capital tax, which leads to a small increase in income dispersion (see Figure 6 a). From 8 % on the negative effect of capital taxation outweighs this effect. Both of these effects are quite small for our current parameterization.

Consumption tax-financed infrastructure investment leads to a decreased wealth dispersion, but to an increase in income dispersion for taxes up to 10 %. For higher consumption taxes the income dispersion declines as well. There is hardly any effect on welfare dispersion (Figure 6 c).

The mechanisms of an increase in the consumption tax are the same as for a labor tax, so (1) to (3) still hold. But the negative effect of labor taxation on the middle-income households' income is missing, so for tax rates above 10 %, the middle-income households' income is affected more strongly by infrastructure spending than the high-income households' income and thus income dispersion declines from this point on. For tax values below 10 % the strong productivity-enhancing effect of infrastructure investment causes the capital component of the income to increase more strongly than the labor component, which leads to an increase in the income dispersion.

4.1.2 Lump-sum tax financing

A lump-sum tax provides a meaningful benchmark, but it is not a feasible policy instrument in real-world politics. We introduce the case of lump-sum tax-financed public spending to exclude the distorting effects the other taxes have on the economy. This allows to decouple to the distributional effect of public spending from that of its financing.[14]

When the model converges to a steady state we find that lump-sum taxes distort the economy far less than the other tax mechanisms and therefore lead to the highest output levels (770 %, see Table 5).

	dY(%)	du_{ILA}(%)	du_{OLG} (%)	$d\sigma_K$ (%)	$d\sigma_u$ (%)	$d\sigma_{Inc}$ (%)
$\tau_Y^{max} = 0.82$	770	92.8	93.1	−50.7	−0.3	−90.1
$\tau_{u,ILA}^{max} = 0.58$	528.7	95.6	95.0	−36.9	1.2	−81.0
$\tau_{u,OLG}^{max} = 0.56$	509.9	95.6	95.0	−35.8	1.1	−78.6

Table 5: Steady-state effects of a lump-sum tax-financed increase in public spending. In the column on the left, the levels of lump-sum tax rates which maximize output and utility of the different agents are given. The remaining columns display the changes in output, welfare and dispersion in percent, as compared to the baseline. The lump-sum tax is given in percentage of output.

Concerning the distributional effects in the steady state (see Figure 7, left), welfare inequality is slightly increased while wealth and income inequality decrease. Those distributional effects are a consequence of the Pasinetti property of the model: The interest rate remains at the level of the high-income

the capital component due to the negative impact of the labor tax. The overall effect is that the middle-income households' income benefits less from infrastructure spending than the high-income households' income.

[14]We implement the lump-sum tax such that each household pays the same amount in per capita terms. Since high-income households only make up 5 % of the population, middle-income households make up 55 % and low-income households are not included, high-income households end up paying 1/12 of the lump-sum tax, while middle-income households pay for the remaining 11/12.

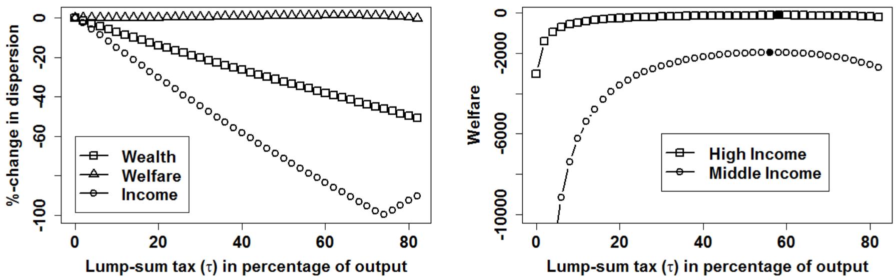

Figure 7: Effects of lump-sum tax-financed public investment on the dispersion of wealth, welfare and income (left side) and on the welfare of both agents (right side).

household's time preference rate, even though increased public spending and increased working hours have an increasing effect on both factor prices. The only control variable for the high-income household to maintain the interest rate at its Pasinetti level is its saving, which is thus reduced compared to the middle-income household's saving, which leads to decreased wealth and income inequality. Welfare inequality remains almost unchanged, since the middle-income household's welfare increase that occurs through increased income, is offset by its leisure reduction. As in the case of capital and labor tax financing, there is a difference between the tax rates that maximize output and those that maximize welfare of the different households (see Table 5 and Figure 7, right).

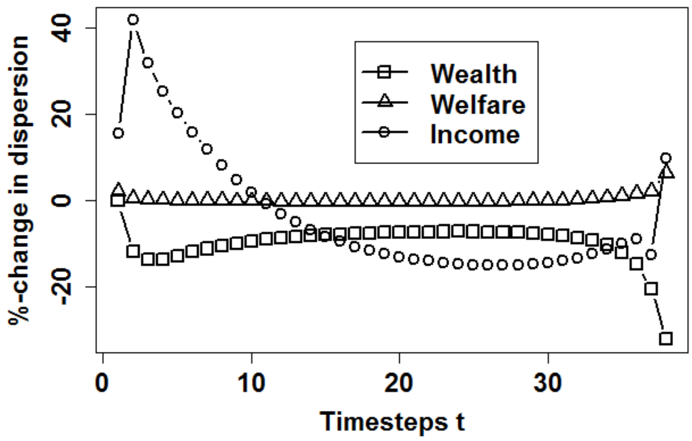

Figure 8: Transitory effects of an unanticipated increase of the lump-sum tax from the baseline steady state to a new steady state (in which the lump-sum tax amounts to 10 % of the economy's output).

The distributional effects in the transition to the steady state are displayed in Figure 8. While welfare inequality converges smoothly to its steady-state levels, inequality in income and wealth converge less smoothly: Through the initial productivity-enhancing effect of public capital both factor prices increase, which causes the high-income household's income to rise faster than that of the middle-income household, so income inequality is increased in the first timesteps after the shock. In the following timesteps the interest rate converges to its steady-state rate from above, while the wage rate converges to its steady-state level from below. This causes income inequality to decrease, eventually below its initial level. Wealth inequality decreases strongly in the beginning, since the high-income household's only reaction to high interest rates is to decrease its saving relative to the saving of the middle-income household. With the interest rate returning to its Pasinetti level, the wealth distribution converges to its steady-state level from below. Figure 8 considers an increase in the lump-sum tax from 0 to 10% of output. [15]

4.1.3 Public debt

Since government debt is frequently observed as a means for financing public investment in the real world, we summarize the results of an analyis on the distributional effects of debt as a financing mechanism in this section. We conduct an experiment in which we compare the transitional dynamics of consumption tax-financed public spending with the dynamics when public spending is financed via debt, with a consumption tax used for debt servicing. The detailed analysis is available from the authors upon request.

We find that, apart from a strong progressive effect in the first period after the shock, debt financing does not smooth the distributional curves in the transition to the steady state, it even increases short-run variations. Furthermore, if debt is serviced by a consumption tax, long-run inequality is increased. This result hints at the fact that government bonds have a regressive effect, since we have shown in Section 3.1.3 that financing public spending via consumption taxes is distribution-neutral.

We limit ourselves to the reduced experiment described above, since a full-scale analysis of the equity and efficiency effects of government debt with all the model variations observed in Sections 3 and 4.1.1 would go beyond of the scope of this article.[16]

4.2 Robustness

In this subsection we give further insights on the robustness of our results across theories and model assumptions (Subsection 4.2.1) and we summarize the results of an extensive sensitivity analysis (Subsection 4.2.2).

4.2.1 Theoretical robustness

Our model is distinguished from previous work on the subject by assuming more sources of household heterogeneity: heterogeneous saving behavior (dy-

[15]Looking at a tax that increases output by 30%, as we did for capital, labor and consumption taxation in Section 3.2, only leads to a lump-sum tax of 0.0162% of output. For this tax level the distributional effects are not pronounced enough for displaying them graphically. We thus decided to rather fix the total amount of revenue to be raised and to set the lump-sum tax accordingly.

[16]Further interesting experiments would include relaxing the assumption that both middle- and high-income households have access to the same type of government bonds, or the assumption that debt is serviced after one period, investigating other channels for debt servicing, or considering the case of externally held debt (to exclude the capital accumulation-reducing effect of internally held debt).

nastic vs. life cycle), income sources and heterogeneous time preference rates. Although we believe that all these sources of heterogeneity are necessary to explain observed wealth disparities in industrialized countries (De Nardi, 2004; De Nardi and Yang, 2014), one may conclude that, from a theoretical point of view, this limits the scope of our analysis.

However, the major advantage of the structure of our model, combining an infinitely-lived with an overlapping generations agent, is great robustness in crucial modeling assumptions: While our main results are formulated in a neoclassical growth framework, we demonstrate in Section 4.1.1 that the results for labor and capital tax financing also hold for the case of endogenous growth. Furthermore, our analysis is conducted with heterogeneous time preference rates across agents. They seem to be the empirically realistic case (Lawrance, 1991; Green et al., 1996), but have not been considered in previous work on the subject. Identical time preference rates are just a special case, leading to no particular change in behavior in our model (in Section 4.2.2 we present the results of a numerical experiment on this).

Previous work on modeling household heterogeneity in a dynamic setting that focused on initial endowments only, either chose endogenous growth models, i.e. constant returns to accumulable factors, or limited itself to the analysis of the transition to the steady state. The reason is that in the neoclassical growth model (i.e. decreasing returns to accumulable factors) with heterogeneity only in initial endowments and no further assumptions, the long-run distribution is indeterminate, in the sense that every possible distribution of capital is consistent with the steady state (Becker, 2006).[17] Heterogeneous time preference rates in the neoclassical model however lead to a steady state in which the agent with the lowest discount rate owns all capital in the long-run, while less patient agents immediately consume all of their income and thus lead a "working poor" existence (Becker, 1980, 2006). We are not aware of any work that looks at the case of heterogeneous time preference rates in an endogenous growth model (Table 6 illustrates this discussion).

	Endogenous growth	Neoclassical growth
Identical ρ	Chatterjee and Turnovsky (2012) Alesina and Rodrik (1994)	Glomm and Ravikumar (1994) Section 4.2.2
Heterogeneous ρ	Section 4.1.1	Section 3.1

Table 6: Selected literature on the equity and efficiency effects of public investment, with and without heterogeneity in the time preference rate ρ across households in neoclassical and endogenous growth models. Our contributions are indicated by the section numbers of this article. Note that in our model it is technically possible to also contribute to the first quadrant of this table (endogenous growth with identical time preference rates), but we do not see the added value of this experiment.

To summarize, our model is both narrower (in the sense that more assumption on heterogeneity are made) and broader (in the sense of more robustness

[17]Chatterjee (1994) points out that in the case of imperfect capital markets, in which each household invests in its privately owned firm, the distribution in the long run would be completely equal, since capital poor agents would get higher rates of return on capital. This is also the mechanism behind the long-run outcome in Glomm and Ravikumar (1994). Chatterjee (1994) furthermore demonstrates that assuming perfect capital markets can also lead to a determinate steady-state distribution, if agents are assumed to have a minimum level of consumption (which leads to different savings rates across agents).

across growth theories) depending on one's viewpoint, when compared to previous work. Whether one considers this an improvement depends on whether one views the further assumptions on household heterogeneity as increasing realism (while maintaining modeling flexibility) or as needlessly sacrificing parsimony. In any case, the previous discussion shows that our model does not nest previous models but provides an independent alternative to exploring the impact of household heterogeneity on the effects of public investment.

4.2.2 Robustness across parameters

We find that the character of our results from Section 3.1 does not change in all of the scenarios described in Table 7. Furthermore, the results for capital and labor tax financing are very robust and are valid even beyond the parameter ranges given in this table. A detailed sensitivity analysis on which Table 7 is based is available from the authors upon request. The three most important results can be summed up as follows:

(i) For $\beta = 0$ a Pareto improvement is still possible even though the composite externality is only utility-enhancing. (ii) In the case of $\theta = 0$, in which the composite externality is only production-enhancing we also have the possibility of Pareto-improving policies. This means that our results do not depend on whether the composite externality affects production or utility, as long as it affects one of them positively. (iii) The results are robust in ε and φ which means that they also hold with a Romer (1986) and a Barro (1990) type of representation of the roles of public and private capital. Thus our assumption about household heterogeneity is the main driver of all observed effects.

Symbol	Parameter	Range
β	Exponent of $X_{p,t}$ in production	$[0, 0.4]$
(ε, φ)	Exponents in composite externality	$(0,1), (0.6,0.6), (1,0)$
l_h	Leisure high-income household	$[0,1]$
l_o	Leisure old middle-income household	$[0.6,1]$
$\rho_h = \rho_m$	Equal time preference rates (yearly)	1.2%
θ	Share of leisure in utility function	$[0.0, 3.5]$
σ_{Intra}	Intratemporal elasticity of substitution	$[0.6, 1.2]$
Standard CES utility $u_t = \left(\frac{1}{b}\right)\left((1-\theta)C_t^a + \theta(X_{u,t}l_t)^a\right)^{\left(\frac{b}{a}\right)}$, $\theta = 0.5$		

Table 7: Sensitivity analysis of the model. The character of the results does not change for these parameter variations.

5 Conclusion

The present article studies the effect of public investment on equity and efficiency. We introduce a concept of household heterogeneity that is based on stylized facts about empirical saving behavior and differences in income sources and time preference. We make two main contributions:

First, we find that in the long run, capital tax-financed public investment can enhance the total levels of wealth, welfare and income up to a certain tax rate and, at the same time, reduces inequality in these economic variables. Consumption tax financing also enhances productivity but leaves inequality in wealth, welfare and income virtually unaffected in the long run. This demonstrates that for these two financing mechanisms there is a tax range in which no equity-efficiency trade-off exists for the financing of public capital. We only find such a trade-off in case of labor tax financing since taxing labor income increases inequality but enhances the total levels of wealth, welfare and income (up to a certain level). We also compute the optimal tax levels for all three financing possibilities and find that agents differ in their preferred level. In sum, these results show that our assumptions about household heterogeneity lead to conclusions on the equity impacts of public investment that partially confirm and partially differ from previous work on the subject: Differences concern the case of consumption tax financing (for all inequality indicators) and capital tax financing, when wealth and welfare are considered as inequality indicators.

Second, the type of model examined in this article yields very robust results with regard to the modeling assumptions. The results neither depend on the assumption of homogeneous time preference rates across households nor on the assumption of endogenous growth.[18] Concerning the role of private and public capital in production, the results remain qualitatively the same if a Romer (1986), a Barro (1990) or an intermediate formulation is chosen, and they do not dependent on the dual role private and public capital play in productivity and utility, as long as it affects one of the factors positively.

We find that the equity and efficiency impacts of public investment are highly sensitive to the way heterogeneity is modeled. In the light of these findings, we agree with Diamond and Saez (2011), who, in a recent article on the policy relevance of modeling results, argue that "we should view with suspicion results that depend critically on very strong homogeneity or rationality assumptions." We thus conclude that a proper analysis of the equity and efficiency effects of public policies should take into account differences in household characteristics which are beyond initial endowments.

The modeling presented in this article could be extended to assess additional questions of public policy, for example climate policy, health spending or pension systems. A further refinement of the model structure could be to include mobility between income classes, the transmission of human capital within families and the existence of public insurance schemes. Optimal policies could be derived by introducing an optimizing government with different welfare functions, in order to evaluate the implications of different welfare norms on equity and efficiency of the economy.

Acknowledgments

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[18] Only the results for consumption tax financing are sensitive to the assumption of endogenous growth.

Appendices

A Transitional dynamics for a labor and a consumption tax

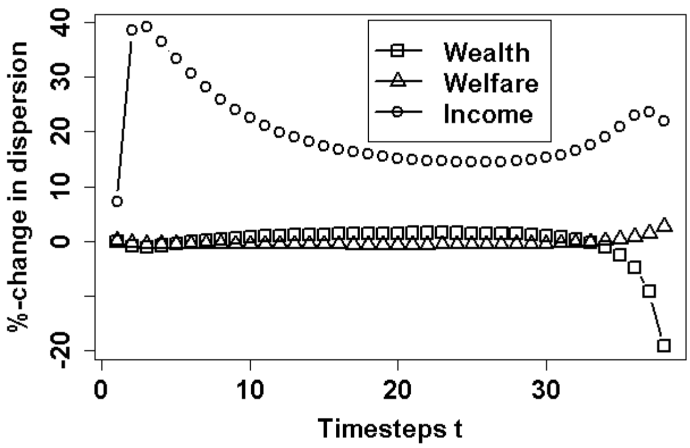

Figure 9: Transitory effects of an unanticipated increase of the labor tax from the baseline steady state to a new steady state. The new steady state has a 30 % higher output level than the baseline. Even though the long-term effects of labor tax-financed public investment is inequality-increasing, it decreases short-term wealth inequality.

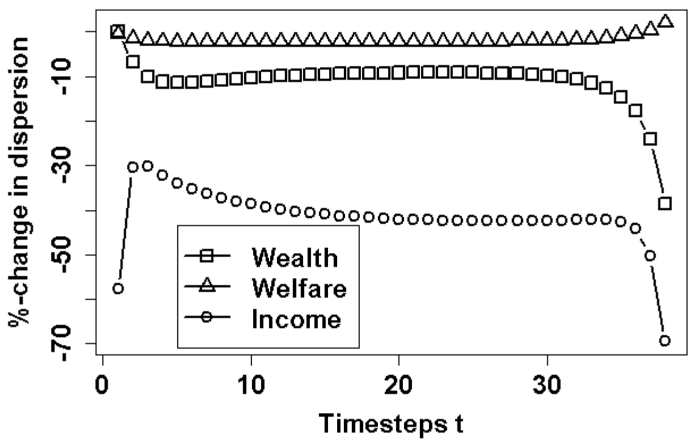

Figure 10: Transitory effects of an unanticipated increase of the capital tax from the baseline steady state to a new steady state. The new steady state has a 30 % higher output level than the baseline. For the case of capital tax financing, the model approximates the steady state monotonically, except for a strong first period decrease in income inequality, which can be attributed to the fact that middle-income households choose their saving level in the period before the shock, whilst the high-income households choose their level of saving already anticipating the shock.

B First-order conditions high-income households

The Lagrangian of the optimization problem of the high-income household can be written as:

$$\mathscr{L} = \sum_{t=0}^{t_{\text{final}}} u_t^{\text{ILA}} \cdot \frac{1}{(1+\rho_h)^t} + \lambda_t \left((1 + (1-\tau_K) r_t) K_{h,t} + (1+\tau_c) C_t - K_{h,t+1} \right).$$

The first-order conditions of the high-income household then are:

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

$$\frac{\partial u_t^{\text{ILA}}}{\partial C_t} \cdot \frac{1}{(1+\rho_h)^t} = \lambda_t (1+\tau_c). \tag{B.2}$$

Calculating the derivations in Equation (7) yields the explicit Euler equation:

$$\frac{\left(C_{t-1}^a + \theta (X_{u,t-1} l_h)^a\right)^{\left(\frac{b}{a}-1\right)}}{\left(C_t^a + \theta (X_{u,t} l_h)^a\right)^{\left(\frac{b}{a}-1\right)}} \left(\frac{C_t}{C_{t-1}}\right)^{(1-a)} = \frac{1 + (1-\tau_K) r_t}{1+\rho_h} \tag{B.3}$$

C First-order conditions middle-income households

The Lagrangian of the optimization problem of the middle-income household can be written as:

$$\mathscr{L} = u_t^{\text{OLG}} - \kappa_t \cdot \left(C_{y,t}(1+\tau_c) + \frac{(1+\tau_c) C_{o,t+1}}{(1 + (1-\tau_K) r_{t+1})} - (1-\tau_w) w_t (1 - l_t) \right).$$

The first-order conditions are calculated as:

$$\kappa_t = \frac{\partial u_t^{\text{OLG}}}{\partial C_{y,t}} \frac{1}{(1+\tau_c)} \tag{C.1}$$

$$\kappa_t = \frac{\partial u_t^{\text{OLG}}}{\partial C_{o,t+1}} \frac{(1 + (1-\tau_K) r_{t+1})}{(1+\tau_c)} \tag{C.2}$$

$$(1-\tau_w) w \kappa_t = \frac{\partial u_t^{\text{OLG}}}{\partial l_{y,t}} \tag{C.3}$$

Combining Equations (C.1) and (C.2) we get the Euler equation (11). By combining (C.1) and (C.3) we get Equation (12). By calculating the partial derivatives of u_t^{OLG} and inserting them into Equation (11) and Equation (12) we get the explicit expressions:

$$\frac{C_{o,t+1}}{C_{y,t}} = \left(\left(\frac{1 + (1-\tau_k) r_{t+1}}{(1+\rho_m)} \right) \cdot \left(\frac{C_{o,t+1}^a + \theta (X_{u,t+1} l_o)^a}{C_{y,t}^a + \theta (X_{u,t} l_{y,t})^a} \right)^{\left(\left(\frac{b}{a}\right)-1\right)} \right)^{\frac{1}{(1-a)}} \tag{C.4}$$

Here we can see that the intertemporal decision is only directly influenced by capital taxation, as this expression only depends on τ_k.

$$\frac{l_{y,t}}{C_{y,t}} = X_{u,t}^{\frac{a}{(1-a)}} \left(\theta \cdot \frac{(1+\tau_c)}{(1-\tau_w)w_t} \right)^{\frac{1}{(1-a)}} \tag{C.5}$$

By contrast, we infer from the second Euler Equation that the intragenerational labor-leisure decision is only directly influenced by consumption and labor taxation: the higher the labor or consumption tax, the higher the chosen levels of leisure.

D Steady-state equations of the economy

By formulating the equations for the system's steady state we can gain important insights about the main drivers of steady-state behavior. Additionally we can verify if the dynamic model, which is solved numerically, is solved correctly.

In the following all steady-state variables are denoted by a tilde. From Equations (6) and (14) it is easy to obtain an expression for the ILA's steady-state consumption $\widetilde{C}$:

$$\widetilde{C} = \rho_h \widetilde{K}_h. \tag{D.1}$$

The middle-income household's first-order conditions (Equations 9, 10, C.4 and C.5) and the first-order conditions of the firm (Equations 3 and 4) remain the same in the steady state.

The steady-state level of public capital $\widetilde{K}_G$ is given by:

$$\delta_G \widetilde{K}_G = \tau_K \cdot \widetilde{r}\widetilde{K} + \tau_w \cdot \widetilde{h}\widetilde{w} + \tau_c \cdot (\widetilde{C} + \widetilde{C}_y + \widetilde{C}_o). \tag{D.2}$$

Together with the Equation (2) we have a system of partially nonlinear equations.

By combining the steady-state Equations (14), (D.1), (D.2) with the first-order conditions of the OLG agent (9, 10, C.4, C.5) and the firm (3 and 4), we can eliminate $\widetilde{r}, \widetilde{w}$ and $\widetilde{C}$:

$$(1+\tau_c)\widetilde{C}_y = (1-\tau_w)\left((1-\alpha)A\widetilde{K}^{\alpha}\right)\widetilde{X}_p^{\beta}(1-\widetilde{l}_y)^{(1-\alpha)} - \widetilde{S},$$

$$\widetilde{C}_o = \frac{(1+\rho_h)}{(1+\tau_c)}\widetilde{S},$$

$$\frac{\widetilde{C}_o}{\widetilde{C}_y} = \left(\left(\frac{1+\rho_h}{(1+\rho_m)} \right) \cdot \left(\frac{\widetilde{C}_o^a + \theta(\widetilde{X}_u l_o)^a}{\widetilde{C}_y^a + \theta(\widetilde{X}_u \widetilde{l}_y)^a} \right)^{\left(\left(\frac{b}{a}\right)-1\right)} \right)^{\frac{1}{(1-a)}},$$

$$\frac{\widetilde{l}_y}{\widetilde{C}_y} = \widetilde{X}_u^{\frac{2a-1}{(1-a)}} \left(\theta \cdot \frac{(1+\tau_c)}{(1-\tau_w)\left((1-\alpha)A\left(\frac{\widetilde{K}}{(1-\widetilde{l}_y)}\right)^{\alpha}\right)} \right)^{\frac{1}{(1-a)}},$$

$$\frac{\rho_h}{(1-\tau_K)} + \delta_K = \alpha A \left(\frac{(1-\widetilde{l}_y)}{\widetilde{K}} \right)^{1-\alpha} \widetilde{X}_p^{\beta},$$

and

$$\delta_G \widetilde{K}_G = \frac{\tau_K}{1-\tau_K} \cdot \rho_h \widetilde{K} + \tau_w \cdot (1-\widetilde{l}_y)(1-\alpha)A\left(\frac{\widetilde{K}}{(1-\widetilde{l}_y)}\right)^{\alpha} \widetilde{X}_p^{\beta} + \tau_c \cdot (\rho_h \widetilde{K}_h + \widetilde{C}_y + \widetilde{C}_o).$$

For the sake of readability we did not insert the expressions for $\widetilde{K} = \widetilde{K}_h + \widetilde{S}$, for $\widetilde{X}_p = \widetilde{K}^{\varepsilon} \widetilde{K}_G^{1-\varepsilon}$ and for $\widetilde{X}_u = \widetilde{K}^{\varphi} \widetilde{K}_G^{1-\varphi}$. Now we only have a set of six partially non-linear equations in $\widetilde{K}_h, \widetilde{S}, \widetilde{K}_G, \widetilde{C}_y, \widetilde{C}_o$ and $\widetilde{l}_y$.

E Including the low-income households

If low-income households are included into the model calibration, 38 % of total net wealth is jointly owned by low- and middle-income households while 62 % is owned by high-income households. This leads to a slight shift in the graphs on the distributional effects of public investment as displayed in Figure 11 (black lines depict the original calibration, red lines the calibration in which low- and middle-income households jointly own 38 % of the capital stock): For consumption tax financing hardly anything changes. However, the inequality-reducing effect of capital tax-financed public investment is weakened a little bit and the inequality enhancing effect of labor tax financing is increased.

We observe these effects since including the low into the middle-income class means lower per capita wealth, welfare and income levels and thus an increased dispersion of these variables.

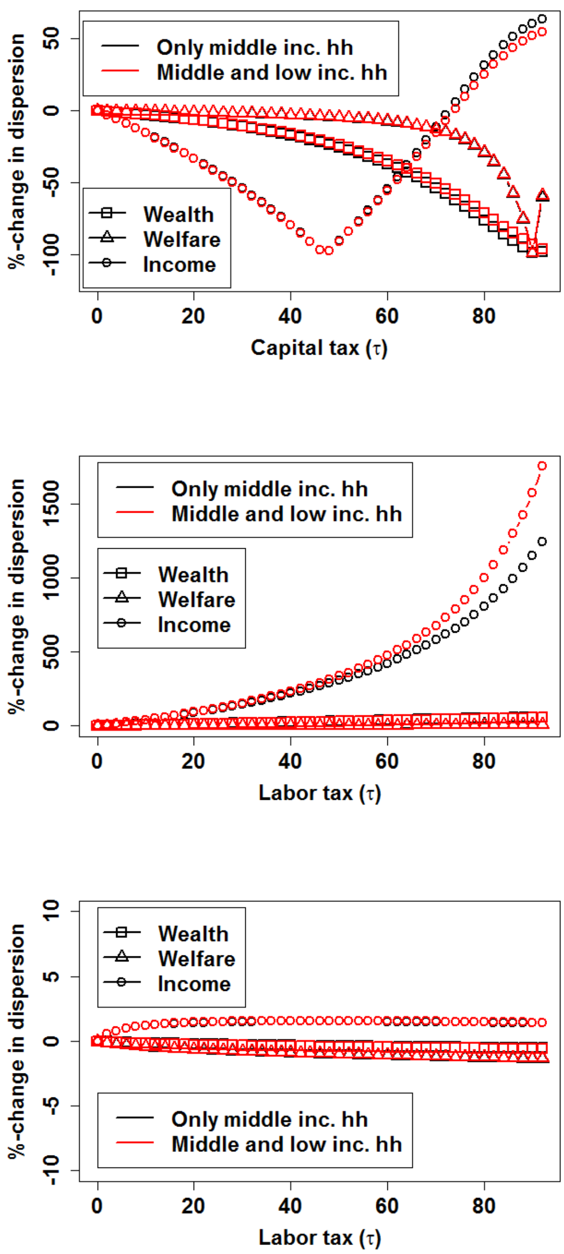

Figure 11: The distributional effects of public investment for capital tax (top), labor tax (middle) and consumption tax financing (bottom). The black lines are the results with the standard calibration, in which high-income households (the top 5 %) own 62 % of total wealth and middle-income households (the next 55%) own the remaining 38%. The case in which low- and middle-income households jointly own 38% of total wealth is displayed with red lines.

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Chapter 8

Happy or Liberal? Making sense of behavior in transport policy design[1]

Linus Mattauch
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Felix Creutzig

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Happy or liberal? Making sense of behavior in transport policy design

Linus Mattauch [*], Monica Ridgway [†], Felix Creutzig [‡]

Abstract

Appropriate microeconomic foundations of mobility are decisive for successful policy design in transportation and, in particular, for the challenge of climate change mitigation. Recent research suggests that behavior in transportation cannot be adequately represented by the standard approach of revealed preferences. Moreover, mobility choices are influenced by factors widely regarded as normatively irrelevant. Here we draw on insights from behavioral economics, psychology and welfare theory to examine how transport users make mobility decisions and when it is desirable to modify them through policy interventions. First, we explore systematically which preferences, heuristics and decision processes are relevant for mobility-specific behavior, such as mode choice. We highlight the influence of infrastructure on the formation of travel preferences. Second, we argue that the behavioral account of decision-making requires policy-makers to take a position on whether transport policies should be justified by appealing to preference satisfaction or to raising subjective well-being. This distinction matters because of the (i) influence of infrastructure on preference formation, (ii) health benefits from non-motorized mobility, (iii) negative impact of commuting on happiness and (iv) status-seeking behavior of individuals. The orthodox approach of only internalizing externalities is insufficient because it does not allow for the evaluation of these effects. Instead, our analysis suggests that transport demand modeling should consider behavioral effects explicitly.

Keywords: mobility behavior, behavioral economics, low-carbon transport, subjective well-being, co-benefits

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1 Introduction

Effective climate change mitigation necessitates, *inter alia*, the decarbonization of the transport sector (IPCC, 2014; Rothengatter et al., 2011). This challenge is arguably more difficult than the analogous transformation of the energy or the buildings sector: Mobility requires high-density fuels as opposed to electricity generation or heating (Sims et al., 2014; Pietzcker et al., 2014). Also, the emissions stemming from passenger transport result directly from the consumption decisions of the individual end-users. As such, behavioral aspects play a much more important role than, for example, in the utility sector, and, as we will argue, pose a challenge for standard welfare theory as applied to mobility.

Options for decarbonizing transportation fall into two groups, which can be delineated with a decomposition of total greenhouse gas (GHG) emissions (Schipper and Marie-Lilliu, 1999; Creutzig et al., 2011; Sims et al., 2014). Carbon and energy intensity can be reduced by technological options. This group was emphasized in former assessments on the decarbonization of transportation, for instance Kahn Ribeiro et al. (2007). However, transport demand and modal share also influence global GHG emissions from transportation. A number of studies indicate that these factors can equally support the decarbonization of transportation (Banister, 2008; Creutzig and He, 2009; Kahn Ribeiro et al., 2012; Sims et al., 2014). While it has been argued that the second set of options can have substantial benefits in addition to reducing emissions (Woodcock et al., 2009; Creutzig and He, 2009; Creutzig et al., 2012; Shaw et al., 2014), the corresponding analyses are often not founded in economic models of decision-making and thus the welfare effects cannot be properly derived.

Here, we provide such a foundation for transport policy-making by addressing two questions: First, can policies based on behavioral findings regarding mobility choices substantiate behavioral change as an appealing option for decarbonizing the transport sector? Second, how do two different normative viewpoints, the satisfaction of preferences and the maximization of subjective well-being, produce diverging policy conclusions? Under the paradigm of rational choice, transport economics was freed of addressing the normative distinction between maximizing subjective well-being and satisfying the preferences of transport users. The idea of preference satisfaction was seen as unproblematic as, for instance, time-inconsistent or ill-defined preferences were deemed irrelevant, or preference satisfaction and maximizing well-being were understood to be identical. This article shows that many particular aspects of mobility behavior deviate from rational choice. Thus, our main claim is that the decision maker must take an explicit position regarding preference satisfaction or the maximization of subjective well-being: the two positions imply different transport policies.[1] We find that taking subjective well-being as a welfare criterion means that climate change mitigation policies become more closely entwined with policies addressing behavioral effects.

We proceed in three steps: (i) we comprehensively classify the choice mechanisms shaping mobility behavior, (ii) we characterize the option space

[1]In this article, we discuss which transport policies follow from different welfare criteria without addressing the question of how institutions should be guided by such criteria. The reason is that the policy domain of transport does not seem particularly different from other policy domains in this regard (see also Section 5.1).

of behavioral mitigation policies in the transport sector and (iii) we propose a refined and normatively explicit welfare analysis of transport policies.

First, we establish which choice mechanisms are the major explanations for mobility-specific behavior.[2] We systematically identify the main drivers of behavior in various modal choice situations, drawing from the large class of choice mechanisms that are well established in behavioral economics, such as time-inconsistency, social preferences, overconfidence, framing, focusing illusion, loss aversion and limited attention.

Second, our classification of choice mechanisms involved in mobility decisions allows us to exhaustively derive the option space for decarbonization policies addressing transport users' behavior. We pinpoint some of the choice mechanisms as the most promising for the design of such policy instruments. Key options include enhancing environmental awareness, addressing behavioral factors that may lead to a higher modal share of non-motorized transport, encouraging the purchase of more fuel efficient cars as well as exploiting the influence infrastructure has on preferences. We highlight the importance of understanding the built environment and choice architectures as crucial leverages for achieving low-carbon transport.

Third, we argue that our descriptive results indicate that understanding transport policy as internalizing the externalities of otherwise optimal behavior is insufficient. Instead, a distinction between two normative viewpoints – the maximization of subjective well-being ('happiness') and the maximization of preference satisfaction – is necessary in order to assess the merits of the potentially beneficial side effects of decarbonization policies. The reason is that the benefits, such as improved health or greater social cohesion, carry greater weight when happiness is maximized instead of preferences fulfilled, since transport users may not have preferences for the outcomes that make them happy. Finally, we delineate the differences between transport policies that follow from the two different welfare conceptions.

This article is connected to the pertinent literature in two ways: First, traditional transport demand modeling relies on the rational choice approach to explaining economic behavior. Underlying the standard disaggregate transport demand models, such as (multinomial) logit or probit models of mode choice and trip scheduling, is utility-maximization based on *revealed* preferences, often expressed as minimizing generalized costs, including time (Quinet and Vickerman, 2004; Small and Verhoef, 2007; van Wee et al., 2013). This does not allow, for instance, for an influence of the physical and social environment on preference *formation*. In contrast, while no canonical transport demand models based on behavioral economics exist; previous behavioral work on mobility choices has produced a great number of findings that highlight the importance of empirical mechanisms for explaining mobility choices successfully. Examples include mass effects and conformity behavior (Abou-Zeid et al., 2013), symbolic and affective motives for car use (Steg, 2005), inertia (van Exel, 2011) or self-value of travel (Mokhtarian and Salomon, 2001). However, such research has not given an overview of which psychological effects generally identified as important for economic decisions matter specif-

[2]In this article, we only discuss behavioral effects in understanding *households'* mobility choices. Arguably, firms' transportation choices may also be subject to behavioral effects and are very important for a complete picture of mobility behavior, yet they are beyond the scope of this article.

ically for explaining mobility (Markovits-Somogyi and Aczél, 2013). Moreover, empirical findings on mobility behavior have not been well integrated into the catalog of 'non-standard' choice mechanisms produced by behavioral economics (DellaVigna, 2009) that are amenable to rigorous welfare analysis (van Wee et al., 2013). An exception is Avineri (2012), who also discusses the relevance of behavioral effects in mobility choices for low-carbon transport policies. Nevertheless, a systematic classification of the relevant effects on choices and the distinction between subjective well-being and preference satisfaction for drawing policy implications methodically are missing.

Second, current research in welfare theory is well aware of the distinction between preference satisfaction and subjective well-being (Loewenstein and Ubel, 2008; Fleurbaey and Blanchet, 2013), but has not addressed the consequences for the field of transportation decisions. Instead, research has focused on the applications for fields such as financial decisions, health (particularly addictions), and public good problems. By contrast, studies in transport science that explicitly deal with the welfare effects of (behaviorally construed) mobility decisions typically have not introduced a clear economic approach to welfare, but have chosen physical welfare metrics such as 'disability adjusted life years' (DALYs) (Woodcock et al., 2009; Shaw et al., 2014). To the best of our knowledge, no normative theories of transport policies exist to date that explicitly take into account the importance of behavioral findings regarding mobility. The added value of our article is thus to assemble the tools for such welfare analysis of transport policy: we examine whether behavioral economics, and its welfare theory, help better justify demand-side regulation, which has been recommended by transport research for a long time, and could lead to more effective policy instruments.

The remainder of this article is structured as follows: Section 2 reviews key aspects of behavioral economics and research on subjective well-being (in which no familiarity is assumed) that matter for analyzing mobility decisions.Section 3 explores systematically which preferences, heuristics and decision processes identified by behavioral economics are relevant for explaining and modeling mobility-specific behavior. The normative part of our analysis consists of three steps: First, in Section 4, we characterize the option space of possible behavioral decarbonization policies. In Section 5.1, we then introduce preference satisfaction and subjective well-being as welfare criteria for evaluating transport policies. Finally, in Section 5.2, we show why the distinction between the two criteria is relevant for designing policies and highlight key differences in the resulting policy packages. Section 6 concludes by considering implications of our analysis for transportation research.

2 Behavioral economics foundations

2.1 Behavioral economics

Traditionally, economics has modeled choices of households by assuming that they maximize a utility function representing their consumption preferences. Under this assumption, households' preferences can be inferred from their observable choices. Utility is *not* to be understood as subjective well-being or 'happiness' (see below and Section 5.1), but rather as a function representing which options are preferred over other options. Transportation economics has adopted this perspective by modeling the preferences of transport users through observed mobility choices and narrowed it further by excluding that mobility itself is a part of the desired consumption as well (van Wee et al., 2013; Mokhtarian and Salomon, 2001): transport demand is 'demand derived' from other consumption.

Laboratory and field experiments have pointed to anomalies and deviations from such 'rational' utility-maximization. Many of such forms of 'non-standard' behavior could, in principle, be 'rationalized', that is, understood as utility-maximizing behavior when the set of desired consumption goods is broadened or suitable 'costs' on some of the choice options are introduced (Gul and Pesendorfer, 2001, 2008). Most researchers on individual decision-making find larger departures from the paradigm of revealed preferences more convincing and believe they increase the explanatory power and accuracy of the predictions: The modeling of human decisions should make room for decision-makers to be both altruistic and envious, have partially incorrect beliefs, rely on heuristics, be influenced by factors unrelated to the consumption outcome and make mistakes in taking decisions (Camerer et al., 2005; Camerer, 2008; DellaVigna, 2009; Kahneman, 2011). Analyzing the economic consequences of such behavior, both in experiments and in reality, is the subject matter of the field of behavioral economics. For the purpose of examining its relevance for mobility decisions, mechanisms underlying human choices should thus be classified into three broad categories: Preferences, beliefs and decision-making (DellaVigna, 2009).

The following summary introduces the reader to the choice mechanisms standardly identified by behavioral economics. It closely follows DellaVigna (2009), with some effects deleted and others added according to the relevance for mobility behavior. It contains all choice mechanisms mentioned in the subsequent sections.

Preferences Preferences are an ordering of possible consumption options. While they are traditionally assumed to be a rational ordering of only one's own benefit of consuming the choices, individuals display a much wider set of preferences in the real world. We discuss four major classes of broader preferences.

First, preferences regarding intertemporal choice options can be *time-inconsistent*. Standard economic theory assumes time consistency, or that individuals discount the future at a constant rate at different points in time. Empirical findings challenge this assumption (Loewenstein and Prelec, 1992; Frederick et al., 2002) and imply that discounting is steeper in the immediate future than in the further future. This is sometimes called hyperbolic discounting. Time-inconsistent preferences give rise to self-control problems: the short-term preference prevails over an existing long-term plan. Combined with naïvety, or the tendency to incorrectly believe that an activity postponed today will be completed tomorrow, self-control problems can lead to infinite procrastination, thereby explaining a "status quo bias". Most people are likely *partially* naïve about their self-control problems (O'Donoghue and Rabin, 2001; DellaVigna and Malmendier, 2006).

Second, with regards to uncertainty, experiments on decision-making under risk show that preferences systematically violate assumptions of expected utility theory. Such non-standard *risk preferences* are explained by Prospect

Theory (Kahneman and Tversky, 1979) using the following characteristics: (i) reference dependence: the value of an option depends on the deviation from a reference point instead of absolute magnitude; (ii) loss aversion: given a specific reference point, losses are valued greater than gains; (iii) diminishing sensitivity: agents are less sensitive to outcomes further from the reference point, (iv) probability weighting: decision makers tend to overweight small probabilities and underweight large probabilities. (Kahneman and Tversky, 1979)

Third, preferences can extend to the needs of others, which are then called *social preferences*. Traditional utility theory assumes individuals are purely self-interested and have a utility function based entirely on their own payoff. However, decision makers often display altruistic behavior, which indicates that individuals also consider how their decisions affect the utility of others.

Fourth, individuals care about their relative position in social hierarchies, leading to *status-seeking behavior*. In contrast to altruism, people's utility may be affected *negatively* by the consumption of others, if they care about consuming more than members of their reference group. Such status-seeking behavior is well-documented for a large variety of "positional" goods (Solnick and Hemenway, 2005).

Beliefs Beliefs concerning (future) states of the world and availability of options, particularly under uncertainty, are another major aspect of explaining choices. Beliefs may be correct or incorrect; systematically incorrect beliefs are called biases. We mention a variety of biases discussed as explanations for observed mobility choices. First, individuals are often *overconfident*, as they tend to overestimate their ability and quality of private information as well as underestimate the occurrence of negative events. Second, individuals often *anchor* their belief in the initial piece of information or cue. Adjustments may be insufficient and the anchor may have a large influence on future assessments. Third, individuals sometimes exaggerate the effect of a specific factor, such as an increase in income, on well-being, the so-called *focusing illusion* (Kahneman et al., 2006).

Fourth, *heuristics*, or simplified rules for practical approaches to problem-solving or processing information, can lead to biases[3]: For instance, people estimate the likelihood of an event based on memorable instances of that event, which may not be an accurate reflection of the true likelihood of its occurrence. This is referred to as the *availability heuristic*. Using this heuristic, individuals tend to overestimate the probability of events with large consequences, familiarity, and visibility. A similar, yet distinct, bias is judgment by the *representativeness heuristic*, which occurs when individuals estimate the likelihood of an outcome based on how similar it is compared to a 'typical' case. However, the fact that an instance is more representative of a certain type of event does not make it more likely (Tversky and Kahneman, 1974).

"*Self-serving*" is a related bias: Decision makers may discount information that challenges their beliefs and support ideas that are consistent with pre-established notions (Miller and Ross, 1975). Finally, *misprediction of adaptation* means that individuals have incorrect beliefs about their ability to adapt to various stimuli, for instance noise or additional income (Frederick and

[3] Heuristics affect choices both as beliefs (about probabilities of events) and as forms of decision-making (as substitutes for solving a maximization exercise).

Loewenstein, 1999; Loewenstein and Schkade, 1999; Frey and Stutzer, 2014). In particular, this is one reason why humans systematically do not choose what makes them happy (Hsee and Hastie, 2006), see the next subsection.

Decision-making Decision-making is not always based on maximizing the utility of the outcome. One reason for this is that it is influenced by factors other than preferences and beliefs, such as the way the options are presented or the obedience of social norms. Another reason is that individuals may face informational or cognitive limitations to calculate which option would maximize their utility. A number of non-standard forms of decision-making are needed to explain mobility choices, as presented below.

First, *framing effects* refer to the influence the presentation of information has on decisions, even if economic considerations are held constant (Tversky and Kahneman, 1981). Second, *limited attention* contradicts standard economic theory, which typically assumes that individuals make decisions using all information available. Empirical evidence shows, however, that individuals tend to simplify complex decisions by focusing only on a subset of information. Inattention to a specific piece of information depends on its salience and the number of competing stimuli. Third, *emotions* sometimes influence decisions directly. For instance, experiments show that mood manipulations and emotional arousal substantially impact decision-making. Fourth, *social pressure*, or the desire to conform to the beliefs of others, can strongly influence an individual's decision-making and may lead to herd behavior, that is, following what others are doing without processing information (Banerjee, 1992). Finally, *default effects* largely influence decisions. In order to simplify complex decisions, individuals may avoid making an active choice and instead favor the default option. This can be due to having a preference for the familiar and/or salient in difficult choice situations. Often, framing influences individuals' propensity to choose the default. Together with loss aversion and limited attention, this form of decision-making can, in particular, lead to choosing the status quo as the default.

Figure 1 provides a summary of the concepts from behavioral economics used in this article and how they relate to the rational choice approach. For the role of the social context, infrastructure and the built environment, see Section 3.7.

Transportation economics has implicitly taken up the above concepts when analyzing mobility choices empirically, but often neglected to make explicit the nature of the underlying choice mechanisms that lead to specific mobility behavior (van Exel, 2011; van Wee et al., 2013). However, a precise analysis of those mechanisms achieves greater clarity for drawing normative conclusions and allows for the design of more successful transport policies. Our analysis in the next section provides such an explicit characterization of the choice mechanisms crucial for explaining mobility behavior. The subsequent sections draw the normative and policy implications and for this also rely on results from research on subjective well-being.

2.2 Subjective well-being

Subjective well-being ('happiness) is a general term for all approaches that seek to determine people's well-being by self-reports. Happiness studies (as a

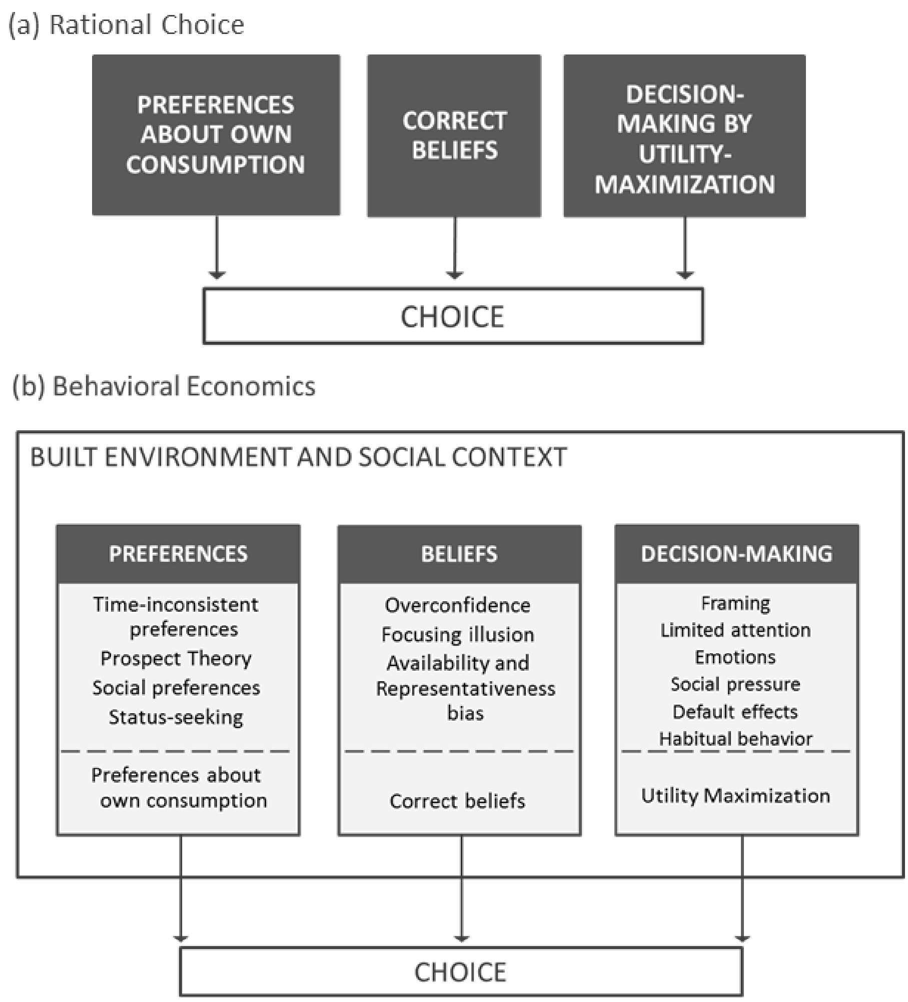

Figure 1: The rational choice approach to decision-making (a) and concepts of behavioral economics used in this article (b). Behavioral economics is distinctively broader than rational choice models, but operates with the same categories for describing choices. The built environment and the social context may influence choice mechanisms, particularly preferences in the long-term.

branch of social psychology) find that measurements of subjective well-being are reliable: self-reported experience of one's quality of life and one's feelings about an activity *do* characterize people's life satisfaction and present mood accurately (Kahneman and Krueger, 2006; Frey, 2008; Diener et al., 2009; Kahneman, 2011; Layard, 2011). For instance, greater happiness in such surveys correlates with more genuine smiles, being characterized as happier by peers as well as reduced suicide rates and changes in brain activity (Kahneman and Krueger, 2006; Frey, 2008; Layard, 2011). Two approaches must be distinguished: measuring *life satisfaction* and measuring *positive affect*. On the one hand, life satisfaction measures assess how people *think about* their life overall. For instance, the World Value Survey assesses this by the question, "All things considered, how satisfied are you with your life as a whole these days?", which is to be answered on a scale from 1 to 10. Many other large scale surveys contain similar questions (Fleurbaey and Blanchet, 2013, Table 5.1 for an overview). On the other hand, it is possible to assess people's feelings in their everyday environment in real time (using 'Experience Sampling' – individuals report their well-being at fixed intervals – or 'Day Reconstruction' – individuals recollect episodes at the end of the day and indicate their feeling along nine dimensions, such as 'happy', 'worried' and 'angry', from 0 ('not at all') to 6 ('very much')). This allows for measuring how people *feel in* their life (Kahneman et al., 2004; Kahneman and Krueger, 2006). Aggregation of individual subjective well-being data into a *cardinal* welfare indicator requires two assumptions (Fleurbaey and Blanchet, 2013, Ch.5): Individual scores must be cardinally meaningful measures and they must be interpersonally comparable. This is implausible for life satisfaction measures and has only been partially recognized by the pertinent studies. In contrast, Kahneman and Krueger (2006) propose a robust cardinal indicator, the 'U-Index', for *affect measures*: it records the proportion of the day in which negative emotions dominate (and thus would need to be minimized as a social welfare measure). Setting the difficulties of aggregation aside, measurements of subjective well-being at least allow one to study economic choices of an individual in a dimension separate from the outcomes: the impact of one's decisions on one's happiness. There is a consensus in behavioral sciences that choices often do not promote happiness: On the one hand, inaccurate predictions about the hedonic value of a choice or failure to follow correct predictions in the decision-making process (e.g. through weakness of will) lead to a deviation between actual and happiness-maximizing choices (Hsee and Hastie, 2006; Frey, 2008; Layard, 2011). On the other hand, humans do not necessarily seek happiness – instead, much behavior is driven by the need for meaning, not by the desire to be happy (Baumeister et al., 2013). In Section 5 we discuss whether or not subjective well-being should be used as a welfare criterion and what this would imply for justifying transport policies. Below, we deliberately blur, for length restrictions, the distinction between life satisfaction and positive affect in the normative discussion to focus on the much greater contrast to preference approaches, of which we also do not discuss competing variants in detail. The empirical findings on mobility and subjective well-being we mention are mostly based on life satisfaction data.

2.3 Method of study

The overview of choice mechanisms given in Section 3 has been produced by systematically screening the literature on mobility decisions and their policy implications for precise explanations or justifications in terms of behavioral effects. The catalog of effects identified by behavioral economics produced by DellaVigna (2009) has been invoked as a standard what counts as a behavioral effect, but has been extended by including some effects too widely known to appear on it, such as status-seeking. The same applies to the presentation of the confirmed effectiveness of behavioral decarbonization measures in Section 4. The results on policy proposals in Section 5 are generated by combining the general differences between subjective well-being and revealed preferences (elaborated in the syntheses of Hsee and Hastie (2006) and Layard (2011)) with all available findings about subjective well-being specific to mobility. The mobility aspects treated below are those that are most often invoked in the literature as domains in which behavior needs to be explained from a sustainability perspective. While classifying behavioral mobility aspects by importance for transport policy design would be desirable, it is beyond scope and purpose of the present article.

We emphasize that we see our contribution not as a comprehensive overview, but rather as a methodological essay designed to bridge the gap between how behavioral effects and their normative implications are treated in economic theory and transportation research, respectively.

3 Classifying behavioral explanations for mobility choices

In this section we identify which types of preferences, beliefs and decision-processes shape behavior for several mobility-specific aspects. Table 1 presents a non-exhaustive summary of the most important relevant behavioral effects and their explanations for each mobility aspect. Subsections 3.1 to 3.6 describe which choice mechanisms are crucial for understanding behavior regarding the mobility aspects of environmental awareness, mode choice, safety, commuting, travel time as well as car purchases and the fuel economy, respectively. For each category, relevant effects appear in the order of preferences, beliefs and decision-making. Subsection 3.7 summarizes what is known about the influence of infrastructure, or the physical environment more generally, and the social context on mobility choices. Notably, physical and social context matter for the *formation* of preferences, which is very different from explaining mobility outcomes by preferences, as in the other subsections (see also Figure 1). van Exel (2011, Chapter 2) also gives a comprehensive summary of the building-blocks of behavioral economics as applied to aspects of mobility, on which we draw for Subsections 3.2, 3.3 and 3.5.

3.1 Environmental Awareness

The level of awareness and concern for the environment of individuals can influence their travel behavior, such as mode or route choice. Significant behavioral factors that affect an individual's awareness and concern for the environment include social preferences and framing.

Social preferences play an important role in observed behavioral shifts to sustainable mobility, which cannot be explained purely by self-interest. In

Mobility aspects	Particular Effects	Behavioral Explanations
Environmental awareness	Willingness-to-pay for fewer emissions	Social preferences, framing
Mode choice	Habitual car use	Time-inconsistent preferences, representativeness, status quo, default effects
Safety	Safety valuation across modes, safety-compromising behavior	Prospect theory, overconfidence, emotions, social pressure
Commuting	Commuting time lowers subjective well-being	Adaptation, focusing illusion, status quo effect
Travel time	Average constant travel time, travel time valuation	Direct utility of travel, Prospect theory
Fuel economy	Undervaluation	Prospect theory
Car purchases	Lower-than-expected-search effort	Status-seeking behavior, limited attention, emotions, social pressure
Infrastructure and social context	Self-selection	Default effects, context shapes preferences

Table 1: Mobility aspects, transport-specific phenomena exemplifying behavioral effects and their behavioral explanations in terms of preferences, beliefs and decision-making processes, as used in Section 3

some segments of the population (Anable, 2005), people's attitudes towards the environment are positively related to their willingness to reduce car use (Salomon et al., 1993; Steg and Vlek, 1997; Nilsson and Küller, 2000), as well as to their attitudes towards public transportation (Murray et al., 2010) and could be used to motivate a change in travel behavior (Anable, 2005). Indeed, some experiments indicate the existence of a "value of green", or willingness to pay for fewer emissions (for example, see Gaker et al. (2010, 2011)).

This suggests that people may alter their travel decisions when provided with information regarding the environmental impacts of their behavior. However, Tertoolen et al. (1998) observed that environmentally-conscious regular car drivers adjusted their attitudes, rather than behavior, and placed the blame on others in order to reduce cognitive dissonance (or the mental stress caused by conflicting attitudes, beliefs, or behaviors (Festinger, 1962)) associated with driving a car. Due to the potential of drivers to adjust their attitudes instead of behavior when provided environmental information, pro-environmental social norms are argued to be essential for the provision of information about the negative environmental effects of driving to effectively encourage more sustainable behavior (Tertoolen et al., 1998).

Framing may affect how individuals perceive the impacts of alternative travel choices. For instance, when presented a comparison of travel modes, individuals perceive the difference in CO_2 emissions to be larger if framed in a negative manner, that is, in terms of potential environmental damage (mode A is worse than mode B), rather than in a positive manner, or the potential benefit for the environment (mode B is better than mode A). Furthermore, the perceived difference between CO_2 emissions of the modes is amplified when presented in larger scales – for instance, a comparison of yearly outputs as opposed to a trip-by-trip presentation (Avineri and Waygood, 2013). Considering that a "value of green" may exist for some travelers, information about the impacts of alternative modes on the environment can be presented in a way that further enhances awareness.

3.2 Mode choice

Understanding how individuals make decisions regarding mode choice is vital in order to enhance the long-term sustainability of global transportation systems. choice mechanisms that are particularly relevant for mode decisions include time-inconsistent preferences, heuristics, status quo and default effects as well as social norms and emotions.

Time-inconsistent preferences may explain the existence of potential self-control problems related to mode choice. This is particularly relevant for health and search costs and should be further investigated as self-control problems have not been elucidated specifically with regard to mode choice, only regarding physical exercise more generally (Sniehotta et al., 2005; DellaVigna and Malmendier, 2006). For instance, active travel modes have significant positive effects on health as they reduce obesity-related diseases, as well as depression and dementia (Woodcock et al., 2009; Creutzig et al., 2012; Shaw et al., 2014). Individuals that prefer to use healthier forms of transportation in the long run could face self-control problems in the short-term, which leads them to choose a form of transportation that requires less immediate physical effort despite their long-term preference for good health and normal weight.[4]

Self-control problems might also arise when people are faced with the search costs of investigating alternative modes. Even if the costs of searching for an alternative mode or other travel information may be more beneficial in the long run (for instance, if a former car user saves time and money by taking public transportation), agents might "underinvest" in searching for alternatives because they inconsistently value their present time more than their future time. Although such behavior has not been described in terms of time-inconsistent preferences for the specific case of mode choices, the experimental results of Bamberg et al. (2003b) point towards such an explanation, see also Section 3.7.

An individual's beliefs may influence absorption of information, and subsequently behavior, regarding mode choice. In particular, the heuristics of judgment by representativeness and by availability as well as the self-serving bias have been invoked to explain habitual car-use. The presence of these biases in mobility choices necessitates a distinction between the transportation alternatives (modes and routes) available to an individual and the alternatives the individual considers to exist (labeled as the objective and subjective choice sets (van Exel, 2011). For instance, car drivers could erroneously believe that

[4] An individual may further exacerbate the effects of self-control issues by showing naïvety towards the problem and falsely anticipating that they will make healthier travel decisions in the future.

public transport is not an option for many of the trips for which it could be a viable alternative. In fact, research has identified a considerable gap between subjective (50-80 %) and objective (10-30 %) car-dependence (Goodwin, 1995, 1997).

The focusing illusion is a different bias that may also hinder car users from making correct predictions about future satisfaction with public transport. Drivers focus too much on the negative aspects of public transit, such as waiting on the platform and overlook the positive ones, like reading on the train (Pedersen et al., 2011b).

Contrary to standard economic theory, people may not analyze travel decisions on a trip-by-trip basis, but rather keep the status quo derived from past evaluations, experiences, or prior commitments (Mondschein et al., 2006) which elicits a "mindless and habitual" (van Exel, 2011) approach to travel decisions. Limited attention, default effects and loss aversion contribute to habitual travel behavior (Kitamura, 2000; Verplanken et al., 1994; van Exel, 2011). The relatively low-scale commitments of holding a drivers license, owning a car or owning a season ticket (Simma and Axhausen, 2001, 2003) as well as the higher-scale commitments of residential and employment location (Ben-Akiva and Lerman, 1985; Domencich and McFadden, 1975) amplify habitual mobility behavior and can explain decisions favoring the status quo. Even when alterations make a particular route less efficient, e.g., a new construction site, repetition causes drivers to overlook these deviations and insufficiently reevaluate travel alternatives, i.e., drivers stick to the old route out of habit despite the existence of better alternatives (van Exel, 2011; Kitamura, 2000; Mondschein et al., 2006; Salomon et al., 1993). Furthermore, the degree of familiarity to a transportation mode influences attitudes about the mode (Diana and Mokhtarian, 2009), contributing to a reliance on the status quo.

Social norms and perceptions regarding different transportation modes can have a large influence on individual's decision-making. For instance, perceived social support plays a considerable role in the willingness to use public transportation (Tertoolen et al., 1998; Bamberg and Schmidt, 2001; Murray et al., 2010). Similarly, motivation to drive a car is influenced by status and role beliefs (Bamberg and Schmidt, 2003).

Car driving can also generate intense feelings of identity, power, independence, ownership, etc (Steg, 2005). These symbolic and affective aspects justify arguments against viewing car use simply as derived demand and can create barriers to behavioral changes (Steg, 2005; Anable, 2005).

3.3 Safety

Safety varies across different transportation modes (Dolan et al., 2008). Three choice mechanisms help explain decisions related to safety: non-standard risk preferences, overconfidence and emotions. Moreover, for the more specific cases of wearing seatbelts and bicycle helmets, individuals' decisions are also illuminated by considering a variety of behavioral factors roughly similar to those discussed in Section 3.2.

First, travelers tend to inaccurately estimate the risk of transport-related accidents occurring (de Blaeij and van Vuuren, 2003), focusing primarily on outcomes rather than probabilities, which is particularly relevant for small probabilities of large catastrophes. The actual valuation of transport-related losses is well represented by aspects of prospect theory (de Blaeij and van Vuuren, 2003) and may explain, for instance, a higher value placed on air transportation safety compared to road safety.

Second, emotional factors, such as feelings of “dread” (Chilton et al., 2006; Sunstein, 1997; Dolan et al., 2008) “lack of control” (Dolan et al., 2008) and “ambiguity” (Bach et al., 2009), may cause perceived risks to deviate from objective risks (Slovic, 1987; Loewenstein et al., 2001). This may enhance people’s willingness to pay to prevent an accident from occurring (Slovic et al. (1980),Carlsson et al. (2004) as cited in Dolan et al. (2008)). Such a higher willingness to pay has also been explained as the avoidance of “mental suffering” evoked by the image of a catastrophic plane crash (Carlsson et al., 2004).

Furthermore, individuals display overconfidence regarding their own driving and safety behavior. The majority of people believe they are more skillful than the average driver and therefore underestimate the risk of being involved in an accident (Svenson, 1981; McCormick et al., 1986). The level of overconfidence varies by age group and gender (Gosselin et al., 2010; Harre and Sibley, 2007; Ulleberg, 2001; White et al., 2011), with young males exhibiting the most overconfidence. Individuals who are more overconfident and underestimate personal transportation safety risks may be less likely to respond to efforts oriented at changing safety behavior (Ulleberg, 2001).

Moreover, behavioral effects have been invoked to explain the use (and non-use) of seatbelts and bicycle helmets. For example, it has been discussed whether seatbelt wearing leads to increased risk-taking due to a change of the reference point, that is, individuals engage more in risky behavior due to the perceived safety gained from wearing a seatbelt (Evans et al., 1982; Janssen, 1994). Furthermore, Goudie et al. (2014) show that happier individuals are more conscientious to wear a seatbelts.

Regarding bicycle helmets, a sizeable amount of literature discusses behavioral factors that may be exploited to promote helmet wearing: Findings from the literature suggest that, similar to the mechanisms that explain persistent car use, overconfidence, biases, non-standard risks preferences as well as limited attention and social pressure prevent a higher share of helmet-wearing among cyclists (Thompson et al., 2002; Rezendes, 2006; O’Callaghan and Nausbaum, 2006).

3.4 Commuting

Making a decision about how far to commute involves balancing its costs with the benefits derived from work or housing. Rational decision-making regarding commuting choices would thus imply that agents compensate the burden of commuting with the greater utility obtained through it: an individual drives a longer distance to a higher paying job or purchases a home further away from her place of work for the sake of more space (Stutzer and Frey, 2008). However, recent research finds that people with longer commutes report systematically lower subjective well-being (see Subsection 2.2) as demonstrated by (Stutzer and Frey, 2008) using life satisfaction data. This is due to the negative effects on people’s social life (Pocock, 2003; Flood and Barbato, 2005), sleeping time, family and interpersonal relationships (Sandow, 2011) and health

(Costal et al., 1988; Kluger, 1998; Evans et al., 2002)[5]. Insights from behavioral economics, therefore, may help explain this seemingly paradoxical behavior regarding commuting decisions.

First, in contrast to the ability to adapt to different levels of income, people are much less able to adapt to high levels of commuting (Frey and Stutzer, 2014). Agents tend to *mispredict* the utility derived from large external rewards, such as a bigger house and a higher salary, and give less attention to other aspects that play a significant role in subjective well-being, such as reduced time for social life due to longer commutes and the stress caused by the commute itself (Frederick and Loewenstein, 1999; Loewenstein and Schkade, 1999). Hence individuals misleadingly focus on the utility derived from the "extrinsic" aspects of a decision, such as its impact on their income, and neglect their "intrinsic" needs, such as time spent socializing (see Frey and Stutzer (2014)).[6] Recent research suggests, more specifically, that the negative effect of commuting on subjective well-being is greatest when using a car instead of choosing an active travel mode (Martin et al., 2014), yet the details of this distinction remain unexplored.

Second, the focusing illusion is another bias well documented to be relevant to income and hence relevant in the context of commuting: people are highly motivated to increase their income – and often justify decisions based solely on economic concerns (Frey and Stutzer, 2014) – despite the weak relationship to their subjective well-being (Kahneman and Deaton, 2010).

Furthermore, due to the repetitive nature of commuting, individuals are likely to form habits and rely on the status quo when choosing a commute mode and route (Verplanken et al., 1997; Fujii et al., 2001; Verplanken and Wood, 2006). Past commuting decisions are good predictors of current behavior since people do not re-evaluate all alternatives for routine trips – rather, they rely on prior assessments of alternative mode and route choices (Salomon and Mokhtarian, 1998; Mondschein et al., 2006). Limited self-control and naïvety about it further enhance the status quo effect and may lead to the 'infinite procrastination' of decisions that might reduce commuting time, such as searching for a job closer to home or an apartment closer to work (Stutzer and Frey, 2008).

3.5 Travel time

A common assumption in transportation economics is that travel demand is derived from other activities. The time spend traveling is therefore considered a cost, or disutility, that individuals seek to minimize (van Wee et al., 2013; Mokhtarian and Salomon, 2001). Several empirical findings, however, challenge this standard assumption and suggest that the direct utility derived from traveling, prospect theory and a constant average time budget need to be invoked to explain the amount of time spent on travel.

Individuals may not engage in travel merely for instrumental purposes, but also pursue the act of travelling itself (Mokhtarian et al., 2001; Brouwer and

[5]For a detailed overview of the private and social costs of commuting, see Koslowsky and Kluger (1995)

[6]Nevertheless, it is of course possible that some individuals deliberately choose to decrease their happiness through a longer commute in order to strive for other goals sought for themselves, such as meaning, power or fame through particular career options (Baumeister et al., 2013).

van Exel, 2005). The direct value of travel arises from fundamental human needs for motion, freedom or independence (Mokhtarian et al., 2001; van Exel, 2011). This means that people may not try to minimize the total time traveled as standard economic theory indicates, particularly regarding travel for recreational purposes (Mokhtarian and Salomon, 2001). Consequently, measures aimed at reducing travel demand may not be as effective as expected if they do not consider the positive utility of traveling for some trips (Salomon and Mokhtarian, 1998).

Furthermore, as predicted by Prospect Theory, travel time delays are valued higher than time savings (Rietveld et al., 2001; Avineri and Bovy, 2008; Parthasarathi et al., 2011; van Exel, 2011, for an overview), as is reliability, or low variability of travel time (Bogers et al., 2008; Asensio and Matas, 2008; Tseng et al., 2009). However, it is important to note that losses refer to deviations from a specific reference point, such as a "desired" commute time (see Avineri and Bovy, 2008), arrival time, or public transportation schedule (see van Exel, 2011), which may not reflect all objective choice sets. Considering the existence of loss aversion in terms of travel time, the occurrence of a one-time, yet substantial delay in public transportation could have long-lasting effects on the daily mode choice of an individual, even if time savings by public transportation are actually more common. Much like the distinction between subjective and objective travel choice sets, people can establish false beliefs about the reliability of a certain mode of transportation based on past experiences or attitudes (Bogers et al., 2008; Tseng et al., 2009; van Exel, 2011, for an overview).

Moreover, instead of minimizing the amount of time spent travelling (according to its dis-utility), the population is observed to have, *on average*, a fairly static daily travel time budget of approximately 70 minutes (Schaefer and Victor, 2000; Hupkes, 1982; Mokhtarian and Chen, 2004, for a more skeptical view). The existence of a daily travel time budget indicates that individuals will continue to spend the same amount of time travelling despite changes in income or improvements to the availability of technology and infrastructure (Metz, 2004, 2008; Schaefer et al., 2009). This undermines the standard reasoning that providing additional transport infrastructures, for instance, by constructing highways, high-speed rail or additional airports, leads to travel time savings (Metz, 2008). In the long-run, people do not shift time savings to pursue other economic activities, but rather to reach farther destinations. Some claim that a constant travel time budget is an anthropological invariant (Marchetti, 1994), while, in general, no encompassing explanation (whether related to behavioral effects or not) has been given how the aggregate constant time budget arises from individually varying travel times (Schaefer et al., 2009).

3.6 Car purchases and fuel economy

As a major source of greenhouse gas emissions, the type of vehicles purchased by consumers is a focus of climate policy. Throughout the article our analysis is limited to behavioral effects of households; however, for the structure of car markets, firms' decisions are particularly important, as for example in the EU around 50 % of new cars bought are company cars (Copenhagen Economics, 2010). Firms' car purchase decisions may indeed be more sophisticated regarding financial aspects than those of households, yet are possibly also influenced by the symbolic motives attached to cars by the employees. Here we only focus on household's purchase decisions because only those matter for the welfare considerations below.

It is well-established that car purchases of households are subject to a variety of behavioral factors– particularly regarding the evaluation of fuel economy – that influence the automobile market. Research suggests that factors such as loss aversion, status-seeking behavior, social pressure, limited attention as well as emotions can affect how consumers evaluate automobile alternatives.

Under expected utility theory, a rational economic consumer consistently discounts (uncertain future) fuel costs over the entire lifetime of a vehicle when making a purchase decision (Greene, 2010). Econometric evidence is inconclusive as to how consumers value fuel economy when selecting an automobile, but many such studies are conducted within the framework of rational utility maximization (Greene, 2010). For instance, Busse et al. (2013) find little evidence of unusually high discount rates with respect to fuel economy valuation. However, others claim that there could be undervaluation of fuel economy in the automobile market due to loss aversion because of the uncertainty about future fuel prices (Greene et al., 2009). Consequently, gains in fuel savings may have to be greater than what standard utility theory would predict in order for consumers to be willing to pay a premium for automobiles with better fuel economy. Consumers may require a short payback period in order to invest in such cars.

Furthermore, insights from Turrentine and Kurani (2007) call into question models for estimating the undervaluation of the fuel economy that assume rational individuals. They conclude, based on in-depth interviews, that "households do not have access to the basic building blocks of information regarding their fuel use and costs" (Turrentine and Kurani, 2007), that they are unable to carry out the required calculations or do not apply them. Instead, they defend the hypothesis that consumers are simply inattentive to fuel economy because their decisions about purchasing cars are driven by "high value meanings, some of which have important but non-quantifiable [...] value" (Turrentine and Kurani, 2007). This is broadly confirmed by Peters et al. (2011) who find that the purchase of fuel efficient cars is directly or indirectly influenced by a person's evaluation of less power and smaller size of cars, perceived ability to perform respective behavior, altruism, perceived response efficacy, social pressure, symbolic motives and awareness of environmental problems. Together these factors explain 29 % variance of the fuel economy. Peters et al. (2015) point to a gap between intention and behavior with regards to the importance of fuel economy in purchase decisions, as stated intention is to a larger degree derived from a sense of adhering to what is socially desirable and influenced by symbolic motives.

Moreover, social influence plays a considerable role in consumption decisions more generally, including automobile purchases: in particular, status consumption (Layard, 2006; Clark et al., 2008; Solnick and Hemenway, 2005) may motivate buyers to purchase an automobile based on attributes such as appearance, speed or reputation (Johansson-Stenman and Martinsson, 2006; Winkelmann, 2012). Car buyers are also influenced by the distribution of ownership choices of their peers (Gaker et al., 2010) and, in particular, the recent automobile purchases of neighbors, which may, however, be due to information transmission rather than envy (Grinblatt et al., 2008).

Rather than making automobile purchase decisions based on all available information, consumers simplify their decision-making by not optimizing their utility over all available information, but using non-standard forms of decision-making. Several cases of limited attention in the decision-making of car buyers can be observed (Furse et al., 1984; Peters et al., 2006; Turrentine and Kurani, 2007).

First, people tend to utilize a two-stage decision process when purchasing an automobile (European Parliament, 2010). In the first stage, alternatives are eliminated using intuition followed by a second stage in which the person rationally weighs the alternatives. Such decision-making process could explain large evidence for the fact that automobile buyers search effort is lower than expected (Furse et al., 1984). Evidence suggests that in the first stage, buyers decide on the car class based on characteristics such as price, safety and style followed by the second stage in which they consider factors such as environmental impact and fuel economy (Peters et al., 2006; European Parliament, 2010). Since the environmental impact and fuel economy is relative to car class, which was decided in the first stage, these factors may not have as large an influence on purchasing decisions as standard theory would suggest. Furthermore, 40 % of Swiss car buyers take less than two weeks for making a purchase decision, while a majority stated to have only considered one brand (and then only one model) pointing to strongly limited attention in decision-making (Peters et al., 2006).

Second, car buyers also have a strong partial inattention to mileage in the used car market, which causes irregular drops in the sale prices of used cars at the 10,000-mile and 1,000-mile odometer thresholds (termed left-digit bias) (Lacetera et al., 2012).

Third, transaction costs and information barriers prohibit people from understanding fuel economy correctly when it is presented in complicated frames, leading to an “MPG illusion” (Larrick and Soll, 2008): car users systematically misunderstand miles per gallon (MPG) as a measure of fuel efficiency. A false linear instead of a correct hyperbolic reasoning about MPG leads car drivers to undervalue small improvements on inefficient vehicles. If expressed as gallons per mile consumers would intuitively understand their petrol use and carbon footprint.[7]

Moreover, the emotional state of a person can have a large impact on consumption decisions. Car manufacturers not only sell cars based on technical features, but also tap into the emotions of potential buyers (Sheller, 2004) by emphasizing the type of lifestyle or community the car symbolizes, making it more appealing and seductive to their target market. The emotional association people have to cars (Steg, 2005) creates a barrier to reducing automobile use despite efforts to raise awareness and enhance access to public transportation (Banister, 2008).

[7] Kahneman (2011, p. 372f.) notes that the Obama administration has partially corrected for this.

3.7 The role of infrastructure, the built environment and the social context

Infrastructure design and urban form are variables within the scope of policy design that influence individual user behavior and should thus be part of an overarching behaviorally explicit policy framework. (Næss, 2006; Sims et al., 2014). Important examples include the provision of cycling networks, tram lines or highways (Ewing and Cervero, 2010). Nevertheless, there is surprisingly little research that explicitly analyzes the links between infrastructure and mobility choices based on behavioral effects. Infrastructure can influence mobility choices through two independent channels. First, it may impact behavior through default effects in the decision-making process (as suggested by the finding of Goodman et al. (2014), see Section 4). Although this influence is a special case of the general ubiquity of "choice architectures" in shaping decisions (Thaler and Sunstein, 2008), there is, to the best of our knowledge, no substantial transportation research on this effect. An exception may be the finding of Bamberg et al. (2003b): individuals moving to a new city with an excellent public transport system were given information material and a free day ticket for public transport. The modal share of public transport more than doubled as a result, compared to a control group moving to the same city. This may indicate the presence of default effects (and/or limited attention and time-inconsistent preferences) when individuals make mobility decisions in a new environment (see also Bamberg et al., 2003a). Second, infrastructures are stocks that are effective for long time scales[8], constituting the template for preferences and user behavior. Infrastructure could thus influence the *formation* of preferences on a longer time-scale. Traditional transport demand modeling, however, is based on the idea that preferences (for instance, for modes) are fixed, while only attributes of modes change. Descriptively, this rules out the idea that preferences themselves are impacted by changing physical and social environments, which may be important for understanding residential self-selection (see below; for normative implications of this assumption, see Section 5.2).

A recent strand of literature on social learning in transportation, however, puts pressure on this approach. Results indicate that individuals who move from city A to city B tend to have modal choice preferences that co-align with the infrastructure of city A, even if city B provides infrastructure that is more suitable for a different mode (Weinberger and Goetzke, 2010, 2011). The built environment one grows up with hence shapes one's modal preferences – preferences are not exogenous but endogenous to one's physical environment. Similarly, one's social environment may also shape individual preferences[9] (Weinberger and Goetzke, 2011; Goetzke and Weinberger, 2012).

Moreover, there is a two-way relationship between the built environment and behavioral preferences. As described, the built environment can impact travel behavior (Næss, 2006; Ewing and Cervero, 2010), but the individual

[8]Infrastructures alone might induce emissions in the order of the remaining carbon budget under ambitious climate protection goals (Davis et al., 2010). On a city scale, the housing sector induces inertia in long-term transport behavior and ensuing GHG emissions (Gusdorf and Hallegatte, 2007). Crucially, transport prices are causally most relevant in determining housing locations and, in turn, long-term GHG emissions from commuting (Creutzig, 2014).

[9]It may, however, be difficult to determine whether the social environment influences the decision-making or the preference formation, similar to the case for the built environment.

preference for a specific built environment, given specific mobility habits, also plays a substantial role that is not easy to quantify (Cao et al., 2009): After controlling for such residential self-selection, several studies nevertheless indicate that there is a distinct influence of the built environment on travel behavior. However, few studies have attempted to quantify the relative size of the two components' influence (see Cao et al., 2009, for an overview).

In summary, mobility preferences are revealed conditional on the availability of infrastructures; a different set of infrastructures thus would also lead to different revealed preferences. Normative implications of this finding are explored in the subsequent sections. In general, it can be expected that not only the built and social contexts influence preference formation, but that introducing policy instruments unlinked to altering those contexts directly may induce preference changes. For instance, traffic control policy might be expected to have an influence on preference formation regarding mode choice in the same way as changes to infrastructure have. The reason we limit our discussion of preference formation to the influence of infrastructure and social context is that we could not find empirical research on the influence of policy measures separate from altering built and social contexts (although one may hypothesize from the strand of urban planning research synthesized in Ewing and Cervero (2010) that this is likely the case).

4 Behavioral policies for mitigating carbon emissions from transportation

In this section, we characterize the option space for mitigation policies based on the above overview of the major behavioral factors relevant for mobility choices. Table 2 summarizes potential behavioral policy measures that foster low-carbon transport. Behavioral measures and demand reduction have long been discussed as options for emission reduction in transportation research (van Wee et al., 2013; Sims et al., 2014) and are generally seen as complementing pricing options, which alone would be insufficient. To our knowledge, however, little attempt has been made to connect an evaluation of their effectiveness to research on the choice mechanisms isolated by behavioral economics.[10] The purpose of this section is to sketch what additional insights one may hope to gain from informing demand-side transport policies by results on choice mechanisms related to mobility. We proceed as follows: For each category of mobility-specific behavior, there are many potentially successful policy instruments to consider that may reduce emissions. Policy-instruments are typically classified in three categories: (i) bans and direct regulations, (ii) monetary incentives, (iii) education and information – sometimes lightheartedly labeled "sticks, carrots and sermons" (Bemelmans-Videc et al., 1998). To these three categories, "context" must be added for the case of transport policy (Shaw et al., 2014): changing the built environment through construction or modification of the transport infrastructure also alters decision-making. For each category, Table 2 gives examples of specific policy measures that may be

[10]Even if one comes from a macroeconomic perspective holding that the ultimate solution to decarbonize the transport sector is through carbon pricing, for instance by including it in national cap-and-trade-systems, behavioral arguments make sense if one is concerned either that high modal shares of non-motorized transport options cannot be reached by pricing instruments or doubts the political feasibility of high carbon prices at a national level.

	Sticks (Bans, regulations)	Carrots (Monetary incentives)	Sermons (Education, information)	Context (Infrastructure, culture)
Environmental awareness	-	Crowding in social preferences	Salient information about emissions; provision of comparison to others	Change of cultural norms: campaigns, first adopter circles
Mode choice	Ban on cars in some parts of cities	Active choosing, free initial PT tickets	Promoting self-control; lower PT search costs; encouraging social learning about NMT	Change of built environment
Commuting	-	Commuting tax, incentives for moving close to work	Education on adaptation, personalized travel plannning	Promote more efficient use of infrastructure: car pool lanes, ...
Travel time	Ban on fast travel options	-	Inform about expected delays and alternative routes	Road diet
Fuel economy and car purchases	Fuel efficiency standards	Taxation of status aspect of cars	Active choosing in purchases, more salient information	Change cultural norms

Table 2: The option space for decarbonization policies concerning behavioral effects. “PT”: public transport, “NMT”: non-motorized transport

useful for changing mobility behavior towards low-carbon options. The following list provides a summary of those measures whose effectiveness can be deduced from extant transportation research.

Regarding **environmental awareness**, providing the accumulated yearly emissions from car use compared to more sustainable modes of transportation is more effective at encouraging a change in behavior compared to daily emission savings. Also, a negatively framed comparison of emissions from different modes is more effective than a positively framed comparison (Avineri and Waygood, 2013)[11]. Furthermore, policies will be more effective if they identify attitudinal differences among segments of the population and frame information accordingly. For instance, population segments that show a high sense of environmental moral obligation should require less persuasion to use alternatives, such as public transportation or cycling, whereas information regarding traffic congestion or reliability may be more persuasive for segments that are less concerned with environmental effects (Anable, 2005).

Concerning **mode choice**, the tendency to favor the status quo provides opportunities for policymakers to influence long-term travel behavior by motivating individuals to break undesirable habits. Policy measures so far tested successfully include:

- Distributing a free bus ticket to regular car users for one month. Attitudes towards the bus improved, and even one month after the end of the intervention, the frequency of car use was decreased while subjects used the bus more often and made it a habit (Fujii and Kitamura, 2003), see

[11]This effect may also be applicable for other information provided i.e., calories burned, time saved waiting in traffic, etc.

also Bamberg et al. (2003b).

- A temporary decrease in car use was observed after subjects with a strong habit of car use were induced to deliberate travel mode options by answering questions before beginning a trip (Garvill et al., 2003).

- A change of residence may be the most promising opportunity to alter mode choice since individuals are then forced to form new habits (Bamberg et al., 2003b; Weinberger and Goetzke, 2010).

- The establishment of social norms that are pro low-carbon transportation modes can be an effective mechanism to encourage more sustainable behavior on an individual level (Banister, 2008, for an overview).

- Finally, it is generally assumed that better infrastructure for walking and cycling promotes a higher modal share of non-motorized mobility. However, research is only beginning to examine the determinants of the efficiency of various possible changes in the infrastructure (Ogilvie et al., 2012): one tentative outcome is that new infrastructure promoting active travel may chiefly attract individuals who are physically active anyway and potentially merely displacing physical activity (Goodman et al., 2013). Over longer time-scales, however, additional active travel is generated by such infrastructure (Goodman et al., 2014).

To reduce **commuting** time, correcting misguided perceptions of certain modes of transportation (e.g., by increasing actual experience with public transportation) could strongly influence long-term commuting behavior. This effect was seen after habitual drivers were given a 30-day trial period public transportation ticket – their reported satisfaction with the mode increased after using it more often (Pedersen et al., 2011a).

Issues of **travel time** need also to be taken into account for well-designed, low-carbon transport. A first aspect is congestion: as providing more road infrastructure does not translate into reduced time traveled (see Section 3.5), additional carbon-intensive infrastructure can only be justified by improved accessibility (and ensuing beneficial effects for the economy), not by travel time savings. However, this well-known aspect of transportation planning can be turned into a potentially effective strategy for climate change mitigation: as people spend a constant fraction of their time traveling on average, banning or reducing speed of carbon-intensive travel options will decrease carbon emissions. Of course, this option is only sensible if the economic costs of reduced accessibility are inessential compared to the environmental benefits, as may be the case for publicly-funded, but uneconomic local airports.

A second issue is to mitigate the negative effects travel delays may have on the travelers view of the (low-carbon) public transportation system. Loss aversion regarding travel time may increase the need for measures such as informational campaigns for planned construction. This is because travelers take their preferred commuting or arrival time as well as a public transport time schedule as the reference point (see Section 3.5).

Finally, regarding **fuel economy** of cars, one policy implication is particularly salient in the literature. If loss aversion explains why consumers do not value fuel economy highly (see Section 3.6), this provides a major behavioral rationale for fuel efficiency standards, even in addition to carbon pricing

(Greene et al., 2009; Greene, 2010). An alternative suggestion is to provide shorter payback periods for automobiles with better fuel economy, for example by instant rebates instead of expecting consumers to take into account long-term fuel savings (Greene et al., 2005). Peters et al. (2008) discuss the success of various feebate schemes on behavioral grounds, exhibiting a trade-off between the range of consumers reached and limited efficiency of schemes.

5 Beyond emissions: Applying behavioral welfare theory to transport policy design

In this Section, we first introduce the impact of behavioral findings on current welfare theory. Two plausible candidates for defining welfare as a policy-goal emerge: a revision of the orthodox preference satisfaction approach and the maximization of subjective well-being. This is essential for evalutating the implications of behavioral economics for transport policy design beyond correcting externalities. In the second part of this section we then outline the major differences in the policies that follow from the two different welfare conceptions, for example, regarding commuting and infrastructure provision.

5.1 Two viewpoints of welfare

The behavioral account of how humans make economic choices renders the traditional normative approach in economics, which underlies most methods of evaluating transport policies, unconvincing (Kahneman and Sugden, 2005; Bernheim and Rangel, 2007; Loewenstein and Ubel, 2008). Several alternative approaches for evaluating economic choices, and thus welfare, are currently explored. The most important two are (i) revising the orthodox (*liberal*) preference-satisfaction approach that maintains the idea that welfare consists in having people obtain what they want; (ii) evaluating choices by their impact on *subjective well-being* (see Subsection 2.2).

It has been so far unexplored what these approaches mean for the evaluation of transport policy. The subsequent analysis adopts a 'social welfare perspective', that is, we analyze the consequences of different normative criteria as an input for public debate (Broome, 2008). The question which (independent) institutions are entitled to base their policies on subjective well-being (Loewenstein and Ubel, 2008) is a separate normative question to which we believe there is little specifically to be said about mobility. In the following, we present the two approaches and describe how they are to be understood in the context of transportation. We then state the main arguments for and against them.

Standard economic welfare analysis assumes that "whatever people choose makes them better off" (Loewenstein and Ubel, 2008). More generally, it is postulated that the goal of public policy, social welfare, is the (weighted) sum of the degree to which citizen's preferences are fulfilled. This normative position is called the preference-satisfaction view of welfare (Hausman, 2012): the optimality of policies is judged from this viewpoint in standard transportation economics. Research in behavioral economics and social psychology highlights two main difficulties for this normative theory: (i) preferences may be ill-defined or inconsistent, (ii) preferences may be systematically influenced by factors that one would not want to have any normative significance, notably the framing of a choice, the choice environment (such as infrastructure or the built environment in the context of transportation) or herd behavior.

Given these two difficulties, modifications to the standard preference-satisfaction (or: liberal) approach have been proposed. Revised versions try to save the idea that welfare is determined by how far human preferences can be fulfilled: they assume that preferences exist in most contexts and that it is possible to detect them. But the attempted revisions acknowledge that preferences sometimes need to be "laundered" (Hausman, 2012): not only because people may make errors in decisions or base their decisions on false beliefs, but also because of the factors highlighted in (i) and (ii) above. "Purification" would thus be required if choices happen in a context in which individuals are no good judges of what is beneficial to themselves, thus when people are ill-informed or preferences are distorted by the context (Hausman, 2012). In this way, a distinction is introduced between people's actual choices and their 'true' preferences: these are not simply revealed by the choices, but only emerge through 'purification' (Thaler and Sunstein, 2008; Bernheim and Rangel, 2009; Hausman, 2012) – with disagreement how exactly the purification should be carried out. With regards to evaluating transport policy, the challenge of determining the 'true' preference of mobility-users can be particularly intricate: The effect of infrastructure and the built environment on the formation of preferences is not fully explored, but it must be assumed that the built environment shapes people's modal choice (see Section 3.7). Moreover, current culture shapes mobility decisions in favor of private motorized transportation (and so creates large externalities that cause harm in all metrics of welfare usually considered). It seems therefore unclear whether it will ever be practically possible to purify preferences about mobility of such influences and whether they should be counted as welfare.

A different approach to policy evaluation is the viewpoint that subjective well-being should be maximized. Its starting point is the well-established finding of happiness studies that human beings make decisions that fail to maximize their subjective well-being (Hsee and Hastie, 2006), see Subsection 2.2. Welfare is taken to be subjective well-being as measured in happiness research (Kahneman, 2011, Part V), (Layard, 2011). Difficulties with inconsistent or undefined preferences over potential choices do not exist for this approach. However, the idea that maximizing subjective well-being is often criticized as 'paternalist', because a regulator adopting this viewpoint would base its policies on what makes people happy even if they have preferences for something else. Nevertheless, it should be emphasized that freedom is an important determinant of happiness (Helliwell, 2003; Layard, 2011, ch.5) – so in practice, any policy that curtails freedom is unlikely to promote subjective well-being. There is to date little research that determines the direct impact of transportation choices on happiness or the impact of happiness on mobility choices. Exceptions, however, include Stutzer and Frey (2008) on commuting as a factor of unhappiness, Abou-Zeid et al. (2012) on the impact of temporary mode switching and Ettema et al. (2012) on the impact of in-vehicle activities on subjective well-being as well as Goudie et al. (2014) on happiness as a driver of seatbelt wearing.

We now briefly summarize the main arguments for preferences-satisfaction and subjective well-being as welfare criteria. The debate has been typically framed around whether the maximization of subjective well-being is a good criterion for welfare because preference satisfaction is the received orthodox approach in economics (Kahneman and Sugden, 2005; Kahneman, 2011; Loewenstein and Ubel, 2008; Loewenstein, 2009; Fleurbaey and Blanchet, 2013; Layard, 2011, Part III).

There seem to be two main arguments in the literature by which authors advocating preference satisfaction theories of welfare criticize subjective well-being as an alternative criterion: (i) happiness neither should be nor is de facto the only thing people care about in life. Other important life goals that are sought for themselves and not to reach greater happiness include achievements, meaning or wisdom. (Loewenstein, 2009; Fleurbaey and Blanchet, 2013) (ii) Happiness is not a good criterion for welfare because it is no good representation of (material) deprivation: there can be 'happy peasants and miserable millionaires' (Sen, 1985, 1999; Frederick and Loewenstein, 1999). Scholars advocating the maximization of well-being typically do so because they are skeptical that procedures for 'laundering' preferences can be successful in practice. Against the two criticisms of subjective well-being as a welfare criterion, it is argued, regarding (ii), that the fact that material deprivation is not decisive for happiness implies a revision of our intuitions about welfare: curing depression should be a primary concern when mitigating inequality (Layard, 2011), and fighting poverty only in as far as it produces bad feelings. Regarding (i) advocates of subjective well-being as a welfare criterion are very skeptical about the prospect of detecting 'true' preferences. This doubt is combined with judging the idea that people want to make themselves unhappy to achieve other goals as secondary or far-fetched (Krueger et al., 2009). Alternatively, they argue that although happiness is not the only intrinsic value which makes life worthwhile (for example, meaning in life might also matter, see Baumeister et al. (2013)), it is certainly the most important one for practical purposes and thus a good first approximation for welfare in policy design (Greene, 2013).

While differences between policies aiming at maximizing subjective well-being and those aiming at preference satisfaction have been explored for the case of the health sector (Dolan and Kahneman, 2008; Loewenstein and Ubel, 2008), an analysis of the differences is lacking for the transport sector. To apply the viewpoints to transport policies, it is, first of all, crucial that both viewpoints endorse the regulation of the main externalities of motorized transportation (such as local air and noise pollution, congestion and greenhouse-gas emissions).[12] Instead, the differences between these viewpoints concern policies that are not targeted at externalities.

5.2 Assessing behavioral change from two distinct viewpoints

The classification of behavioral effects introduced in Section 3 suggests that even in a transport system in which the main externalities of road transport are internalized there are many important policy choices to be made regarding the specifics of mobility – in particular concerning mode choice. We substantiate this claim by discussing four important cases in which the behavioral account of mobility choices yields different policy recommendations from the two dif-

[12] For liberalism, correcting an externality increases welfare by the first fundamental theorem of welfare economics. Although it is not true in principle that from the viewpoint of maximizing subjective well-being correcting externalities always enhances welfare, it is true in practice for the main externalities of the transport sector due to their adverse impact on a (longer) happy life.

	Subjective well-being	**Liberalism**
Env. awareness	Rewards for individual altruistic behavior	No particular rewards
Mode choice	Incentives for NMT, change in social norms and cues against biases	Degree of incentivizing NMT depends on type of liberalism
Safety	Disincentives for risky behavior	No disincentives for risky behavior unless: others at risk or preferences about risk inconsistent
Commuting	Disincentives for commuting	No disincentives for commuting
Car purchases	Vehicle tax according to status component of car	Imposition of 'status tax' depends on type of liberalism
Infrastructure	NMT priority, urban planning for short commutes	Not directly applicable, alternative: elicit preferences in simplest context

Table 3: Transport policies for various mobility aspects that can be justified by either maximizing subjective well-being or satisfying preferences (liberalism). "NMT": Non-motorized transport

ferent viewpoints on welfare: (i) the influence of infrastructure and the built environment, (ii) health benefits from non-motorized transportation, (iii) the fact that commuting causes significant unhappiness and (iv) status-seeking behavior about mobility choices. Table 3 provides a summary.

First, transport infrastructure and the built environment shape people's preferences and influence how their preferences translate into choices (see Section 3.7). For liberalism, this implies that people's *actual* preferences are no sound basis for transport project appraisal. This is because if transport infrastructures influence preferences and decisions *subconsciously*, as is mostly the case, one would not want to count them as normatively relevant. Potentially, liberal approaches could circumvent this difficulty by eliciting preferences over hypothetical residential choices or designing experiments that uncover people's true preferences over the built environment. If, alternatively, one takes subjective well-being as a welfare criterion, this difficulty does not arise: changes to the built environment would be beneficial if they raise subjective well-being, regardless of whether or not preferences are influenced by these changes. While no research on this exists, it seems conceivable to determine the influence of various different possible transport infrastructures on the population's subjective well-being by field experiments.

Second, assessing the health benefits from non-motorized transport (see Section 3.2) depends crucially on the normative viewpoint chosen. For the view that welfare consists in subjective well-being, improvements in health through more physical exercise can be straightforwardly counted in terms of a subjective well-being metric, but also in terms of increased life span.[13] For

[13]Measures of the burden of disease such as 'disability adjusted life years' (DALYs) or 'quality adjusted life years' (QALYs), which are widely used in public health research, implicitly and partially take the view that welfare is subjective well-being. Although these are not based on state-of-the-art happiness measurement, this is so because these metrics count welfare improvements through better health in terms of greater quality and greater length of life. They do so independently of whether individuals have a preference for living longer and healthier when confronted with a range of healthier or less healthy options, for instance, regarding drug use

the view that welfare consists in the satisfaction of preferences, an assessment of such health benefits depends strongly on the normative treatment of time-inconsistent preferences (Bernheim and Rangel, 2007): is people's 'true' preference regarding modal choice in cities to opt for a comfortable drive that is adverse to their health in the long-run or is their 'true' preference to stay healthy while they are unsuccessful in getting themselves to travel by other options?

Third, should the negative impact of commuting on subjective well-being influence project appraisal or not? Commuting is a non-negligible cause of human unhappiness (see Subsection 3.4) as people systematically choose larger houses and higher salaries over more leisure time for socializing. From the viewpoint of liberalism, this effect is not relevant for transport policy. For the viewpoint of subjective well-being, one should curtail commuting (for instance, Kahneman and Krueger (2006) suggest to tax it) and also take the finding into account when assessing the merit of infrastructure projects.

Finally, the effect that there exists status-seeking behavior regarding vehicle ownership means that, for the purpose of raising subjective well-being, one would regulate such behavior because it creates an efficiency loss in subjective well-being (Layard, 2006). On the contrary, whether regulating status-seeking behavior would be mandated from the viewpoint of liberalism depends on whether one judges status-seeking as a proper externality or believes that people engage willfully in it.

Beyond the four cases described above, there may also be minor differences regarding environmental awareness, because altruism generally leads to greater happiness (Post, 2005), and safety (overriding preferences for risky behavior – or not).[14]

6 Conclusion

This article presents a descriptive and normative analysis of behavioral effects in mobility decisions to improve the design and justification of transport policies. The main descriptive conclusion is that the preferences, heuristics and forms of decision-making identified by behavioral economics are indispensable to explain mobility behavior methodically. A particularly policy-relevant class of effects arises from the influence of transport infrastructures on decision-making through framing and the formation of preferences regarding mode choice. We argue that our descriptive analysis necessitates a revision of the standard approach to policy evaluation in transportation. Either the orthodox economic understanding of welfare as preference satisfaction must incorporate differences between actual and 'true' preferences of transport users. This matters particularly when the infrastructure influences decisions and for time-inconsistent preferences yielding health benefits of non-motorized transport. Or transport policies can be grounded in the aim of maximizing subjective well-being. Key differences to the preference approach concern status-

and dietary choices.

[14] A potentially further important reason for distinguishing the two viewpoints in transportation is the argument that reduced geographical mobility and quieter urban quarters lead to greater social cohesion and better mental health and thus greater happiness (Layard, 2011), despite individual preferences for car-friendly road design and anonymity. We exclude it here, because the arguments have not (yet) been based on specific behavioral effects.

seeking behavior and commuting, as agents systematically do not choose what makes them happy when traveling.

There are potential applications of our analysis to transport modeling and policy design. First, standard transport demand modeling, based almost exclusively on the rational choice approach, may be enhanced by incorporating the behavioral effects that are particularly relevant for the given context, such as mode choice or trip scheduling, which may vary widely across levels and world regions. Notably, *dynamic* models (with long time horizons) would need to consider the issue of the influence of the physical and social context on preference *formation*. In other words, preferences should be, to some degree, endogenous in such models. Second, behavioral effects in the decision-making of firms likely matter for explaining mobility – particularly with respect to car purchases –, but these are typically neglected in discussions of behavioral approaches to transport policy and should be taken into account. Third, our analysis of the possible justifications for transport policies may lead to a more consistent policy design according to policy-makers' tastes. It sharpens the debate concerning trade-offs in transportation, for instance, between better health and shorter commutes as opposed to greater individual liberties. Fourth, a systematic understanding of the available behavioral policy options to decrease emissions emerges from our work.

Beyond the specific details of our analysis for the field of mobility, some more general lessons may emerge for behavioral economic approaches to climate change mitigation: For instance, the behavioral effects explaining why individuals have a propensity to maintain the status quo may be suspected to present obstacles for decarbonizing emissions from buildings. Further, preference formation may play an important role not only for understanding mobility, but also for dietary choices. Altogether, whenever end-user behavior is particularly relevant, the design of mitigation policy packages likely benefits from taking behavioral effects into account.

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Chapter 9

Synthesis and outlook

This thesis is organized around two distinctions. When applied in economic theory of climate change mitigation, these may lead to a better understanding of the extent to which the two narratives about market economies sketched in the introduction are valid: is capitalism exploitation or liberation? The first distinction is about the nature of production factors. When rents from fixed factors are distinguished from interest on capital, rent taxation can be distortionary, but both efficiency-enhancing and inequality-reducing. This is thus the most desirable means of generating fiscal revenue, at least when private capital is under-accumulated. The second distinction is about evaluating the welfare derived from consumption. Under the behavioral account of decision-making, subjective well-being is different from preference satisfaction, because humans do not always rationally pursue their own interests and do not necessarily choose what makes them happy.

Throughout this thesis, these distinctions have been applied to the challenge of determining the best way of financing public investment for the transition to the low-carbon economy, considering both efficiency and equity. A third theme that has emerged from the findings of this work is thus that trade-offs between equity and efficiency in financing public investment are not in line with the received view that redistribution leads to an efficiency loss. Instead, reducing inequality may lower or raise efficiency, or leave it unaffected, depending on the financing-mechanism. This final chapter reviews the results of the previous chapters in the light of these three themes – rent taxation, equity-efficiency trade-offs and behavioral welfare theory – and discusses the broad implications of the results. It subsequently surveys opportunities for future research and finally comments on the policy relevance of the findings.

9.1 Synthesis

This section summarizes the main findings of the previous chapters on the welfare effects of financing low-carbon public investment. Rent taxation as a financing option was the central theme of Part I. New conclusions about the relationship between equity and efficiency aspects of climate-friendly public investment were reached in both Part I and II, notably in Chapters 3, 4, 6 and 7. Behavioral welfare economics needed to be applied to understand the effects of providing low-carbon transport infrastructure in Chapter 8. The results are subsequently related to the research questions posed at the end of Chapter 1.

9.1.1 Rent taxation

Part I of this thesis considered how taxing the land or climate rent and recycling the revenue can lead to socially optimal outcomes. Two options for revenue recycling were considered across chapters: financing productive public investment and redistribution through direct payments targeted at specific generations. Finally, Chapter 5 considered decarbonization as a transition phenomenon and pointed out that the timing of low-carbon infrastructure investments can help avoiding a lock-in. The main findings are discussed in turn, each paragraph below corresponding to one of the four questions highlighted at the end of the introductory chapter:

- How can the efficiency aspects of (land) rent taxation be evaluated normatively? How can socially optimal outcomes be achieved when redistribution of revenues may be age-dependent?
- Is the distortion due to the appropriation of the climate rent beneficial?
- Can the idea of using revenues from rent taxation for productive public investment be adapted to a macroeconomic scale?
- How does the timing of infrastructure investment matter? How can socially optimal outcomes be achieved when infrastructure enhances substitution between carbon-intensive and low-carbon production?

Chapter 1 rehearsed the traditional argument that taxing the rent of a fixed factor is non-distortionary. It then discussed the insight of Feldstein (1977) that when households hold both productive capital and a fixed asset and there is underaccumulation of private capital, rent taxation can in fact be *distortionary, but beneficial*. Households must be heterogeneous for this to occur, so that land will actually get traded. This leaves open the question whether this beneficial effect can be *socially optimal* and how this depends on the revenue recycling. Also, taxing the rents from exhaustible resources, not just those from statically fixed factors, such as land, should be positively distortionary, but this has only been conjectured by Feldstein (1977). One way a climate policy regime could limit the effects of global warming is to define a scarce disposal space of carbon in the atmosphere. In that case, appropriating the rent associated with this scarcity, the climate rent, would correspond to auctioning instead of grandfathering permits in an emission trading scheme.

Social optimality through redistribution

To examine the social optimality of distortionary, but beneficial rent taxation when the stock of private capital is suboptimally small, the continuous (Yaari (1965)-Blanchard (1985)) overlapping generations model was extended to include a fixed factor, land (Chapter 3). In this model, generations face uncertain lifetimes and new generations that are fundless are perpetually born. The social optimality of a policy in this model was assessed following the approach of Calvo and Obstfeld (1988): under the natural extension of the orthodox definition of welfare as the satisfaction of preferences of all generations, the optimal aggregate dynamic allocation is independent of the static one.

The main result was that rent taxation can be socially optimal when combined with recycling the revenues as transfers that are biased towards the young, poorer generations. A uniform revenue recycling, for example, cannot be socially optimal. Moreover, the feasibility of reaching the socially optimal allocation can be characterized as follows: the missing capital share of the newborn generations must be smaller than the transfers that they can receive, which can be at most the entire land rent (see Chapter 3, Theorem 2 and Proposition 1). This condition is fulfilled by a wide margin for a diverse set of countries (see Chapter 3, Section 4.2). The main message was thus that rents should be taxed not only for an efficiency reason, but for a distributional motive: the social optimum can *only* be reached with redistribution, not without, in stark contrast to the paradigm that redistribution leads to efficiency losses.

The case of the climate rent: distortionary and beneficial as well?

Chapter 4 modified the set-up of Chapter 3 to study appropriation of the climate rent under the same condition of heterogeneous households and capital underaccumulation. To generate balanced paths, government-funded technological progress was assumed to offset reduced availability of fossil resources or of the atmospheric disposal space. The chapter proved that taxing the climate rent is indeed distortionary and beneficial, as appropriating it fosters capital accumulation, when households hold both capital and fossil resources as assets (Chapter 4, Theorem 1). Furthermore, it was examined how this "portfolio effect" translates to various ways of correcting the climate externality. For the case of an emission trading scheme that limits the atmospheric carbon disposal space, rent appropriation corresponds to auctioning, instead of grandfathering, permits. It was shown that both for the case of short- and long-lived permits, the beneficial effect occurs (Chapter 4, Corollary 2). A carbon tax would not define a scarce atmospheric resource, but appropriate rents from the fossil resource stocks. For the case of a constant carbon tax, the existence of the beneficial portfolio effect can be proved. However, in the setting of Chapter 4, if a carbon tax shall induce resource conservation (and thus climate protection) it must be *decreasing* (Sinclair, 1994). For this case, the effect could only be conjectured because a part of the resource rent is nevertheless appropriated by the tax. Finally, when households are given a share of the atmospheric stock (instead of revenues from extracting fossil resources), this also induces the portfolio effect.

Moreover, it was shown that the results on the social optimality of a policy carry over from the case of taxing the fixed factor land. When the climate rent is greater than the amount needed to finance fossil resource-augmenting technological progress, the remainder can be used to reduce intergenerational inequality and potentially reach the social optimum, according to the conditions derived in Chapter 3. Environmental economics traditionally assumes that auctioning, instead of grandfathering permits is important for distributional, but not for efficiency reasons. In summary, a new reason, shown in Chapter 4, for auctioning permits, instead of grandfathering them, is that auctioning also improves macroeconomic efficiency while reducing inequality between generations. In contrast to the ‘classical’ double dividend of cutting pre-existing distortionary taxes, the effect exhibited here is *unambiguously* welfare-enhancing as long as private capital is underaccumulated.

Social optimality through productive public investment

The problem of the global commons consists not only in overuse of natural common-pool resources, but also in underprovision of some public goods, notably public capital stocks, such as infrastructure and those underlying health and education services (as outlined in Section 1.2). This thesis examined, specifically, whether revenues from rent taxation can be used for financing productive *public* investment. It was concerned with deriving conditions for when such a policy can be socially optimal, both when rent taxation is distortionary and when it is not.

Chaper 2 discussed the case of non-distortionary rent taxation with an infinitely-lived agent model. When investment into a stock of productive public investment needs to be financed by the government, the social optimum can be reached by taxing the rents of a fixed factor, as long as the rent is higher than the socially optimal investment. This is a macroeconomic analog of the Henry George Theorem of urban economics, which shows that a local public good is fully capitalized in the differential urban land rent. The result of Chapter 2 provides a weaker condition for optimal financing because the tax on the rent of the fixed factor need not be 100 %, it must only be so high as to reach the socially optimal investment. It is a very robust relationship, as it holds both in a steady-state as well as during the transition to it. It also holds for both the case of decreasing or constant returns to scale in private and public capital, and thus neoclassical or endogenous growth. While the *socially optimal* level of public investment is difficult to determine empirically, Chapter 2 also illustrated that resource rents are (much) higher than *actual* public investment in many countries.

The main result of Chapter 2 notably also carried over to the setting of distortionary rent taxation in Chapter 3 and 4: With overlapping generations and capital underaccumulation, the revenue from taxing the rents can be used to finance productive public investment. However, the result will only be socially optimal if the rent from the fixed factor is greater than *the sum* of the missing capital share of the newborn generations *and* the socially optimal amount of public investment (see Chapter 2, Section 5.2 and Chapter 3, Section 4.3).

In summary, Chapters 2–4 proved that rent taxation can achieve the social optimum if one can fulfill the revenue requirements from investing in public capital, supporting disadvantaged cohorts and financing low-carbon technologies, depending on which of them are relevant for the case at hand.

Rent taxation and public investment: an issue of timing

However, Chapters 2–4 did not consider that taxing (the climate) rent and investing in public capital happens during a *transition* to the low-carbon economy. The concept of a transition should be understood in two ways in this context. First, alternative low-carbon technologies and infrastructures are or may become available that one might not want to conceptualize as fossil resource-augmenting technological progress, but as a separate sector to which production switches over time. Second, additional insights about policy options may be gained by considering decarbonization (mathematically) as a transition between two steady states of a dynamical system and not to be described by balanced paths.

The nature of the transition, encompassing both these senses, was the subject of Chapter 5. There, the impact of the timing of low-carbon public investment on a possible “carbon lock-in” through imperfect climate policy was studied, not its financing. An approach similar to that of Kalkuhl et al. (2012), who assume a positive learning-by-doing externality for carbon free technologies, was adopted to generate a lock-in.

Low-carbon infrastructure investment was modeled as increasing the substitution elasticity between “clean” and “dirty” intermediate production. To study its effect, a two-sector neoclassical growth model with a stylized climate module was examined numerically. The main finding was that the substitution elasticity plays an ambivalent role for the prospect of a carbon lock-in through uninternalized learning-by-doing in clean technologies: a high elasticity leads to a greater lock-in for the unregulated equilibrium, but requires less drastic policy interventions to reproduce the social optimum. The reason is that a low elasticity generates some intermediate demand for clean production, even if it is initially not competitive and thus fuels learning-by-doing in the clean sector. Further, the policy measures need to be in place permanently for stabilizing the climate. It could hence be shown that the policy implications of Acemoglu et al. (2012) are limited in scope, as those authors call for a merely transient policy intervention, based on the mechanism of directed technical change in an otherwise similar model set-up.

Further, simulations showed that low-carbon public investment that increases the elasticity impacts the lock-in as follows: if the investments are carried out too early, they may exacerbate welfare losses from the lock-in if carbon pricing or technology subsidies do not correct the respective externalities adequately. If infrastructure investments are made too late, sufficient mitigation requires very high carbon pricing.

9.1.2 Equity and efficiency effects of financing options for public investment

Beyond rent taxation, this thesis considered, in Part II, the equity and efficiency aspects of financing public investment. The main message was that there is not an equity-efficiency trade-off as such: welfare-enhancing public investment does not necessarily perpetuate or raise inequality. By contrast, whether equity and efficiency are conflicting goals depends chiefly on the financing-mechanism. While capital taxation lowers inequality, it is the least efficient way to raise the funds needed for the investment. For rent taxation as a financing option, it was already shown in Part I that using it to finance public investment may both enhance productivity and decrease inequality, albeit this conclusion was reached by assuming that households are homogenous in preferences and income sources. Part II considered the case of households that are heterogeneous in their saving behavior and their income source: wealth owners were either dynastically saving and owners of capital income only, or life-cycle savers, saving out of their labor income for retirement. This stylized division is in accordance with empirical evidence about the wealth distribution (see Section 1.3) and takes up concerns that distinctive behavior of social classes may matter, as emphasized in classical economics. It was formalized by modifying a (neoclassical version of a) two-class model due to Michl (2009). The model contains a version of the Pasinetti (1962) Paradox when there are decreasing returns to private and public capital: in the long run, dynastically saving households determine the interest rate, while life-cycle savers determine the distribution of wealth between the two classes. In this context, capital, labor and consumption taxation were examined as financing options for public investment and their impact on efficiency and equity was examined in Chapters 6 and 7. To assess the effects of labor and consumption tax financing, a labor-leisure choice was considered, with public investment both enhancing aggregate productivity and the quality of leisure. The results are summarized below, with reference to the research questions posed at the end of the introductory chapter.

- Can productive public investment be financed in a way that at the same time reduces inequality? How does the heterogeneity in saving motives and income sources across households matter for this? What are the differences between capital, labor and income taxation as financing options in this context?

Capital income taxation

Taxing capital and using the revenues for financing productive public investment was identified, in both Chapters 6 and 7, as enhancing efficiency, while at the same time decreasing inequality (in wealth, income and welfare). When there are decreasing returns to private and public capital, the reason for this is the Pasinetti Paradox: a capital tax makes saving less attractive, so that high-income households reduce their investment. By the Pasinetti Paradox, the interest rate is, in the steady state, solely determined by the high-income household's time preference rate and the tax rate, regardless of how the tax proceeds are used. As the interest rate increases due to applying the tax (less capital is supplied by the high-income household who determines the aggregate capital stock), middle income households are induced to save more, so that inequality – in wealth, and consequently in income and welfare – is reduced. At the same time, for lower tax rates, the efficiency gains through increased public investment can lead to Pareto-improvements. Nevertheless, for high-income households a lower tax rate is optimal than for low-income households, who prefer a higher capital tax.

Chapter 7 also numerically explored the transitional dynamics of a change in the tax rate and found that in terms of inequality measures, there is monotone convergence to the new steady state except for some initial behavior. For the case of endogenous growth through constant returns in accumulable factors, in which there is no Pasinetti Paradox occurring, the above is still valid, except for small values of the capital tax. However, an analysis of differing optimal tax rates across classes or Pareto-improvements is not appropriate, since all aggregate quantities grow at the same rate.

These results are in contrast to related literature (Glomm and Ravikumar, 1994; Chatterjee and Turnovsky, 2012) that finds that, in the long-run, capital taxation for public investment increases inequality in wealth or is distributionally neutral, despite some empirical observations to the contrary (Calderón and Servén, 2014). The reason for our deviating conclusions is the assumed household heterogeneity in preferences and income sources, while those studies rely on heterogeneity in initial endowments only. However, I confirm that capital tax financing is, unsurprisingly, the least efficient financing option.

Labor income taxation

Labor income taxation for financing public investment, by contrast, is the most efficient financing option for tax rates greater than 20%, but raises strong equity concerns. Under the assumption that households face a labor-leisure choice, inequality in wealth and welfare – but most strongly in income – rises in the long-run, the higher the labor tax. Middle-income households naturally prefer a lower labor tax rate than high-income households, who were modeled as not earning any income from labor. Despite the endogenous labor supply decision of middle-income households, labor taxation is very efficient. The reason is that public investment is assumed to enhance utility derived from leisure, dominating the negative influence of the tax on the labor supply. Transitional dynamics are influenced by the Pasinetti property of the model: wealth dispersion decreases initially and income inequality converges to its new (higher) steady-state level from above.

The results for the case of endogenous growth are similar, except that wealth dispersion slightly decreases for tax rates up to 20 %, the reason being the very high productivity of public capital in this case.

Consumption taxation

Consumption tax financing of public capital has no substantial long-run distributional impacts, as one would expect, and is the most efficient financing option for tax rates below 20 %. Out of the three possibilities it has the broadest tax base. It is outperformed by the labor tax for high tax rates. This is so, because for high labor tax rates, middle-income households' savings are strongly disincentivized, which is very efficient due to the complementarity of private and public capital, noting that total capital is fixed by the Pasinetti property anyway. For both types of households, approximately the same consumption tax rate is optimal. Transitory effects of a consumption tax increase are similar to those of the labor tax.

The picture is very different for the case of endogenous growth. In this case, consumption tax financing is not distributionally neutral anymore. While there are no substantial effects on the welfare dispersion, consumption tax financing produces a substantially declining wealth dispersion in this case, while yielding an increasing income dispersion for lower tax rates. These effects are present because public capital is enormously more productive than in the case of decreasing returns to accumulable factors (for a detailed explanation see Chapter 7, Section 4.1).

9.1.3 Behavioral welfare theory: lessons from mobility behavior

Low-carbon public investment not only has distributional effects, but may also induce behavioral change in some sectors. Chapter 8 examined the policy implications of applying the behavioral account of decision-making (DellaVigna, 2009; Kahneman, 2011) to mobility choices. It analyzed which behavioral effects particularly matter for mobility decisions and judged the effectiveness of behavioral interventions in the decarbonization of mobility. It also analyzed the requirements for a satisfactory welfare conception to evaluate the ancillary benefits from climate change mitigation in that sector. The role of the urban transport infrastructure (as an example of low-carbon public investment) was particularly highlighted. The chapter's results are linked to the research questions of the introduction below:

- When does the behavioral account of decision-making matter for climate policy? How does it explain mobility choices? What are implications for designing mitigation measures and more generally for welfare analysis of transport policies? What can be learned from the influence of the transport infrastructure, as an example of productive public investment, on mobility decisions?

Mobility behavior

Behavioral effects are relevant for designing policies reducing emissions from several carbon-intensive sectors, particularly transportation, the buildings sector and food consumption. Whenever consumers' choices significantly affect the carbon content of products, behavioral effects matter. Even for electricity, a very homogenous good, some form of status quo-bias or inertia (in changing electricity providers) may be highly relevant for designing mitigation policies (Sunstein and Reisch, 2013).

Mobility decisions are particularly subject to large behavioral effects (as testified by a large literature on transport psychology, see *Transportation Research Part F: Traffic Psychology*) because they are about choices between diverse and heterogeneous options. So the idea that individuals do not necessarily maximize a utility function representing their stable preferences about only their own consumption (see Subsection 1.4.1) means for transport economics that mobility choices are about more than cost and travel time. Chapter 8 argued that the standard division of behavioral economics to distinguish preferences, beliefs and decision-making in order to understand choices (DellaVigna, 2009) is useful to organize findings from transport psychology and facilitates an evaluation of their policy relevance. It found that in particular the following effects matter for the explanation of mobility behavior (see Chapter 8, Table 1):

Regarding *preferences,* time-inconsistent behavior explains self-control problems in using non-motorized transport options. Loss aversion is a major explanation for a variety of mobility behaviors, including the valuation of safety measures, the reliability of public transport and fuel economy. Social preferences sometimes motivate individuals to make pro-environmental mobility choices, whereas, by contrast, status-seeking behavior is present in car purchases.

Regarding *beliefs,* much risky traffic behavior is caused by overconfidence in own (driving) abilities. Further, a misprediction of one's adaptation to the value of money and housing explains why some individuals choose longer commutes although these are a source of unhappiness.

Regarding *decision-making,* framing effects are likely to be ubiquitous in mobility behavior and have been in particular demonstrated for the presentation of information about the public transport network and the environmental impact of a decision. Further, decision-making regarding safety aspects of a journey and car purchases is sometimes determined by feelings and not by utility-maximization. Limited attention and social pressure also explain trip, safety and purchase decisions.

Notably, the infrastructure may influence decisions both through framing (although there is little research on this) and *preference formation:* the built environment that individuals live in shapes their preferences underlying mode choices. Preferences are thus not fixed, but endogenous to the infrastructure in place over long time-scales.

Welfare and low-carbon transport

For policy design, the message of the descriptive analysis of Chapter 8 is that, when designed appropriately, one can indeed "nudge" (Thaler and Sunstein, 2008) individuals into low-carbon mobility behavior, given the particular significance of framing, social preferences, loss aversion, time-inconsistent preferences and limited attention for mobility choices. Behavioral interventions whose effectiveness in exploiting such determinants of choices has been confirmed were summarized: fuel efficiency standards effectively address loss aversion, myopia and bounded rationality with respect to fuel economy considerations in car purchases. Framing effects may be exploited for increasing environmental awareness. Status quo biases in mode choice can be overcome using various strategies for facilitating social learning about other modes. Preliminary evidence suggests that providing more attractive infrastructure for walking and cycling increases their modal share. When pricing transport emissions at a national or urban level is not politically feasible, a systematic understanding of the available effective behavioral policy options (see Chapter 8, Table 2) may thus make substantial decarbonization of urban mobility possible nevertheless.

But low-carbon transport systems have large ancillary benefits beyond climate change mitigation, for instance promoting better health (Woodcock et al., 2009). The distinction between welfare as subjective well-being or as preference satisfaction has been shown to elucidate transport policy appraisal in this context: it was argued that the distinction leads to a different set of desired transport policies because of four behavioral effects. First, the infrastructure shapes preferences. Second, there are health benefits from non-motorized mobility that many individuals do not reap, which is likely due to self-control problems and limited attention. Third, commuting is a source of unhappiness. Fourth, status-seeking behavior is present in car purchase decisions. For each of these four contexts, the two welfare conceptions will evaluate policies differently: the preference satisfaction view will put more emphasis on individual liberty (even if preferences may need to be 'purified', see Subsection 1.4.2) than the happiness view. The chapter thus made explicit the trade-offs between greater individual freedom and better health and mood implicit in transport policy debates. The case most difficult for the preference satisfaction view to deal with is that mobility preferences may be shaped by urban infrastructures. It is at present unclear how a liberal definition of welfare could be resurrected to be applicable when this matters. Options include eliciting preferences about urban environments through hypothetical residential choices or counting availability of choice options, not preference satisfaction, as welfare.

The broader message of the chapter is thus that the behavioral account of decision-making should be considered more when designing climate policy for those sectors in which household's decisions have a strong impact on the carbon-intensity. Further, mobility has served as a concrete example for applying the distinction between subjective well-being and preference satisfaction to illustrate how one can conceptualize consumption as potentially sometimes good and sometimes bad for welfare (see also below).

9.1.4 Common insights and their broader significance: evaluating the validity of the two narratives about capitalism

This thesis studied the welfare implications of low-carbon public investment by applying three methods: first, Ramsey-type growth models and the continuous overlapping generations model were used to study aggregate efficiency and *inter*generational redistribution when investment is financed by rent taxation. Second, a two-class model examined aggregate efficiency and *intra*generational redistribution when investment is financed by capital, labor or consumption taxes. Third, effects on consumption decisions of low-carbon investment in the transport sector were evaluated, drawing from the emerging welfare theory of behavioral economics. Here I discuss common insights and explore their broad implications.

Commons insights

First, to understand the financing options for public investment, a crucial distinction is to divide production factors into those that are fixed, yielding rents, and capital, which can be accumulated and yields interest. In summary, Chapters 2–4 endorse the received view that rent taxation is a good thing, but do so for a number of new reasons. The results prove that rent taxation can achieve the social optimum if one can fulfill the revenue requirements from investing in public capital, supporting newborn cohorts and financing low-carbon technologies, depending on which of them are relevant on a macroeconomic scale. The reason is that rent taxation is distortionary when capital is underaccumulated, but beneficially so: it is thus not only a financing option that does essentially no harm to aggregate efficiency. This thesis showed that it can even *increase aggregate efficiency by reducing intergenerational inequality*. The additional effects exhibited in Chapter 5 could, in principle, be incorporated in the models of Chapters 2–4, without generating new effects. The results of the chapter are in line with the idea that the global commons problem is economically about taxing rents from overused natural resources to fund underprovided public goods, but focuses on the particular aspect of a lock-in through unappropriated learning-by-doing during a transition.

The second theme of this thesis is that financing public investment leads to no straightforward equity-efficiency trade-offs, once one takes into account a credible microfounded representation of household heterogeneity. It applied a characterization of wealth ownership by the existence of two groups of households, wealthy, self-employed dynasties and a life-cycle saving middle-class. The common insight of Chapters 6 and 7, using a two-class model reflecting such a division is that the intragenerational redistribution of public investment depends strongly on how revenue for this is raised. Capital taxation reduces inequality and raises efficiency at the same time, but labor and consumption tax financing are more efficient.

Can these first two strands be unified? A model incorporating all aspects seems out of reach, because of the difficulty of combining the two-class approach with the distinct effects generated by the continuous overlapping generations model. However, the two-class model could be modified by incorporating aspects of Part I of the dissertation: first, wealthy households could well own both capital and a fixed factor. So the results of Chapter 2 on financing public capital by rent taxation (with dynastic households only) can be conjectured to be valid in that context as well.[1] Second, public investment in the two-class model could be understood as being explicitly about low-carbon investment, for instance about improving resource efficiency (as in Chapter 4).

The thesis finally looked at the behavioral effects of providing low-carbon infrastructure for urban mobility. Since the first two strands of the thesis are based on macroeconomic modeling and the behavioral welfare theory that is the subject of the last strand is based on microeconomic analysis of consumer behavior, no attempt will be made here to unify the two.[2] Instead, I contend that the macroeconomic applicability of the welfare analysis of transport policies lies in its potential to evaluate critiques of materialism. The distinction between subjective well-being and preference satisfaction is not only useful for evaluating sectoral ancillary benefits in climate change mitigation. On the contrary, the analysis for the case of transportation suggests a wider signifi-

[1] A different approach to unifying the two strands is taken by Franks et al. (2015), who present a model that integrates them by considering *heterogeneous tastes for bequests* in a discrete overlapping generations model.

[2] Economists seem to often eschew the question whether phenomena of macroeconomics can be reduced to microeconomics or whether they are emergent, thereby obfuscating the epistemic status of macroeconomics (Hoover, 2014). While "providing microfoundations" is usually considered an academic achievement, the "microfoundations" typically embodied in macroeconomic work are extremely stylized and, given the behavioral account of decision-making, do not seem adequate for the reductionist perspective. I suspect that the philosophical debate over reductionism and emergence, widely agreed to be relevant for some other scientific disciplines, might fruitfully inform the issue, for example concluding in a reductionist vain that macroeconomics often needs microfouncations that are properly behavioral (Akerlof, 2002). By contrast, if opting for emergence, macroeconomic models would not need to insist on microfoundations, at least not on ones that represent credible micro-behavior (Hoover, 2007), but might at times "involve turning away from hard math back toward rough-and-ready assumptions based on empirical observation." (Krugman, 2014a)

cance, because behavioral effects such as time-inconsistency or status-seeking seem decisive in understanding when one should deem consumption as *not* increasing welfare.

Finally, a model unifying both the effects of infrastructure investments on productivity *and* preferences would need to treat consumption very differently from production. For the effects on production, several modeling perspectives are well established (see Section 1.2.2). By contrast, work on the effects on consumption does not exist, at least from a macroeconomic perspective. The conclusions of Chapter 8 suggest that somehow distinguishing "superficial" from "fundamental" preferences is needed to come to terms with the influences of the choice-environment on preferences over long-time scales.

The extent of the validity of the two narratives

I began this thesis with the insight from social psychology that there are only two major narratives about capitalism that dominate discourses about economic policy: does a market economy promote liberation or exploitation? (Haidt, 2015, see also Greene, 2013, p. 341) I am finally in a position to evaluate the claim that the results of this thesis might contribute to a better understanding about the extent to which the two narratives are valid in a climate-constrained world.

First, distinguishing fixed factor rents from capital income matters. A recent blog exchange between Paul Krugman and Gregory Mankiw illustrates this. Krugman (2014c), discussing the significance of the messages of Piketty (2014) for U.S. economic policy, claims that the tax cuts of the George W. Bush administration benefited the "unearned income [...of] coupon-clippers and heirs to large real estates", in short, the rentiers. He concludes that "America's nascent oligarchy may not yet be fully formed – but one of our two main political parties already seems committed to defending the oligarchy's interests." (Krugman, 2014c)

By contrast, Mankiw (2014), in view of Krugman's conclusions, attests that the latter "takes a policy favored by the right, attributes the most vile motives to those who advance the policy, and ignores all the reasonable arguments in favor of it." Mankiw continues to point out that "...there is a large [body of] literature in economics suggesting that an optimal tax system imposes much lower taxes on capital income than on wage income (or consumption). I can personally attest that President Bush's economic advisers were well aware of this literature." In the context of this thesis, Mankiw's reply highlights that mainstream economic theory is dominated by the liberation narrative and the political importance of this.

Distinguishing in this thesis capital that can be accumulated from fixed factors that yield rents, as the economics of the 19th century did, has been shown to be a way to make sense of the idea that there may be different kinds of wealth that are "good" and "bad" for economic performance. Further, reintroducing fixed factor rents into a growth model opened new ways for mitigating intergenerational inequality. As Mankiw's statement testifies, embedded in the liberation-narrative is the claim that capital taxation is undesirable.[3] Supporters of the exploitation narrative, by contrast, often express an ardent desire for more capital taxation, not only for a distributional motive, but also to tame the mischief of the greedy rich, as exemplified by Krugman's view. The distinction between rents and capital might help to reconcile these viewpoints: this thesis confirms that capital should not be taxed or should even be subsidized, at least disregarding concerns for *intra*generational equity, thus siding with the liberation view. By contrast, rent taxation can enhance aggregate efficiency, partially validating the exploitation view. In particular, there may be an additional distributional reason why rent taxation is desirable, notably when the revenue is recycled as a subsidy to the current young.

This delineation of the extent to which the two narratives are valid also carries over to climate policy: supporters of the liberation narrative agree that externalities should be corrected (to enhance efficiency), which is of course the major rationale of environmental policy. The exploitation view adds that unmitigated environmental problems are not only bad for the environment – but may distort economic outcomes because not regulating them often means not appropriating rents for the common benefit. Chapter 4 corroborates the latter idea, highlighting that auctioning permits of an emission trading scheme is not only desirable because of distributional concerns, but also in order to enhance aggregate efficiency.

Second, when intragenerational equity is the focus of economic policy, the validity of each narrative *inter alia* depends on whether one believes that class structures exist and influence the formation of the interest and saving rate. This thesis reconfirmed this lesson familiar from the debates between classical and neoclassical growth theory (Michl, 2009) and applied it to the case of public investment. Previous studies on the distributional effects of infrastructure-financing find either a trade-off between aggregate efficiency and redistribution or that public investment is distributionally-neutral (Alesina and Rodrik, 1994; Glomm and Ravikumar, 1994; Chatterjee and Turnovsky, 2012). These studies use the "classless" view that households have identical preferences and income sources, but differ in their initial endowments only (which are potentially subject to uninsurable random shocks). By contrast, the empirical evidence on widely differing saving behavior across the wealth distribution lends some support to the view that "class structure" is economically relevant, and Chapters 6 and 7 highlighted that it can influence aggregate economic outcomes.

Regarding public expenditure, the liberation narrative seems embodied in the idea that this is desirable whenever it enhances aggregate efficiency, including in the relevant cost-benefit-analysis any welfare losses from the distortions involved in raising revenue (see Barro, 1990). By contrast, the exploitation view stresses that concerns about inequality cannot be separated from efficiency aspects of public investment: an exclusive focus on efficiency is for its proponents the wrong framing for assessing any kind of government action. Chapters 6 and 7 can be seen as a reconciliation of these views as follows: efficiency can still be the focus of analyzing the effects of public investment even when considering class distinctions – and these can matter for assessing efficiency. If one considered the magnitude of the numerical results of Chapter 7

[3] At least since Mill pointed out that capital taxation means to tax income twice (Mill, 1848/1909, V.2.22).

as capturing something about economic reality, they would provide a good reason to agree with the liberation view on the question of financing public investment. Labor or consumption tax financing is much more efficient then capital tax financing (although it is a separate question whether such efficiency gains could actually be used also to combat inequality).

Finally, the behavioral account of decision-making may shed new light on the question whether capitalism is liberation or exploitation regarding consumption choices. The case study of behavioral effects in mobility decisions stressed that they are to a large degree shaped by their context, notably by the built environment over the long term. It also underscored the idea that a transport system based on automobility with corresponding residential location choices and urban design is detrimental to the environment, conducive to obesity and fostering unhappiness through unsatisfactory social lives. From this descriptive view of urban mobility, one can deduce that if welfare is subjective well-being, urban transport systems should be designed very differently from how is currently the case. Underlying such a view is often the idea that the urban system of automobility has been brought about by a class of exploiters, including car and housing companies and conservative politicians, a narrative frequently popular with researchers on transport and the environment. But this 'urban exploitation narrative' neglects that automobility and the demand for suburban housing initially arose from fundamental desires for freedom and autonomy in mobility, as well as tranquility and privacy in family life. These motives fuel the idea that the automotive urban system is really liberation of the cramped existence of workers in extremely dense cities of previous times. This is the larger background against which Chapter 8 argued that the orthodox view of economics that welfare is preference satisfaction needs to be revised to make room for behavioral findings: mobility decisions are often heavily biased towards the status quo due to effects beyond people's genuine preferences. But there is nothing "liberal" in perpetuating the status quo. Nevertheless, whatever revisions to the preference view are proposed, they evidently do not change the basic tenet of the liberation narrative that personal preferences on mobility and residential choices are all that counts for assessing transport policies, even if such preferences lead to unhappy urban lives.

To illustrate this last point from a concrete finding discussed in Chapter 8: what are we to make of the fact that commuting is the unhappiest part of the day (Kahneman et al., 2004)? The liberation narrative will paint this finding as confirming that the good life is more than the happy life. Consumers will know best how to weigh their emotional well-being against other life goals such as achievements, fame and reputation. The exploitation view may instead call for protection of the workforce against the fallacy of overly focusing on salary and housing in residential choices. My conclusion is that making these viewpoints explicit in policy debates would be a great improvement over current practice.

Beyond mobility and urban design, the normative distinction between preference satisfaction and subjective well-being may also allow for an evaluation and better framing of critiques of materialism more generally – of which lamenting the drawbacks of car-dependent cities is a small part. Consider whether the following behavioral phenomena should provide reasons for policy interventions to guide consumers or not: first, status-seeking behavior and misprediction of adaptation seem largely responsible for the fact that the impact of higher income on subjective well-being is rather weak (Layard, 2006, 2011; Clark et al., 2008). For many on the political left, prevalence of status-seeking and adaptation *are* good arguments that consumption is not so much welfare-enhancing. Second, time-inconsistent preferences are common in human behavior beyond decisions about physical activity (see Chapter 8), for example concerning food choice (McCormick and Stone, 2007) or work deadlines (Ariely and Wertenbroch, 2002), with economics mostly elaborating on their role in "sub-optimal" saving decisions (Thaler and Benartzi, 2004; Bernheim and Rangel, 2007). One may wish to hold that the long-term preference is the one that matters normatively. Third, concerns about its influence on preference formation not only apply to infrastructure and the built environment but also to advertising (Layard, 2011).[4] When such behavioral effects are studied in contexts other than urban mobility, similar normative considerations to those put forward in Chapter 8 apply (Loewenstein and Ubel, 2008; Loewenstein, 2009; Fleurbaey and Blanchet, 2013). The viewpoint that welfare should be understood as happiness could provide a justification for many policy interventions regarding these effects. On the other hand, the preference satisfaction view would justify policy interventions to a much smaller degree in the above cases.

All these arguments on behavioral grounds that consumption is not necessarily welfare-enhancing are, however, largely ignored by liberation narrative-dominated economic theory. Instead normative implications of behavioral effects are largely swept under the carpet. I contend that critiques of materialism might be better framed and evaluated when happiness and preference satisfaction are distinguished and explicitly highlighted as frequently conflicting societal focal points for policy design. This thesis has focused on the case of urban mobility to examine this claim by applying it to a specific example for policy design and highlight its relevance for climate change mitigation. A systematic analysis of these considerations was beyond the scope of this work, but constitutes an area for future research.

9.2 Future research

The models employed in this thesis could be extended in various ways to address further research questions. I outline potential topics for future research for rent taxation, distributional aspects of funding public investment and behavioral welfare theory of transport policy in turn.

Rent taxation

Concerning the welfare effects of rent taxation, Chapters 2–4 studied the land rent and the climate rent separately. It would be desirable to develop an (overlapping generations) model that includes both global land and the atmosphere

[4] An even more fundamental critique of consumerism that has been voiced is that shopping not only causes stress but may be a coping strategy for coming to terms with existential needs in a secular society (Jackson, 2013; Ruvio et al., 2014), although this claim seems hard to evaluate. But its validity would matter much if *meaning* (Baumeister et al., 2013; Oishi and Diener, 2014), not happiness, is considered a proxy for welfare.

as explicit stocks, so that the wealth effects of bioenergy use or climate damages falling on land can be studied more comprehensively. For instance, while the integrated assessment model REMIND-MAgPIE (Leimbach et al., 2010; Popp et al., 2011) considers both the atmosphere and land explicitly, it is not built on the structure of overlapping generations and land is not a tradable asset. Ongoing work partly fills this gap and introduces land and the atmosphere within one overlapping generations model (Dao and Edenhofer, 2015): Schultes et al. (2015) study the growth impacts and implications for climate policy of climate damages that explicitly fall on land – but do not consider the atmosphere (or fossil resources) as an asset. They find that climate damages on land create a portfolio effect in the sense of Chapters 3 and 4 that is *detrimental* because these damages increase the scarcity of land.

Moreover, econometric work could clarify the importance of the beneficial portfolio effect exhibited in Chapters 3 and 4: beyond the calibration of Chapter 3, Section 4.1, one would need to estimate how large the price changes following a rent tax change are. This would illuminate the strength of the portfolio effect and the potentially positive impact of such a policy on growth. Devising ways of determining the true causes and size of underaccumulation could then completely clarify the welfare effects of rent taxation empirically.

The results on rent taxation in this thesis could also be useful for understanding whether low-carbon public investment could be *self-financing* across generations. Climate change mitigation corrects an externality, so it should be a Pareto-improving policy when combined with adequate transfers from those benefiting most from mitigation to those paying for it. Since the benefits from mitigation will be much larger in the future, such a transfer must run from future to current generations. (Foley, 2008; Broome, 2010) A sizeable literature has sought to construct such intergenerational transfers (Rezai et al., 2012; von Below et al., 2013, see Siegmeier et al., 2015, Section 3.6., for an overview), but has neither considered public capital and its capitalization in land rents, nor the portfolio effect of Chapters 3 and 4. However, for a land rent tax, Ricardian equivalence holds even in an overlapping generations model (Buiter, 1989). Organizing an intergenerational transfer by debt-financed public investment may thus only be feasible if some other reason beyond imperfect altruism why Ricardian equivalence does not hold is taken into account. A notable mechanism for this is time-inconsistent saving behavior of households (Laibson, 1997).

Finally, the questions studied regarding policy interventions vis-à-vis a carbon lock-in could be extended to a setting with distortionary pre-existing fiscal policy. Some believe that if capital income taxation distorts the size of capital stocks, an optimal carbon tax would need to be set below its Pigouvian level (Barrage, 2014). This finding might not hold in the setting of Chapter 5, where clean and dirty capital stocks were differentiated. One can conjecture that at a point where the lock-in is partially overcome, carbon taxes may need to be set *higher* than the Pigouvian level in view of a sectorally-neutral capital tax, at least for the second-best case that the carbon tax is also used to induce clean innovation (O. Edenhofer, pers. comm., 12 March 2014).

Distributional effects of public investment

In the models of Chapters 6 and 7, public capital was considered as a generically productivity-enhancing factor. Instead, one could consider explicitly low-carbon public investment to study the distributional effects of decarbonization. Public investment could be treated as explicitly mitigating climate damages or alternatively conceptualized as infrastructure investments that reduce mitigation costs. Moreover, one could explore in the two-class context whether a typically regressive carbon tax reform could be made progressive by (generic) public investment. (See also Siegmeier et al., 2015, Section 3.5. for a discussion of this point.)

Two further extensions to the models of Chapters 6 and 7 seem desirable. First, it seems more satisfying if one could study the formation of the interest rate not just by two polar cases: so far, either all households have homogenous preferences – the "neoclassical view" – or households have heterogeneous preferences and then the "capitalist class" solely determines the interest rate – the "classical view" embodied in the Pasinetti Paradox and explored above. A model that allows for different weights of heterogeneous agents in determining aggregate savings, ideally nesting the neoclassical and the classical view, might be considered an improvement.

Second, Chapters 6 and 7 only evaluated the welfare effects of public investment by considering Pareto-improvements and inequality measures. No social planner perspective was set forth because this would require to endorse a cardinal view of utility functions even in the case that they represent (very) heterogeneous preferences. Moreover, it would require normative choices about which discount rate(s) should be applied to the intertemporal aggregation of the utility of the different classes. Normative work spelling out the pros and cons of various potential views about social welfare in models with distinct classes thus seems desirable.

Behavioral welfare theory and decarbonization of mobility

The approach of Chapter 8 could be extended in four different ways: first, if the focus was on climate change mitigation (and its beneficial side effects), it might be worthwhile to study behavioral interventions promoting low-carbon consumption in other sectors subject to behavioral effects, notably energy consumption of buildings and choice of diet. Second, the hypothesis that stressing the normative distinction between subjective well-being and preference satisfaction could clarify the discourse about the legitimacy of behavioral policy interventions should be tested further. Beyond transportation, one could examine whether the distinction can be usefully applied to examine the validity of critiques of materialism more generally (see Subsection 9.1.4). Third, for integrating the conceptual work of this thesis better into transportation research, a geographically explicit case study may be useful, for instance highlighting normative trade-offs in the design of the transport system of a specific city. Finally, the claim that the built environment can shape mobility preferences (beyond its influence through framing) calls for formal modeling of this effect. Existing work on the descriptive and normative implications of preference changes (von Weizsäcker, 1971, 2005; Bar-Gill and Fershtman, 2005) has been motivated differently and is unlikely to do justice to the case of (mobility) behavior being shaped by (transport) infrastructure and the built environment. Dietrich and List (2015), building on the idea by Lancaster (1966) that consumers care about (a subset of the) properties of goods, not the goods *themselves*, recently present an adequate framework to analyze framing effects. By contrast, modeling how specific tastes are derived from more fundamental preferences over long time-scales conditional on long-lived infrastructures remains an open challenge for future research.

9.3 Epilogue: are the findings of this thesis policy-relevant?

Is there a significance of the results of this thesis beyond their scientific contribution, that is for actual policy-making? For example, could one hope that the results of this thesis facilitate the implementation of sufficient carbon pricing? In this last section, I give reasons why I believe that the results may be more useful for the very long term than for the short term and current political debates.

Regarding the short term, consider the distributional implications of rent taxation as an example. In a recent New York Times op-ed on “Pollution and Politics”, Paul Krugman makes the point that the current political opposition in the U. S. to stricter environmental legislation is in part due to rising inequality. This is because, in Krugman’s words, “environmental protection is, in part, a class issue, even if we don’t usually think of it that way. Everyone breathes the same air, so the benefits of pollution control are more or less evenly spread across the population. *But ownership of, say, stock in coal companies is concentrated in a few, wealthy hands.* Even if the costs of pollution control are passed on in the form of higher prices, the rich are different from you and me. They spend a lot more money, and, therefore, bear a higher share of the costs.” (Krugman, 2014b, *emphasis added*).

However, publicly highlighting the fact that within national economies, climate change mitigation has tough distributional consequences, as pointed out by Krugman,[5] does not necessarily make implementation of climate policy any easier. Similarly, linking the climate problem to already existing wealth disparities may not help to combat inequality. Instead, some might go as far as suggesting that sweeping distributional issues of climate policy under the carpet in policy proposals may lead to more mitigation – or at least claim, as does Sarewitz (2011), that it is erroneous to believe that “political disputes centered around climate change could be tamed through scientific argumentation and explication”. Economic policy-making being dominated by the two narratives of liberation and exploitation, indeed other strategies for generating better climate policy may be more effective. Creating fora for deliberation, when designed the right way (Sunstein and Hastie, 2008), including making individuals explain their view (Fernbach et al., 2013), may help to build consensus as these lead to less polarization. Even striking compromises by giving

[5]Concerns about the potential regressivity of a carbon tax – due to carbon-intensive subsistence consumption (Grainger and Kolstad, 2010; Klenert and Mattauch, 2015) – are also a case in point.

particular weight to special interests may help short-term policy-making more to achieve reforms than highlighting normative trade-offs and pointing to inaccurate descriptions of reality within economic theory. In this sense, I am skeptical about the impact of new theoretical findings.

By contrast, in the (very) long term, new results of economic theory might have a much greater impact on policy making. Keynes (1936/1954), in an excessively quoted passage from the final section of his *General Theory* defended this opinion very strongly:

> "...the ideas of economists and political philosophers, both when they are right and when they are wrong, are more powerful than is commonly understood. Indeed the world is ruled by little else. Practical men, who believe themselves to be quite exempt from any intellectual influences, are usually the slaves of some defunct economist. Madmen in authority, who hear voices in the air, are distilling their frenzy from some academic scribbler of a few years back. I am sure that the power of vested interests is vastly exaggerated compared with the gradual encroachment of ideas. Not, indeed, immediately, but after a certain interval; [...] it is ideas, not vested interests, which are dangerous for good or evil."

Whether this view is true is notoriously difficult to assess.[6] At least, Keynes was mostly right about his own legacy on short-term macroeconomic policy, Keynesianism (Hall, 1989). Stiglitz (1994), discussing the collapse of the central-planning economies in Eastern Europe, remarks regarding Keynes' words that "[a] strong case could be made for the proposition that ideas about economics had led close to half the world's population to untold suffering." A more recent and slightly different example may be the two degree target, which arguably serves as a focal point for coordinating international mitigation efforts *because* some scientists convinced politicians of its merit (Jaeger and Jaeger, 2011).

Recently, Keynes' point of view was reinforced by philosopher and psychologist Joshua Greene in the context of how moral progress is achieved (Greene, 2013, Ch. 11). He provides, in my opinion, a credible basis for Keynes' dictum. Greene takes into account the recent consensus of moral psychology that ethical and political debates are most of the time driven by emotional intuitions: changing one's moral views typically happens through a situation that elicits emotions, not by being exposed to good arguments (Haidt, 2001, 2007). Nevertheless, Greene defends the power of arguments to transform the political discourse over the course of decades or even centuries, as follows: everyday politics may well be mostly about whose special interest prevails and be driven by which narratives feel familiar, for example because they are endorsed by one's social environment. It may be true that in this way arguments do not determine which position people defend on a particular topic. Yet, arguments are needed *initially*, before somebody can ever *feel* the familiarity of a narrative. "A good argument is like a piece of technology. Few of us will ever invent a

[6] Keynes' statement is ultimately an empirical claim about the nature of policy-making, but on the time scale of at least *decades*. It is unclear how the claim could be confirmed or disproved by some empirical investigation; I do not know of any empirically sound method to assess the influence of ideas over such time scales, controlling for the cross-influence of political events.

new piece of technology, and on any given day it's unlikely that we'll adopt one. Nevertheless, the world we inhabit is a product of good moral arguments. [...] I believe that without our capacity for moral reasoning, the world would be a very different place." (Greene, 2013, note on p. 346).

I reaffirm that it is unclear whether revealing the distributional conflicts behind climate policy is a blessing in the short-term and whether the insistence on a difference between happiness and preferences does not make life of the urban planner harder, given current "vested interests". It may also be that advancing economic theory is simply irrelevant in the short-term.

However, in accordance with Keynes and Greene, I am hopeful that changing the framing of economic theory so as to include both narratives about capitalism may do some good for political practice, but over very long time frames. Contributions to economic theory may at least bring about the extent to which each narrative is valid or, better still, deliver a better paradigm, one between the two narratives of liberation and exploitation. The contribution of this thesis is humble by comparison: I tried to point out two building blocks for this for the case of low-carbon public investment: wealth owners must be distinguished and identified as entrepreneurs stimulating capital accumulation, or as rentiers harming welfare to build a sound theory of optimal taxation in a climate-constrained world. Depending on one's taste for liberty or happiness, consumption patterns may look more like liberation or like exploitation of consumers by firms, determining one's attitude towards policies designed to promote low-carbon choice architectures.

For the economic policy choices considered in this thesis, in Keynes' terminology, the policy-makers that are currently "the slaves of some defunct economists" are those under the influence of those "neoliberal" scholars that believed that "capitalism as liberation" is the only story to tell. The drawbacks of capitalism are conceptualized as mere easily rectifiable market imperfections, welfare is equated with economic growth, behavior is well explained by rational choice, selfish acts are 'natural' in strategic contexts and the solution to the climate problem is completely solved by a globally uniform carbon price set at the level determined by a cost-benefit-analysis. Nevertheless such scholars of course accurately suggest that a free market economic system is the source of the wealth of currently rich countries. The influence of the proponents of the liberation narrative on economic theory has been so strong that arguments for the exploitation view currently rarely come from within economics. But excluding one half of a major societal conflict does not seem desirable for the subject's credibility and reputation over the long-term and may be even harmful to the cohesion of societies. This thesis has been an attempt to show that distinguishing fairly between the good and the bad sides of market-based economies is sometimes possible with relatively minor modifications to existing economic theory, notably keeping the subject's analytical rigor and focus on designing market-based policy instruments.

I thus conclude this thesis by inviting the reader to contemplate two verdicts of some notable "academic scribbler[s] of a few years back"...

> I am in favor of cutting taxes under any circumstances and for any excuse, for any reason, whenever it's possible [...] because I

> believe the big problem is not taxes, the big problem is spending. (Friedman, 2003)[7]

> [...] we are proposing the hypothesis that widespread and/or persistent human behavior can be explained by a generalized calculus of utility-maximizing behavior, without introducing the qualification 'tastes remaining the same.' (Stigler and Becker, 1977)

...and to compare them with two others, of which the results of this work indicate that it would be desirable if future "practical men" would be their "slaves":

> In the not-so-old (and definitely not-so-good-old) days of economics, when it was widely assumed that people were reliable pursuers of self-interest, measuring welfare was (comparatively) easy. [...] The emergence of behavioral economics, with its multiple challenges to the view that people rationally pursue self-interest, complicated this tidy picture. Once one accepts that people are unreliable, and indeed often biased, pursuers of self-interest, it can no longer be assumed that increasing affluence will make them better off. (Loewenstein, 2009)

> What I, therefore, propose, as the simple yet sovereign remedy, which will raise wages, increase the earnings of capital, extirpate pauperism, abolish poverty, give remunerative employment to whoever wishes it, afford free scope to human powers, lessen crime, elevate morals, and taste, and intelligence, purify government and carry civilization to yet nobler heights, is – *to appropriate rent by taxation.* (George, 1879/2006, Bk. 8 Ch. 2).

To me, these four verdicts epitomize that distinguishing rent from capital and subjective well-being from preference satisfaction is decisive for coming to terms with the two great narratives about capitalism.

[7] To be fair, see his view on rent taxation stated on page 13.

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Statement of contribution

The main parts of this thesis (Chapters 2–8) are the product of collaborations among the author, his advisor, Ottmar Edenhofer, and other researchers. The contributions of all authors involved, in particular to framing questions, developing models, proving analytical results, implementing simulations and writing the articles, are detailed below.

Chapter 2: The author developed the model. He and Jan Siegmeier proved and framed the results. The author wrote the article, with contributions from Jan Siegmeier, who also provided the illustration of the empirical relevance and collected the data used there. Ottmar Edenhofer proposed the research question. Ottmar Edenhofer and Felix Creutzig contributed to the results in the case that no balanced growth path exists and to their interpretation. They also provided comments on the manuscript in many discussions.

Chapter 3: Ottmar Edenhofer suggested the model. Jan Siegmeier and the author proved the results and wrote the article in very close collaboration. Jan Siegmeier provided the empirical estimation, while the author contributed the discussion of normative validity. Ottmar Edenhofer also contributed to several results by refining them in extensive discussions.

Chapter 4: Jan Siegmeier and the author developed the model. Jan Siegmeier proved the results. He wrote the article, with contributions of the author, in particular to the analysis of the "stock instrument". The author, Jan Siegmeier and Ottmar Edenhofer jointly developed the research question. Ottmar Edenhofer provided comments on the manuscript in many discussions.

Chapter 5: The author developed the question and the model, in close collaboration with Felix Creutzig. The author is solely responsible for the programming of the optimization problems with GAMS. He also wrote the article and generated the figures, with input from Felix Creutzig. Ottmar Edenhofer contributed in design and framing of the question in many discussions.

Chapter 6: Ottmar Edenhofer proposed to study the model developed in this chapter. Sophie Bénard and the author refined the model and derived some preliminary conclusions and numerical results, presented in the Master Thesis of Sophie Bénard ("Distributional Effects of Financing Public Capital in a Two-Class Society", October 2012, TU Berlin). Building on this, the author and David Klenert proved the propositions. David Klenert contributed the simulations. The author wrote the article, with input from David Klenert.

Chapter 7: The basic research idea is due to Ottmar Edenhofer. David Klenert developed the model with input from all co-authors. He is solely responsible for implementing the optimization problem in GAMS. The article was written by David Klenert, with input from Linus Mattauch. All authors contributed to fruitful discussions of the model results. Kai Lessmann and Linus Mattauch helped to improve the manuscript.

Chapter 8: Felix Creutzig and the author developed the research questions while teaching a seminar on "The behavioral economics of mobility" at TU Berlin in the Summer Semester 2012. The author developed the normative argument. Monica Ridgway and the author surveyed the empirical literature on mobility behavior. The author wrote the article, with input from Monica Ridgway and Felix Creutzig.

Tools and resources

All chapters of this thesis were written with $\LaTeX\,2_{\varepsilon}$ using Miktex (Schenk, 2012) und Texniccenter (TeXnicCenter, 2013). Moreover, in some chapters additional resources have been used for simulations, data analysis and generating graphical output, as indicated:

Chapter 2: Figure 1 was generated with Microsoft Excel 2010 (Version 14.0).

Chapter 3: Figure 1–3 were drawn with Microsoft PowerPoint 2010 (Version 14.0). The empirical estimates reported in Section 4.1 were carried out with Microsoft Excel 2010.

Chapter 4: Numerical experiments (not used in the final manuscript) were conducted with XPP-Aut (Ermentrout, 2012); Figure 1 was drawn with Microsoft PowerPoint 2010.

Chapter 5: The optimization problem was implemented in GAMS, Version 23.7 (GAMS Development Corporation, 2008) and solved with CONOPT 3 (Drud, 1994). The postprocessing of numerical output and the design of the figures was carried out with MATLAB (Versions 7.11. and 8.3) by The MathWorks.

Chapter 6: Simulations (as well as numerical experiments informing the economic intuition, which are not part of the manuscript) were carried out with GAMS, version 23.7. Numerical output was post-processed with Microsoft Excel 2010. The figures were generated with R, Version 3.1.1 (Ihaka and Gentleman, 1996).

Chapter 7: The optimization problems were carried out with GAMS, notably CONOPT 3. R and Microsoft Excel 2010 were used for post-processing of output and designing the figures.

Chapter 8: Figure 1 was drawn with Microsoft PowerPoint 2010.

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