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Policies for Sustainable Development through the Lens of Endogenous Growth

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You can be deprived of everything, but your spirit and knowledge.

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Thesis Summary

Nowadays the concept of sustainable development demands a shift from an economy of quantity to one of quality. Limited fossil energy resources available for production, along with the imminent threat of man-made climate change - due to the over-use of polluting fossil fuels - point towards greater investment in non-material inputs like technology, knowledge, and human capital. The target is to redirect the economy towards and along the sustainable path. Modern economic thinking, represented by the new growth theory, rejects earlier Malthusian doomsday scenarios when resources are depleted, and describes ways in which sustainability can be achieved endogenously.

Climate policy is key to sustainable development. However, in a world where an action only occurs if its marginal benefit does not fall short of its marginal cost, we should start questioning whether our costs and benefits are correctly measured. If non-diminishing economic growth is what we are after, can this co-exist with an environmental policy that reduces the use of one of the primary inputs to production, namely fossil fuels? Have we put all the components in place when pricing polluting non-renewable resources? How should we best redirect economic activity towards green innovation and restore its correct intensity? Each chapter of this thesis employs endogenous growth theory to respond to one or more of these questions.

The first chapter introduces the concepts of sustainability, the energy-growth nexus, and the modern economic tools that can lead to sustainable development

despite the depletion of primary inputs to production, namely fossil fuels. It also discusses the policies that can be implemented to redirect economic activity but also missing components, when designing such policies.

The second chapter deals with an environmental tax reform (ETR) policy in a real growing economy. This policy aims at reducing the burden of welfare distorting taxation by redistributing revenues from taxation on environmentally damaging activities. Another positive outcome is that it may redirect investments towards green innovation, leading to enhanced growth. For our purposes we will focus on the case of Switzerland, which has decided to implement an ETR from 2021. The analysis features both a theoretical and a numerical section. In the theoretical section, input reallocation between manufacturing and R&D may allow for enhanced growth if certain conditions are met. We then apply the core theoretical model to the economy of Switzerland and find that a boost to economic growth following such a carbon policy is a possible outcome. Redistribution of additional carbon tax revenues by lowering capital taxation performs best in terms of aggregate welfare, while in terms of equity among social segments the progressive character of lump-sum redistribution fails for very high emission reduction targets.

One of the important characteristics of sustainability policies is that they necessitate consideration of a very long time horizon. Myopic political decisions, mostly taken upon current observations, are likely to downplay the effects of our actions on future generations. Therefore, chapters 3 and 4 of this thesis deal with the inclusion of time lags in the diffusion of general information, as discussed below.

The third chapter is concerned with climate change stemming from the over-use of polluting non-renewable resources, its destructive effects on our capital stock, and the optimal carbon tax that can put the economy back on the sustainable track. Its main contribution is to introduce and explore the natural time lag of the climate system between emissions and damages to capital accumulation. This allows us to investigate how optimal climate policy, and its interplay with climate dynamics, affect long-run growth and the transition of the economy towards it.

Poor understanding of the emissions diffusion process leads to suboptimal carbon taxes, resource extraction and growth.

Redirecting investment towards green technology and knowledge accumulation is very important for our sustainable development. Moreover, private R&D is undertaken at a lower-than-optimal level due to externalities associated with knowledge spillovers. Therefore, chapter 4 asks how governments should best allocate their budget to support private research activities. The consensus in the literature is that sector-specific R&D support policies should be increasing in the degree of compatibility of sectoral innovation with the practices of the wider economy. Using a multi-sector endogenous growth model with in-house R&D and knowledge spillovers, it is shown that accounting for the time it takes for knowledge to diffuse modifies this widely-accepted result.

Kurzfassung

Das Konzept der nachhaltigen Entwicklung erfordert eine Abkehr von quantitativem zu qualitativem Wachstum. Limitierte fossile Energiequellen und die unmittelbar bevorstehende Bedrohung durch den vom Menschen verursachten Klimawandel aufgrund der Übernutzung von fossilen Energieressourcen erfordern einen Richtungswechsel der Wirtschaft zu einem nachhaltigen Wachstumspfad. Dafür rücken Investitionen in nicht-materielle Inputs wie Technologie, Wissen und Humankapital in den Fokus. Modernes Wirtschaftsdenken steht im Gegensatz zu früheren malthusianischen Katastrophenszenarien, wo Ressourcenbestände komplett erschöpft werden. Die neuen Wachstumstheorien beschreiben stattdessen verschiedene Möglichkeiten, wie endogene Faktoren zu einer nachhaltigen Entwicklung führen können.

Klimapolitik ist ein zentraler Treiber von nachhaltiger Entwicklung. In einer Welt, wo eine Handlung nur erfolgt, wenn der Grenznutzen höher ist als die Grenzkosten, müssen wir uns jedoch die Frage stellen, ob Kosten und Nutzen richtig kalkuliert werden. Kann nicht-abnehmendes wirtschaftliches Wachstum einhergehen mit einer Umweltpolitik, die den Verbrauch eines primären Produktionsinputs, nämlich fossilen Energien, reduzieren will? Sind alle Komponenten einberechnet, wenn wir für umweltschädliche, nicht-erneuerbare Energieressourcen einen Preis bestimmen? Wie können ökonomische Tätigkeiten am besten in die Richtung gelenkt werden, sodass sie zu sauberen Innovationen führen und so die richtige Wirtschaftsintensität wiederhergestellt werden kann? Jedes Kapitel dieser Doktorarbeit beantwortet eine oder mehrere dieser Fragen mittels endogener Wachs-

tumstheorie.

Das erste Kapitel gibt eine Einführung zum Konzept der Nachhaltigkeit, dem Zusammenhang zwischen Energie und Wachstum und den modernen ökonomischen Instrumenten, die nachhaltige Entwicklung fördern können trotz dem Verbrauch von primären Produktionsfaktoren, wie fossilen Energieressourcen. Es werden einige Politikmassnahmen vorgestellt, welche zu nachhaltigeren ökonomischen Aktivitäten führen können, aber auch fehlende Komponenten bei diesen Ansätzen.

Im zweiten Kapitel wird eine ökologische Steuerreform als politische Massnahme in einer wachsenden Volkswirtschaft diskutiert. Diese Massnahme hat zum Ziel, die Wohlfahrtsminderung durch allgemeine Steuern zu senken, indem stattdessen Steuern auf umweltschädlichen Tätigkeiten erhoben werden. Ein weiteres positives Resultat ist, dass Investitionen in eine saubere Richtung getätigt werden und so das Wachstum antreiben. In dieser Arbeit fokussieren wir auf die Schweiz, welche entschlossen hat, eine ökologische Steuerreform per 2021 einzuführen. Die Analyse umfasst sowohl einen theoretischen als auch einen empirischen Teil. Eine Neuverteilung der Inputfaktoren zwischen Herstellung und F&E führt unter gewissen Konditionen zu grösserem Wachstum. Basierend auf dem theoretischen Modell untersuchen wir anschliessend die möglichen Auswirkungen auf die Schweizer Wirtschaft. Ich zeige, dass ein Wirtschaftswachstum mit einer solchen CO2-Steuer möglich ist. Eine Umverteilung durch Kapitalsteuerung resultiert im höchsten aggregierten Wohlstand. Was die Fairness zwischen verschiedenen sozialen Schichten betrifft, eine Lump-Sum Umverteilung führt die progressive Ausgestaltung gleichzeitig nicht zu enorm hohen Emissionsreduktionszielen.

Eine wichtige Besonderheit von Nachhaltigkeitsmassnahmen ist, dass sie einen sehr weiten Zeithorizont beachten müssen. Kurzsichtige politische Entscheidungen, die oftmals nur auf aktuellen Beobachtungen basieren, führen dazu, dass die Auswirkungen unseres Handelns auf zukünftige Generationen zu wenig berücksichtigt werden. Aus diesem Grund widmen sich Kapitel drei und vier dieser Doktorarbeit dem Einbezug der Zeitkomponente im Bezug auf die Verbreitung von Informationen, wie unten diskutiert.

Im dritten Kapitel befasse ich mich mit dem Klimawandel aufgrund der Übernutzung von umweltschädlichen, nicht-erneuerbaren Ressourcen und deren vernichtenden Effekt auf unseren Kapitalstock. Anschliessend diskutiere ich die optimale CO2-Steuer, welche die wirtschaftlichen Aktivitäten zurück auf einen nachhaltigen Wachstumspfad führen kann. Der zentrale Beitrag ist die Einführung und Untersuchung einer natürlichen zeitlichen Verzögerung der Klimaveränderungen aufgrund von Emissionen und Verlusten bei der Kapitalakkumulation. Dies erlaubt uns zu untersuchen, wie sich eine optimale Klimapolitik und ihr Zusammenspiel mit den Dynamiken des Klimas auf das langfristige Wachstum und die Übergangszeit auswirken. Ungenügendes Verständnis der Emissionsverbreitung führt zu einer suboptimalen CO2-Steuer, übermässiger Ressourcenextraktion und nur geringem Wachstum.

Der Richtungswechsel zu Investitionen in saubere Technologien und Wissensakkumulation ist enorm wichtig für eine nachhaltige Entwicklung. Investitionen vom Privatsektor in F&E sind jedoch zu niedrig aufgrund von Externalitäten in Verbindung mit spillover-Effekten. Kapitel vier diskutiert deshalb, wie eine Regierung öffentliche Mittel optimal einsetzt, um private Forschung zu unterstützen. Der allgemeine Konsens in der Literatur ist, dass sektorspezifische F&E-Unterstützungsmassnahmen erhöht werden sollen – abhängig von der Kompatibilität einer Innovation in einem Sektor mit den anderen Wirtschaftssektoren. Mit einem endogenen Multi-Sektor-Wachstumsmodell und firmeninterner F&E zeige ich, dass sich das allgemein akzeptierte Resultat verändern kann, wenn eine Zeitkomponente im Bezug auf die Wissensverbreitung eingeführt wird.

Chapter 1

Introduction

The Brundtland report defines *sustainable development* as "the kind of development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (United Nations 1987). The term *development* indicates an on-going process characterized by change and innovation. Innovation is a social process motivated by the effort of whole generations to solve production problems, gain deeper understanding of occurring phenomena, and in general improve their well-being. This process has led to positive economic growth over longer periods of time.

When thinking about the present well-being, we think in terms of our current financial wealth, of the tremendous increase in our living standards reflected by our increased life expectancy, increased literacy rate around the world, increased access to electricity on global scale, our increasing taste for variety of goods and services but also by our ability to enjoy them. And yet, it is this desire for continuous improvement, along with our myopia about the future consequences of our actions, that has created imminent threats like global warming, pollution-induced natural catastrophes, scarce clean water supplies, and local air pollution, that can bring the very thing we are striving for to the ground.

Nowadays the concept of sustainable development has "prominently entered the political debate, documenting the rising number of bridges between economy and ecology." (Bretschger 2015b). However, in a world where an action only occurs if its marginal benefit does not fall short of its marginal cost, we should start questioning whether our costs and benefits are correctly measured. Have we put all the components in place when pricing polluting non-renewable resources? If non-diminishing economic growth is what we are after, can this co-exist with an environmental policy that reduces the use of one of the primary inputs to production, namely fossil fuels? How should we best redirect economic activity towards green innovation and restore its correct intensity? Each chapter of this thesis employs endogenous growth theory to contribute to the answer to one or more of these questions.

1.1 Energy and economic growth

Energy has always played a crucial role in social development and economic growth. Jevons (1866), in his book *The Coal Question*, was the first to raise concerns about Britain's reliance on coal as a scarce energy input to production by asking rhetorically "Are we wise in allowing the commerce of this country to rise beyond the point at which we can long maintain it?". Apart from the contribution of Hotelling (1931), who formulated the optimal path of price development of a non-renewable resource, questions regarding resource scarcity only arose again in the 1970s with the Malthusian perspective of the Club of Rome and its *Limits to growth* movement as portrayed by Meadows et al. (1972). This, along with the first oil-crisis in the beginning of that decade, refreshed the interest in the topic of resource scarcity and triggered the contributions of prominent economists as Dasgupta and Heal (1974, 1979), Solow (1974) and Stiglitz (1974) to what is known as the Dasgupta-Heal-Solow-Stiglitz (DHSS) model.

The DHSS model incorporates a non-renewable resource as a primary input to the production process of a neoclassical economy – the other inputs being capital and labor. Its main result is that sustainable development (defined as non-decreasing growth of consumption per capita) can only exist if any of the following conditions are met: good substitutability between the non-renewable resource and the accumulated stock of capital; exogenous technical progress; increasing returns to scale. Solow (1974) also observes that "earlier generations are entitled to draw down the pool [of the finite resources] (optimally, of course!) as long as they add (optimally, of course!) to the stock of reproducible capital.", later generalized in Hartwick (1977) as the *Hartwick rule* of investment.

As the most plausible way around input scarcity was technical change and efficiency improvements, which were kept exogenous, many things were left unanswered by the previous strand of literature. At the time, empirical observations of sustained economic growth over longer periods of time required rethinking of the workhorse economic modeling. Closer examination of the market processes leading to economic growth pointed to the conclusion that innovation is most important for economic growth, is the costly result of intentional R&D, and arises because of market incentives. Suzuki (1976) was first to add endogenous technical change in the DHSS model, while with the subsequent contributions of Romer (1986), Lucas (1988), Romer (1990), Grossman and Helpman (1991), Rebelo (1991) and Aghion and Howitt (1992) the *endogenous growth theory* emerged.

Characteristic feature of these models is that sustained economic growth arises endogenously, based on the investment decisions of profit maximizing agents without the support of any exogenous factor, and is actually possible because of the increasing returns in the scale of operation of a firm (Romer 1990, Peretto 2015). Another important implication of these models is that policy can affect economic growth not only temporarily – during transition to the steady state – as in the neoclassical growth model, but also permanently - it can change the steady state itself (Groth and Schou 2007).

Several contributions from the late 1990s on coupled endogenous growth theory with non-renewable energy resources and/or environmental problems, as for example Aghion and Howitt (1998, Chapter 5), Grimaud and Rouge (2005, 2014), Groth and Schou (2007), Daubanes and Grimaud (2010), Bretschger and Smulders (2012). This new micro-founded theory could cast light on the long-run development of the economy despite resource scarcity or the negative effects of pollution by focusing on the quality, rather the quantity of the primary inputs to production, and could thus give an answer to the Malthusian approach of the Club of Rome and its limits to growth doomsday scenario. The static growth accounting exercise implying reduction in living standards as natural resources decline no longer applied. An endogenous growth model with polluting non-renewable resources and climate change that harms capital accumulation has been developed in Chapter 3.

The fact that a price increase of a primary input of production can lead to innovation, and this in turn to technical progress, was not something new: as pointed out in Hicks (1932) “changes in the relative prices of the factors of production is itself a spur to invention [...] directed to economizing the use of a factor which has become relatively expensive”. The application of this in the discussion around sustainability occurred in Porter (1991), and became known as the *Porter hypothesis*, according to which stringent environmental policies can increase welfare and spur innovative activity to substitute for polluting energy. This result was later empirically observed by several authors such as Newell et al. (1999), Popp (2002), and Lanoie et al. (2011). More recently, Bretschger (2015a) studied several industrialized nations and found, indeed, no support for the hypothesis that energy price increases lead to reduction of economic growth; quite the contrary: in the long run increasing energy prices may enhance capital accumulation and growth.

Economic growth is driven by the accumulation of capital stocks. The accumulation of physical, human, social or knowledge capital can in fact compensate for the diminishing use of energy as the society focuses on the most economical way to use its current resources and develops energy saving technologies and/or clean substitutes. A mechanism at work is that a lower energy input can lead to the reallocation of resources towards innovation and capital accumulation and this itself to higher economic growth (Bretschger 1998, Bretschger and Smulders 2012). Chapter 2 shows that in fact this mechanism can lead to enhanced growth and mitigate the costs of environmental policies in a real growing economy.

1.2 Policies for Sustainable Development

Man-made climate change caused by the over-use of polluting fossil fuels is an imminent threat to sustainability. The usual political discussion around sustainable development, speaks of very high costs of environmental policies, which could vary between carbon taxes, emission permits, energy rating standards, green subsidies, or combinations of the above. Under the school of thought of neoclassical economics, that usually politicians follow, claims that limiting the use of polluting resources causes output, and hence consumption, to sink to levels below the current standards of living. As we established previously, however, endogenous market mechanisms triggered by a reduction in the use of polluting inputs can shift innovation and capital accumulation into a cleaner direction and mitigate these negative level effects.

These two forces are identified theoretically and numerically in Chapter 2, where we study the outcome of an environmental tax reform in a real growing economy using endogenous growth theory. Imposing additional taxes usually exacerbates the distortions in the economy. By using the proceedings from carbon taxation to reduce other distorting taxes – for instance income taxes – an environmental tax reform could potentially increase the disposable income of agents and improve the efficiency of the fiscal system, in terms of higher welfare. The problem with this policy is that the lower tax rate on labor or capital income does not fully compensate agents for the adverse effect of the pollution tax on the real after-tax wage. This reflects the fact that shifting the tax burden from a wide tax base, as in the case of income and capital tax, to a narrow one, like the energy input, is likely to further increase rather than reduce pre-existing tax distortions (Parry

1998, Bovenberg and Goulder 2002). In a dynamic setting, the tax base reduction is aggravated as agents lower their consumption of polluting energies. On the other hand, higher economic growth, resulting from endogenous input reallocation towards green innovation, can mitigate the costs of the carbon policy. Along these lines Kruse-Andersen (2016) notes, in favor of an endogenous growth setting, that "static models and exogenous growth models [...] leave out an important welfare effect of environmental policy".

Finally, an important point in favor of environmental policies is that policies that promote green innovation need only be temporary: once technical change is redirected towards clean activities the economy can continue growing on the sustainable path without further government intervention (Acemoglu et al. 2012). Technological change is therefore key to economic growth and sustainability. As Romer (1990) points out in his seminal contribution, it arises partly due to intentional individual actions motivated by market incentives and benefits largely from the non-rivalry and only partial excludability attributes of innovation in the form of positive knowledge spillovers. It is this incomplete appropriability of the returns to research that creates less than optimal innovation incentives. Therefore, a holistic policy towards sustainable development should not only redirect innovation towards cleaner activities but also restore its optimal level, for example via research subsidies (Popp et al. 2010). Chapter 4 deals with the optimal level of industrial policies that promote private research activities.

1.3 Adding components: the inherent time lag of systems under study

To achieve the highest possible sustainable growth and a rising living standard policies of sustainable development usually focus on a very long time horizon. The usual political process, however, has high inertia and is rather short sighted. Myopic policy makers not taking into account the consequences of market actions in the distant future, only act once problems get realized. Examples regarding environmental issues are the Montreal Protocol in 1989 on banning substances that deplete the ozone layer, the ban of asbestos in 1989, or the Kyoto protocol in 1992 on the reduction of greenhouse gases. The underlying problem is that several systems exhibit time lags between the initiation of a process and its observable outcome. Time lags are usually included in many biological models, such as models of population dynamics, biochemical kinetics, and epidemics (MacDonald 1978), in models of meteorological forecasting (Lu et al. 2007), or models of diffusion of product information (Bass 1969, Mahajan et al. 1995, Rogers 2003).

An approximation of the natural time lag between emissions and their effects on climate change is also used in several numerical integrated assessment models (IAMs) that couple the environment with macroeconomic modeling, like the DICE model (Nordhaus 1991, 1992, 2011). Chapter 3 deals with the inherent time lag of the climate system in an endogenous growth model with polluting non-renewable resources where climate change destroys the stock of capital. Chapter 4 includes such a process for the diffusion of private research information in the market in a study about the optimal subsidization policy of private R&D. An important implication of including a distributed lag for the underlying processes in these models is that it changes not only the transition towards the steady state, but the steady state itself.

1.4 Outline of the Thesis

This thesis employs endogenous growth theory to develop policy recommendations towards sustainability. Each chapter responds, analytically and numerically, to the following questions:

- Chapter 2: What are the growth and welfare effects of an environmental tax reform in a real growing economy? Do higher carbon taxes lead to enhanced innovation and sustainable growth when we consider all inter-sectoral linkages and several household categories?

- Chapter 3: How does the timing of emissions diffusion affect the optimal carbon tax when climate change destroys our capital stock?
- Chapter 4: How does the timing of diffusion of knowledge spillovers affect the optimal research subsidy to private R&D?

Chapter 2 studies an environmental tax reform in Switzerland, for the country to reach its stringent 2050 emission targets. In the theoretical section, we extend the model of Bretschger (1998) to a general equilibrium economy with pre-existing taxes, elastic labor supply, and R&D that uses both labor and direct investments. An increase in the energy tax has both a level and a growth effect. First, in the realistic case of poor substitution between labor and energy in the production process of the final good, an increase in the energy tax can drive labor out of production and reallocate it to innovative activities which enhances growth; a positive growth effect. The increase in the consumer price of energy propagates in the economy and reduces the level of final output, and in turn direct investment in the lab; a negative level effect. The scope for innovation is further reduced when we consider elastic labor supply. In the numerical part we find that a boost in economic growth following such a carbon policy is a plausible outcome. Pro-growth policies – e.g. using carbon tax revenues to reduce capital taxation – can also compensate for the reduction in the use of polluting energy leaving final output unaffected. Redistribution of additional carbon taxes by lowering capital taxation performs best in terms of efficiency measured by aggregate welfare, while in terms of equity among social segments, the progressive character of lump-sum redistribution fails when we consider very high emission reduction targets, supporting the common belief that carbon taxation is inherently regressive.

In Chapter 3 we study the optimal carbon tax in an economy in which climate change, stemming from polluting non-renewable resource, affects the economy's growth potential. The main contribution is to introduce and explore the natural time lag of the climate system between emissions and damages to capital accumulation in an endogenous growth setting based on Rebelo (1991). This allows us to investigate how optimal climate policy, and its interplay with climate dynamics, affect long-run growth and the transition of the economy towards it. We explore analytically both cases, with and without pollution decay, the latter being the usual assumption in theoretical modeling. Our findings are the following. Without pollution decay, a higher speed of emissions diffusion steepens the growth profile of the economy: economic growth decreases monotonically towards its positive steady state value, when polluting resources are depleted, while the transition becomes faster. With pollution decay, a higher speed of diffusion leads to lower short-run but higher long-run economic growth during transition. This model reveals both the transient and the steady state character of the diffusion process. Poor understanding of this process leads to suboptimal carbon taxes, resource extraction and growth.

Finally, having established the value of restoring the optimal level of innovative activities in a sustainable economy, Chapter 4 demonstrates the importance of including a time lag in the information diffusion process when studying optimal R&D subsidization policies. To simulate the knowledge spillovers diffusion process a distributed lag formulation is used. How should governments best allocate their budget to support private research activities? The consensus in the literature is that sector-specific R&D support policies should be increasing in the degree of compatibility of sectoral innovation with the practices of the wider economy. Using a multi-sector endogenous growth model, based on Peretto and Smulders (2002), with in-house R&D and knowledge spillovers, it is shown that accounting for the time it takes for knowledge to diffuse modifies this widely-accepted result. With the crucial assumption that firms whose technology is highly compatible with that of the wider market are more likely to create knowledge spillovers, the optimal research subsidy behaves non-monotonically when we consider a time lag in knowledge diffusion.

Chapter 2

Green tax reform and endogenous innovation: the growth dividend*†

Abstract

We study the effects of an environmental tax reform using endogenous growth theory. In the theoretical segment, mobile labor between manufacturing and R&D activities, and elasticity of substitution between labor and energy in manufacturing lower than unity allow for a growth dividend, even if we consider preexisting tax distortions. The scope for innovation is reduced when we consider direct financial investment in the lab, or elastic labor supply. We then apply the core theoretical model to a real growing economy and find that a boost in economic growth following such a carbon policy is a possible outcome. Redistribution of additional carbon tax revenue by lowering capital taxation performs best in terms of aggregate welfare. In terms of equity among social segments the progressive character of lump-sum redistribution fails when we consider very high emissions reduction targets.

*This chapter represents joint work together with Prof. Lin Zhang (City Univ. of Hong Kong).

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2.1 Introduction

The purpose of this chapter is to explore theoretically and computationally the existence of the growth dividend of an environmental tax reform (ETR) in a real growing economy.[1] There are three social and economic dividends associated: The first one relates to the environmental quality improvement. The second is an enhancement in welfare by reducing distorting taxation, using polluting emission tax revenues. The third one relates to the Porter hypothesis (Porter 1991), an extension to environmental policies of the Hicks induced innovation hypothesis (Hicks 1932). Existing empirical evidence supports the growth dividend hypothesis of an ETR and indicates that increases in the price of energy inputs have positive effects on innovation: Newell et al. (1999) show that following oil price shocks in the 70's, air conditioners became more energy efficient; Popp (2002) provides systematic evidence of price-induced improvements in energy efficiency by using U.S. patent data; Lanoie et al. (2011) study 4,200 companies in seven OECD countries and find strong evidence of environmental innovations due to stricter environmental policies; Aghion et al. (2016) document that car manufacturers tend to innovate more in clean technologies when they face higher tax-inclusive fuel prices.

The theoretical literature initially failed to confirm positive results associated with an ETR due to the static nature of the models used. Bovenberg and De Mooij (1994) using a static model of general equilibrium, examine the effect of environmental levies in the presence of preexisting distorting taxes where the government uses pollution tax revenues to lower distorting taxation. Using comparative statics they find that, due to preexisting distortions, "..environmental taxes typically exacerbate, rather than alleviate preexisting tax distortions...". There are two effects in a static setting that indicate whether the welfare cost of an environmental tax reform is positive or negative in an economy with various goods and factors of

[1] We define the term "environmental tax reform", or "green tax reform", as the tax reform that attempts to reduce the burden of welfare distorting taxation by redistributing back to consumers revenues from taxation on environmentally damaging activities.

production: the positive *revenue recycling effect*, and the negative *tax interaction effect*. The former arises by employing the environmental tax revenues to cut distortionary taxes. This leads to an alleviation of inefficiencies in the existing tax system and can increase disposable income, labor supply, and welfare.[2] The latter, however, arises because typically an environmental tax drives up firm production costs, which reduces the real household wage, and discourages labor supply; this reflects the fact that shifting the tax burden from a wide tax base, as in the case of income and capital tax, to a narrow one, like the energy input, is likely to further increase rather than reduce preexisting tax distortions, (Parry 1998, Bovenberg and Goulder 2002). Which effect dominates depends on three main conditions that allow the exploitation of a potentially inefficient tax system: i) the burden of the environmental tax should fall on factors with relatively low marginal efficiency costs, ii) the revenue should be used to reduce taxes on factors with relatively high marginal efficiency costs and iii) the tax base of the environmental tax should be large and subject to low demand elasticities (Goulder 1995). This strand of literature tended to reject the second dividend of such a tax reform. An exception is Bento and Jacobsen (2007) where the authors show that a double dividend is likely to occur by incorporating a fixed-factor in the production of the polluting good.

Contrary to that, and in favor of using dynamic settings when examining such policies, Bovenberg and de Mooij (1997), using a growth model of Barro (1990), with a pollution externality, however without labor or research, show that higher welfare and growth is an option – even though unlikely – and determine the conditions for it. Hettich (1998) using a modified Uzawa-Lucas model with elastic labor supply finds that a higher pollution tax might boost long term economic growth and that a tax reform which cuts distorting taxation can further increase this boost. However in the case of that contribution the polluting factor is the capital itself,

[2]Even though a lump-sum redistribution does not improve the efficiency of the fiscal system, it increases the disposable income of households, which might also be welfare promoting. This applies especially to poorer households, because such a redistribution makes a big part of their income.

an ever-increasing tax base, and no substitution possibilities away from this input arise, a rather unrealistic assumption. Positive growth effects arise also in Oueslati (2014) who uses a similar framework with a convex capital adjustment cost. Using a multi-sector model of endogenous growth with R&D, Bretschger (1998) shows that, in an economy with no preexisting distortions, an increase in the price of energy has a first order effect: it leads to sectoral reallocation and pushes more labor to the R&D sector, which boosts growth. Structural change helps sustain research investments also in Bretschger and Smulders (2012). Kronenberg (2010) using a directed technical change framework with clean and dirty goods, based on the model of Smulders and de Nooij (2003), finds a support for the second dividend, but no for the third one. Finally, Kruse-Andersen (2016) using an endogenous growth framework with research in both production and pollution abatement technologies shows that a stricter environmental policy increases the scope for research in abatement at the expense of research into production methods. He also notes in favor of endogenous growth settings that "even small changes in growth rates [due to environmental policy changes] have large level effects in the long-run", and "[...] static models and exogenous growth models (like the DICE model) leave out an important welfare effect of environmental policy."

Our study comprises of both a theoretical and a numerical segment, the latter studying an environmental tax reform in a real growing economy. The analytical model extends the theoretical part of Bretschger and Ramer (2012) in several directions.[3] First, we include both preexisting labor and energy taxation. This feature allows us to study a revenue neutral environmental tax reform where the additional energy tax revenue is redistributed by lowering labor income taxation. Second, we include leisure in the model. Since input reallocation towards innova-

[3] Bretschger and Ramer (2012) extend the increasing variety model of Romer (1990) to include energy in the intermediate good firms and examine how the substitutability between labor and energy might affect economic growth when the price of the latter increases. In their case – as in ours – each intermediate firm holds a blueprint, or patent, that allows it to produce. This is the costly result of intentional R&D and constitutes the capital of the economy.

tion – and hence towards capital formation – will be crucial for our results, adding leisure to the model might decrease both employment in the manufacturing sector but also in the lab when policy is implemented. This acts negatively on growth and welfare. Third, staying closer to reality, we allow for a combination of scientific labor employment and direct investment in the lab.

We then bring our theory to the data. Using a fully dynamic multi-sectoral general equilibrium model of endogenous growth, which keeps the core components of our theory, we examine numerically the effects of a green tax reform in Switzerland, which has recently agreed upon implementing an environmental tax reform from 2021. The numerical model extends the structure of Bretschger et al. (2011) in the following ways. First, we consider a detailed representation of the Swiss fiscal system. Second, we include several heterogeneous households. Third, in the more complex computational model labor is mobile not only within manufacturing and R&D, but also between these sectors. Fourth, we examine different redistribution schemes for the carbon tax implemented and show the results in terms of growth and welfare, in aggregate, but also for each household group.

Our contribution to the literature is twofold. In the theoretical part we identify the modeling conditions that can lead to higher economic growth due to an increase in energy taxation. We show that when the energy tax increases, mobile labor between manufacturing and research, and limited substitution possibilities in manufacturing between labor and energy inputs, can lead to enhanced growth: higher energy taxes reduce the demand for the energy good; with limited substitutability between inputs this reduces also the demand for labor in manufacturing and pushes it towards innovation. A positive *growth effect.* Contrary to the general consensus, this occurs even in the case of preexisting tax distortions. Exactly the same environmental policy is detrimental for growth in the typical case where new capital formation is the result of foregone consumption ("lab equipment model"): part of the final output is used as direct financial investments in the lab; as its demand declines due to an increase in the energy tax, so does investment activity into new forms of capital. A negative *level effect*. The scope for investment and subsequent higher growth gets further reduced if labor is mobile within the manufacturing sector, or if a leisure option exists. In general the effect of an environmental tax reform on induced innovation and growth is ambiguous.

Turning to the numerical segment, related to the crowding-out effects underlined above, we show that when considering limited substitution possibilities away from polluting energy sources, low to medium CO2 emissions reduction targets can induce innovation and higher growth in the long-run if the tax proceedings are used to reduce preexisting capital taxation. When the tax on polluting energy steadily increases over time, to achieve a very ambitious target, the positive growth effects are outweighed by negative level effects in the long-run: increasing energy taxes increasingly suppress output each period, leaving less room for investment; this reduces growth. An environmental tax reform is always growth-promoting – although marginally – even at very stringent CO2 emissions reduction targets when substitution away from CO2-intensive energies is possible. Efficiency considerations in terms of aggregate welfare speak in favor of redistributing additional tax revenue by lowering capital taxation. In general shifting the tax burden from a large and ever increasing tax base – like capital – to a small and shrinking one – polluting energy – is inefficient when the first dividend of the green tax reform is not monetized. On the other hand lump-sum redistribution is the least efficient option since in this case the positive revenue recycling effect is absent. The results on equity are not straightforward: low emissions reduction targets follow the consensus in the literature and speak in favor of lump-sum redistribution; the results turn, however, regressive when one considers a very stringent emissions reduction, exposing the inherently regressive character of carbon taxation.

In the next section we present the theoretical model which allows us to identify the sufficient conditions for higher growth inspite of higher energy taxes. The computational model is presented in section 2.3. Section 2.4 analyzes different redistribution scenarios in Switzerland in terms of efficiency, equity and growth.

Section 2.5 concludes by giving the appropriate policy recommendations.

2.2 Green tax reform in a model of endogenous growth

The growth dividend of a green tax reform, based on the Hicks hypothesis, should be the result of induced entrepreneurial activity leading to higher innovation. Accordingly, we propose an endogenous growth framework in the spirit of Romer (1990) and Grossman and Helpman (1991) as modified in Bretschger and Ramer (2012) to include energy inputs subject to environmental regulation; here we go one step further by considering preexisting distorting labor and energy taxes, direct investment as additional input in R&D, and elastic labor supply. In what follows we present the theoretical foundations of the more complex and more detailed computational model and explore the conditions that could lead to a growth dividend.

2.2.1 Aggregate economy

Consider a representative household that derives instantaneous utility $U(C, L_U)$ from consumption C, and leisure L_U. We normalize total labor supply to 1 and no population growth is considered. The aggregate economy features two sectors: manufacturing and R&D. The final good composite Q is ensembled from a continuum of intermediate goods x_j produced in the manufacturing sector in a Dixit-Stiglitz fashion:

$$Q = \left(\int_0^N x_j^\beta dj \right)^{1/\beta}, \tag{2.1}$$

where $\beta \in (0, 1)$ and N is the number of intermediate varieties. Each intermediate variety corresponds to a patent held by one firm in the manufacturing sector so that N is also the number of intermediate firms, the capital of the economy. Each patent is the costly outcome of research activity in the R&D sector. In a symmetric equilibrium where each intermediate firm produces the same quantity, $x_j = x$ per variety, the final good reads

$$Q = N^{\frac{1-\beta}{\beta}} X, \tag{2.2}$$

with $X \equiv Nx$ the aggregate output from manufacturing and the exponent $(1-\beta)/\beta$ reflecting gains from diversification. Gross output can be used to meet the demand for consumption by households, investments by R&D firms, and energy imports by firms in the manufacturing sector, i.e.

$$p_Q Q = p_Q C + p_Q I + p_E E, \tag{2.3}$$

with p_Q the price of the final good and p_E the – exogenous – world's price of energy. Agents allocate their unit time budget between manufacturing L_X, research L_J, and leisure L_U. Labor market clears:

$$L_X + L_J + L_U = 1. \tag{2.4}$$

2.2.2 Manufacturing

In equilibrium final good producers maximize profits facing symmetric prices p_X for the use of intermediates x. This leads to the following goods market equilibrium,

$$p_Q Q = p_X X. \tag{2.5}$$

Each firm in the manufacturing sector has to buy a patent that allows it to produce according to the same technology. The aggregate production of intermediate machines follows a constant returns to scale function described by $X = f(L_X, E)$, with L_X and E aggregate labor and energy demand. We thus specify:

$$X = \left[\alpha_X L_X^{\frac{\epsilon_X - 1}{\epsilon_X}} + (1-\alpha_X) E^{\frac{\epsilon_X - 1}{\epsilon_X}} \right]^{\frac{\epsilon_X}{\epsilon_X - 1}}, \tag{2.6}$$

with $\alpha_X \in [0,1]$ and ϵ_X the elasticity of substitution between labor and energy in manufacturing. Labor is paid its marginal cost w; a carbon tax t_E is also paid to the government. Due to imperfect substitutability in (2.1), the suppliers of intermediate machines charge a monopoly price as a markup over their unit cost of production c_X, i.e. $p_X = c_X/\beta$. Assuming an interior solution, the first order conditions, giving the demand for energy and labor, are:

$$\beta p_X \frac{\partial X}{\partial E} = (1 + t_E) p_E, \tag{2.7}$$

$$\beta p_X \frac{\partial X}{\partial L_X} = w. \tag{2.8}$$

Profits of intermediate good producers cover the upfront costs of obtaining a patent. Profit per variety reads $\pi = p_X x - c_X x$, or with $x = X/N$ and $c_X = \beta p_X$,

$$\pi = (1 - \beta) \frac{p_X X}{N}. \tag{2.9}$$

This profit, paid as dividend to equity holders, is only part of the return to the owner of a firm producing x. Equity holders would also expect a change in the market value of the company. In equilibrium investors would be indifferent between investing into new capital varieties or into a riskless bond at the market interest rate r. With V representing the equity value of a firm, this no-arbitrage condition follows:

$$\pi + \dot{V} = rV. \tag{2.10}$$

2.2.3 Research and Development

Additional capital varieties emerge in the research lab following

$$\dot{N}/N \equiv g = \eta J, \tag{2.11}$$

$$J = \left[\alpha_J L_J^{\frac{\epsilon_J - 1}{\epsilon_J}} + (1 - \alpha_J)(zI)^{\frac{\epsilon_J - 1}{\epsilon_J}} \right]^{\frac{\epsilon_J}{\epsilon_J - 1}}, \tag{2.12}$$

with $\alpha_J \in [0, 1]$, ϵ_J the elasticity of substitution between labor and direct investments in research, and $\eta > 0$ a scaling parameter. According to (2.2) and (2.6), the growth rate of output Q, and thus of investment I, is $\frac{1-\beta}{\beta}g$, with g from (2.11). Through variable z, with $\dot{z}/z = -\frac{1-\beta}{\beta}g$, we impose negative spillovers from higher capital accumulation for two reasons: conceptually, it reflects the fact that the more advanced the state of the art becomes, the harder it is for innovation to occur; technically, it ensures that the growth rate of the economy is constant on a balanced growth path.

The representative R&D firm that devotes L_J units of labor and I part of the final good to R&D for an infinitesimal time interval of length dt builds upon existing knowledge and produces $\eta JNdt$ new varieties. The total cost of this endeavour is $(wL_J + p_Q I)dt$. This effort should then create at least a value of $VN\eta Jdt$, since V is the market value of each variety. We assume an interior solution with positive demand for both inputs.[4] The optimal employment of L_J and I for an active R&D sector is given by the following first order conditions, where the marginal benefit from employing each input equals its marginal cost:

$$\eta NV \frac{\partial J}{\partial L_J} = w, \tag{2.13}$$

$$\eta NV \frac{\partial J}{\partial I} = p_Q, \tag{2.14}$$

while in a competitive equilbrium $\eta NVJ = wL_J + p_Q I$.

2.2.4 Households and the Government

The representative household holds the assets of this economy, i.e. total equity value $A = NV$. It then chooses its levels of consumption and leisure in order to maximize its intertemporal utility, $U = \int_0^\infty (\log C_t + \theta \log L_{Ut})e^{-\rho t}dt$, subject to its dynamic budget contraint, $\dot{A} = rA + (1 - t_L)w(1 - L_U) - p_Q C + T$, with ρ the time discount rate, t_L the labor tax rate set by the government, and $\theta \geq 0$.[5] This

[4] An equilibrium without labor or investment in R&D could exist if $\epsilon_J > 1$, so that inputs in R&D were substitutes. Since $\epsilon_J \leq 1$ is more realistic we rule out such an outcome by focusing on an interior solution with positive demand for both inputs.

[5] In the theoretical part we use logarithmic utility for ease of exposition. We will be using the more general CRRA function in the numerical exercise.

optimization involves the usual Keynes-Ramsey rule, and a condition for leisure that equates the marginal rate of substitution between consumption and leisure, to the marginal rate of transformation of the two inputs, i.e. their relative price (the hat notation represents the growth rate of a variable, i.e. $\hat{M} \equiv \dot{M}/M$.):

$$\widehat{p_Q C} = r - \rho, \tag{2.15}$$

$$\theta \frac{C}{L_U} = \frac{w(1 - t_L)}{p_Q}. \tag{2.16}$$

The government levies a tax t_L on labor income, a carbon tax t_E on energy expenditures, and redistributes the proceedings back to households in a lump-sum fashion.[6] It then chooses its fiscal instruments in order to optimize household utility subject to the budget constraint, $t_L w(1 - L_U) + t_E p_E E = T$, and the optimizing decisions by firms and households.

2.2.5 Conditions for a Balanced Growth Path

For ease of exposition, we follow Grossman and Helpman (1991) and choose aggregate expenditure as the numeraire, i.e. $p_Q Q = 1$, so that $\hat{p}_Q = -\hat{Q}$ and from (2.5), $p_X X = 1$, $\hat{p}_X = -\hat{X}$. Moreover, in equilibrium $\hat{C} = \hat{I} = \hat{Q}$, such that from (2.3), $\widehat{p_Q C} = \widehat{p_Q I} = \widehat{p_E E} = 0$. The Euler equation (2.15) then sets $r = \rho$. On the BGP, the wage rate (w) grows with total expenditure, i.e. is constant after the normalization. Ad-valorem tax rates (t_L, t_E), and labor in its different uses (L_X, L_J, L_U), are also constant. By virtue of (2.6), so is energy demand in manufacturing (E) so that $\hat{X} = 0$, and from (2.2) $\hat{Q} = \frac{1-\beta}{\beta} g$. Following our previous discussion with $\hat{z} = -\frac{1-\beta}{\beta} g$ we get $\hat{J} = 0$. The budget constraints of the government and households point to a constant asset value $\hat{A} = 0$ and tax transfers $\hat{T} = 0$. Finally with $\hat{\pi} = -g$ from (2.9), the no-arbitrage condition (2.10) gives $\hat{V} = -g$. To summarize, we make the following definition:

[6] We normalize the carbon intensity of the energy input to unity so that the energy input corresponds to polluting energy.

Definition 1 *A balanced growth path (BGP) is an equilibrium path with $\hat{N} = g$, constant, on which aggregate variables $\{Q, C, I\}$ grow at $\frac{1-\beta}{\beta}g$, $\{p_Q, z\}$ at $-\frac{1-\beta}{\beta}g$, and $\{V, \pi\}$ at $-g$. All other variables stay constant on the BGP (but not during a policy shock).*

To facilitate the analysis we define $\gamma_X \equiv \frac{\partial X}{\partial L_X}\frac{L_X}{X}$ and $\gamma_J \equiv \frac{\partial J}{\partial L_J}\frac{L_J}{J}$ the production elasticities of labor in manufacturing and reseach, respectively, constant in equilibrium. Constant returns to scale in the production of X and J implies that their complements, $1 - \gamma_X$ and $1 - \gamma_J$, are the production elasticities of the energy input in manufacturing and investment in research. In order to identify the conditions that allow for a growth dividend in our economy, we proceed as follows: first, we log-linearize equations (2.2) to (2.16) around the steady state; then relative changes in the growing variables are presented relative to the relative change in the stock of intellectual capital that corresponds to them. For example, Q grows with $N^{1-\beta/\beta}$ so that $\tilde{q} = \tilde{Q} - \frac{1-\beta}{\beta}\tilde{N}$; L_X does not grow so that $\tilde{l}_X = \tilde{L}_X$. The model in relative terms is provided in Appendix 5.1.4.

2.2.6 Implications for growth and welfare

To keep the results tractable we take the world price of energy as given implying that any environmental policy leaves it unaltered, i.e. $\tilde{p}_E = 0$. Moreover, we assume that the tax reform is revenue-neutral and that any additional tax revenue due to higher energy taxes are redistributed back to the representative household by reducing labor taxation, i.e. $\tilde{T} = 0$.

An increase in the energy tax has two first order counteracting effects on growth through equation (2.12): first it makes the final good more expensive and investment in innovation less attractive which suppresses growth; second, it reduces the real wage making labor employment in the lab cheaper, and thus more attractive, which promotes growth. However, such a reform entails also the standard static effect on labor supply: If the reduction of the real wage acts negatively on labor supply by increasing the demand for leisure and thus by reducing the available human resources to R&D, the latter positive effect on growth might fail. By combining equations (5.23)-(5.31) of the Appendix 5.1.4 we get the relative change in the growth rate followed by a relative increase in energy taxation $\tilde{g}(\tilde{t}_e)$, as

$$\tilde{g}(\tilde{t}_e) = -\frac{1-\gamma_X}{\Delta}\left[s_J(1-\gamma_J)\epsilon_J + s_X(\epsilon_X - \gamma_J)\right]\tilde{t}_e - \frac{\gamma_X(1-\gamma_J)+\gamma_J}{\Delta} s_U \tilde{l}_U(\tilde{t}_e), \tag{2.17}$$

with $\tilde{l}_U(\tilde{t}_e)$ the relative change in leisure following the policy shock, $\Delta \equiv s_X \frac{g}{\rho+g}[\gamma_X + \epsilon_X(1-\gamma_X)] + s_J\left[\gamma_X + (1-\gamma_X)\left(\gamma_J + \frac{g}{\rho+g}\epsilon_J(1-\gamma_J)\right)\right] > 0$, and $s_J = wL_J$, $s_X = wL_X$, $s_U = wL_U$, the expenditure shares for labor in R&D, manufacturing, and leisure (remember $p_Q Q = 1$), constant in equilibrium.

Assume first that the demand for leisure is unaffected by policy, i.e. $\tilde{l}_U = 0$ (or that there is no leisure in the model, i.e. $s_U = 0$). In this case, according to (2.17), growth is promoted, supressed or unaffected by the tax policy if the first term of equation (2.17) is, respectively, positive, negative or zero. If our modeling assumptions consider labor as the main driver of research, as done in Grossman and Helpman (1991) and Bretschger and Ramer (2012), then $\gamma_J \to 1$. In this case, with limited substitutability between labor and energy in manufacturing, $0 \leq \epsilon_X < 1$, growth is promoted, i.e. $\tilde{g}(\tilde{t}_e) > 0$. In the "lab equipment" version, with research expenditure being part of the final product of the economy, $\gamma_J \to 0$ and $\tilde{g}(\tilde{t}_e) < 0$, i.e. growth is unambiguously suppressed. In the general and more realistic case where research combines scientists with financial investment in R&D, the effect of an environmental tax reform on growth is ambiguous.

According to (2.17), ambiguous are also the results if another option for labor exists, here proxied by the labor-leisure choice assumption. As explained in Parry (1998) and Bovenberg and Goulder (2002) in an economy with preexisting tax distortions, a carbon policy that increases the consumer price of energy might reduce labor supply, i.e. $\tilde{l}_U(\tilde{t}_e) > 0$, because the environmental tax drives up firm production costs which is passed onto the consumers through higher product prices, acting as an implicit labor tax. This negative *tax interaction effect* of higher energy taxes that reduces the disposable income of households, usually outweighs the positive *revenue recycling effect* of redistributing additional tax revenues back to the society, which increases it. Hence, we have proved the following:

Proposition 1 *In our model of endogenous growth with energy input in manufacturing subject to environmental policy, an increase in the energy tax has the following effects on growth:*

- *if leisure is disregarded (inelastic labor supply), labor is the only input in research activity, and labor and energy in manufacturing are complements, an increase in energy taxation promotes growth; the opposite occurs if research activity is the sole outcome of investment being part of the final output;*
- *in the realistic case of a labor - investment combination as inputs in R&D, or if leisure is considered (elastic labor supply), the results on growth are ambiguous.*

Proof: See equation (2.17) and the paragraph following it. ■

Even though usually neglected by models of an environmental tax reform due to their static nature, a positive growth dividend is important for higher welfare: following Bovenberg and de Mooij (1997), the welfare effects of an increase in energy taxation can by measured by the marginal excess burden, defined as $\tilde{\lambda} = d\lambda/C$. This amounts to the additional consumption that should be provided to the representative household after the policy shock in order for it to keep welfare at its initial level. It is straightforward to show that in our theoretical model

$$\tilde{\lambda} = -\tilde{C} - \theta\tilde{L}_U - \frac{1-\beta}{\beta}\frac{g}{\rho}\tilde{g}, \tag{2.18}$$

with $\frac{1-\beta}{\beta}g$ the consumption growth rate and $r = \rho$ the interest rate along the BGP. A policy that increases current and future consumption, e.g. its growth rate, is welfare promoting. Hence, negative level effects of an environmental tax reform on consumption or labor supply can be compensated in terms of welfare by positive growth effects and vice versa.

2.2.7 Lessons from theory

The theory in this section exhibited the core mechanism behind the computational model used for our simulations and showed that a growth dividend is theoretically possible due to the input reallocation towards innovation. Moreover, we stressed through equation (2.18) the importance of the growth effects of an environmental policy on the welfare of households. This endogenous adjustment of economic growth and its effect on welfare is neglected by static models or models of exogenous growth. There are several effects on growth and welfare to consider. First, a positive *growth effect* due to higher labor employment in R&D: with limited substitutability between labor and energy in manufacturing, an increase of the energy tax can drive more labor out of manufacturing and into research which acts positively on growth. However, higher energy taxes that increase the price of the final good, suppress output and subsequently investment, which acts negatively on growth; a negative *level effect*. This is essentially the same effect that suppresses labor supply, and reduces current consumption, the *tax interaction effect*, as identified in Bovenberg and De Mooij (1994). The latter can be counteracted by the positive *revenue recycling effect* of redistributing additional tax revenues back to the society that increases the disposable income of the representative household which is beneficial both for welfare and growth. The presence of leisure in the model might additionally dampen the positive growth effect. In general, the results are ambiguous.

The model used in the theory part is highly stylized and can only capture part of the processes that occur in reality. In a real growing economy with more inputs and manufacturing sectors, the production functions of manufacturing and R&D need to be enhanced to match the data: inputs from different sectors are needed for any production process, and supplied labor is mobile also across and within manufacturing sectors leaving even less available labor to R&D. Moreover, changes in relative prices between sectors due to higher energy taxes lead to input reallocation, which may favor direct investment in capital accumulation. Finally, the analytical model considers a representative household for analytical convenience. Such a framework cannot capture heterogeneous welfare effects, although such effects become important when studying a real world economy. Hence, in the numerical segment we include several heterogeneous consumer groups in order to study the effects of our policies on heterogenous agents. Using our numerical model in the subsequent sections we study the effects of an environmental tax reform on production, growth and welfare of different households in a real growing economy, for various emissions reduction targets and tax revenue redistribution options. For our computational part we will conveniently focus on the case of Switzerland, which has recently agreed upon implementing an environmental tax reform from 2020 on.

2.3 Estimating the dividends of an ETR in the Swiss economy

2.3.1 Background

The Swiss Federal Council (SFC) announced in September 2013 a set of proposed fiscal measures as a means of reaching its energy and environment related strategic targets up to 2050 (Energy Strategy 2050). In the context of the announced proposal the existing promotional measures, including energy and CO2 emission related contributions and taxes, used to finance subsidies to renewables and building renovations, will be replaced after 2020 by a “steering” system. In this system, fiscal measures will lead to the agreed upon energy and environmental targets, by setting appropriate price signals through the market. Moreover, the revenues of these fiscal measures could be redistributed back to the public in various ways. Redistribution schemes considered include lump-sum redistribution, reduction of income taxation, reduction of the VAT tax, reduction of social contributions, or a mix of these measures.

Following this, a tax revenue redistribution by skipping the VAT was rejected by referendum in March 2015. To avoid any political tension, the SFC decided in October 2015 through a Federal Message that tax revenues from higher environment-related taxes are only to be recycled in a lump-sum way.[7] The strand of applied economic literature used in this consultation consists of static CGE models replicating the Swiss economy without considering any growth effects. As we already explained, this approach neglects innovation and sectoral change, which are very important aspects of the environmental tax reform. Furthermore, estimating the growth effect of tax reform with static models becomes a moot point.

The proposed fiscal measures by the SFC are mainly based on Ecoplan (2012), Ecoplan (2013). Using a static but detailed model of the Swiss economy based on the Swiss Input-Output Table (IOT) with different household categories, these studies present the social consequences of an environmental tax reform for different redistribution schemes. They find that only a small second dividend can be achieved and then only under a certain scenario of redistribution through lower direct federal taxes. Equity issues are being addressed by redistributing part of the revenues in a lump-sum fashion. A version with the most relevant results from the first two previous papers can be found in Boehringer and Müller (2014). Mostly negative welfare results from an ETR in Switzerland has been also found in Imhof (2012).

2.3.2 Numerical model

This model extends the theoretical framework presented in section 2.2 to a multi-sectoral numerical general equilibrium model of endogenous growth, where inten-

[7] In German: Botschaft zum Verfassungsartikel über ein Klima- und Energielenkungssystem, 28.10.2015.

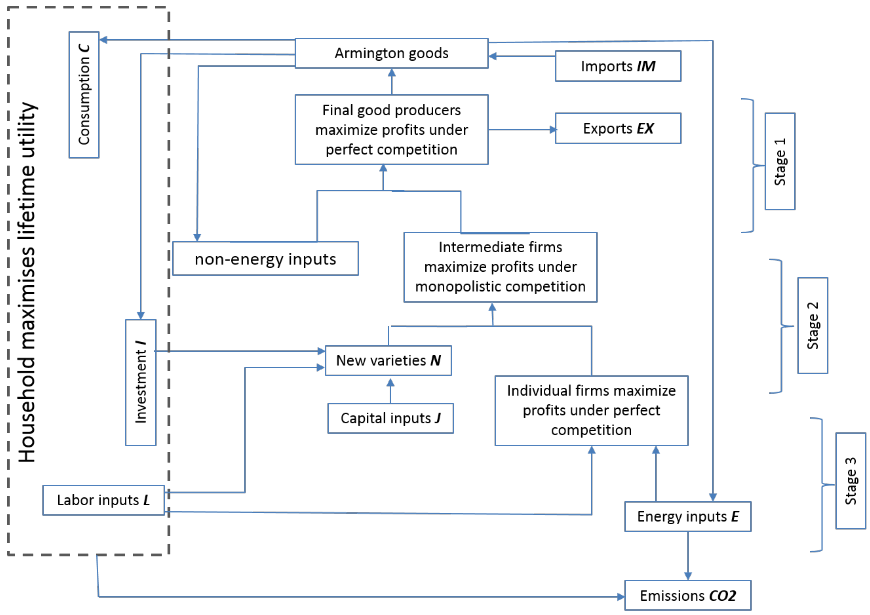
tional investments in R&D endogenously determine the growth rate of each sector and the economy as a whole. The model gives a detailed representation of the input/output linkages of the Swiss economic sectors, imports-exports and has a detailed technological representation of the energy outlook of Switzerland. It can capture directed technical change in the sense that it allows for the reallocation of R&D activities depending on the relative prices among sectors. While the model is a fully-fledged multi-sector dynamic general equilibrium model, we restrict the model description in this section to a non-technical summary of the main characteristics. A more detailed description of the model's basic structure can be found in Bretschger et al. (2011) where it has been employed to study the growth effects of environmental policies in Switzerland. This model has been also used in Bretschger and Zhang (2016) for evaluating the economic cost of a nuclear phase-out policy.

Here, we extend the structure of Bretschger et al. (2011) in several directions. First, we consider a detailed representation of the Swiss fiscal system. In the previous versions of the model preexisting taxation was not considered, which is however essential when studying an environmental tax reform. Second, we keep the multi-sectoral representation of the Swiss economy, but we include several household categories with heterogeneous economic behavior as found in the benchmark data. Third, we include leisure in the model and the possibility that labor is mobile not only within manufacturing and R&D, but also between these sectors. Fourth, we examine different redistribution schemes for the carbon tax implemented and show the results in terms of growth and welfare, in aggregate, but also for each household group. Figure 2.1 sketches the model.

Technology and production

As illustrated in Figures 2.1 and 2.2, sectoral output Y_i, is produced through a three-stage production process. At the highest level, final good producers, operating in a competitive market, use both sector-specific inputs along with commodities from all other non-energy sectors. The second nesting corresponds to the sector-

Figure 2.1: Sketch of the model (one good)



specific Dixit-Stiglitz production function of section 2.2, i.e.

$$Q_i = \left(\int_{j_i=0}^{N_i} x_{j_i}^{\beta} dj_i \right)^{1/\beta}. \tag{2.19}$$

Intermediates use labor in manufacturing and energy directly as factors of production, while capital used in Q accumulates using labor and direct investments. Labor is mobile between every economic activity (manufacturing and research), leisure, and sector of production.

Each firm in the same sector produces symmetric products with limited substitutability (equation (2.19)). This fact supports a degree of market power so firms in the intermediate sector operate in a setting of monopolistic competition. As in (2.2), to raise the output of sectoral specific intermediates, one can increase the production of individual firms, or expand the number of firms in the sector. Since new firms need blueprints embedded in the capital for production, this effectively indicates a growing process of capital build-up. In the capital formation sector (R&D) firms enter freely into investment activity producing the sector-specific capital with research labor and direct investments. The law of motion of capital in the model reads:

$$N_{i,t+1} = \left[\alpha_{Ni} I_{Pi,t}^{\frac{\tau-1}{\tau}} + (1-\alpha_{Ni}) I_{Ni,t}^{\frac{\tau-1}{\tau}}\right]^{\frac{\tau}{\tau-1}} + (1-\delta_t) N_{i,t}, \tag{2.20}$$

with investments in physical capital denoted by $I_{Pi,t}$, and in non-physical capital by $I_{Ni,t}$. Parameter τ represents the elasticity of substitution between the two investment types, α_{Ni} is the value share of physical investment, and δ_t is the depreciation rate. New investments can be directed to any sector according to its expected profitability. Similar to (2.12), non-physical investments I_{Ni}, are determined by scientific labor L_{Ji}, and non-labor inputs in research I_{Ji}.

Finally, the production of the energy sector differs slightly in that it assumes an additional level at the top of the nested production function, where sectoral output is being produced with fossil energy and electricity.[8] They are assumed to be imperfect substitutes with elasticity of substitution ϵ_E. Non-fossil energy is produced in the same way as regular goods, while fossil energy consists of refined oil, gas and district heating, with different carbon intensities (amount of carbon emitted per unit).[9]

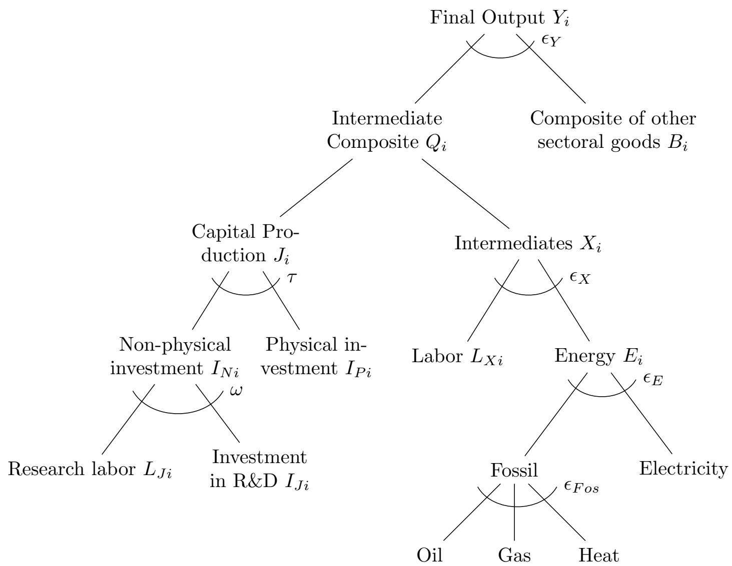
Preference and household consumption

We distinguish different household categories based on their working status (active - retired) and on their income level. Each household, holding ownership of intermediate firms in all sectors, the capital of the economy, supply this along with labor in manufacturing and research. Households maximize intertemporal utility by allocating their time endowment between work and leisure, and their income between consumption and saving for investment under perfect foresight.

[8]Electricity in Switzerland is almost CO2-free, so electricity and fossil fuels are differentiated in the model.

[9]District heating uses heat from large thermal power plants or waste incineration facilities and delivers hot water to consumers via pipelines. We therefore consider it as fossil fuel technology. Carbon intensities in the model are 1.35 for oil, 1.01 for gas and 1 for district heating.

Figure 2.2: Production structure of each regular good

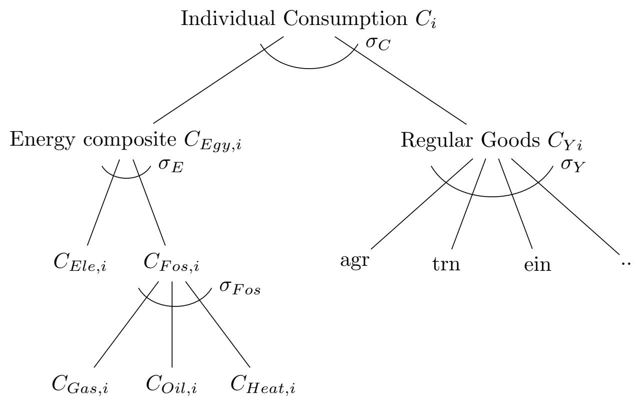


Their total income consists of net factor income and transfers by the government and other households, while their expenditure of gross consumption expenses, tax payments, social security contributions, direct transfers to other households and investments. Instantaneous utility is composed of commodity consumption where each household group presents its own preference for different consumer goods, and leisure. Commodity consumption includes the consumption of energy goods and non-energy goods. Within the aggregate energy demand, electricity trades-off with fossil energy which comprises of gas, oil, and district heat. Substitution possibilities within each nesting are given by CES preferences. Figure 2.3 shows the consumption structure of an individual.

Government and international trade

The government collects taxes in order to finance transfers and to provide public services, which are produced with commodities purchased at market prices. In the model, we keep the level of public service provision fixed and balance the public

Figure 2.3: Consumption structure of individual households



budget through lump-sum transfers proportional to the benchmark share of persons in each household class. This is the equal-yield instrument we choose for our policy comparison.

The economy is small but open to international trade in goods. Goods produced in domestic firms can be used for the domestic market or the export market with a trade-off ruled by a constant-elasticity-of-transformation function. We assume imports are Armington substitutes for domestic goods due to product heterogeneity; the demand for good i can be covered by domestic output Y_i and imports M_i according to

$$A_i = \left[\alpha_A Y_i^{\frac{\xi-1}{\xi}} + (1-\alpha_A) M_i^{\frac{\xi-1}{\xi}}\right]^{\frac{\xi}{\xi-1}}, \tag{2.21}$$

with α_A the value share of output Y_i, and ξ the elasticity of substitution between Y_i and M_i. Trade is balanced in every period. As in section 2.2, due to the small country assumption foreign prices are exogenous. Trade in assets is also not considered. Finally, even though our model is based on endogenous innovation and the sectoral spillovers it creates (see for example equation (2.11)), we do not include international knowledge spillovers. The effects of international knowledge diffusion on growth and on the costs of climate policy for different aggregated regions have been studied in Bretschger et al. (2017).

Data and parameterization

This study makes use of a Swiss social accounting matrix (SAM) for 2008 which comprises of different sources: the manufacturing sectors come from the Swiss Input-Output table for 2008. The household sector is disaggregated using household budget surveys from 2007 to 2009, both by the Swiss Federal Office of Statistics. Data on tax payments and transfers are taken from the Swiss National Accounts for the year 2008. Our sources were used in the following ways:

IOT data was used to calibrate the production of the Swiss economy. Sectors are aggregated into 10 non-energy sectors, which are agriculture (agr), chemical industry (chm), machinery (mch), costruction (con), transport (trn), banking and financial services (bnk), insurances (ins), health services (hea), other services (oth), and other industries (oin).[10] Energy disaggregation follows Bretschger et al. (2011). We identify three fossil energy sources (gas, oil, district heat (dhe)), and electricity (eles), which is almost CO_2 free in Switzerland, as found in the input-output table.

To infer the tax payments across sectors, households, and the government we use the Swiss National Accounts . The model features a detailed representation of the Swiss tax system: it includes value-added taxes, income taxes on both the federal and the cantonal level, social security contributions, output taxes and import tariffs for firms, but also Swiss specific environmental taxes such as the Mineral-oil tax and the Climate-cent tax.[11] Other minor taxes and subsidies were also included as taxes on sectoral inputs by firms and consumption for households.

Furthermore, we use the household budget surveys from 2007 to 2009 to calibrate the households consumption, investment, and transfers. We have divided the Swiss population in five groups according to their professional status (active-

[10] We have limited the number of regular sectors to 10 due to the computational complexity of the dynamic model. However, all the important sectors for the Swiss economy are presented in the model. Moreover, we have a detailed representation of the Swiss fiscal system and several household categories.

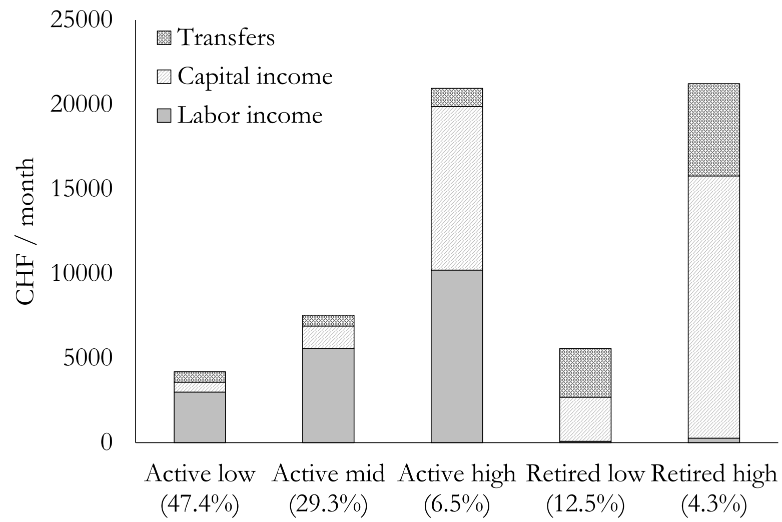
[11] These two taxes on fuels made together about 5.5 billion CHF in 2008, or about 3% of total tax revenue. Even though their contribution is small, we include them for the sake of completeness.

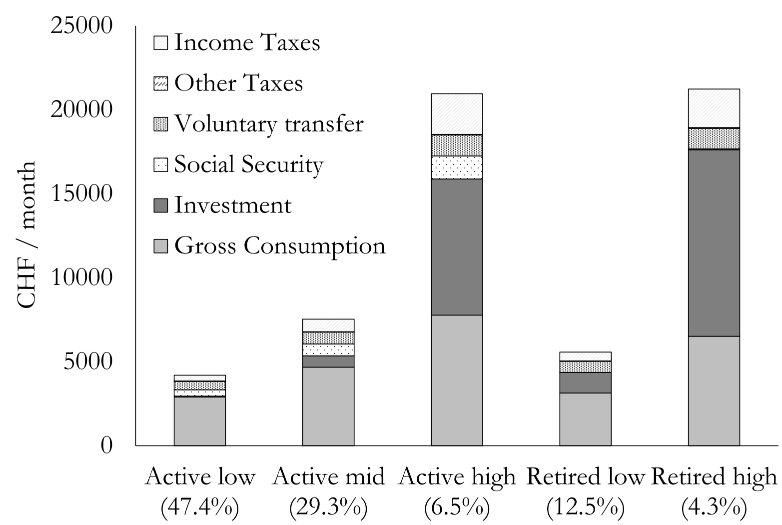
retired) and income. Each household group features also its own labor-leisure choice with data taken from the Swiss Federal Office of Statistics.[12] Figure 2.4 presents the demographics of the representative households. The active low income group accounts for around 47% of the total population in Switzerland with an average income of approximately 4200 CHF per month, where 80% of the total income is from labor earnings. The average income of the active high income group is more than four times larger than the active low income group. Both capital and labor earnings contribute equally to the total income of the active high group households. Similarly, for retired households, the high income group receives most of its income from capital earnings. In terms of expenditure, high income groups (both active and retired) are the major sources of investment while low income groups spend most of their income on consumption.

The elasticities of substitution between polluting fossil fuels and CO2-free electricity in production (ϵ_E), and consumption (σ_E), are obviously very important for our results as poor substitutability leaves less room for the economy to respond to a carbon policy and substitute away from polluting energy technologies; this might dampen the whole production process and impair economic growth and household welfare. The estimated values in the literature range from 0.5 (Boehringer and Rutherford 2008, Goulder and Schneider 1999) to 1.5 (Gerlagh and van der Zwaan 2003). We will use a low value of 0.7 for our main simulations while in the sensitivity analysis we present the results in terms of growth and welfare for a high elasticity of substitution. Table 5.1 in Appendix 5.1 presents the chosen values for the elasticities used along with their sources.

[12]We use the complement of the labor participation rate as a proxy for leisure. The Swiss Federal Office of Statistics publishes data on income and on the labor force participation rate for several age groups. We therefore do a mapping for the time endowment of the households between age groups and income groups according to our household categories: Active low (0.15), Active mid (0.1), Active high (0.25), Retired low (0.9), Retired high (0.9). In the Appendix we run a sensitivity analysis with a uniform time endowment of 0 and 1.

Figure 2.4: Income and expenditure structure of household groups. In parentheses the population share.





Calibration for the balanced growth path

In the model, a general equilibrium is a set of prices and quantities which clears goods and factor markets and satisfies the first order conditions for firms and households. On the balanced growth path (BGP) all variables grow at a constant rate. Let g_Q and g be, respectively, the growth index (in the discrete time framework of the numerical model this is one plus the growth rate) for final output and the number of varieties. According to (2.2) and (2.19) on the BGP final output grows at $g_Q = g^{1/\beta}$. To ensure that a BGP exists, following Bretschger et al. (2011) and Bretschger and Zhang (2016), we calibrate the model so that each sector's capital expenditure is a share $1 - \beta$ of the value of intermediate composite Q with $\beta = 0.25$. Accordingly, on the BGP all sectors grow at the same rate. We calibrate the model to a steady-state baseline extrapolated from the Swiss SAM for 2008 using exogenous assumptions on the growth rate of output, the interest rate, the intertemporal elasticity of substitution, and capital depreciation rate in time. The choice of the annual interest rate is important for the results of a long-term analysis like the present one. We use a value of $\bar{r}$=0.01 for the, net-of-tax, return on capital. To waive the gains from specialization effect in (2.20), which ensures a growing investment over time, the depreciation rate δ_t rises moderately every year, with δ_0 set to 0.07.[13] The benchmark growth rate of the economy is set to 1.33 percent reflecting roughly an annual average of Switzerland in the last two decades. The discounting rate ρ is thus endogenously determined by the model along a balanced growth following the usual Keynes-Ramsey rule of consumption growth (Euler equation).[14]

Computational strategies

To approximate the infinite horizon by a finite-dimensional computational model, we use the state-variable targeting approach proposed by Lau et al. (2002). Impor-

[13] This is equivalent with introducing the z variable in (2.12).

[14] For a detailed explanation of how to calibrate a growth model to a BGP see Rutherford (1999).

tantly, this allows us to target the terminal capital stock of each sector individually. After policy is implemented, this leads to an endogenous growth rate for the overall economy on a new balanced growth path, by using a series of complementarity constraints on the growth rates of sectoral investments. We use the General Algebraic Modeling System (GAMS) software and the GAMS/MPSGE higher-level language (Rutherford 1999) together with the PATH solver (Dirkse and Ferris 1995) to solve the numerical mixed-complementarity problem. The baseline model includes the current fiscal status of the Swiss economy.

2.3.3 Design of computational policy experiments

Switzerland has one of the lowest CO2 emission levels among the OECD countries with about 5 tons per capita in 2010. Part of its ambitious plan of sustainable development is to reduce this number by about 60-65% in 2050. The "business as usual scenario" (BAU) includes all the existing energy related contributions and taxes that are in place in the Swiss economy as reflected in the base year data. To comply with the aforementioned CO2 reduction target we impose carbon allowances where the level of CO2 tax is determined by the shadow prices of quotas in equilibrium. We will present results on growth and welfare for $20\%, 40\%$, and 60% emissions reduction in 2050 compared to 2010.

The revenue from CO2 emissions taxation is collected by the Swiss government and enters the government budget. Regarding the revenue neutral tax swap we keep the level of public good provision constant, while the government recycles the excess income through lowering preexisting taxation or through a lump-sum redistribution. We consider three alternative revenue recycling schemes: i) lump-sum per-capita transfers to households; ii) proportional cuts of federal labor income taxes; iii) proportional reduction of capital income taxes. Due to the fact that the VAT in Switzerland is already very low (8% for normal goods, 3.8% for lodging, and 2.5% for basic goods) and that a redistribution of tax revenues by skipping the existing VAT tax was rejected by referendum in 2015, this scenario will not be examined.[15]

Our model does not explicitly simulate external effects such as environmental benefits from emission mitigation activities, i.e. we do not consider the first dividend of the environmental policy in our calculations. An ex-post monetization of the reduction of externalities associated with pollution can be introduced by using exogenous estimates. For example in Boehringer and Müller (2014), external environmental effects from an environmental tax reform amount to an increase in welfare by $0.2 - 0.5\%$, depending on the stringency of the emission reduction target. Finally, we also do not assume any exogenous energy efficiency improvements or escalating costs for non-renewable resources. We do that in order to focus on the dynamic response of the benchmark economy to the carbon policy, and on the quantification, in terms of economic growth and welfare, of the maximum cost that the Swiss society has to incur.

2.4 Simulation results

2.4.1 The carbon tax

Table 2.1 shows the CO2 tax needed for Switzerland to reach 60% reduction in CO2 emissions in 2050 in comparison to 2010. We choose a linear increase in the CO2 reduction target until 2050 relative to 2010. The tax profile is very similar for all the tax recycling schemes: the standard deviation from the mean is 2.2 CHF/tonCO2 in 2030, increasing to 9 CHF/tonCO2 in 2050. The level of the tax is in-line with other studies made for Switzerland: for example in Ecoplan (2015) for a 63% emissions reduction a uniform carbon tax on all emitting sources of 336 CHF/ton CO2 in 2030 is calculated. Below we present the effects of this increasing tax on economic growth and welfare of the Swiss society.

[15] If anything the VAT tax in Switzerland is too low: evidence that a shift of direct income taxes to VAT can be welfare and growth promoting can be found in Albi and Martinez-Vazquez (2011) and Fuentes (2013).

Table 2.1: Carbon tax in CHF/tonCO2 for 60% emissions reduction in 2050 and different redistribution options

Year	Capital tax	Fed. Income tax	Lump-sum
2020	107	107	106
2030	314	311	310
2040	722	717	716
2050	1717	1705	1706

2.4.2 Effects of carbon policy on production

In the theoretical part we showed that, following a green tax reform, the positive growth effect of induced innovation can counteract the negative level effect of increasing production costs and can lead to higher growth rate of output, while the results are in general ambiguous. In this section we exhibit and discuss the results of our carbon policy on investment, sectoral growth and aggregate production.

Table 2.2 presents the growth rate of total output in 2050 for the different emissions reduction targets and different tax revenue redistribution scenarios. There are three points to raise here: first, out of all the redistribution scenarios the one that performs best in terms of economic growth is redistribution through lowering capital taxation. This result is intuitive since a lower price of capital leaves room for more investment into capital formation. The impact of the green tax reform on economic growth is independent of the redistribution scheme for the other two scenarios. In general, the effects are small. Second, Switzerland can reach a long term environmental target of 60% CO2 emissions reduction with a small reduction in economic growth up to 0.5% in 2050 compared to the BAU. Third and most important, a moderate carbon reduction target of up to 40% in 2050 can still lead to enhanced investment activity. For high emission taxes, however, one is to expect slightly negative results on investment and growth as the stringent carbon policy imposes restrictions on the economy which cannot be overcome by stronger innovation or substitution between energy and other factor inputs. This can be best seen in Figure 2.5 where we plot the growth paths (normalized to the BAU trajectory) of aggregate output, R&D labor expenditure, and total investment in the lab for 20% and 60% emissions reduction in 2050 and two redistribution scenarios, reduction in capital taxation and lump-sum redistribution.[16]

Table 2.2: Long-run aggregate output growth (% p.a.) for different CO2 emissions reduction targets in 2050 and different redistribution options

Target	BAU	Capital tax	Fed. Income tax	Lump-sum
20%	1.33	1.35	1.31	1.31
40%	1.33	1.34	1.30	1.30
60%	1.33	1.31	1.28	1.28

Our discussion in sections 2.2.6 and 2.2.7 is relevant for explaining the results of such a carbon policy on investment and growth in our endogenous growth framework. On the one hand, as explained in part 2.3.2 and in particular using the top two nestings of figure 2.2, to raise sector-specific output one can increase the input of other sectoral goods, of intermediates, or the number of intermediate firms, each entitled to a blueprint of production, i.e. the capital stock of the economy. Accordingly, higher growth through induced innovation in the research lab can translate to higher levels of production and investment in subsequent periods.

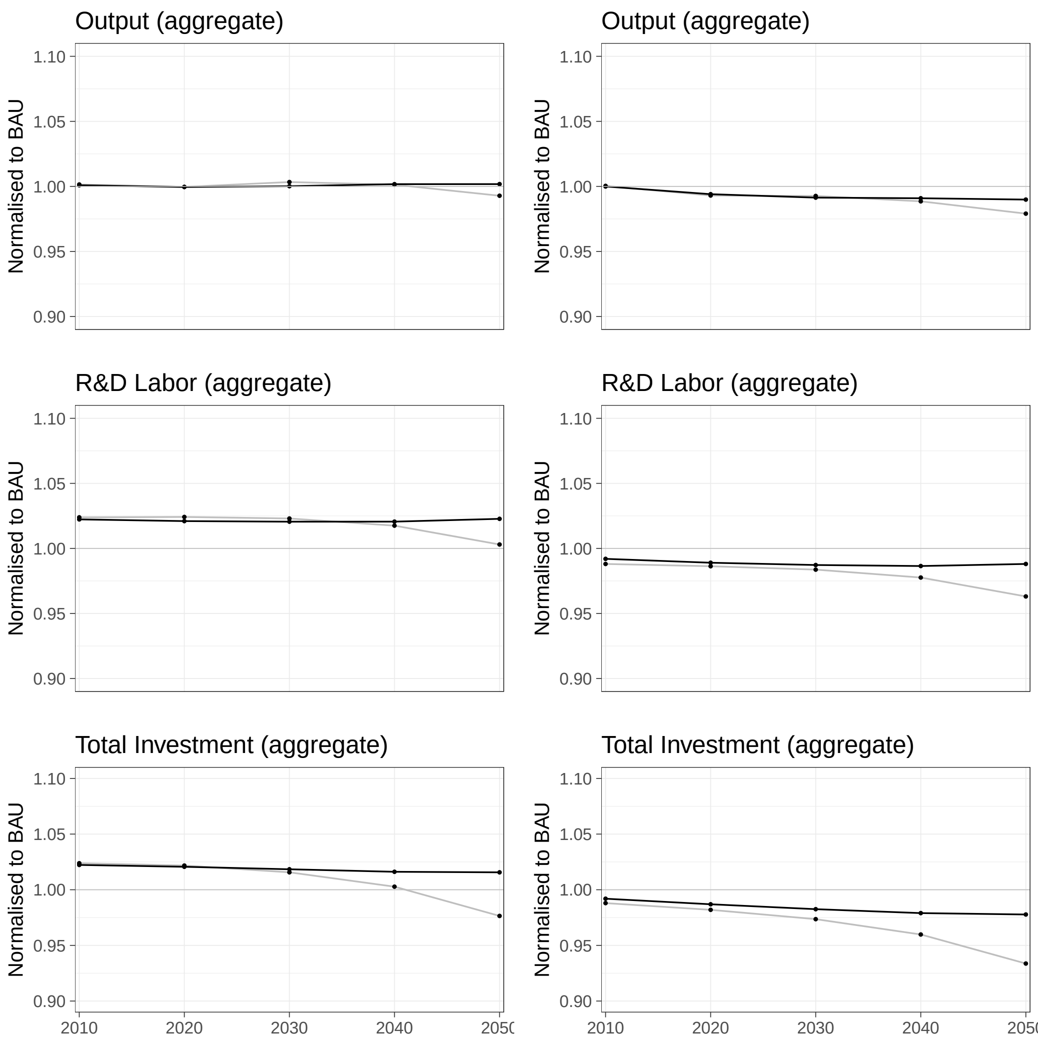
An increase in the consumer price of energy exerts a downward pressure on the real wage rate making labor in the lab cheaper which can promote growth. This of course can be counteracted by a reduction in aggregate labor supply, as explained in the theoretical part. Counter to the positive growth effect runs a level effect that reduces the demand for the final good and leaves less available resources to investment; a carbon policy that suppresses the demand for energy

[16] As in (2.12), total investment uses labor in R&D and final output from the different sectors in the form of direct investments in the lab.

intensive goods might dampen the whole production process. Our results show that redistributing additional tax revenue by lowering capital taxation is beneficial for investment, resulting also in aggregate production being relatively unaffected. However, the increasing carbon tax that continuously dampens production, turns the results negative in the long-run when we aim at a high emission reduction target. A lump-sum redistribution is the least favorable option for entrepreneurial activity. In this case the path of investment is always lower than in the BAU and the growth dividend of an environmental tax reform fails instantly; the level of aggregate production is also subsequently lower since the loss in demand caused by the high energy price in not compensated by higher investment in innovation and growth.

Our numerical model of endogenous growth shows that, in a real economy with a detailed representation of its sectoral linkages and preexisting tax distortions, an environmental tax reform is not detrimental either in terms of production levels or output growth; see Figure 2.5 and Table 2.2. On the contrary, even in the relatively pessimistic case of limited substitutability between clean and dirty energy inputs, higher growth through induced innovation is a plausible outcome for not very stringent carbon taxation. In Appendix 5.1.6 we also present the effects of such a policy on the primary, secondary, and tertiary sector of the Swiss economy.

Figure 2.5: Production, R&D labor expenditure, and total investment (normalized to BAU) for 20% (black) and 60% (grey) CO_2 emissions reduction in 2050 - aggregates.



(a) Capital tax redistribution

(b) Lump-sum redistribution

2.4.3 Effect of carbon policy on consumers

A central feature of the green tax reform reform is that the efficiency of the economic system should be promoted while existing inequalities between social segments should be minimized. Our indicator for the efficiency of the economic adjustment is welfare, including both the discounted stream of consumption and leisure for each individual household group. Aggregate welfare is measured by introducing population-based weights of each household group shown in Figure 2.4. This metric quantifies the aggregate efficiency impact of our policy experiments in comparison to the BAU scenario, according to which Switzerland follows its current environmental and energy policy.

As we already noted, we do not consider the first dividend of the environmental policy in our calculations. An ex-post monetization of the reduction of externalities associated with pollution can be introduced by using exogenous estimates as in Boehringer and Müller (2014). In this contribution external environmental effects from an environmental tax reform amount to an increase in welfare by $0.2 - 0.5\%$, depending on the stringency of the emission reduction target. This increase is potentially larger if we take into account the economic cost of continuously increasing future climate degradation (see Chapter 3). Accordingly, our welfare indicator includes the second and the third, but not the first dividend of the policy.

Aggregate welfare

The aggregate efficiency of the green tax reform crucially depends on the stringency of the environmental targets, on the redistribution option, and on the tax base considered. A high CO2 emissions tax, on a rather narrow tax base, creates distortions in the economy that cannot be overcome by any redistribution scenario. Labor and capital income tax rates in Switzerland, both applying on a wide tax base, are not that big compared to energy taxes.[17] Hence, labor and capital are

[17]On net basis, labor income tax rate varies between 9-20%, capital income tax rate between 8-11%, while energy taxes associated with the environment between 30-45%.

"undertaxed" in comparison to polluting energy sources, and so, using additional carbon tax revenues to further reduce labor or capital taxation is inefficient and leads to welfare losses. As we already indicated, a lump-sum redistribution is bound to perform even worse in terms of economic efficiency since it does not correct any distortions in the fiscal system.

The positive effects of reduced tax distortions from the various redistribution schemes along with the potentially induced growth effects are not able to exactly offset the negative tax interaction effects of higher carbon taxes. In addition, the inefficiency increases over time as demand for polluting energy is decreasing and the carbon tax base is effectively shrinking; apart from missing any growth considerations, static models tend to underestimate the effects of such a tax reform on welfare. Our results indicate that an environmental tax reform does not allow for higher welfare when the first dividend is absent. On the premise, however, that a green tax reform will promote a cleaner environment, one should search for the least distortive option. Table 2.3 suggests that the welfare loss under capital tax redistribution is the smallest. Building on equation (2.18) and our discussion in the previous section, this option is preferable for capital accumulation which then promotes the growth effects of the policy on the aggregate level.

Table 2.3: Welfare change (in % from BAU) for different CO2 emissions reduction targets – excludes the first dividend

Target	Capital tax	Fed. Income tax	Lump-sum
20%	-1.19%	-1.24%	-1.33%
40%	-2.09%	-2.13%	-2.25%
60%	-3.79%	-3.83%	-4.00%

Distributional considerations

Figure 2.6 presents the effects of a environmental tax reform in Switzerland on the welfare of the different social groups for each redistribution scheme for a low and a high emission reduction target. In a static setting, household consumption expenditure is affected by the positive revenue recycling effect that increases their disposable income and the negative tax interaction effect of higher energy taxes that reduces it (Bovenberg and De Mooij 1994). As already discussed, our model includes additionally distorting effects of an ever shrinking tax base – the polluting energy goods – and the potential positive growth effects of induced innovation. The first dividend is not quantified.

Table 2.4 shows the energy expenditure share of total disposable income for different household categories: the least well-off spend a larger part of their disposable income on polluting energy. Accordingly, higher emission taxes are more likely to harm poor segments of the population, i.e. carbon taxation is inherently regressive. Apart from that, one needs to consider the main income sources of the different social groups.

Redistributing tax revenues from additional environmental taxes by lowering capital or labor taxation produces in general regressive results because capital and labor income is relatively low for poor households in comparison to the middle or rich segment. If the emission reduction target is low, the welfare of the upper social segments is least distorted when the government uses additional carbon tax revenue to cut income taxation. Moreover, an increase in welfare results for the upper social group of the active population and the retirees if, respectively, cuts in labor and capital income taxation are considered, because in this case existing market distortions are reduced. However, stringent emissions reduction targets coupled with high carbon taxation, tend to reduce available income more than they reduce distortions in the active population and individual welfare is worsened. This does not apply to the rich retirees since they spend only 1.2% of their disposable income on polluting energy; a welfare increase is possible in their case.

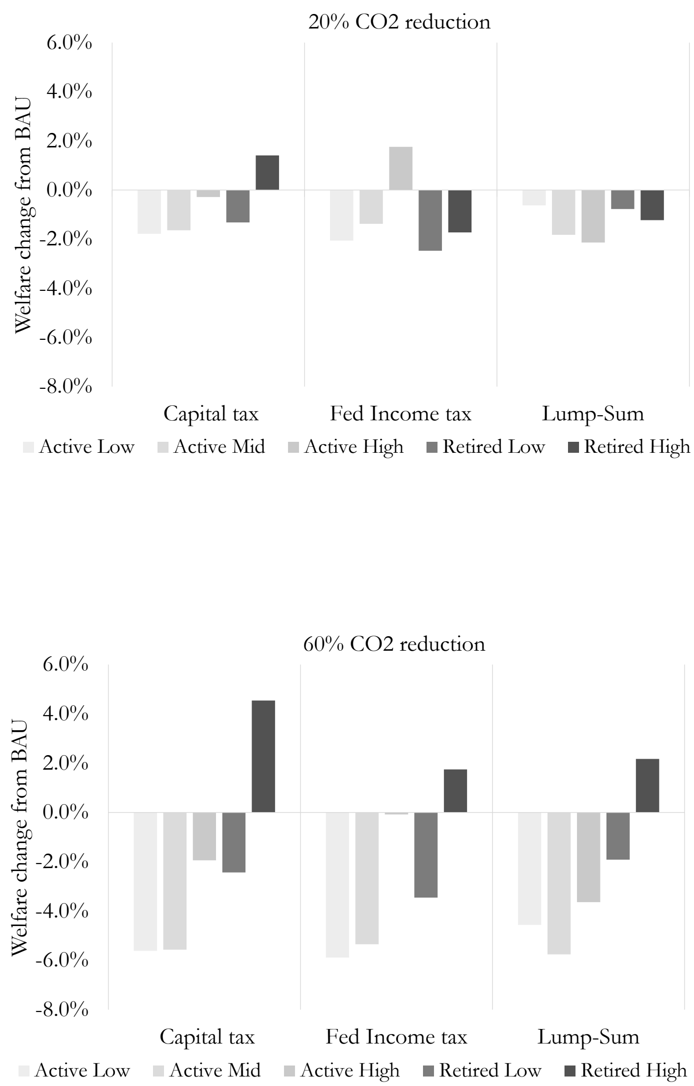
When it comes to pure equity considerations in Switzerland the consensus in the literature speaks in favor of a lump-sum redistribution; see for example Imhof (2012) and Boehringer and Müller (2014). This redistribution scenario that increases the available income of households without reducing any distortions in the fiscal system is more beneficial to the poor. If the emission reduction target is not too high, redistributing tax revenues in a lump-sum fashion mitigates the reduction in disposable income, from higher energy prices, and consumption of the poor segments due to higher energy taxes. In this case we also get that a lump-sum redistribution produces progressive results. Nevertheless, the progressive character of the lump-sum tax redistribution fails when we consider a very high emission reduction target.

In the case of the lump-sum per-capita redistribution and the stringent CO2 emission reduction target, the difference between the first two groups of the active population, which are mostly dependent on polluting energy, can be understood as follows: for a low emission reduction target the additional lump-sum income allocated to the poor almost compensates the income reduction from the higher energy tax because lump-sum transfers consider a big part of the household income for the least well-off. Since, however, such a scenario does not correct distortions in the labor market, the middle segment is genuinely worse-off. The same comparison applies between the poor and the rich social group. However in this case the CO2-intensive energy expenditure share of the total disposable income for the rich group is almost the half compared to the poorer, i.e. higher energy taxes do not affect their disposable income that much.

Table 2.4: CO2-intensive energy expenditure share of total disposable income for different household categories

Active Low	Active Mid	Active High	Retired Low	Retired High
3.9%	3.7%	2.3%	2.3%	1.2%

Figure 2.6: Welfare change (in % from BAU) for 20% and 60% CO2 emissions reduction in 2050 – excludes the first dividend



2.4.4 Policy implications

The Swiss Federal Council decided to go forward with an environmental tax reform from 2020 on as a means of reaching its energy and environmental targets up to 2050. To comply with the stringent CO2 reduction targets we impose a carbon tax on polluting energy sources according to their carbon intensity. The redistribution of the tax revenues should take into account its effect on economic growth, aggregate welfare and equity among social segments.

Production side considerations would speak in favor of lowering capital taxation. This result is intuitive since by reducing distortions in the capital market, investment is promoted. Increasing capital varieties make the use of other inputs like energy more efficient. This can counteract the negative level effects of increasing energy taxes compensating for the additional tax burden, and resulting to higher economic growth if a low CO2 emission reduction target is followed. Higher growth translates to higher output in subsequent periods; the level of output is subsequently only minimally impaired even for a very stringent environmental policy. In general the results on economic growth are not detrimental even in the case of limited substitutability away from polluting energy sources.

Concerning welfare, in aggregate, relatively low capital and labor taxation, along with a narrow, and ever-shrinking, tax base of the energy input end up exacerbating rather than alleviating preexisting tax distortions. Lump-sum redistribution produces the least efficient option since the positive revenue recycling effect of the green tax reform is absent. If CO2 reduction target is not too ambitious redistributing tax revenues by lowering capital taxation allows for a welfare increase to the upper segment of the retired population; lowering labor income taxes benefits the upper segments of the active. A more stringent environmental policy mostly benefits the richer social segments due to their low expenditure share on CO2-intensive energy. When it comes to lump-sum redistribution, our results are also aligned with those of the Swiss economic literature but only for a low emission reduction target: a 20% emissions reduction in 2050 compared to 2010 produces progressive results; considering, however, the more stringent target of 60% reduction, produces regressive results. Accordingly, using lump-sum tax redistribution from a stringent environmental fiscal policy to address equity considerations might not be the best option for Switzerland.

Even though there is still a long way to go to fight climate change, there has been a great improvement in terms of international cooperation. As an example, the Paris climate change agreement has been a worldwide diplomatic success. Yet, although many countries have signed the agreement, the collective efforts from all those countries are still far away from saving our planet. This study suggests to policy makers in individual countries that the effects of carbon policy on the economy's performance could be limited through the positive growth effects of induced innovation, and that a stringent climate policy does not necessary hurt the country's economy. To that respect, at the global level, Bretschger et al. (2017) show that knowledge diffusion can lower the costs of climate policy for all countries, in particular for developing countries like China. Hence, if carbon tax revenue is used for the capital investment for research and new technology development, the spillover effects of knowledge will spread across the border and finally reduce the costs of climate policy for the world at large.

2.4.5 Robustness

The elasticities of substitution between polluting and clean energy (electricity) in production and consumption are crucial for the results, while their values vary greatly within the literature. Low elasticities reduce the substitution possibilities away from polluting sources which dampens the economic performance of the market at stringent emissions reduction targets. So far we have assumed limited substitutability in order to be on the safe side and reduce the risk of understating the economic costs of a green tax reform. Here we are presenting also the results for a high value of 1.5 for both ϵ_E and σ_E.[18] Table 2.5 shows the results in 2050 for a 60% emissions reduction, in terms of carbon tax, economic growth and aggregate welfare.

As expected, a high value for the elasticities of substitution between polluting and non-polluting energy in production and consumption, $\epsilon_E/\sigma_E = 1.5$, is beneficial for the performance of the economy considered. That is exactly because the economy is able to substitute away from polluting energy sources and thus the effects of the environmental policy are not detrimental. This adds on top of the growth effect we identified of reallocating resources to the R&D sector and growth is raised further. Accordingly, economic growth is higher in the long-run, the carbon tax needed for Switzerland to reach the ambitious target of emissions reduction is lower than in the main simulation, and the impact of the carbon policy on aggregate welfare is smaller. Between the redistribution options nothing has changed: redistributing additional tax revenues through lower capital taxes performs best in terms of economic growth, while lump-sum redistribution is the preferred option for a smaller welfare loss in aggregate welfare.

Table 2.5: Robustness check for the elasticities ϵ_E/σ_E and ϵ_X. Results in 2050 for 60% emissions reduction

$\epsilon_E/\sigma_E = 1.5$	Capital tax	Fed. Income tax	Lump-sum
Carbon tax (CHF/tCO2)	1209	1200	1200
Output growth (% p.a.)	1.36	1.33	1.33
Aggr. welfare (% from BAU)	-2.65	-3.12	-3.19

[18] Ramer (2011) has run sensitivity analysis on a similar numerical model without taxes and with only one representative household that supplies labor inelastically for most of the parameters used here. The results for most of the parameters are qualitatively comparable; repeating this analysis here would, therefore, not add any insight. Same applies for a sensitivity analysis on the time endowment of households, as well as on the elasticity of substitution between consumption and leisure, as shown in Imhof (2012).

2.5 Conclusions

In this paper we examined theoretically and computationally, using endogenous growth theory, the effect of a green tax reform on a growing economy. We first identified in a framework of endogenous growth the modeling conditions that lead to higher economic growth due to higher energy taxes.

The theoretical model showed that in a setting where R&D activity is the growth mechanism of the economy, an environmental tax reform can result in a positive growth dividend through input reallocation if two conditions are met: first, labor input should be mobile between manufacturing and R&D; second, the elasticity of substitution in manufacturing between the scarce factors and energy should be lower than unity. In such a case, increasing taxation of the polluting factor of production pushes more labor into innovative activities and promotes growth; a positive *growth effect*. The growth dividend fails to realize if investment in innovation is the sole result of foregone consumption. In such a case increasing the consumer price of the polluting factor makes output and direct investment more expensive, which suppresses growth; a negative *level effect*. Adding elastic labor supply reduces the scope for growth. In general the results of a green tax reform on economic growth are ambiguous.

For the numerical part we used the case of Switzerland, which has recently agreed upon implementing an environmental tax reform from 2020. To test our theoretical results we expanded our core theory model to a fully-fledged dynamic computational general equilibrium model of endogenous growth with multiple sectors and consumer categories. In this model investment in innovation arises endogenously, and so does economic growth. We consider three redistribution scenarios for the additional revenues of the tax reform and five social groups according to their employment status (active - retired), and income level.

When substituting away from polluting energies is not an option, the growth dividend fails in the long-run for very stringent emissions reduction targets, while it can succeed for low and medium stringency; induced innovation is effective when we redistribute additional tax revenues through lower capital taxation. Again for limited substitution possibilities away from polluting energy sources, as displayed in the simulation part, the negative level effect is, in general, dominating the positive growth effect when taxes are increasing over time. In total, an environmental tax reform in Switzerland is not detrimental for its economic performance, whichever the redistribution scenario followed, while the sensitivity analysis showed that high substitutability between clean and dirty energy in manufacturing can lead to enhanced growth through input reallocation even for very stringent environmental targets, thus giving indication of a positive growth dividend. Aggregate welfare would also speak in favor of a redistribution of additional carbon tax revenues through lower capital taxes. Equity issues are addressed by a lump-sum redistribution only for a low emissions-reduction target; the progressive character of such an option fails when we consider very high reduction targets, contradicting the consensus in the literature and showing the importance of using an endogenous growth framework over a static or an exogenous growth one when studying environmental policies.

Chapter 3

Optimum Growth and Carbon Policies with Lags in the Climate System*

We study the optimal carbon tax in an economy in which climate change, stemming from polluting non-renewable resource, affects the economy's growth potential. Our main contribution is to introduce and explore the natural time lag of the climate system between emissions and damages to capital accumulation in an endogenous growth setting. This allows us to investigate how optimal climate policy, and its interplay with climate dynamics, affect long-run growth and the transition of the economy towards it. Without pollution decay, a higher speed of emissions diffusion steepens the growth profile of the economy. With pollution decay, this leads to lower short-run but higher long-run economic growth during transition. Poor understanding of the emissions diffusion process leads to suboptimal carbon taxes, resource extraction and growth.

*This work is a joined effort with Lucas Bretschger (ETH Zurich).

3.1 Introduction

Climate change has certain characteristics that impede the implementation of optimal environmental policies: it has a global dimension, necessitating difficult international negotiations and agreements; it requires mitigation policies that create economic costs and benefits which are substantial and unevenly distributed across different countries, and finally; it asks for a policy design that necessitates consideration of a very long time horizon. This poses a major challenge for a usually myopic political decision making process: past environmental policies were mostly implemented after major environmental damages had been publicly observed, creating political necessity to act.[1]

The effects of climate change will only be fully visible after several decades because greenhouse gas emissions cause economic damages only with a major time lag. The Stern Review states “climate models project that the world is committed to a further warming...over several decades due to past emissions.”, (Stern 2007, p. 15). Looking into the future and the potentially large damages from climate change, one would expect a time lag of about 50 to 150 years, depending on the scenario followed, (Stern 2007, p. 178). A certain degree of uncertainty remains in any case, an example for which is prominently given in the new IPCC fifth assessment report: “...due to natural variability, trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends. As one example, the rate of warming over the past 15 years [...] is smaller than the rate calculated since 1951” (IPCC 2013). The existence and form of this delay in the natural system has major implications for optimum growth and carbon policies, which we study in this chapter.

The model is motivated by the evidence that natural disasters have a substantial impact on the economy, destroying part of its physical capital stock (Stern 2013, Bretschger and Valente 2011). At the same time, economic growth exacerbates the

[1] From example the Montreal Protocol on the ozone layer or the ban of asbestos.

impact of natural disasters as the economy accumulates capital, so that each new event has a higher damaging potential. Since 1900, reported economic damages related to weather phenomena and climate change such as floods, droughts, storms, extreme temperatures, and wildfires account for about 75% of all the natural disasters recorded (EM-DAT The International Disasters Database 2015). Moreover reported damages have increased greatly since the late 1980s.

This chapter develops a theoretical model of a growing economy that is harmed by climate change. The model framework used here is based on the endogenous growth approach of Rebelo (1991), enhanced by a polluting non-renewable resource as an essential input to production. We incorporate relevant features such as carbon emissions from non-renewable resources, the slow adjustment of the stock of pollution to emissions, and climate change that affects capital depreciation. Using this endogenous growth setup we characterize the optimal carbon tax when climate change affects the economy's growth potential. We also study how climate dynamics interact with resource extraction and growth in the case of optimal and suboptimal policies. Our main contribution in the theoretical literature is twofold.

First, with our specification of damages in capital accumulation – linear to the level of pollution – and logarithmic utility, the optimal tax is proportional to current consumption, in line with the literature; for instance Gerlagh and Liski (2012), Golosov et al. (2014), Grimaud and Rouge (2014), van den Bijgaart et al. (2016). In the case of a more general CRRA utility, it asymptotically approaches this behavior. Climate change policy postpones resource extraction and consumption, and induces economic growth to start from a higher level, converging asymptotically to a lower positive constant, the latter being unaffected by policy. If all carbon in the atmosphere is removed through carbon decay, there is no climate problem in the long run; if carbon decay is absent, the long-run growth rate is affected by cumulative extraction.

Second, we introduce in continuous time a well-specified time lag between emissions from polluting non-renewable resources and the damages they cause. With our specification, a unit of emissions follows a diffusion process in which it only gradually increases the stock of harmful pollution; taken together with carbon decay this allows for a hump-shaped impulse response function. This process proves to be crucial for the transition of the economy towards its steady state: without pollution decay, a higher speed of emissions diffusion steepens the growth profile of the economy; with pollution decay this leads to lower short-run but higher long-run economic growth during transition. It follows that poor understanding of the emissions diffusion process can lead to suboptimal carbon taxes, resource extraction and growth. We use this result to argue that if emission taxes are not set by the social planner but by a regular political process, there is a risk of setting tax rates at too low a level.

To the best of our knowledge, this is the first contribution which combines endogenous growth with polluting non-renewable resources to derive the impact of a time lag in pollution dissemination in terms of closed-form solutions. Several contributions have studied the dynamic response of the economy to pollution. Withagen (1994) shows that the introduction of pollution from non-renewable resources in the utility function delays optimum resource extraction. Hoel and Kverndokk (1996) abstract from the finiteness of non-renewable resources by focusing on the economic recoverability of the resource stock. They also note that in the presence of greenhouse effects it will be optimal to slow down extraction and spread it over a longer period. Tahvonen (1997) additionally allows for a non-polluting backstop technology and defines different switching regimes between non-renewable resources and the backstop, which depend on initial pollution and the price of non-renewable resources and the backstop. These models, in partial equilibrium, abstract from capital accumulation, which is crucial for growth, and capital destruction due to climate change, which represents climate damages in a more realistic way.

Sinclair (1994) argues, however, that "If global warming is taken to be a serious phenomenon, [...] interest rates need to be co-endogenized with other relevant variables", and studies the impact of environmental pollution in general equilibrium. The impact of pollution on growth has also been studied by Bovenberg and Smulders (1995) and Michel and Rotillon (1995).[2] In a Ramsey growth model, van der Ploeg and Withagen (2010) analyze optimal climate policy based on the social cost of carbon and the existence of renewable resources. Ikefuji and Horii (2012) develop a model with capital destruction due to climate change and conclude that growth is sustainable only if the tax rate on the polluting input increases over time. Contrary to our model they abstract from resource finiteness and the inherent time lag in climate change. Using an endogenous growth model, Bretschger and Valente (2011) show that less developed countries are likely to be hurt more than developing ones, with greenhouse gas emissions inducing negative growth deficits and possible unsustainability traps. Grimaud and Rouge (2014) analyze how the availability of an abatement technology affects optimal climate policies using an endogenous growth model based on the expansion-in-varieties framework and show that when such a technology is available, the optimal carbon tax that postpone resource extraction is uniquely determined. Another related paper is Golosov et al. (2014), which introduces non-renewable resources as in our model but abstracts from any capital stock.[3] Including the stock of capital is crucial for our approach to capture both endogenous growth and climate damage.

Time lags in the climate system are usually implemented in integrated climate assessment models. Prominent examples are Nordhaus (1992, 2011) that calibrate a Ramsey growth model to show a significant Pareto-improvement due to climate mitigation investment. Most theoretical models on climate change have sidestepped time lags in the climate system. Important exceptions are the contributions of Gerlagh and Liski (2012) and van den Bijgaart et al. (2016). In the former the authors rely on the assumption of full capital depreciation in each period and

[2]For a survey of the literature on the relationship between environmental pollution and growth, see Brock and Taylor (2005)

[3] In this paper the closed-form solution of the Pigouvian tax depends on the assumption of constant savings rate all along the optimal path. This can be ensured if capital depreciates fully each period which makes it a flow rather than a stock variable.

using quasi-hyperbolic preferences find that the equilibrium carbon price exceeds the imputed externality cost by multiple degrees of magnitude. The latter derives the social cost of carbon in closed-form for a general neoclassical economy whose development is approximated by a balanced growth path.

The remainder of the chapter is organized as follows. Section 3.2 presents the climate dynamics and the technologies of our economy. In Section 3.3 we characterize the social cost of carbon, i.e. the first best (Pigouvian) per-unit tax that restores the socially optimal allocation. In section 3.4 we solve for the decentralized equilibrium. Section 3.5 analyzes the effect of climate dynamics and different taxation policies on economic growth. In section 3.6 we provide simulations in the case of a general CRRA utility and explain our results. Section 3.7 concludes.

3.2 The Basic Model

3.2.1 Climate System

Producers of consumption goods use polluting non-renewable resources, R_t, which generate a flow of emissions ϕR_t; $\phi \geq 0$ denotes the carbon content of the resource and t the time index. Emissions add to the stock of harmful pollution P_t, which depreciates at rate $\theta \geq 0$. In our model the pollution accumulation process differs from the usual assumption of instantaneous emissions diffusion. We realistically assume that emissions slowly diffuse into the stock of harmful pollution, reflecting the inherent time lag of the climate system.

Take first the usual assumption of instantaneous emissions diffusion and let $Z_t = \phi R_t$ be the flow of emissions that effectively adds to the stock of pollution according to $\dot{P}_t = Z_t + \theta(\bar{P} - P_t)$; P_0 given. A dot denotes the time derivative. Thus, at each date t, the stock of carbon increases by the flow of emissions, Z_t, and decreases by the natural removal $\theta(\bar{P} - P_t)$; with $\bar{P} \in (0, P_0]$ we proxy the long-run level of carbon concentration when $\theta \neq 0$; we set it to P_0 without loss of generality.[4]

Let us now include a distributed time lag formulation for the flow of emissions, i.e. $Z_t \equiv \int_{-\infty}^{t} \kappa e^{-\kappa(t-s)} \phi R_s ds$. Variable Z_t represents now the history of man-made emissions that effectively adds to the stock of pollution with a lag. Parameter $\kappa \geq 0$ is the speed of this diffusion process; limiting cases are instantaneous diffusion ($\kappa \to \infty$), i.e. $Z_t = \phi R_t$, and no diffusion ($\kappa \to 0$), i.e. $Z_t = 0$ at all times. We show in Appendix 5.2.1 that, given $P_0 \geq 0$ and $Z_0 = 0$, the dynamic evolution of the climate system follows

$$\begin{cases} \dot{P}_t = Z_t + \theta(\bar{P} - P_t), \\ \dot{Z}_t = \kappa(\phi R_t - Z_t). \end{cases} \tag{3.1}$$

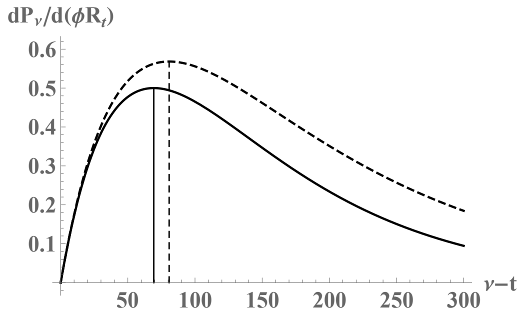
From the solution of (3.1), the marginal increase in the stock of carbon in period ν from a marginal unit of emissions in period t, i.e. its impulse response, reads:

$$\frac{dP_\nu}{d(\phi R_t)} \equiv f_{\nu t} = \kappa \frac{e^{-\theta(\nu-t)} - e^{-\kappa(\nu-t)}}{\kappa - \theta} > 0, \qquad \text{for all } \nu \geq t. \tag{3.2}$$

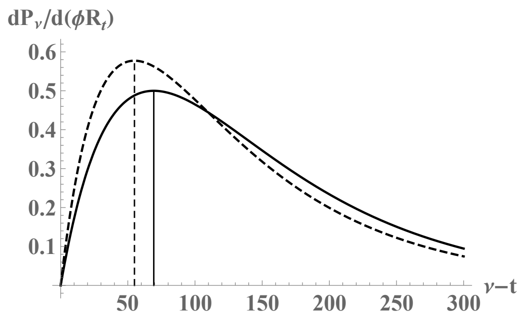
The impulse response function (3.2) is hump-shaped with a peak at $\nu - t = \ln(\kappa/\theta)/(\kappa - \theta)$; see Figure 3.1. The maximum emissions-damage response reads $(\kappa/\theta)^{\frac{1}{1-\kappa/\theta}}$ and is therefore a monotonically increasing concave function in κ/θ, which converges to unity as κ/θ grows to infinity. For a constant speed of emissions diffusion κ, a decrease in the decay rate θ increases the maximum emissions-damage response and shifts it towards the future; see Figure 3.1a. Conversely, for constant decay rate θ , an increase in κ increases the emissions-damage peak, shifts it towards the present but puts a relatively larger damaging impact on the short run in comparison to the long run; see Figure 3.1b.

[4] We thereby assume that even if carbon emissions seize, the stock of harmful pollution will not decrease further than its initial level; see for example Grimaud and Rouge (2014) for an equivalent treatment.

Figure 3.1: Emissions-damage response function for different values of κ and θ. Left for constant κ, right for constant θ.



(a) $\kappa = 0.02$, $\theta_{\text{solid}} = 0.01$, $\theta_{\text{dashed}} = 0.007$



(b) $\theta = 0.01$, $\kappa_{\text{solid}} = 0.02$, $\kappa_{\text{dashed}} = 0.03$

Gerlagh and Liski (2012) arrive at the discrete-time equivalent expression of (3.2). Using their values for the parameters of the climate system, $\kappa = 0.02$ and $\theta = 0.01$, we confirm their result of a peak emissions-damage response of about 70 years. It is important to note that the speed of emissions diffusion has a dual effect on the marginal damages from the extraction and use of the polluting resource: a level effect on the magnitude of marginal damages and a delay / discounting effect. This can be seen as follows.

For very small time intervals this equation can be approximated by $f_{\nu t} \approx \kappa(\nu - t)$; a marginal unit of resources extracted and burned increases harmful pollution within this small time interval by κ. It follows that in the very short run our specification has a relatively larger damaging impact of a marginal increase in emissions the larger κ is. For a given decay rate θ, this will lead to a higher peak of the pollution response, closer to the current date. For longer time periods, the marginal increase of harmful emissions will result in a marginal increase in the stock of pollution determined by the adjustment term $\frac{e^{-\theta(\nu-t)}-e^{-\kappa(\nu-t)}}{\kappa-\theta}$, which accounts for pollution decay and the slow diffusion of emissions into the stock of harmful pollution. If pollution decay is disregarded, i.e. $\theta = 0$, the damage response accounts only for the probability that a marginal unit of emissions emitted in period t has reached the stock of pollution in period v, $f_{vt} = 1 - e^{-\kappa(v-t)}$. These effects of κ have a big impact on the transition of the economy towards its steady state, which we study here.[5]

3.2.2 Aggregate economy

Markets are fully competitive. Production in each period t is based on constant returns to scale technologies and on two inputs: capital K_t, and polluting non-renewable resources R_t. The stock of capital is a generic reproducible factor in this economy that includes both physical and human capital; we will call it "capital" for convenience. As proposed by Stern (2013) and Bretschger and Valente (2011) physical capital is exposed to climate disasters. Natural events like floods, droughts, wildfires, and extreme temperatures caused by anthropogenic climate change can destroy *non-durable* forms of capital like buildings, equipment, crops, roads, and public infrastructure. This fact puts a natural drag on economic growth, since part of the economic resources have to be allocated to fixing these damages. Conversely, there are *durable* forms of capital like human skills and ideas that cannot be depleted; we will therefore allow, without loss of generality, for only a part η of the

[5] Our emissions-damage response does not allow for a thick-tailed concentration of the carbon stock, where some part of the stock stays in the atmosphere for thousands of years, as proposed by natural scientists. We could have captured such a behavior with a richer "multi-box" climate module as in Gerlagh and Liski (2012). This added complexity would however not alter the results in any fundamental way while it would make the model less tractable.

capital stock to be affected by harmful pollution.[6]

Following Rebelo (1991) there are two production sectors in this economy: the consumer goods sector and the investment sector. The consumer good is the numeraire, and is produced with both inputs; the investment good sector is assumed to be capital intensive and uses only capital. The economy features the following aggregate production functions for the consumption good Y_t, and the investment good I_t,

$$Y_t = A(\epsilon_t K_t)^\alpha R_t^{1-\alpha}, \tag{3.3}$$

$$I_t = B(1 - \epsilon_t)K_t, \tag{3.4}$$

where $\epsilon_t \equiv K_{Yt}/K_t \in [0, 1]$ is the aggregate fraction of capital devoted to the consumption good, and R_t the total demand for the non-renewable resource. Investment leads to capital accumulation according to

$$\dot{K}_t = I_t - D(P_t)\eta K_t, \tag{3.5}$$

with $K_0 > 0$, and η the share of non-durable capital, which we assume to be constant. The part of capital that is exposed to wear decays according to the damage function $D(P_t)$ due to natural depreciation and higher pollution levels. Costless resource extraction R_t depletes the existing stock of the non-renewable energy resource S_t (with $S_0 > 0$), according to the standard law of motion and the stock constraint

$$\dot{S}_t = -R_t, \qquad \int_0^\infty R_t dt \leq S_0. \tag{3.6}$$

[6] In a previous version, in order to capture the idea of the *durable* versus the *non-durable* part of the capital stock, we differentiated between two stocks, one of them unaffected by pollution. Non-durable capital was accumulated as in the present version – but with $\eta = 1$ – while we assumed that creation of new durable forms of capital used only itself as an input. However the widely-used Cobb-Douglas specification for (3.3), implying constant expenditure shares among inputs, makes the use of two differentiated stocks inessential; the results are qualitatively identical as in the current approach, while the model is now more tractable. For an endogenous growth framework with only durable (knowledge) capital and flow pollution directly affecting utility see Grimaud and Rouge (2005).

Finally, the economy admits a representative household with preferences $U(C_t)$ that owns all the financial wealth, i.e. capital and energy resources. In the general CRRA form we have $U(C_t) = \frac{C_t^{1-\sigma}}{1-\sigma}$ while with $\sigma = 1$ we get the logarithmic form, i.e. $U(C_t) = \log(C_t)$; parameter σ is the intertemporal elasticity of substitution.

Assumption 1 *The utility function is logarithmic, i.e.* $U(C_t) = log(C_t)$*.*

The assumption of log-utility ($\sigma = 1$) is the most widely used case in the literature of endogenous growth with polluting non-renewable resources, as it allows for closed-form solutions and a full characterization of the macroeconomic model features. We will also use it in the basic approach so that we can directly compare our results with the relevant literature. As an extension, we treat and discuss the case of $\sigma \neq 1$ in section 3.6. In particular, we will derive how the interplay between the time lag in emissions diffusion and the substitution and income effect that arise in the non-log-utility case affect the dynamics and the steady state of the economy. We will show that when $\sigma = 1$ and capital damages are linear to the stock of pollution, the optimal emissions tax rate grows with consumption while this condition is asymptotically reached with $\sigma \neq 1$.

Assumption 2 *Capital damages are linear to the level of pollution, i.e.* $D(P_t) = \delta + \chi P_t$*.*

Parameter δ is the natural depreciation of the capital stock and χ the damage sensitivity to pollution; see Ikefuji and Horii (2012) for a similar specification.

3.2.3 Discussion about the model

In equilibrium, aggregate demand for the consumption good must equal its total supply, i.e. $C_t = Y_t$. The resource stock is finite and extraction and use of the non-renewable resource has to stop in finite or infinite time. This puts an upper bound on pollution and capital damages under all assumptions regarding the decay of the pollution stock. Furthermore, due to the specification of the production function

(3.3), and the fact that damages due to pollution accumulation are bounded, the resource stock is essential in the sense that an additional unit of resources used in the production of the consumption good is always welfare enhancing. Accordingly, resource extraction will be positive in each time period and the resource stock will only be asymptotically depleted so that (3.6) holds with equality; see for example Daubanes and Grimaud (2010) for a similar argumentation. Following the same logic, the share of capital allocated to the consumption good sector has to obey $\epsilon_t \in (0, 1)$ for all $t \geq 0$; formal proofs are given in Appendix 5.2.3.

In the face of pollution, the economy at hand is always in transition. The only possible steady state is the one where resources are asymptotically depleted and pollution asymptotically reaches its steady state value, $P_\infty = P_0 + \phi S_0$, if $\theta = 0$, or $P_\infty = \bar{P} = P_0$, if $\theta > 0$. When that happens the growth rate of resource extraction, $g_{Rt} \equiv \dot{R}_t/R_t$, and the share ϵ_t must have also reached their steady state values.[7] It follows from our specifications for the consumption good and capital accumulation that in the steady state the economy asymptotically reaches a balanced growth path which can be defined as follows:

Definition 2 *An equilibrium path is an asymptotic balanced growth path, if capital allocation and the growth rate of resource extraction are asymptotically constant, i.e.* $\lim_{t\to\infty} \epsilon_t = \epsilon_\infty$, *and* $\lim_{t\to\infty} \dot{R}_t/R_t = g_{R\infty}$; *then* $\lim_{t\to\infty} \dot{K}_t/K_t = g_{K\infty}$ *and* $\lim_{t\to\infty} \dot{C}_t/C_t = g_{C\infty}$, *asymptotically constant.*

Below we solve the planning problem and characterize the social cost of carbon. In section 3.4 we show that this is the first-best carbon tax that optimally corrects for the externality.

3.3 Social Optimum

The social planner chooses the fraction of capital allocated to the consumption good, ϵ_t, and the resource extraction, R_t, in order to maximize $\int_0^\infty U(C_t)e^{-\rho t}dt$ with

[7] In general we define $g_V \equiv \dot{V}/V$ the growth rate of variable V.

$C_t = Y_t$, subject to equations (3.1), (3.3)-(3.6). Let $\lambda_{Ct}, \lambda_{St}, \lambda_{Zt}$ be respectively the shadow prices for the consumption good C_t, the stock of the non-renewable resource S_t, and the history of lagged emissions Z_t. The first-order condition for resource extraction follows:

$$(1-\alpha)\frac{C_t}{R_t} = \frac{\lambda_{St}}{\lambda_{Ct}} - \phi\kappa\frac{\lambda_{Zt}}{\lambda_{Ct}}. \tag{3.7}$$

According to equation (3.7), in each point of time, the marginal benefit from extracting and using the resource (left-hand-side) equals the marginal cost of resource use (right-hand-side), in terms of the consumption good. The cost consists of the scarcity cost of the exhaustible resource, $\lambda_{St}/\lambda_{Ct}$, i.e. its producer price in a competitive market, and of the social cost of carbon (SCC), i.e. the marginal externality damage of an additional unit of emissions, $X_t \equiv -\phi\kappa\lambda_{Zt}/\lambda_{Ct}$. X_t captures the externality from carbon emissions and as we show in section 3.4 is equal to the optimal Pigouvian tax. We prove in Appendix 5.2.2 that it can be written as

$$X_t = C_t\frac{\alpha\eta\phi}{\rho}\kappa\int_t^{\infty}\left[\int_s^{\infty} D'(P_v)\left(\frac{\bar{\epsilon}}{\epsilon_v}\right)\left(\frac{C_t}{C_v}\right)^{\sigma-1} e^{-(\rho+\theta)(v-s)}dv\right]e^{-(\rho+\kappa)(s-t)}ds, \tag{3.8}$$

with $\bar{\epsilon} = \rho/B$. The intuitive explanation of (3.8) is the following. The remaining portion in year $\nu \geq s$, after decay, of a marginal unit of emissions from year t, that has reached the stock of pollution in year $s \geq t$, has a negative impact in all years $\nu \geq t$. The first term inside the square brackets is the marginal damage of pollution on capital accumulation, $D'(P_v)$. The second term comes from the utility denominated shadow price of capital and is responsible for allocating capital between the consumption and the investment sector, while the third term reflects preferences of agents regarding intertemporal consumption smoothing. The exponential terms reflect the delay/decay structure of the climate system: $e^{-\theta(\nu-s)}$ is the share of emissions remaining in year ν from emissions that reached the stock of pollution in year s, while $\kappa e^{-\kappa(s-t)}$ accounts for the slow adjustment of the stock of pollution from the marginal unit emitted in year t.

The cost of the externality is greater, when the following are larger: the emissions intensity parameter ϕ, the part of non-durable capital η, and the share of capital in the production of the consumption good α. It is also greater when the following are smaller: the discount rate ρ, the pollution decay θ, and, *ceteris paribus*, the path of capital allocated to consumption $\{\epsilon_v\}_t^\infty$, since higher investment translates to a larger stock of capital in subsequent periods, creating larger damaging potential in the future.[8] Finally, we point out the effect of the slow emissions diffusion as a suppressing factor on the magnitude of marginal damages by the multiplicative term in the beginning of (3.8). As discussed in section 3.2.1, the speed of emissions diffusion has a dual effect on the marginal damages from the extraction and use of the polluting resource: i) a level effect on the magnitude of marginal damages and ii) a delay effect.

At this point, a direct comparison of our results to the literature seems appropriate. A similar expression to (3.8) has been found in van den Bijgaart et al. (2016). There the authors consider a general neoclassical economy, with climate dynamics similar to ours, where climate change destroys part of the final output. We show instead that similar results can be obtained in an endogenous growth framework, and in the case where pollution harms capital accumulation. Moreover, in several models of growth with polluting non-renewable resources the marginal externality damage is a linear function of the consumption good all along the optimal path, irrespective of whether lags in emissions dissemination are considered or not; see for example Gerlagh and Liski (2012), Golosov et al. (2014).

The linearity of the marginal externality damage in the consumption good stems from three factors: first, from the log-utility assumption; second, from the damage specification; third, from a constant savings rate at all times. While in the case of the general neoclassical economy one needs to impose the last condition (by assuming full capital depreciation in each period), as in the aforementioned contributions, in the case of endogenous growth, as in Grimaud and Rouge (2014) or in

[8] We will discuss the effect of $\sigma \neq 1$ on the SCC, and thus on the Pigouvian tax, in section 3.6.

the present model, this condition is immediately satisfied with logarithmic utility: take (3.8) with Assumption 1, i.e. $\sigma = 1$. We show in Appendix 5.2.2 that in this case $\epsilon_t = \bar{\epsilon}$ at all times, i.e. there will be a constant fraction of capital allocated to investment; the equivalent of the constant savings rate in the neoclassical economy. Equation (3.8) now reads

$$X_t = C_t \frac{\alpha\eta\phi}{\rho}\kappa \int_t^{\infty} \left(\int_s^{\infty} D'(P_v) e^{-(\rho+\theta)(v-s)} dv \right) e^{-(\rho+\kappa)(s-t)} ds.$$

The linearity of X_t in C_t is granted if $D(P_t)$ is also linear in pollution. Applying Assumption 2 readily leads to the following proposition:

Proposition 2 *Given Assumptions 1 and 2, the marginal externality damage of emissions is proportional to the consumption good and given by*

$$X_t = \tilde{X} C_t \qquad \textit{with} \qquad \tilde{X} = \kappa \frac{\alpha\eta\phi\chi}{\rho(\rho+\theta)(\rho+\kappa)}; \tag{3.9}$$

$\tilde{X}$ *is an increasing and concave function of* κ*, independent of time.*

Proof See last paragraph above. ■

In the log-utility case, with linear and separable damages due to climate change in the utility function, as in Grimaud and Rouge (2014), or multiplicative exponential damages in the production function, as in Gerlagh and Liski (2012) and Golosov et al. (2014), or even linear damages in capital accumulation, as in the present approach, the social cost of the externality, X_t, is a linear function of the consumer good. In addition, we find that the fraction $\tilde{X}$ is increasing in the speed of adjustment between emissions and pollution, κ, in a concave way reaching its upper limit, $\frac{\alpha\eta\phi\chi}{\rho(\rho+\theta)}$, as $\kappa \to \infty$.

Below we proceed by characterizing the decentralized equilibrium. We show that X_t is the Pigouvian tax needed to optimally correct for the externality, and study how the economy responds to more general taxation policies.

3.4 Decentralized Equilibrium

3.4.1 Firms

Each sector in the economy is populated by a unit mass of competitive firms $j \in [0,1]$. Specifically, the production of consumption good Y_{jt} uses capital K_{Yjt}, and resources R_{jt}, according to $Y_{jt} = AK_{Yjt}^{\alpha}R_{jt}^{1-\alpha}$. The production of the investment good I_{jt} reads $I_{jt} = BK_{Ijt}$. A, B are productivity parameters. The producer of consumer good Y_{jt} solves

$$\max_{K_{Yjt},R_{jt}}\{AK_{Yjt}^{\alpha}R_{jt}^{1-\alpha} - p_{Kt}K_{Yjt} - (p_{Rt}+\tau_t)R_{jt}\},$$

while one in the investment good sector solves

$$\max_{K_{Ijt}}\{p_{It}BK_{Ijt} - p_{Kt}K_{Ijt}\},$$

with p_{Kt} the rental price of capital, p_{It} the price of investment, p_{Rt} the producer price of the non-renewable resource and τ_t a per-unit tax on resource extraction. Because production has constant returns to scale, firms face identical factor input ratios. Hence, the economy admits a representative firm active in both sectors with $Y_t \equiv \int_0^1 Y_{jt}dj$ for total production, $K_t \equiv \int_0^1 (K_{Yjt} + K_{Ijt})dj$ for the total stock of capital demanded, and $\epsilon_t = K_{Yt}/K_t$, the aggregate fraction of capital allocated to the consumption good. The first order conditions of these maximizations give the demand functions for non-renewable resources and capital in the consumption good sector, and a no-arbitrage condition which equates returns from the two usages of capital in this economy, i.e. in the consumption good sector and in the investment sector, namely,

$$p_{Rt} + \tau_t = (1-\alpha)\frac{Y_t}{R_t}, \qquad p_{Kt} = \alpha\frac{Y_t}{\epsilon_t K_t}, \qquad p_{Kt} = p_{It}B. \tag{3.10}$$

3.4.2 Households

There is a continuum of infinitely lived households $i \in [0,1]$ that have the option to allocate their income to consumption, through the consumption good sector, or to additional capital formation, through the investment sector. The representative household i owns a share of the stock of energy resources S_{it}, and capital, K_{it}. In each time period a share of resources R_{it} is extracted and sold to firms at a price p_{Rt}. Furthermore, K_{it} is rented to firms at prices p_{Kt}. With T_t denoting lump-sum transfers, individual income amounts to $p_{Kt}K_{it} + p_{Rt}R_{it} + T_t$ while expenditures equal $C_{it} + p_{It}H_{it}$, with C_{it} denoting the flow of consumption and H_{it} reflecting the purchase of additional capital through the investment sector at price p_{It}. Capital and resource stocks evolve according to

$$\dot{K}_{it} = H_{it}^K - D(P_t)\eta K_{it}, \qquad \dot{S}_{it} = -R_{it}, \tag{3.11}$$

while income equals expenditure, so that the income balance reads

$$p_{Kt}K_{it} + p_{Rt}R_{it} + T_t = C_{it} + p_{It}H_{it}. \tag{3.12}$$

Differentiating the household's assets, $a_{it} = p_{It}K_{it} + p_{Rt}S_{it}$ with respect to time, using (3.11), (3.12), and the fact that $p_{Kt} = p_{It}B$, yields the household's dynamic budget constraint

$$\frac{\dot{a}_{it}}{a_{it}} = \beta_{it}^S \frac{\dot{p}_{Rt}}{p_{Rt}} + (1 - \beta_{it}^S) \left[\frac{\dot{p}_{Kt}}{p_{Kt}} + B - \eta D(P_t) \right] - \frac{C_{it}}{a_{it}} + \frac{T_t}{a_{it}}, \tag{3.13}$$

with $\beta_{it}^S \equiv p_{Rt}S_{it}/a_{it}$, the share of the individual's resource wealth in her total assets. The household's objective is to choose the time path of consumption and share β_{it}^S which maximize its lifetime utility

$$\int_0^\infty U(C_{it})e^{-\rho t}dt,$$

subject to the budget constraint (3.13). In the general CRRA form we have $U(C_{it}) = \frac{C_{it}^{1-\sigma}}{1-\sigma}$ while with $\sigma = 1$ we get the logarithmic form, i.e. $U(C_{it}) = \log(C_{it})$. From combining the first order conditions of household optimization we find

$$\sigma \frac{\dot{C}_{it}}{C_{it}} = r_t - \rho, \tag{3.14}$$

$$\frac{\dot{p}_{Rt}}{p_{Rt}} = r_t, \tag{3.15}$$

$$\frac{\dot{p}_{Kt}}{p_{Kt}} + B - D(P_t)\eta = r_t. \tag{3.16}$$

These are the Keynes-Ramsey rule for consumption growth, the Hotelling rule for resource price development, and the return on investing in capital formation, with r_t being the economy-wide interest rate. By equating (3.15) with (3.16) we see that both assets, i.e. non-renewable resources and capital, should yield equal returns. The optimization is complemented by the appropriate transversality condition, reading

$$\lim_{t\to\infty} a_{it} C_{it}^{-\sigma} e^{-\rho t} = \lim_{t\to\infty} \left(\frac{p_{Kt}}{B} K_{it} + p_{Rt} S_{it}\right) C_{it}^{-\sigma} e^{-\rho t} = 0. \tag{3.17}$$

Finally we need to impose the restriction that χ satisfies $\alpha(B - \eta(\delta + \chi P_\infty)) > \rho$ so that households have enough incentives to invest in capital formation.

3.4.3 Equilibrium

In equilibrium total demand for the consumption good must equal its total supply, i.e. $C_t = \int_0^1 C_{it} di = Y_t$. Given the initial values K_0, S_0, P_0 and the dynamic evolution of the tax rate, the dynamics of the climate system (3.1), capital accumulation (3.5), resource depletion (3.6), the first order conditions for the representative firm (3.10), the aggregate version of the Keynes-Ramsey rule (3.14), the Hotelling rule for the price evolution of the non-renewable resource (3.15), the return on investment in capital formation (3.16), and the transversality condition (3.17), completely characterize the dynamic behavior of the decentralized economy.

3.4.4 The Pigouvian tax

In section 3.3 we characterized the socially optimal solution and derived the expression for the social cost of carbon, X_t. Here we show that this is in fact the Pigouvian tax in the decentralized equilibrium that produces the first-best allocation.

As shown in Appendix 5.2.5, with $\sigma = 1$, the capital share ϵ_t immediately jumps to its optimal steady state value $\bar{\epsilon} = \rho/B$ also in the decentralized case.

By comparing the social planner's optimality condition (3.7) with its equivalent from (3.10), using $C_t = Y_t$, it is straightforward to see that the resource extraction will follow its optimal path if the producer's price for the non-renewable resource equals its scarcity rent ($p_{Rt} = \lambda_{St}/\lambda_{Ct}$), and if the per-unit carbon tax equals the marginal externality damage of emissions found in (3.9) ($\tau_t = X_t$). This is the optimal tax which we denote by τ_t^o.

Since $\tau_t^o \equiv X_t$, when Assumptions 1 and 2 are satisfied, the optimal tax is a constant fraction of the consumption good. The important point about this result is that it provides appropriate incentives to the economy to stretch the path of resource extraction. To be more precise, the per-unit tax that postpones extraction has to grow at a slower rate than the price of the non-renewable resource. Then, the unit price paid for the resource by consumers increases less rapidly than the price received by producers, which grows at the market's interest rate, giving them the incentive to postpone extraction: with $\sigma = 1$ the price received by producers p_{Rt}, grows at the rate r_t (from (3.15)) while τ_t^o grows with consumption, i.e. at $r_t - \rho$ (from the aggregate version of (3.14)).[9]

Furthermore, it is a known result from the theory of non-renewable resource taxation that any term in the optimal per-unit tax that grows with the interest rate has no effect on the extracting behavior of the economy, suggesting that there is an infinite number of optimal taxes that give the same resource extraction incentives; see Dasgupta and Heal (1979), and Gaudet and Lasserre (2013).[10] We show in Appendix 5.2.6 that this is also the case here.

[9]In fact this implies an equivalence between the per-unit tax that grows with consumption, as in our case, and a decreasing ad-valorem tax, as usually proposed by growth models with polluting resources, e.g. Groth and Schou (2007). To see this, note that the consumer price for the resource is $p_{R,t} + \tau_t^o = \pi_t p_{Rt}$, with $\pi_t \equiv 1 + \tau_t^o / p_{Rt}$, i.e. a decreasing ad-valorem tax rate.

[10]Grimaud and Rouge (2014), however, using a model of endogenous growth with polluting non-renewable resources, show that in the presence of Carbon-Capture-and-Storage (CCS) activity the optimal tax rate is linear in consumption, yet unique. In the presence of a CCS activity agents should be indifferent between instruments as long as they have the same results in protecting from climate change, which uniquely pins down the optimal tax rate.

3.4.5 Response to taxation

In light of the previous discussion, we will only study taxation policies proportional to consumption according to the following assumption:

Assumption 3 *All taxes considered are proportional to consumption:* $\tau_t = \tilde{\tau} C_t$, *with* $\tilde{\tau}$ *constant.*

Proposition 3 *Suppose that Assumptions 1, 2, and 3 apply. Then in a decentralized equilibrium,*
(i) the fraction of consumption $\tilde{\tau}$ *determines the dynamics of resource extraction; a higher value stretches resource extraction to the future;* $\tilde{\tau} = 0$ *(no tax) results in the fastest equilibrium extraction,*
(ii) economic growth starts from a higher level, the higher $\tilde{\tau}$ *is, converging asymptotically to a positive constant* $g_{C\infty}$*, which is lower than initial growth and unaffected by policy.*

Proof (i) Following the same procedure as in Appendix 5.2.6, the time path of resource extraction and its growth rate can be calculated to be only dependent on $\tilde{\tau}$ as,

$$R_t(\tilde{\tau}) = \frac{1-\alpha}{\tilde{\tau}\left[1 + e^{\rho t}\left(e^{\frac{S_0 \rho}{1-\alpha}\tilde{\tau}} - 1\right)^{-1}\right]} > 0, \tag{3.18}$$

$$g_{Rt}(\tilde{\tau}) = \frac{-\rho}{1 + e^{-\rho t}\left(e^{\frac{S_0 \rho}{1-\alpha}\tilde{\tau}} - 1\right)} < 0. \tag{3.19}$$

With our assumptions $\tilde{\tau}$ is decisive for the dynamics of resource extraction: with tax, $g_{Rt} > -\rho$ and $g_{R\infty} = \lim_{t\to\infty} g_{Rt} = -\rho$; zero tax entails the fastest resource depletion, $g_{Rt} = -\rho$ in all time periods. When environmental policy is implemented, resource extraction is stretched to the future: $dg_{Rt}/d\tilde{\tau} > 0$ (i.e. a flatter resource extraction profile)

(ii) By log-differentiating (3.3), with $\epsilon_t = \bar{\epsilon} = \rho/B$, using (3.5), we get the growth rate of consumption in the decentralized equilibrium, $g_{Ct} \equiv \dot{C}_t/C_t$, as a function of $\tilde{\tau}$

$$g_{Ct}(\tilde{\tau}) = \alpha\left[B - \rho - \eta D(P_t)\right] + (1-\alpha)g_{Rt}(\tilde{\tau}). \tag{3.20}$$

With ϵ jumping immediately to its optimal steady state and P_0 given, differentiating (3.20) at $t = 0$ w.r.t. $\tilde{\tau}$ implies $dg_{C0}/d\tilde{\tau} = (1-\alpha)dg_{R0}/d\tilde{\tau} > 0$, i.e. a higher value for $\tilde{\tau}$ induces the economy to start from a higher level of economic growth, converging to the positive constant $g_{C\infty} = \alpha\left[B - \rho - \eta D(P_\infty)\right] - (1-\alpha)\rho$. Furthermore, because $P_\infty = P_0 + \phi S_0$, if $\theta = 0$, or P_0 if $\theta > 0$, and $g_{R0} > -\rho$, the steady state level of economic growth is always lower than initial growth. ■

Two things are worth noting here. First, resource extraction is independent of climate damages. In general since pollution affects capital accumulation and the interest rate, one would anticipate damages to affect the path of resource extraction. This is not the case in the present setup due to logarithmic preferences: consider for convenience the FOC for R_t in (3.10) with a given ad-valorem tax, π_t, i.e. $(1-\alpha)C_t/R_t = \pi_t p_{Rt}$. Log-differentiating this expression using the log-differentiated version of the second FOC in (3.10) along with (3.5), and (3.14)-(3.16) leads to $\sigma g_{Rt} = -(\rho + (1+\alpha(\sigma-1))g_{\pi t} + \alpha(\sigma-1)(B - \eta D(P_t))$; with $\sigma \neq 1$ resource extraction responds to pollution. With $\sigma = 1$, however, we get $g_{Rt} = -\rho - g_{\pi t}$.[11] In general this result, as well as the fact that ϵ jumps immediately to its steady state, is the outcome of the substitution and income effect that arise due to pollution exactly offsetting each other when $\sigma = 1$; we study this in more detail in section 3.6.

Second, it sounds counter-intuitive that higher taxation induces the economy

[11] Note also that, consistent with the literature, there are infinite ad-valorem taxes with the same dynamics (decreasing at the same rate) but different levels that give the same incentives to postpone extraction; see Dasgupta and Heal (1979), Grimaud and Rouge (2005), Gaudet and Lasserre (2013).

to start from a higher point of economic growth. However, according to result (i) of the proposition, it is the constant $\tilde{\tau}$ that determines the extraction path. Thus, higher taxes that stretch resource extraction to the future impose a lower drag on growth in earlier periods.

3.5 Effect of climate dynamics on growth

The level of harmful pollution at each time period, with $\bar{P} = P_0$, in the general case with pollution decay reads[12]

$$P_t = P_0 + \int_0^t f_{ts} \phi R_s ds, \tag{3.21}$$

with f_{ts} from (3.2) and R_t from (3.18); see Appendix 5.2.1. In the no-tax case the stock of pollution in each time period reads

$$P_t = P_0 + \kappa \rho \phi S_0 \left[\frac{e^{-\rho t}}{(\theta - \rho)(\kappa - \rho)} - \frac{e^{-\theta t}}{(\kappa - \theta)(\theta - \rho)} + \frac{e^{-\kappa t}}{(\kappa - \theta)(\kappa - \rho)} \right].$$

Next we discuss the transition process towards the steady state in the decentralized equilibrium. This will depend on the speed of emissions diffusion κ, the decay rate θ, and the policy τ_t, since these parameters govern the dynamics of resource extraction, of the climate system, and in turn affect the growth rate of the economy. We will thoroughly study the case of $\theta = 0$ as only this case allows for a rigorous mathematical analysis. We will then present the results graphically and their intuition based on the presentation of the climate system in section 2.1 and equation (3.21).

[12] The complexity of the climate cycle does not allow for an explicit analytical solution. We can, however, approximate the solution, using any mathematical software, as an infinite sum of terms according to $P_t = P_0 + \kappa \frac{1-\alpha}{\kappa-\theta} \tilde{\tau}^{-1} \sum_{n=0}^{\infty} \left(\frac{1}{1 - e^{\frac{S_0 \rho}{1-\alpha} \tilde{\tau}}} \right)^n \left(\frac{e^{-\kappa t} - e^{\rho n t}}{\kappa + \rho n} - \frac{e^{-\theta t} - e^{\rho n t}}{\theta + \rho n} \right)$. The interested reader can validate this expression to get the qualitative features of our climate system.

3.5.1 Effects of climate dynamics on the decentralized equilibrium

The effects of pollution decay in the market solution are given in the following proposition and can be studied graphically in Figures 3.2 and 3.3.

Proposition 4 *Suppose that Assumptions 1, 2, and 3 apply. Then in a decentralized equilibrium,*
(i) without pollution decay, $\theta = 0$, the growth rate of consumption converges monotonically from above towards the steady state, $g_{C\infty}$; higher κ speeds up the transition process and results in lower economic growth at all times,
(ii) with positive decay, $\theta > 0$, the growth rate of consumption converges towards the steady state, $g_{C\infty}$, in a non-monotonic way (i.e. in a U-shaped manner); higher κ leads to a lower minimum growth, which is shifted forward to the present, and in lower short-run but higher long-run economic growth.

Proof (i) When pollution decay is disregarded, $\theta = 0$, pollution starts from P_0 and monotonically reaches its higher steady state $P_\infty = P_0 + \phi S_0$ when resources are asymptotically depleted, i.e. $\dot{P}_t > 0$ and $\lim_{t\to\infty} \dot{P}_t = 0$. Moreover from (3.19), $\dot{g}_{Rt} < 0$ and $\lim_{t\to\infty} \dot{g}_{Rt} = 0$. From (3.20) this leads to $\dot{g}_{Ct} < 0$, with $\lim_{t\to\infty} \dot{g}_{Ct} = 0$, i.e. growth follows a monotonic path towards its steady state. A higher speed of emissions diffusion under the same tax policy will not affect resource extraction, i.e. $dR_t/d\kappa = dg_{Rt}/d\kappa = 0$; from (3.18), (3.19). Moreover with $\theta = 0$, $df_{ts}/d\kappa > 0$ and $\lim_{t\to\infty} df_{ts}/d\kappa = 0$; from (3.2). The previous lead to $dg_{Ct}/d\kappa < 0$ and $\lim_{t\to\infty} dg_{Ct}/d\kappa = 0$; from (3.20).

(ii) When pollution decay is taken into account, $\theta > 0$, the pollution stock is hump-shaped starting and finishing at P_0. From (3.20), the growth rate of consumption will have an inverse hump shape, i.e. a U-shape. We show in Appendix 5.2.1 that a higher κ, will lead, *ceteris paribus*, to a higher pollution peak which will be also brought closer to the present; moreover, it still holds that $dR_t/d\kappa = dg_{Rt}/d\kappa = 0$; from (3.18), (3.19). From the last two points and equation (3.20) it follows that higher κ leads to to a lower minimum growth, shifted forward to the present. ■

Proposition 4 can be understood intuitively by considering the cases for θ: if there is no pollution decay, $\theta = 0$, higher speed of emissions diffusion, κ, will increase the marginal effect of emissions from all preceding periods on the current pollution level. Taking together the finiteness of the resource, this will speed up the transition process towards the lower steady state resulting in lower economic growth at all times. A lower $\tilde{\tau}$ would have the same effect on growth: the lower the tax is, the lower the initial level of economic growth and the faster the non-renewable resource extraction in earlier periods; see Proposition 3. Resource depletion is brought forward to date and so does pollution accumulation and its harmful effect on growth. If $\theta > 0$, with higher κ, the marginal emissions-damage response will be relatively higher in the short-run but relatively lower in the long-run, and the stock of pollution will follow a lower trajectory towards its steady state in later time periods. Since resource extraction will be unaffected when the $\tilde{\tau}$ fraction stays constant, a higher speed of emissions diffusion, κ, will result in economic growth of the decentralized equilibrium being lower in the short run, reaching a minimum level when pollution peaks and converging at a higher rate towards $g_{C\infty}$. A higher $\tilde{\tau}$ smooths out such behavior: resource extraction and use is stretched to the future, which, for the same decay structure, will lead to a lower peak of pollution occurring at a later time period. Accordingly, when $\theta > 0$, there are two counter-acting forces on growth from κ and $\tilde{\tau}$.

3.5.2 Effects of cllimate dynamics on the social optimum

Above we established that there are two counter-acting forces on growth arising from the speed of diffusion, κ, and the policy, $\tilde{\tau}$: when carbon decay is absent, $\theta = 0$, higher κ speeds up the transition process towards the lower steady state; higher $\tilde{\tau}$ has a mitigating effect: it induces the economy to start from a higher level of economic growth and stretches resource extraction and pollution accumulation to the future which acts positively on growth. When $\theta > 0$, other things being

Figure 3.2: Pollution and consumption growth for different $\tilde{\tau}$ and κ, ($\theta = 0$ in both cases).

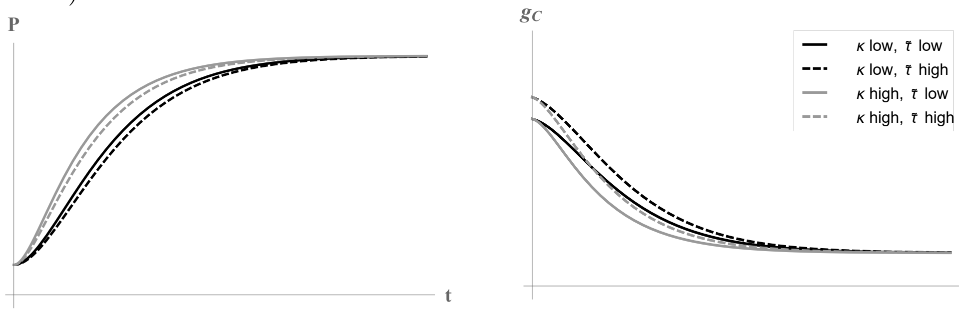
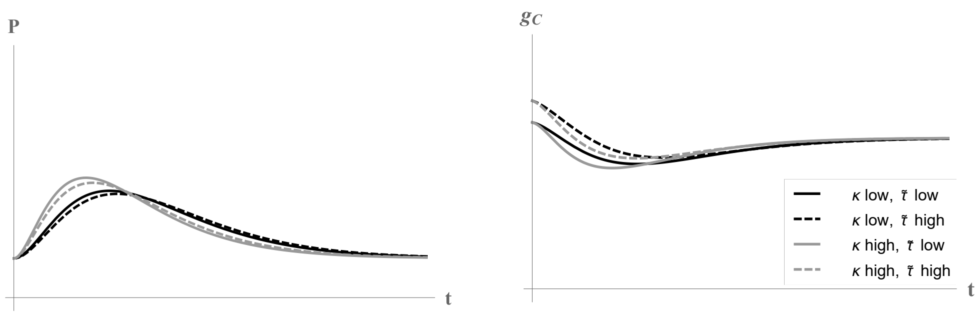


Figure 3.3: Pollution and consumption growth for different $\tilde{\tau}$ and κ, ($\theta > 0$ in both cases).



equal, a higher speed of emissions diffusion induces a relatively higher marginal damaging impact in the short run relative to the long run and leads to a higher pollution peak, closer to the present. Economic growth that has a U-shape, reaches a lower minimum which is also brought forward. A higher $\tilde{\tau}$ smooths out such a behavior. Since $\tilde{\tau}^o = \tilde{X}$, from Proposition 2, $\tilde{\tau}^o$ is increasing in κ. Accordingly, the negative "direct" effect of a larger κ through its influence on climate dynamics, is mitigated by a positive "indirect" effect of κ through a higher optimal $\tilde{\tau}^o$. The previous can be summarized in the following proposition:

Proposition 5 *Given Assumptions 1 and 2, in a social optimum solution without pollution decay, $\theta = 0$, a larger κ steepens the growth profile of the economy; with $\theta > 0$, a larger κ creates ambiguous results on the timing and level of minimum economic growth.*

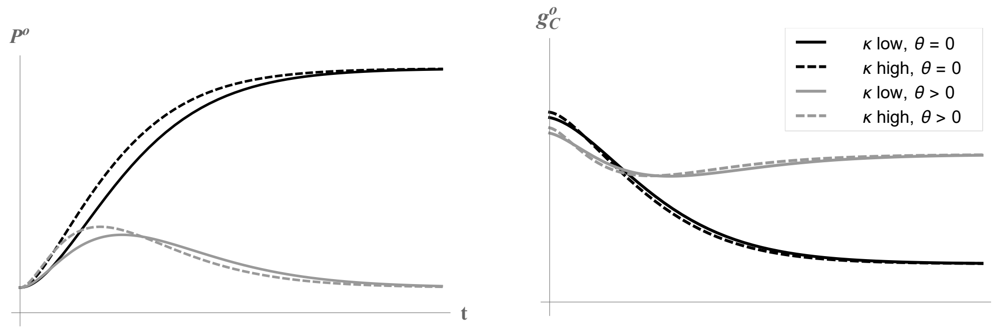
Proof Remember that $\tilde{\tau}^o = \tilde{X}$, given by (3.9). Differentiate the social optimum version of (3.20), $g_C^o \equiv g_C(\tilde{\tau}^o)$, w.r.t. κ to get

$$\frac{dg_{Ct}^o}{d\kappa} = -\alpha\eta\chi\phi \int_0^t \left[\underbrace{\frac{df_{ts}}{d\kappa}}_{\text{direct}} R_s^o + f_{ts} \underbrace{\frac{dR_s^o}{d\tilde{\tau}^o} \frac{d\tilde{\tau}^o}{d\kappa}}_{\text{indirect}} \right] ds + (1-\alpha) \underbrace{\frac{dg_{R_t^o}}{d\tilde{\tau}^o} \frac{d\tilde{\tau}^o}{d\kappa}}_{\text{indirect}}, \tag{3.22}$$

with f_{ts} from (3.2), $R_s^o \equiv R_s(\tilde{\tau}^o)$, from (3.18), and $g_{Rt}^o \equiv g_{Rt}(\tilde{\tau}^o)$, from (3.19). The two effects, direct and indirect, in the social optimum, tend to offset each other and in general create ambiguous results about the timing and the magnitude of minimum economic growth when $\theta > 0$. In the case of no pollution decay, $\theta = 0$, since pollution peaks only in the steady state, the direct effect of a larger κ is only about current emissions translating faster into pollution destroying capital. Hence, according to Proposition 3, the economy starts from a higher level of economic growth due to a higher optimal tax, and transitions faster to the lower steady state. A larger κ then only steepens the growth profile of the economy. ■

For our discussion above on the impact of emissions diffusion, κ, on the transition of economic growth towards its steady state in the social optimum we provide Figure 3.4 as an illustration. Note also that for the same value of κ, the economy starts from a higher level of economic growth for $\theta = 0$. This is due to the discounting character of the pollution decay: from Proposition 1, other things being equal, $\theta = 0$ results in a higher optimal tax than in the $\theta > 0$ case because the discounted value of marginal damages is higher. This results in a higher optimal tax which according to Proposition 3 induces the economy to start from a higher level of economic growth.

Figure 3.4: Optimal level of pollution and consumption growth for different values of κ in the $\theta = 0$ and $\theta > 0$ case.



Below, we discuss as an extension the case of CRRA utility and the interplay between the climate dynamics and the risk aversion of the representative household.

3.6 Non-Logarithmic CRRA Utility

As we established in section 3.3, the common feature of our model and those in the literature, of the optimal tax rate being a constant fraction of the consumption good all along the optimal path is a consequence of assuming log-utility function. In this section we will study the case of non-logarithmic utility. Since pollution affects the return on investment in capital formation, with a general CRRA utility the substitution and income effect that arise do not necessarily cancel out. We will see that the Pigouvian tax rule does not anymore start off growing with consumption, even though it asymptotes to such behavior. Whether it starts off above or below its steady state value will depend on the intertemporal elasticity of substitution.

In the steady state where resources have been asymptotically depleted, and the share ϵ has already reached its steady state value and consumption grows at a constant rate, the optimal tax rate asymptotically becomes a constant fraction of consumption according to $\lim_{t\to\infty} \tau^o_t/C_t = \tilde{\tau}^o$, with

$$\tilde{\tau}^o = \kappa \frac{\alpha\eta\chi\phi}{[\frac{\rho+\alpha(\sigma-1)\Theta_\infty}{\sigma}][\frac{\rho+\alpha(\sigma-1)\Theta_\infty}{\sigma}+\theta][\frac{\rho+\alpha(\sigma-1)\Theta_\infty}{\sigma}+\kappa]}, \tag{3.23}$$

with $\Theta_\infty = B - \eta(\delta + \chi P_\infty)$, and $P_\infty = P_0 + \phi S_0$, if $\theta = 0$, or $P_\infty = P_0$, if $\theta > 0$; see Appendix 5.2.7.

The assumption of non-logarithmic utility does not allow for further analytical solutions; hence, we will confine ourselves to numerical simulations. To this end, we can rewrite the dynamic system of the social planner in variables which are asymptotically constant on a balanced growth path and then linearize the model in the proximity to the steady state. Our calculation procedure is explained in detail in the Appendix 5.2.7, while here we present only the main results of our simulation.

We consider a simplified version of the basic model without pollution decay for simplicity, i.e. $\theta = 0$. Pollution starts from P_0, asymptotically reaching $P_0 + \phi S_0$ when resources have been depleted. From the no-arbitrage condition (3.16) we see that climate change affects the interest rate of the economy. This in principle creates a counteracting substitution and income effect. By combining the budget constraint (3.13), the Hotelling rule (3.15), and (3.16), we get the usual household budget constraint as, $\dot{a}_t = r_t a_t - c_t + T_t$. Let's think of an average interest rate between times 0 and t as $\bar{r}_t = (1/t)\int_0^t r_s ds$. The propensity to consume out of wealth is determined from[13]

$$\int_0^\infty e^{-(\bar{r}_t(\sigma-1)/\sigma+\rho/\sigma)t}dt. \tag{3.24}$$

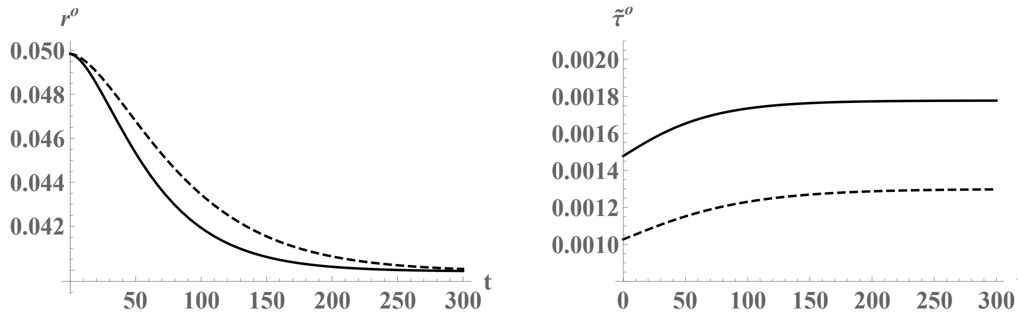
A decreasing average interest rate due to pollution accumulation makes future consumption increasingly expensive compared to consumption today, motivating

[13]See, Barro and Sala-i-Martin (2003), Ch. 2.1.

households to shift consumption from future to the present, i.e. an intertemporal substitution effect. This results in a falling capital share ϵ_t. On the other hand, agents experience a decreasing interest rate income which tends to reduce consumption levels in all periods. In the latter case, capital allocation in the investment sector is decreasing, indicating an increasing share ϵ_t. Which effect dominates will depend on the intertemporal elasticity of substitution, $1/\sigma$. From (3.24), if $\sigma > 1$, the propensity to consume out of wealth is increasing with falling $\bar{r}_t$, i.e. the substitution effect dominates. If $\sigma < 1$ the propensity to consume out of wealth decreases with falling $\bar{r}_t$, i.e. the income effect dominates. If $\sigma = 1$ they both cancel out and the shares jump to their steady state values as in sections 3.3 and 3.4. A slow diffusion of emissions into the stock of harmful pollution tends to mitigate these effects: if the full effects of pollution on capital accumulation appear with a time lag, the reduction in the interest rate is purely delayed.

The same reasoning can be applied to the demand for the non-renewable resource and by extension to the carbon tax rate. Because of the Cobb-Douglas specification of the consumption good, indicating constant expenditure shares, a forward shift of consumption, for $\sigma > 1$, will result in a relatively higher demand for the non-renewable resource in earlier time periods, disregarding its scarcity. The social planner will then have to set a low $\tilde{\tau}_t^o$ which is increasing as ϵ_t falls. Following (3.8), a higher κ will have a magnifying effect on the net present value of marginal damages so the tax rate will be shifted upwards. In the Appendix we solve for the socially optimal allocation when $\sigma \neq 1$. The model is then linearized and solved computationally. The choice of the values for the parameters and the initial conditions is explained in Appendix 5.2.7, while Figure 3.5 provides the results to illustrate our previous discussion for the standard case of $\sigma > 1$, as commonly used in the literature of endogenous growth; see Ikefuji and Horii (2012). Finally, as explained in Appendix 5.2.1, the speed of emissions diffusion is the reciprocal of the mean time lag. We choose a low value to reflect a time lag of 50 years, i.e. $\kappa = 0.02$, and a high value to reflect a time lag of 25 years, i.e. $\kappa = 0.04$; see van den Bijgaart et al. (2016).[14]

Figure 3.5: Optimal interest rate and carbon tax for CRRA utility.



$t_0 = 2010, \rho = 0.015, \sigma = 1.5, \alpha = 0.9, \theta = 0, \delta = 0.05, B = 0.106, \chi = 1.7 \times 10^6$ \$/GtC, $\phi = 1, \eta = 1, \kappa_{\text{low}} = 0.02$ (dashed), $\kappa_{\text{high}} = 0.04$ (solid)

3.7 Conclusion

In this part of the thesis we use an endogenous growth model to study the effects of climate change caused by the extraction and use of nonrenewable resources. The central feature is the inclusion of a lag between greenhouse gas emissions and their effect on the stock of harmful pollution, which follows a well-defined time pattern. The time lag between emissions and their impact on the economy, here on capital accumulation, although important, has in general drawn little attention. The standard assumption in the literature of an instantaneous diffusion is the limiting case in our model.

Confirming results in the literature, with logarithmic utility, and our specification of damages to capital from the stock of pollution, the Pigouvian tax is a constant proportion of the consumption good in each time period. We therefore

[14]In 2010 global consumption was around 49.8 billion US\$ (about 76% of global GDP); World Bank Indicators, 2015. With this value, our calibration implies a carbon tax in 2010 between 50 \$/tC ($\kappa = 0.02$) and 75 \$/tC ($\kappa = 0.04$).

focus on general policies proportional to consumption and find that with log-utility, resource extraction is only determined by the tax rate. We also derive the crucial impact of climate dynamics on growth and resource extraction in private and social optimum. As regards optimal policy, the optimal per-unit emission tax rate increases in the dissemination speed; higher dissemination speed induces the economy to start at a higher level of economic growth. When pollution decay is not considered economic growth converges monotonically from above to its lower steady state, which is unaffected by policy; when pollution decay is considered, it may exceed the optimal level in the long-run. Finally, we study the effect of a more general CRRA utility function on the optimal carbon tax. We find that for a relevant value of the elasticity of intertemporal substitution above unity, and no pollution decay, the optimal tax grows initially faster than consumption while they asymptotically reach the same growth rate.

Political action is usually triggered only after environmental damages become visible. Therefore, a wrong perception of the speed of diffusion, e.g. a lower value for κ, can lead to a suboptimal taxation policy, i.e. a lower tax rate. We draw from our results in the decentralized equilibrium and note that, in the general case of $\theta > 0$, an environmental policy that mistakenly sets a lower than optimal tax will force the economy to start from a point of lower economic growth, reach faster a relatively lower level of minimum growth but then recover at a faster rate towards the steady state; in the case of pollution decay economic growth might exceed the social optimum during transition in the long run. If no pollution decay is considered, $\theta = 0$, an erroneously set environmental policy will result in a lower than optimal economic growth at all times. In this case the economy will start from a low point of economic growth while resource extraction will be brought forward and the harmful results of extracting and using the polluting non-renewable resource will arrive sooner.

We can argue that if emission taxes are not set by the social planner but by a regular political process, there is a risk of setting tax rates at too low a level when actors underestimate the true pollution dissemination speed. Underestimation of climate change and pollution dissemination has different reasons. The usually observed myopia of decision makers and short-run targets like elections are one component. Moreover, climate sciences provide results and predictions which naturally include a certain degree of uncertainty because they concern the very long run. Finally, reactions and decisions might rely on cognitive experience. When environmental damages become visible they have the best conditions to trigger political action. Because this is not yet the case for climate change, the concerns of too little political action appear to be warranted.

Chapter 4

On the importance of the speed of knowledge diffusion for optimal R&D support policies

Abstract

How should governments best allocate their budget to support private research activities? The consensus in the literature is that sector-specific R&D support policies should be increasing in the degree of compatibility of sectoral innovation with the practices of the wider economy. Using a multi-sector endogenous growth model with in-house R&D and knowledge spillovers, it is shown, that accounting for the time it takes for knowledge to diffuse modifies this widely-accepted result.

4.1 Introduction

Recent empirical evidence suggests that governments in advanced economies should invest on average 40 percent more in R&D to account for the knowledge spillovers created by local firms (International Monetary Fund 2016). Yet, for every public intervention that spurs entrepreneurial activity, there are many failed efforts that waste taxpayer money (Lerner 2009). Hence, even though the level of subsidization of private R&D is of great importance, there is still a lot of room for improvement in the way governments allocate their budget among private research activities. This chapter argues about the differentiation of research subsidies among economic sectors based on two aspects of knowledge spillovers: the degree of compatibility of sectoral innovation with the practices of others – the inter-sectoral aspect, and the time it takes for sector-specific knowledge to diffuse – the inter-temporal aspect.

Not all ideas produced within a firm are useful to others; the compatibility of a firm-, or sector-specific innovation with the practices and technologies of other sectors in an economy is a necessary condition for it to diffuse (Rogers 2003). The fact that R&D-promoting policies should take the inter-sectoral compatibility aspect of knowledge spillovers into account has been widely supported by economists; see for example Goulder and Schneider (1999), Smulders and de Nooij (2003). In support of this, Dechezleprêtre et al. (2014) find strong evidence of larger spillovers from clean technological innovation – electric cars, wind turbines, etc. – in comparison to dirty ones – coal power plants, combustion engines, etc. – and give clear policy recommendations that subsidies to clean R&D should be higher even if we abstract from the environmental externality. The same support towards environmentally beneficial technologies can be found in Jaffe et al. (2005).[1]

[1] Inter-sectoral spillovers become more severe as we move from applied to more basic research (Trajtenberg et al. 1992). However, basic research usually occurs within publicly funded institutes, is mostly driven by the deeper need for improving the understanding of how and why natural and social phenomena occur, and is most of the times publicly accessible. The framework used here is based on the profit seeking behavior of private firms and is therefore not suited for answering

The contribution of this chapter is to demonstrate the importance of a second dimension to the analysis of knowledge spillovers when studying optimal R&D policies: time. Diffusion in this context is the process by which an invention is communicated through certain channels over time among the members of a social system (Rogers 2003). Empirical data supports the thesis that research subsidies should differentiate not only on the basis of inter-sectoral compatibility but also on the time it takes for knowledge to diffuse. For example Mansfield (1985) finds the time needed for confidential firm information on new in-house processes to reach rivals to be industry-specific and mostly above one year. However, the most widely-accepted approach is to assume that spillovers increase proportionally to technology adoption. Related to this Sultan et al. (1990) calculate the time lag between invention and marketable application of medical technologies to be about 20 years, while Popp (2015) estimates for green technologies time lags in the range of 8-10 years.

To our end, we will use endogenous growth theory in the spirit of Romer (1990) and Aghion and Howitt (1992), as modified in Peretto and Smulders (2002) to consider in-house R&D. The inter-temporal dimension is added in a similar fashion as in the analysis in Grossman and Helpman (1991), Chapter 3, with lags in knowledge dissemination.[2] One of the two key parameters of the model used is the *speed*

questions on basic research occurring in public institutes. A thorough discussion on guiding public investment policy in the area of basic research can be found in Gersbach et al. (2015) and Gersbach and Schneider (2015).

[2]The framework used here falls under the category of endogenous growth models exhibiting scale effects. The critique against the empirical relevance of the "linearity" that leads to endogenous sustained economic growth was raised in Jones (1995). Peretto (2015) using a model of endogenous growth without scale effects discusses the within-industry forces that could have led to the S-shaped historical path of economic growth from the industrial revolution: an initial phase of sluggish development, followed by rapid acceleration in economic growth, leading to a modern sustained growth rate. The current chapter of the thesis serves as a mere exposition of the importance of taking into account the speed of diffusion of knowledge spillovers when designing R&D-support policies and is, therefore, in the interest of the author to use a model that, for all its criticisms, is both concise and widely understood.

of diffusion of research results; the rate at which a sector-specific invention creates positive knowledge spillovers that increase the productivity of other sectors. The second important component is the *degree of compatibility* of sector-specific practices with the technological status of the wider economy; the more specific a firm's practices within a sector are, the fewer spillovers it creates. Such a firm is able to appropriate higher returns to its research investment and, according to the general consensus in the literature, should be granted lower R&D support. It is shown, however, that once we account for the timing of knowledge diffusion, the optimal R&D policy responds non-monotonically to a change in the degree of compatibility, contradicting this common belief.

The next section presents the multi-sector R&D model. Section 4.3 provides a qualitative analysis in partial equilibrium and explains the main mechanism driving the results. This is then followed by section 4.4 with the general equilibrium version of the model and its numerical solution; this section closes the model by introducing the spillovers diffusion technology and solves for the optimal subsidy. Section 4.5 serves as an extension to the basic model and presents the optimal subsidy when information follows a more complex diffusion process with endogenous speed of diffusion. Finally, section 4.6 concludes with policy recommendations and a possible future research agenda.

4.2 The R&D model

4.2.1 General setup

Consider an infinite horizon economy in continuous time admitting a representative household with logarithmic preferences, i.e. $U(C) = logC$, with C being the flow of consumption in each time period. Variable t is the time index.[3] The representative household is endowed with L units of labor, supplied inelastically to manufacturing and R&D; no population growth is considered. The unique consumption good

[3] Time index t will be dropped within the text when no confusion arises.

(Y) is produced by combining labor (L_Y) and a continuum of intermediates (x_j), each available at a certain quality (q_j), in a Cobb-Douglas fashion. Total output is allocated to consumption (C) and production of intermediates. The representative firm of each manufacturing sector, j, is responsible for its own research and improves upon its existing technological status by hiring scientific labor (L_{Sj}). In light of empirical evidence (see section 4.2.3), firm-specific research uses its own knowledge stock but benefits also from economy-wide knowledge spillovers. Higher quality of intermediate inputs translates into a higher labor productivity in the production of the final good and thus in a higher consumption growth. The externality associated with knowledge spillovers is corrected by a research subsidy raised by the government in a lump-sum way from the representative household.

4.2.2 Decentralized equilibrium

The consumption good is the numeraire; the representative household's problem is standard and implies the usual Keynes-Ramsey rule for the growth rate of consumption, $\dot{C}/C = r - \rho$; parameter ρ is the constant rate of time preference, and r the economy-wide interest rate. Production follows:

$$Y_t = \frac{1}{\beta} L_{Yt}^{1-\beta} \int_0^1 q_{jt} x_{jt}^{\beta} dj, \qquad j \in [0,1],$$

where L_Y is the aggregate labor input in manufacturing, x_j the amount of an intermediate good from sector $j \in [0,1]$, used at time t, and q_j the quality of that good. Each good is supplied by one firm and each firm produces one good. This production function supports monopolistic competition in the intermediates sector. Following the usual procedure we can derive the equilibrium in this economy.[4] With $Q = \int_0^1 q_j dj$ denoting the average technology level in the economy, the labor wage rate reads $w = (1-\beta)Q$, while $Y = QL_Y$ and $C = (1-\beta)Y$. The last equation implies that $g \equiv \dot{C}/C = \dot{Y}/Y$ is the growth rate of the economy. The monopoly

[4] See for example Acemoglu (2008, Chapter 14).

profit flow from supplying good j (before R&D) reads

$$\pi_{jt} = (1 - \beta) q_{jt} L_{Yt}. \tag{4.1}$$

Labor market clears so that $L = L_Y + L_S$, with $L_S = \int_0^1 L_{Sj} dj$ being the aggregate level of scientific labor employed.

4.2.3 Inventive activity and innovation

Prescott and Visscher (1980) define a firm by its organizational capital: a firm-specific practice or technology is an asset that affects its production possibilities and can be accumulated through investment over time. As a matter of fact, a large strand of literature documents that research happens mostly in-house, and that established firms undertake incremental innovation improving their existing products (Malerba et al. 1997, Acemoglu and Cao 2015). A firm's research also benefits from knowledge spillovers. Accordingly, each firm j hires L_{Sj} units of scientific labor and builds on the firm-specific knowledge base in order to improve upon quality q_j with the following technology:

$$\dot{q}_{jt} = \eta q_{jt}^{\omega} K_t^{1-\omega} L_{S_{jt}}. \tag{4.2}$$

The elasticity parameter $\omega \in [0, 1]$ proxies the *degree of compatibility* of firm-specific practices with the technological status of the economy-wide knowledge spillovers, K. It is the extent to which a firm bases its research activity on its own firm-specific technology. A large value, $\omega \to 1$, means that this firm's practices are very firm-specific; such a firm can appropriate the return to its research investment creating at the same time spillovers that are only minimally useful to the wider economy. Conversely, a model with an R&D technology fully compatible with the practices of other firms, $\omega \to 0$, implies a knowledge base that mainly depends on the aggregate pool of knowledge, i.e. the basic model of R&D-driven endogenous growth, e.g. Romer (1990). This crucial assumption can be justified if we think of firms clustering into technology classes in which they seek to improve. Coinciding interests between firms creates opportunity for exchange of knowledge (Peretto and Smulders 2002); however, the more specific a firm's technology is, the less it can benefit from or contribute to external knowledge.

So far the terms innovation and invention have been used interchangeably. However, according to the scope of this chapter, these terms need to be differentiated to reflect their true use in the economy. An invention is the product of research efforts, the creation of something new, while innovation introduces the concept of usefulness, the appreciation of an invention. A firm's technology, q_j, creates innovative knowledge spillovers, k_j, the aggegation of which makes up the pool of knowledge, $K = \int_0^1 k_j dj$, accessible by all firms in the economy. We will allow for innovation, k_j, to lag behind invention q_j, following a distributed lag formulation (see section 4.4.1). With this specification research results enter the aggregate pool of knowledge upon announcement but their initial contribution as positive externality to innovation is small and increases with time and acceptance from the market. The standard assumption of immediate knowledge diffusion would be $k_j = q_j$ so that $K = Q$.

4.2.4 Dynamic labor allocation

The supplying firm of the j good, taking into account a research subsidy ϕ that lowers the labor cost of R&D, employs L_{Sj} units of scientific labor in order to maximize its discounted stream of profit (net of research expenditure) according to

$$\max_{L_{Sj}} V_{jt} = \int_t^\infty \left[\pi_{js} - w_s(1-\phi)L_{Sjs}\right] e^{-\int_t^v r_v dv} ds,$$

subject to (4.2), and π_j defined in (4.1). Assuming active research, the first order condition for scientific labor employment and the law of motion for the shadow price of the firm-specific technology, λ_j, read:

$$w_t(1-\phi) = \lambda_{jt}\eta q_{jt}^{\omega} K_t^{1-\omega}, \tag{4.3}$$

$$(1-\beta)L_{Yt} + \lambda_{jt}\eta\omega q_{jt}^{\omega-1}K_t^{1-\omega}L_{Sjt} + \dot{\lambda}_{jt} = r_t\lambda_{jt}. \tag{4.4}$$

Equation (4.3) states that scientific labor will be employed up to the point where the marginal cost from employing an additional unit of labor equals the marginal quality improvement that this unit can offer. Equation (4.4) is a no-arbitrage condition between investing in research and in a riskless asset at the market interest rate, r.[5] In the interest of tractability and in order to focus on the main mechanism of the model, we will assume symmetry across firms, i.e. $q_j = Q$ and $L_{Sj} = L_S$. Using the hat-notation to denote the growth rate of a variable we obtain (see Appendix 5.3.1 for the derivation):

$$\hat{L}_{Yt} = \frac{\eta}{1-\phi}\left(\frac{K_t}{Q_t}\right)^{1-\omega} L_{Yt} - (1-\omega)\hat{K}_t - \rho. \tag{4.5}$$

From (4.2), each firm's research intensity depends on the scientific labor it employs. Accordingly, equation (4.5) is key to the results since it indicates in which way policy influences the labor allocation between manufacturing and R&D. We can first qualitatively identify the channels that affect labor allocation and the optimal policy response in partial equilibrium, i.e. keeping K/Q and $\hat{K}$ exogenous. This is done in the next section. These variables shall be subsequently endogenized in section 4.4, in order to analyze how the optimal policy depends on the inter-sectoral and inter-temporal dimension of knowledge spillovers.

4.3 Qualitative results in partial equilibrium

Let us assume that we are on a balanced growth path (BGP) in the decentralized equilibrium so that $\hat{K}_t = \hat{K}$, $K_t/Q_t = K/Q$, and $L_{Yt} = L_Y$. In this case the LHS of (4.5) is zero. The control variable, L_Y, must adjust accordingly to any changes so that the RHS remains zero.

[5] In fact the value of the firm can be re-written as $V_j = \lambda_j q_j$. Differentiating w.r.t time gives $\dot{V}_j = \dot{\lambda}_j q_j + \lambda_j \dot{q}_j$. Combining this with (4.4), (4.2), and (4.1) gives $\pi_j + \dot{V}_j = rV_j$, the standard no-arbitrage condition between investing in research and in a riskless bond.

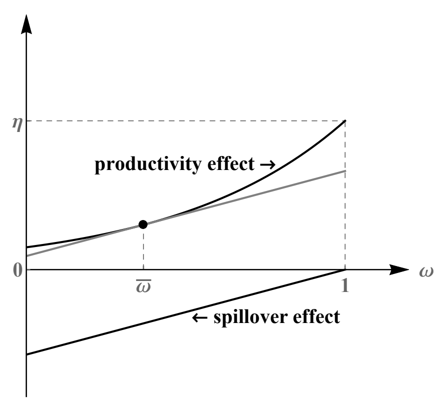
From (4.5) we can identify two direct effects and one indirect, that influence labor allocation among manufacturing and research. The first direct effect is the standard effect of an increase in the research subsidy, ϕ: an increase in the subsidy rate lowers the marginal cost of research (see (4.3)), increasing the incentives to perform R&D and thus to hire scientific labor. It decreases the denominator of the first term on the RHS stimulating lower employment in manufacturing and thus higher employment in research. The effect of an increase in the productivity factor, $(K/Q)^{1-\omega}$, the *productivity effect*, works in the same direction. We now turn to the indirect effect which works in the opposite direction. An increase in $\hat{K}$, the growth rate of knowledge spillovers, lowers the cost of research in the future. Thus firms which can benefit from that tend to postpone research activity and hire less scientific labor, the *spillover effect*. A large value of ω mitigates these effects since firms rely mainly on their own knowledge stock. In the limiting case of $\omega \to 1$ both the productivity and the spillover effects cancel out as the externality vanishes.

The only policy parameter is the subsidy rate, ϕ. Hence the social planner can increase the optimal R&D support whenever scientific labor falls short of its optimal level in order to give the correct research incentives. Below follows the intuition on how the timing of knowledge diffusion affects the way that the optimal subsidy depends on ω.

Take first the typical case of instantaneous knowledge diffusion, i.e. $K = Q$. In that case the productivity effect cancels out and the optimal policy response should address only the spillover effect which falls in ω: as the degree of compatibility of firm-specific innovation decreases, so does the externality. This is the main argument in the literature in favor of differentiated sector-specific subsidies that increase with the degree of compatibility. According to this argument, firms with higher technological compatibility should be granted greater support as in the case of clean R&D (Dechezleprêtre et al. 2014). Conversely, for very slow knowledge adoption rate (long time lags) it holds that $K \ll Q \to K/Q \ll 1$. In this case, due to the concavity of the productivity factor in ω, we do not get the same monotonic behavior of the optimal policy. For slow knowledge diffusion and low values of ω, there are too few incentives to perform research: inventive activity benefits largely from the economy-wide stock of innovation, K, which, however, expands at a very slow rate. In such a case a marginal increase in ω increases the productivity effect less than it mitigates the spillover effect. Thus, the productivity effect suffers most, indicating an increasing optimal subsidy rate in ω until research is sufficiently stimulated. For high values of ω the opposite occurs: a marginal increase in ω results in a proportionally larger marginal increase of the productivity factor resulting in a decreasing optimal subsidy as ω grows.

The previous discussion for low speed of knowledge diffusion can be qualitatively summarized in Figure 4.1. This shows for exogenous $K/Q \ll 1$ and $\hat{K}$, how both the productivity factor, $(K/Q)^{1-\omega}$, and the spillover factor $-(1-\omega)\hat{K}$, in equation (4.5), depend on ω. For slow diffusion, there exists a threshold, $\bar{\omega}$, where the two slopes are equal. For $\omega < \bar{\omega}$ the slope of the productivity effect is smaller than that of the spillover effect. In this case the positive productivity effect should be promoted more relative to dampening the adverse spillover effect; this requires an increase in the optimal subsidy. The contrary occurs for $\omega > \bar{\omega}$.

Figure 4.1: Qualitative representation of the productivity effect vs. spillover effect for slow knowledge diffusion ($K \ll Q$). Point $\bar{\omega}$ is where the two slopes coincide.



4.4 General equilibrium results

4.4.1 Adding Knowledge diffusion

So far we have not specified the exact process of knowledge diffusion. As stated earlier, each individual invention creates innovative knowledge spillovers, the sum of which makes up the general pool of knowledge, K. In order to include a time lag between an invention and its effect on the aggregate pool of knowledge we shall consider the following distributed lag formulation, commonly used in the literature; see for example Grossman and Helpman (1991, Chapter 3), or Eaton and Kortum (1999):

$$k_{jt} = \int_{-\infty}^{t} \kappa e^{-\kappa(t-\tau)} q_{j\tau} d\tau.$$

The rate of adjustment, denoted by κ, measures the speed of adoption by the wider economy of an innovation made in sector j. As in Appendix 5.2.1 for Chapter 3, it can be interpreted as the reciprocal of the mean time-lag using the same exponential distribution function; $\bar{\tau} = \int_0^\infty \kappa e^{-\kappa\tau} \tau d\tau = 1/\kappa$. The limiting case of $\kappa \to \infty$ corresponds to instantaneous knowledge diffusion with $\lim_{\kappa\to\infty} k_j = q_j$ and $\lim_{\kappa\to\infty} K = Q$. Differentiating the previous expression using the Leibniz rule gives

$$\dot{k}_{jt} = \kappa(q_{jt} - k_{jt}). \tag{4.6}$$

4.4.2 Dynamics

Section 4.3 gave a qualitative explanation of the dominant forces that drive the results in partial equilibrium. However, in (4.5) both the productivity effect and the spillover effect, we previously identified, depend on ω and κ, and should be endogenously determined. Symmetry still holds so that equation (4.2) gives the growth rate of the aggregate quality level, and (4.6) the growth rate of innovative spillovers:

$$\hat{Q}_t = \eta \left(\frac{K_t}{Q_t}\right)^{1-\omega} L_{St}, \tag{4.7}$$

$$\hat{K}_t = \kappa \left(\frac{Q_t}{K_t} - 1\right). \tag{4.8}$$

We define $\gamma \equiv K/Q \in (0, 1]$. Using the labor market clearing condition, the growth rate of this ratio with (4.7) and (4.8) reads

$$\hat{\gamma}_t = \kappa \left(\frac{1}{\gamma_t} - 1\right) - \eta\gamma_t^{1-\omega}(L - L_{Yt}). \tag{4.9}$$

Furthermore (4.5) with the definition of γ gives the growth rate of labor allocated to manufacturing as

$$\hat{L}_{Yt} = \frac{\eta}{1-\phi}\gamma_t^{1-\omega} L_{Yt} - (1-\omega_t)\kappa \left(\frac{1}{\gamma_t} - 1\right) - \rho. \tag{4.10}$$

Equations (4.9) and (4.10) give the dynamics of the economy in the $\{L_Y, \gamma\}$ space for an active R&D sector. Here we are interested in the effect of policy along the balanced growth path and abstract from a thorough analysis of the dynamic system.[6] In fact, in a recent contribution Grossmann et al. (2013), using a Jones (1995) model, study the optimal dynamic policy response to R&D externalities without time lags and find that the error of neglecting the transitional dynamics when designing the optimal R&D subsidy is small.

4.4.3 Optimal subsidy

Balanced growth can only exist if $\gamma_t = \gamma$ and $L_{Yt} = L_Y$, constant. In this case $g = \dot{C}/C = \dot{Y}/Y = \dot{Q}/Q = \dot{K}/K$. The optimal subsidy rate, ϕ^*, is the one needed

[6] Using equations (4.9) and (4.10), the determinant Δ of the Jacobian matrix of the autonomous dynamic system reads

$$\Delta = -\frac{\eta}{1-\phi}\tilde{\gamma}^{-(1+\omega)} \left[\kappa[1 + (1-\omega)(1-\phi)] + (1-\omega)\eta L\tilde{\gamma}^{1+(1-\omega)}\right] < 0,$$

which is negative for any of the permissible values of the parameters of the model, for any steady-state value $\tilde{\gamma} \in (0, 1]$, indicating a global saddle path stability.

to be imposed on the equilibrium allocation $\{\gamma, L_Y\}$ (second best), in order to equate this with the socially optimal allocation $\{\gamma^*, L_Y^*\}$ (first best). Equation (4.8) gives the steady state growth rate as a function of γ, and the speed of knowledge diffusion, κ:

$$g = g_{Tech} = \kappa \left(\frac{1}{\gamma} - 1 \right). \tag{4.11}$$

This equation, denoted by g_{Tech}, represents the knowledge diffusion technology and holds for both allocations; the first and the second best. By setting (4.10) equal to zero, solving with respect to L_Y and substituting in (4.9), while taking (4.11) into account, one gets the equilibrium steady state growth rate as a function of γ and the policy parameter, ϕ. This equation is defined as g_{Dec}:

$$g = g_{Dec} = \frac{\eta L \gamma^{1-\omega} - (1-\phi)\rho}{1 + (1-\omega)(1-\phi)}. \tag{4.12}$$

The intersection of (4.11) and (4.12) in the $\{\gamma, g\}$ space gives the equilibrium steady state allocation depending on κ, ω and the policy ϕ. Furthermore, solving (4.12) for ϕ, with g given by (4.11), gives $\phi(\gamma)$. We are now in position to study the decentralized equilibrium with the help of two functions: $g(\gamma)$ and $\phi(\gamma)$. These are plotted in Figure 4.2. Equation (4.12), the g_{Dec} line, is shown for two levels of the subsidy rate; zero subsidy and the optimal subsidy. An increase in the subsidy rate leaves the g_{Tech} line unaffected but shifts and turns the g_{Dec} upwards, resulting in an increase in g and a decrease in γ: higher subsidies stimulate research which, for a constant speed of knowledge diffusion, κ, increases Q relative to K, thus lowering their steady-state ratio, γ.

The social planner seeks to maximize the present discounted value of utility taking into account $C = Y(1-\beta)$, with (4.7) and (4.8). The result of this maximization is the g_{SP} line that gives the optimal growh rate as a function of γ (see Appendix 5.3.2):

$$g^* = g_{SP} = \frac{1 + \frac{\rho}{\kappa}\gamma}{1 + [1 + (1-\omega)]\, \frac{\rho}{\kappa}\gamma} \left(\eta L \gamma^{1-\omega} - \rho \right). \tag{4.13}$$

The optimal $\{\gamma^*, g^*\}$ can be found at the interection of g_{SP} with g_{Tech}. The optimal subsidy rate, ϕ^*, is the subsidy rate needed to turn and lift the g_{Dec} line to the point that $g_{Dec}(\gamma^*) = g^*$. The above reasoning is illustrated in Figure 4.2. At this point it would be instructive to study the behavior of the economy for the limiting cases of the relevant parameters κ and ω and to confirm the qualitative findings of the previous section. The limiting case of instantaneous knowledge diffusion, $\kappa \to \infty$, implies $\gamma \to 1$ and so we can analytically get the optimal policy response as $\phi^* = 1 - \frac{\rho}{\eta L - \omega(\eta L - \rho)}$, showing that ϕ^* is a monotonically decreasing concave function of ω. As the compatibility of firm-specific innovation reduces, so does the externality and thus the optimal subsidy. For $\kappa \to 0$ innovation peters out and so subsidizing research becomes a moot point.

Interestingly, as we expected from our qualitative discussion, when one considers the timing of the knowledge diffusion process, optimal policy does not follow a clear cut rule anymore (see Figure 4.3). For high speed of knowledge diffusion (e.g. $\kappa = 0.2$, i.e. $\bar{\tau} = 5$ years), the spillover effect dominates, and since diminishing compatibility mitigates this effect, optimal policy falls in ω. For low κ (e.g. $\kappa = 0.05$, i.e. $\bar{\tau} = 20$ years), the optimal subsidy is non-monotonic in ω. Ceteris paribus, ϕ^* is increasing in κ: fast adoption of sector-specific research results speaks in favor of higher optimal subsidies.

4.4.4 Comparative Statics

Using equations (4.11), (4.12) and (4.13) we define the implicit functions

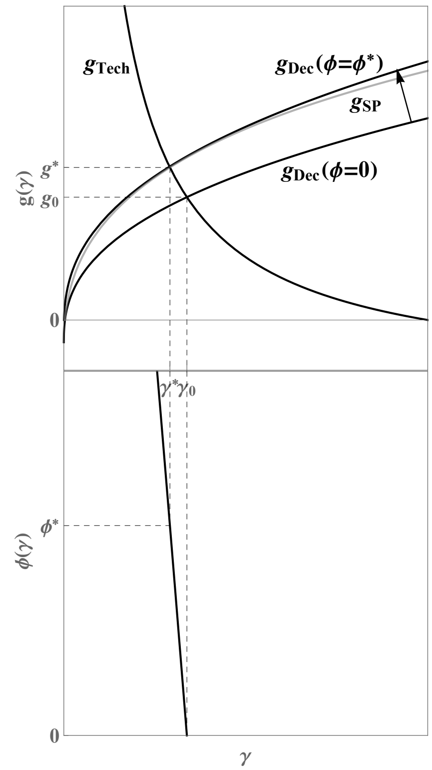
$$f_{Tech}(g^*, \gamma^*, \phi^*, \kappa, \omega) = g^*_{Tech} - g^* = 0,$$

$$f_{Dec}(g^*, \gamma^*, \phi^*, \kappa, \omega) = g^*_{Dec} - g^* = 0,$$

$$f_{SP}(g^*, \gamma^*, \phi^*, \kappa, \omega) = g^*_{SP} - g^* = 0,$$

and study the comparative statics of the optimum allocation for extreme cases of the relevant parameteres κ and ω. The procedure can be found in the Appendix

Figure 4.2: Graphical estimation of the optimal subsidy rate.



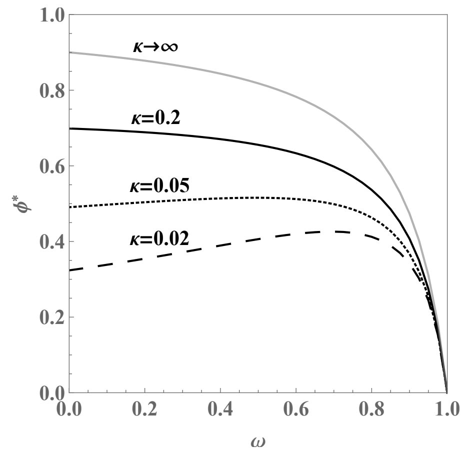
Parameters: $\rho = 0.05, \eta = 0.5, L = 1, \kappa = 0.05, \omega = 0.6$.

while the results in Figure 4.4. Since the behavior of the optimal policy in κ and ω has been already extensively discussed, we present below only a brief summary.

- $d\gamma^*/d\kappa > 0$: higher speed of diffusion expands the aggregate pool of knowledge at a higher rate, thus increasing the K/Q ratio.

- $d\gamma^*/d\omega < 0$: parameter ω is used throughout as a proxy for the compatibility of firm-specific technological improvements with the average technology level of the market. Accordingly, an increasing ω implies less usable inter-sectoral knowledge spillovers and a decreasing K/Q ratio.

Figure 4.3: Optimal subsidy ϕ^* for different values of κ and ω.



Parameters: $\rho = 0.05, \eta = 0.5, L = 1$.

- $d\phi^*/d\kappa > 0$: As we explained in the previous paragraph, a firm whose results are faster appreciated should deserve higher support since it expands the aggregate pool of knowledge at a higher rate.

- $d\phi^*/d\omega$ ambiguous: for low κ and ω the firm lacks incentives to innovate and the productivity effect, which increases convexly in ω, suffers most. The optimal response is then increasing in ω. For large values of ω, the social planner should give priority to correcting for the spillover effect. The spillover effect decreases current research activities, since entrepreneurs are anticipating falling R&D cost in the future, and is linearly mitigated by ω, indicating a decreasing optimal subsidy rate in ω.

- $dg^*/d\kappa > 0$: see equation (4.13) with $d\gamma^*/d\kappa > 0$.

- $dg^*/d\omega > 0$: combine (4.11) with $d\gamma^*/d\omega < 0$. In general, increasing ω lowers spillovers, increases the appropriability and stimulates research activity and growth.

Figure 4.4: Comparative statics for different values of κ and ω.

	dκ	dω
dγ^*	+	−
dϕ^*	+	+
dg^*	+	+

(a) $\kappa = 0.05$, $\omega = 0.1$

	dκ	dω
dγ^*	+	−
dϕ^*	+	−
dg^*	+	+

(b) $\kappa = 1$, $\omega = 0.1$

	dκ	dω
dγ^*	+	−
dϕ^*	+	−
dg^*	+	+

(c) $\kappa = 0.05$, $\omega = 0.9$

	dκ	dω
dγ^*	+	−
dϕ^*	+	−
dg^*	+	+

(d) $\kappa = 1$, $\omega = 0.9$

Parameters: $\rho = 0.05, \eta = 0.5, L = 1$.

4.5 Extension: endogenous speed of diffusion

It is reasonable to assume that nowadays, in the era of technology and social media, information spreads faster that it used to in earlier times. Comin and Hobijn (2010) find that the average lag in technology adoption falls with the invention date of technologies, while Comin and Mestieri (2014) report a time lag of 121 ± 53 years for steam and motor ships (invented in 1788), 12 ± 6 for open heart surgery (invented in 1968), but only 7 ± 3 years for the internet (invented in 1983).

There are several ways to access firm-specific information over a practice or technology: internet research, through peers, by reverse engineering, or by imitation from others who have already accessed this information at an earlier stage. All of these processes become increasingly effective as the technology frontier of the market advances. In our model, at every instance of time, Q is the technological level of the representative firm while K the attained technology frontier of the market. Since the spillovers of advancements in Q expand K, variable K still lags behind Q so that $K/Q \leq 1$ as in section 4.4.2.

Subsequently, we can think now of the *effective* speed of diffusion, κ, to be comprised of two parts: a technology-specific part, as before, and another part modulated by the K/Q ratio, i.e. $\kappa \equiv a + b\frac{K}{Q}$, with $a, b > 0$; once firm-specific information starts diffusing into the market it becomes increasingly easy to do so as the market's technology benefiting from spillovers advances. This is in essence the basic Bass diffusion model for forecasting the adoption of a product / innovation, widely used in the marketing science, modified here to include an ever expanding technological potential Q; see Bass (1969). Accordingly, equation (4.8) becomes:

$$\hat{K}_t = \underbrace{\left(a + b\frac{K_t}{Q_t}\right)}_{\kappa=\kappa\left(\frac{K_t}{Q_t}\right)} \left(\frac{Q_t}{K_t} - 1\right). \tag{4.14}$$

With this specification equations (4.9) and (4.10) become, respectively:

$$\hat{\gamma}_t = (a + b\gamma_t)\left(\frac{1}{\gamma_t} - 1\right) - \eta\gamma_t^{1-\omega}(L - L_{Yt}), \tag{4.15}$$

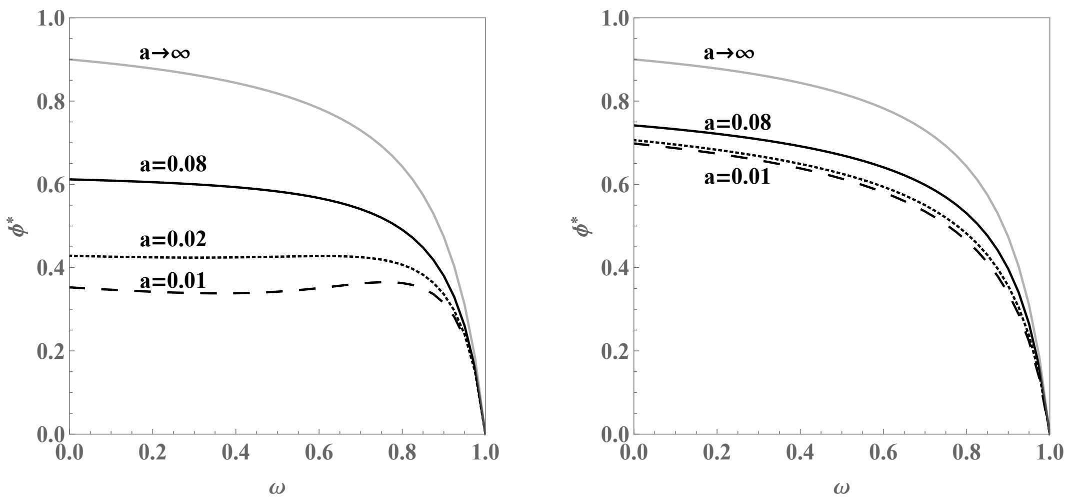
$$\hat{L}_{Yt} = \frac{\eta}{1-\phi}\gamma_t^{1-\omega}L_{Yt} - (1-\omega)(a + b\gamma_t)\left(\frac{1}{\gamma_t} - 1\right) - \rho. \tag{4.16}$$

It can be proven that the dynamic system in $\{\gamma, L_Y\}$ is again globally saddle stable. Following the same procedure as before we calculate the optimal subsidy rate that depends on the model's parameters: parameters a and ω remain technology / sector-specific, whereas b is now market specific.[7]

Figure 4.5 presents the optimal subsidy rate with the new diffusion specification. There are several things to note. First, the resulting optimal subsidy is highly nonlinear in ω for low values of a and b (left panel). Second, as before, *ceteris paribus*, the optimal subsidy increases with a; technologies that diffuse faster should be granted higher support. Third, a higher value for b produces monotonic results even for low values of a. This is intuitive because even if spillovers start diffusing at a very low speed, the effective speed of adoption continuously increases at an increasing rate; comparing the results here with Figure 4.3, in effect there is an upward shift in regimes from a low to a high value of κ. Finally, we confirm the thesis on the importance of the inter-temporal dimension of spillovers for optimal R&D support policies.

[7]Using the original version of the Bass diffusion model that gives for a certain market potential the rate of technology adoption over time, Sultan et al. (1990) and Teng et al. (2002) estimate a and b for several technologies: while a can vary greatly within $0.005 - 0.08$, with a mean of 0.03, parameter b falls mostly within the range of $0.1 - 0.5$, with a mean of 0.38.

Figure 4.5: Optimal subsidy ϕ^* using the Bass diffusion technology



(a) $b = 0.1$ (b) $b = 0.5$

Parameters: $\rho = 0.05, \eta = 0.5, L = 1$.

4.6 Conclusion

Empirical evidence suggests that there is room for improvement in the public budget allocation to private research activities. Motivated by findings on the inter-sectoral and inter-temporal aspects of knowledge spillovers, we study the effect of the timing of knowledge diffusion on the optimal industrial policy promoting research. Knowledge dissemination does not occur simultaneously, as commonly postulated in the literature, but rather with a time lag. We also differentiate between inventive activity in the lab and applicable innovation. This distinction reflects their true use in the economy, but also highlights the fact that the latter typically lags behind the former.

It is shown that, for large time lags, the optimal subsidy evolves non-monotonically in the parameter that proxies the compatibility of a sector-specific invention with the practices of the wider economy. This result contradicts the consensus in the literature that optimal subsidies should fall as innovation becomes more sector-specific and gives more room for improvement of R&D promoting policies. According to our results, the optimal R&D support policy should be sector-specific and such that it takes into account both the inter-sectoral and the inter-temporal aspect of knowledge spillovers. The results also highlight the importance of including the inter-temporal dimension of knowledge spillovers in frameworks with more realistic market dynamics of the Schumpeterian type when studying firm-heterogeneity, reallocation, and endogenous entry and exit.[8] This is left for future research.

[8] See for example Klette and Kortum (2004), Acemoglu et al. (2013).

Chapter 5

Appendices

5.1 Appendix for Chapter 2

5.1.1 Definitions: relative change in the marginal products

Take a general production function $Y = f(m, n)$. Y exhibits constant returns to scale so that $\frac{Y}{m} = f(1, \frac{n}{m})$, or, $\psi = \psi(b)$, with $\psi = Y/m$ and $b = n/m$. Then:

$$\frac{\partial Y}{\partial n} = \psi', \qquad \frac{\partial Y}{\partial m} = \psi - b\psi'. \tag{5.1}$$

The elasticity of substitution between m and n is defined as

$$\frac{1}{\epsilon} = -\frac{\partial\left(\frac{\partial Y/\partial n}{\partial Y/\partial m}\right)}{\partial(n/m)} \frac{n/m}{\frac{\partial Y/\partial n}{\partial Y/\partial m}} = -\frac{b\psi''}{\psi'} \frac{\psi}{\psi - b\psi'}. \tag{5.2}$$

With the definitions (5.1) we can calculate,

$$\frac{\partial(\partial Y/\partial n)}{\partial n} = \frac{\partial \psi'}{\partial n} = \psi'' \frac{b}{n}, \tag{5.3}$$

$$\frac{\partial(\partial Y/\partial n)}{\partial m} = ... = -\psi'' \frac{b}{m}, \tag{5.4}$$

$$\frac{\partial(\partial Y/\partial m)}{\partial n} = \frac{\partial(\psi - b\psi')}{\partial n} = -\psi'' \frac{b^2}{n}, \tag{5.5}$$

$$\frac{\partial(\partial Y/\partial m)}{\partial m} = ... = \psi'' \frac{b^2}{m}. \tag{5.6}$$

The production elasticity of m is defined as $\gamma = \frac{\partial Y}{\partial m}\frac{m}{Y}$. The relative change in the marginal product of m and n reads

$$\frac{\Delta \partial Y/\partial m}{\partial Y/\partial m} = \frac{1}{\partial Y/\partial m}\left[\frac{\partial(\partial Y/\partial m)}{\partial n}dn + \frac{\partial(\partial Y/\partial m)}{\partial m}dm\right],$$

and

$$\frac{\Delta \partial Y/\partial n}{\partial Y/\partial n} = \frac{1}{\partial Y/\partial n}\left[\frac{\partial(\partial Y/\partial n)}{\partial n}dn + \frac{\partial(\partial Y/\partial n)}{\partial m}dm\right].$$

The last two equations with (5.3)-(5.6), (5.1), and (5.2) give

$$\frac{\Delta \partial Y/\partial m}{\partial Y/\partial m} = \epsilon^{-1}(1-\gamma)(\tilde{n}-\tilde{m}), \tag{5.7}$$

$$\frac{\Delta \partial Y/\partial n}{\partial Y/\partial n} = -\epsilon^{-1}\gamma(\tilde{n}-\tilde{m}). \tag{5.8}$$

With equations (5.7) and (5.8) we can calculate the relative change of the marginal products in equations (2.7), (2.8), (2.13), and (2.14).

5.1.2 Definitions: relative change in the tax rates and value shares

$$\tilde{t}_l = \frac{dt_L}{1-t_L}, \qquad \tilde{t}_e = \frac{dt_e}{1+t_e}, \qquad p_Q Q \equiv 1.$$

$$s_X = wL_X, \qquad s_J = wL_J, \qquad s_U = wL_U, \qquad s_\Pi = \pi N,$$

$$s_C = p_Q C, \qquad s_I = p_Q I, \qquad s_E = p_E E, \qquad s_A = A, \qquad s_\tau = T.$$

5.1.3 Relations between the shares

Market clearing for goods (2.3)

$$s_C + s_I + s_E = 1 \tag{5.9}$$

Market clearing for labor (2.4)

$$s_X + s_J + s_U = w \tag{5.10}$$

No profit condition for X

$$s_X + s_E(1 + t_E) + s_\Pi = 1 \tag{5.11}$$

First order conditions (2.7) and (2.8)

$$s_E(1 + t_E) = \beta(1 - \gamma_X) \tag{5.12}$$

$$s_X = \beta\gamma_X \tag{5.13}$$

Profit function (2.9)

$$s_\Pi = 1 - \beta \tag{5.14}$$

No arbitrage condition (2.10)

$$\frac{s_\Pi}{s_A} = g + \rho \tag{5.15}$$

R&D technology (2.11)

$$gs_A = s_J + s_I \tag{5.16}$$

First order conditions (2.13) and (2.14)

$$gs_A\gamma_J = s_J \tag{5.17}$$

$$gs_A(1 - \gamma_J) = s_I \tag{5.18}$$

Leisure - consumption tradeoff (2.16)

$$\theta s_c = (1 - t_L)s_U \tag{5.19}$$

5.1.4 The Model in relative changes

Final good composite (2.2)

$$\tilde{q} = \tilde{x} \tag{5.20}$$

Goods market equilibrium (2.5) with $p_Q Q = 1$ and (5.20)

$$\tilde{p}_x = \tilde{p}_q = -\tilde{x} \tag{5.21}$$

Market clearing for goods (2.3) with $\tilde{p}_e = 0$ and (5.20)

$$-(s_C + s_I)\tilde{x} + s_C\tilde{c} + s_I\tilde{i} + s_E\tilde{e} = 0 \tag{5.22}$$

Market clearing for labor (2.4)

$$s_X\tilde{l}_X + s_J\tilde{l}_J + s_U\tilde{l}_U = 0 \tag{5.23}$$

Aggregate output in manufacturing (2.6)

$$\tilde{x} = \gamma_X\tilde{l}_X + (1-\gamma_X)\tilde{e} \tag{5.24}$$

Labor demand in manufacturing (2.8) using (5.7) and (5.21)

$$\tilde{w} = -\tilde{x} + \epsilon_X^{-1}(1-\gamma_X)(\tilde{e} - \tilde{l}_X) \tag{5.25}$$

Energy demand in manufacturing (2.7) using (5.8) and (5.21)

$$\tilde{t}_e = -\tilde{x} - \epsilon_X^{-1}\gamma_X(\tilde{e} - \tilde{l}_X) \tag{5.26}$$

No arbitrage condition (2.10) with (5.15)

$$g\tilde{g} = -(g+\rho)\tilde{a} \tag{5.27}$$

Innovation technology (2.12) with $\tilde{g} = \tilde{j}$

$$\tilde{g} = \gamma_J\tilde{l}_J + (1-\gamma_J)\tilde{i} \tag{5.28}$$

Labor demand in the R&D sector (2.13) using (5.7) and (5.21)

$$\tilde{w} = \tilde{a} + \epsilon_J^{-1}(1-\gamma_J)(\tilde{i} - \tilde{l}_J) \tag{5.29}$$

Investment demand in the R&D sector (2.14) using (5.8) and (5.21)

$$-\tilde{x} = \tilde{a} - \epsilon_J^{-1}\gamma_J(\tilde{i} - \tilde{l}_J) \tag{5.30}$$

Leisure - consumption tradeoff (2.16) with (5.21)

$$\tilde{c} - \tilde{l}_U = \tilde{w} - \tilde{t}_l + \tilde{x} \tag{5.31}$$

5.1.5 Used elasticities in the numerical part

Table 5.1: Elasticities and their sources

Parameter	Description	Value
ϵ_Y	Elasticity of substitution between Q and inputs B	0.392 (AGR); 0.568 (OIN); 1.264 (CON); 0.848 (FOSS, CHM); 0.518 (MCH); 0.352 (TRN); 0.100 (ELES); 0.492 (rest)
ϵ_X	Elasticity of substitution between labor L_X and energy E	0.7 (AGR, MCH, ELES, FOSS); 0.52 (CON); 0.55 (CHM, TRN, OIN); 0.4 (rest)
ϵ_E/σ_E	Elasticity of substitution between fossil energy and electricity	0.5-1.5 (chosen 0.7)
$\epsilon_{Fos}/\sigma_{Fos}$	Elasticity of substitution between different fossil fuel sources	1
τ	Elasticity of substitution between physical investments (I_P) and non-physical capital (I_N)	0.3
ω	Elasticity of substitution between investments in R&D (I_R) and research labor L_J	0.3
σ_C	Elasticity of substitution between energy and non-energy goods	0.5
σ_Y	Elasticity of substitution between different regular goods	0.5
$1/\zeta$	Inter-temporal elasticity of substitution in the welfare function	0.6
σ_L	Elasticity of substitution between consumption and leisure in the welfare function	0.65
ξ	Trade (”Armington ”) elasticities	3.2 (AGR); 4.6 (MCH); 3.8 (ELES, OIN); 2.9 (rest)
χ	Elasticity of transformation	1
υ	Elasticity of substitution between sectoral outputs for the input B	0

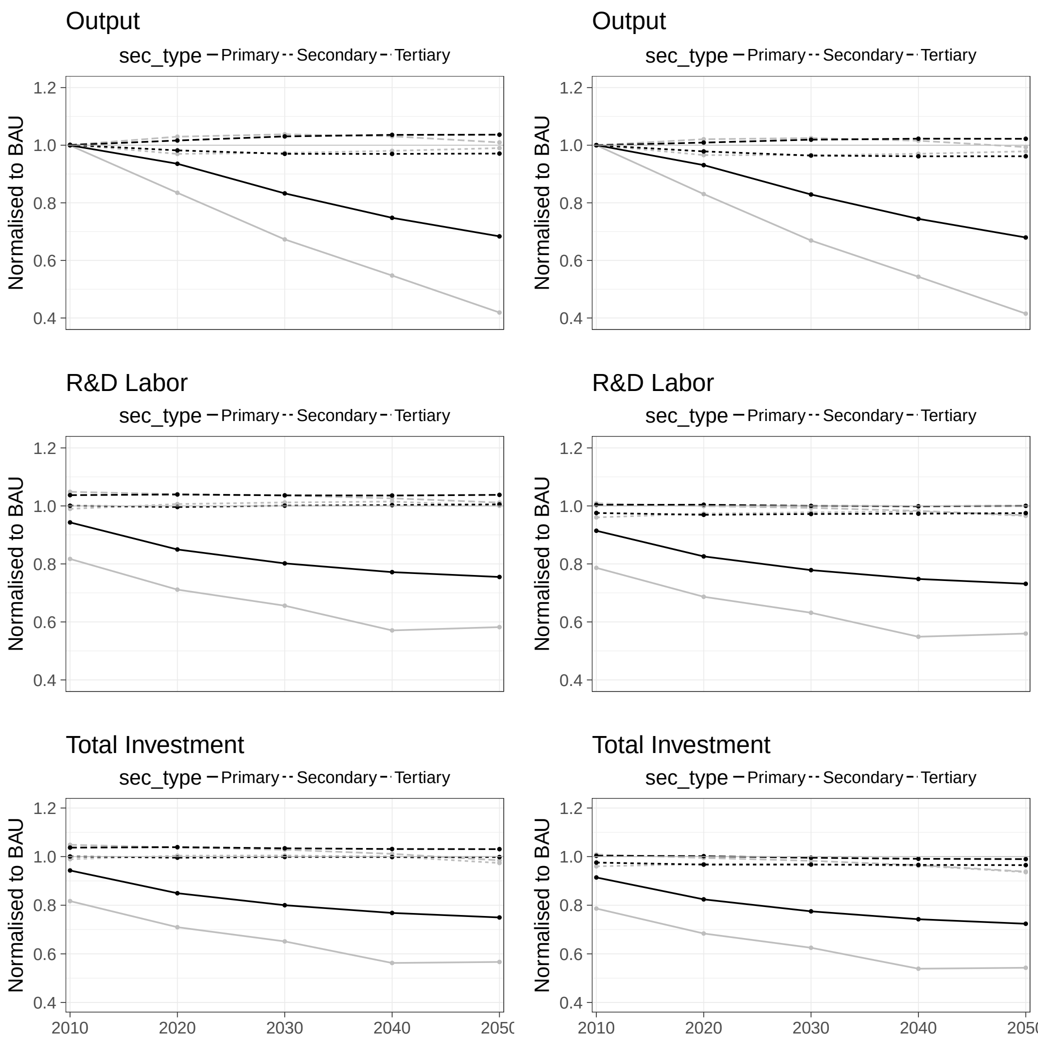
Sources: ϵ_Y Okagawa and Ban (2008); ϵ_X van der Werf (2007), Mohler and Mueller (2012); ϵ_E/σ_E Goulder and Schneider (1999), Gerlagh and van der Zwaan (2003); $\epsilon_{Fos}/\sigma_{Fos}$ Bretschger and Zhang (2016); $\tau/\omega/\chi$ Bretschger et al. (2011); σ_C/σ_Y Ecoplan (2007); $1/\zeta$ Hasanov (2007); σ_L Imhof (2012); η Donnelly et al. (2004); υ Paltsev et al. (2005)

5.1.6 Sectoral impacts

In this part of the Appendix we present the structural effects of an ETR on the Swiss economy for the primary, secondary – or manufacturing –, and tertiary sector – or services. Figure 5.1 presents the output, R&D labor, and total investment for the three economic sectors, following a carbon policy that reduces CO2 emissions by 20% and 60% in 2050, relative to the BAU scenario, for two redistribution options – capital tax reduction and lump-sum per capita redistribution.

An environmental tax reform is expected to exert a high pressure on the domestic production of the primary sector. However, since this sector only amounts to a very small part of the Swiss economy, it is not expected to influence the aggregate levels of production; see figure 2.5. The manufacturing sector, on the other hand, is expected to be only minimally influenced, while the tertiary to be promoted, even for very stringent CO2 emission targets.

Figure 5.1: Production, R&D labor expenditure, and total investment (normalized to BAU) for 20% (black) and 60% (grey) CO_2 emissions reduction in 2050 - economic sectors.



(a) Capital tax redistribution

(b) Lump-sum redistribution

5.2 Appendix for Chapter 3

5.2.1 Time lags in the climate system

In this part of the Appendix we present the mathematic modeling of distributed time lags in the climate system and its properties. For the analysis we rely largely on MacDonald (1978). Take first the case of instantaneous diffusion of emissions. In this case the usual assumption is that the use of a pollutant, R_t, increases the harmful stock of emissions P_t at a rate

$$\dot{P}_t = \phi R_t + \theta(\bar{P} - P_t), \qquad P_0 \geq 0 \text{ given}, \tag{5.32}$$

with $\phi > 0$ representing the carbon intensity of the polluting energy resource, $\theta \geq 0$ the carbon decay parameter, and $\bar{P} \in (0, P_0)$ the pre-industrial level of carbon concentration in the atmosphere. Now let's introduce a distributed lag in the model in order to relax the usual assumption of instantaneous pollution accumulation and let this process depend on the history of resource use

$$\dot{P}_t = \int_{-\infty}^{t} G_{t-s}\phi R_s ds + \theta(\bar{P} - P_t), \qquad P_0 \geq 0 \text{ given}. \tag{5.33}$$

With this formulation (5.32) becomes an integro-differential equation. The function G_x represents the memory of the system (or the delaying function) with $\int_0^\infty G_x dx = 1$. Function G_x could be also interpreted as the probability density function of the inherent time lag of the particular system so that the mean time lag $\bar{T}$ for a given memory function would read $\bar{T} = \int_0^\infty x G_x dx$. With a special choice of the memory function one can replace (5.33) with a set of linear differential equations. For this purpose it is a standard approach to exploit the properties of the exponential functions by using the exponential distribution

$$G_x = \kappa e^{-\kappa x}, \qquad \kappa > 0. \tag{5.34}$$

The parameter κ measures the speed of emissions diffusion, or speed of adjustment, and is the reciprocal of the mean time lag $\bar{T}$ from the same memory function, i.e. $\kappa = \bar{T}^{-1}$. We can then define the lagged history of carbon emissions as $Z_t \equiv \int_{-\infty}^{t} G_{t-s}\phi R_s ds$, and by using the Leibniz rule of integration to get the familiar equivalent system of differential equations, with P_0 and Z_0 given:

$$\begin{cases} \dot{P}_t = Z_t + \theta(\bar{P} - P_t), \\ \dot{Z}_t = \kappa(\phi R_t - Z_t). \end{cases} \tag{5.35}$$

It can be proven that the corresponding system is globally stable for the relevant range of the parameters $\kappa, \phi, \theta > 0$ and $\bar{P} > 0$. Since in general the initial value of Z_t cannot be defined, Z_0 is chosen such that $lim_{\kappa \to \infty} P_{t=0} = P_0$, as expected, i.e. $Z_0 = 0$. The solution for the climate system given the rate of resource extraction for each time period, R_t, now reads

$$P_t = P_0 + (\bar{P} - P_0)(1 - e^{-\theta t}) + \int_0^t \kappa \frac{e^{-\theta(t-s)} - e^{-\kappa(t-s)}}{\kappa - \theta} \phi R_s ds. \tag{5.36}$$

The limiting cases for $\kappa \to 0$ and $\kappa \to \infty$ follow readily from the last equation. From (5.36), the marginal increase in the stock of carbon in period ν from a marginal unit of emissions in period t reads:

$$\frac{dP_\nu}{d(\phi R_t)} \equiv f_{\nu t} = \kappa \frac{e^{-\theta(\nu - t)} - e^{-\kappa(\nu - t)}}{\kappa - \theta} > 0, \qquad \text{for all } \nu \geq t. \tag{5.37}$$

5.2.2 Social optimum

The social planner chooses the share ϵ_t, and resource extraction R_t in order to maximize lifetime utility $\int_0^\infty U_t e^{-\rho t} dt$, with $U_t = \log(C_t)$ if $\sigma = 1$ and $U_t = \frac{C_t^{1-\sigma}}{1-\sigma}$ otherwise, subject to equations (3.3) - (3.6). The Hamiltonian of the social planner reads

$$\begin{aligned} H_t = \frac{C_t^{1-\sigma}}{1-\sigma} &+ \lambda_{Ct}\left[A(\epsilon_t K_t)^\alpha R_t^{1-\alpha} - C_t\right] + \lambda_{Kt} K_t \left[B(1-\epsilon_t) - D(P_t)\right] \\ &- \lambda_{St} R_t + \lambda_{Pt}[Z_t + \theta(\bar{P} - P_t)] + \lambda_{Zt}\kappa[\phi R_t - Z_t], \end{aligned}$$

with $\lambda_{Ct}, \lambda_{Kt}, \lambda_{St}, \lambda_{Pt}, \lambda_{Zt}$, the shadow prices of the consumption good, C_t, capital stock, K_t, stock of non-renewable resources, S_t, stock of pollution, P_t, and the lagged history of emissions, Z_t. Assuming an internal solution, the first order conditions w.r.t. the C_t, ϵ_t, R_t, i.e. $\partial H_t/\partial(\cdot) = 0$ imply

$$C_t^{-\sigma} = \lambda_{Ct}, \tag{5.38}$$

$$\alpha \frac{C_t}{K_t} = \frac{\lambda_{Kt}}{\lambda_{Ct}} B\epsilon_t, \tag{5.39}$$

$$(1-\alpha)\frac{C_t}{R_t} = \frac{\lambda_{St}}{\lambda_{Ct}} - \phi\kappa \frac{\lambda_{Zt}}{\lambda_{Ct}}. \tag{5.40}$$

Moreover $\partial H_t/\partial(\cdot) = \rho q_t - \dot{q}_t$ for every state variable, K_t, S_t, P_t, Z_t, with q_t its shadow price. This leads to

$$(\widehat{\lambda_{Kt} K_t}) = -\alpha \frac{\lambda_{Ct} C_t}{\lambda_{Kt} K_t} + \rho, \tag{5.41}$$

$$\hat{\lambda}_{St} = \rho, \tag{5.42}$$

$$\hat{\lambda}_{Pt} = D'(P_t) K \frac{\lambda_{Kt}}{\lambda_{Pt}} + \theta + \rho, \tag{5.43}$$

$$\hat{\lambda}_{Zt} = -\frac{\lambda_{Pt}}{\lambda_{Zt}} + \kappa + \rho, \tag{5.44}$$

Finally, the relevant transversality conditions read

$$\lim_{t\to\infty} \lambda_{St} S_t e^{-\rho t} = 0, \tag{5.45}$$

$$\lim_{t\to\infty} \lambda_{Kt} K_t e^{-\rho t} = 0, \tag{5.46}$$

$$\lim_{t\to\infty} \lambda_{Pt} P_t e^{-\rho t} = 0, \tag{5.47}$$

$$\lim_{t\to\infty} \lambda_{Zt} Z_t e^{-\rho t} = 0. \tag{5.48}$$

Equation (5.42) gives the usual Hotelling rule for the extraction of the non-renewable resource. Equation (5.39) shows indifference about allocating capital between the two activities: producing the consumption and the investment good. When $\sigma = 1$ we can combine (5.39), with $\lambda_{Ct} C_t = 1$, from (5.38), and (5.41), to get $\dot{\epsilon}_t = B\epsilon_t^2 - \rho\epsilon_t$. With the use of the transversality condition (5.46), we get that the capital share jumps immediately to its steady state value, $\bar{\epsilon} = \rho/B$.

5.2.3 Asymptotic constancy of capital share and resource depletion rate

In this part of the Appendix we derive the asymptotic constancy of the capital share ϵ, and the resource depletion rate $u = R/S$, in the general case of $\sigma \neq 1$. In the main text we explained that the economy at hand is always in transition while it reaches a balanced growth path at the limit when resources get asymptotically depleted and pollution reaches its steady state value. The transversality condition (5.46) implies that $\widehat{\lambda_{Kt} K_t} - \rho < 0$ while (5.41) with (5.39) can be rewritten as $\widehat{\lambda_{Kt} K_t} = -B\epsilon_t + \rho$. We combine these two conditions to get that $\lim_{t\to\infty} \epsilon_t > 0$. From (3.5), asymptotic constancy of $\hat{K}_t$ implies $\lim_{t\to\infty} \hat{\epsilon}_t \leq 0$. Since ϵ_t is strictly positive, the last inequality implies that $\lim_{t\to\infty} \hat{\epsilon}_t = 0$. From the transversality condition for the stock of resources, (5.45), we get that $\hat{\lambda}_{St} + \hat{S}_t - \rho < 0$. We substitute $\hat{\lambda}_{St} = \rho$ and $\hat{S}_t = -u_t$ to get $\lim_{t\to\infty} u_t > 0$. We then log-differentiate the production function for the consumption good, (3.3), with constant ϵ at the limit. Asymptotic constancy of $\hat{C}_t$ then demands that $\lim_{t\to\infty} \hat{u}_t \leq 0$. The last two conditions indicate that $\lim_{t\to\infty} \hat{u}_t = 0$, i.e. u asymptotically constant and positive, i.e. $g_{Rt} \equiv -u_t$ asymptotically constant and negative. The upper bound $\epsilon_t, u_t < 1$ follows from the essentiality of the resource and capital in the production function.

5.2.4 The Social Cost of Carbon

We defined as $X_t = -\phi\kappa\lambda_{Zt}/\lambda_{Ct}$ the marginal externality damage from burning an additional unit of polluting non-renewable resource. We will now prove that this is equivalent to expression (3.8). From (5.36), it follows that $P_\nu \geq P_s e^{-\theta(\nu - s)}$, for each $\nu \geq s$. We combine the previous inequality with the transversality condition (5.47) to get that $0 = \lim_{\nu\to\infty} \lambda_{P\nu} P_\nu e^{-\rho\nu} \geq \lim_{\nu\to\infty} \lambda_{P\nu} P_s e^{-\theta(\nu-s)} e^{-\rho\nu}$ or that

$$\lim_{\nu\to\infty} \lambda_{P\nu} e^{-(\rho+\theta)(\nu-s)} = 0, \qquad \text{for all} \qquad \nu \geq s. \tag{5.49}$$

Following the same procedure for the transversality condition (5.48) we get

$$\lim_{s\to\infty} \lambda_{Zs} e^{-(\rho+\kappa)(s-t)} = 0, \qquad \text{for all} \qquad s \geq t. \tag{5.50}$$

We multiply equation (5.43) with $e^{-(\rho+\theta)(\nu-s)}$ to get that $\dot{\lambda}_{P\nu} e^{-(\rho+\theta)(\nu-s)} - (\rho + \theta)\lambda_{P\nu} e^{-(\rho+\theta)(\nu-s)} = \eta D'(P_v)\lambda_{K\nu} K_\nu e^{-(\rho+\theta)(\nu-s)}$, i.e. $d\left[\lambda_\nu e^{-(\rho+\theta)(\nu-s)}\right]/d\nu = \eta D'(P_v)\lambda_{K\nu} K_\nu e^{-(\rho+\theta)(\nu-s)}$. Using (5.49) we can then calculate the definite integral from $\nu = s$ to $\nu \to \infty$ as

$$-\lambda_{Ps} = \int_s^\infty \eta D'(P_v)\lambda_{K\nu} K_\nu e^{-(\rho+\theta)(\nu-s)} d\nu, \tag{5.51}$$

while the same procedure for (5.44) gives

$$\lambda_{Zt} = \int_t^\infty \lambda_{Ps} e^{-(\rho+\kappa)(s-t)} ds. \tag{5.52}$$

Substituting λ_{Pt} from (5.51) into (5.52) and using (5.38) we get that

$$X_t = -\kappa\phi \frac{\lambda_{Zt}}{\lambda_{Ct}} = \frac{\kappa\phi}{\lambda_{Ct}} \int_t^\infty \left(\int_s^\infty \eta D'(P_v)\lambda_{K\nu} K_\nu e^{-(\rho+\theta)(\nu-s)} d\nu \right) e^{-(\rho+\kappa)(s-t)} ds. \tag{5.53}$$

Using (5.38) and (5.39) we get expression (3.8). If $\sigma = 1$, X_t rewrites as in (3.9), all along the optimal path. If $\sigma \neq 1$, on the asymptotic BGP, due to constancy of the ϵ share, it holds, by combining (5.41) with (5.39), that $\lim_{t\to\infty} \widehat{\lambda_{Ct} C_t} = \lim_{t\to\infty} \widehat{\lambda_{Kt} K_t} = -B\epsilon_\infty + \rho$, constant. Accordingly, the double integral in (5.53) gives at the limit $\frac{\chi\eta}{(B\epsilon_\infty+\theta)(B\epsilon_\infty+\kappa)} \lambda_{Kt} K_t$, and with (5.39), (5.53) can be written as

$$\lim_{t\to\infty} X_t/C_t = \kappa \frac{\alpha\eta\phi\chi}{B\epsilon_\infty(B\epsilon_\infty + \theta)(B\epsilon_\infty + \kappa)}. \tag{5.54}$$

In Appendix 5.2.7 we will calculate the steady state value $\epsilon_\infty = (B\sigma)^{-1}(\rho + \alpha(\sigma - 1)(B - \eta(\delta + \chi P_\infty))$ in the general case of $\sigma \neq 1$. Substituting the result in (5.54) leads to equation (3.23) in the main text.

5.2.5 Decentralized equilibrium with log-utility

For ease of exposition we define $\psi \equiv p_{Rt}/(p_{Rt}+\tau_t)$, the fraction of the producers' price in the total price for the non-renewable resource. Log-differentiating this expression gives $\hat{\psi}_t = (1-\psi)(\hat{p}_{Rt} - \hat{\tau}_t)$, where we define $\hat{V}_t = g_{Vt} \equiv \dot{V}_t/V_t$ the growth rate of variable V_t. The equations that characterize the decentralized economy can be found by log-differentiating the production function (3.3) with $Y_t = C_t$, the FOC (3.10) for the capital share and resource demand, together with the aggregate version of the Keynes-Ramsey rule, (3.14), the Hotelling rule, (3.15), the no-arbitrage condition, (3.16), and the aggregate capital accumulation, (3.5). Solving the occuring system in $g_C, g_K, g_R, g_\epsilon, g_\psi, g_{pK}, g_{pR}, r$ in the case of $\sigma = 1$ leads to the following dynamic equation for ϵ:

$$\dot{\epsilon}_t = B\epsilon_t^2 - \rho\epsilon_t \tag{5.55}$$

with a solution given by $\epsilon_t = \left(\frac{B}{\rho}(1-e^{\rho t}) + \frac{e^{\rho t}}{\epsilon_0}\right)^{-1}$. Combining the demand for capital in (3.10) and the aggregate version of the transversality condition (3.17) for capital pins down the initial level of the capital shares $\epsilon_0 = \rho/B$. Substituting this back to the solution we get that $\epsilon_t = \bar{\epsilon} = \rho/B$ for every t.

5.2.6 Dynamics of the optimal per-unit tax

To see why any term in the optimal per-unit tax that grows with the interest rate has no effect on the extracting behavior of the economy proceed as follows. Given Assumptions 1 and 2, apply the optimal tax on the FOC for the non-renewable resource, (3.10), with $C_t = Y_t$ in equilibrium: $R_t^o = (1-\alpha)\left(\frac{p_{Rt}}{C_t} + \frac{\tau_t^o}{C_t}\right)^{-1}$; R_t^o is the optimal path of resource extraction. Substituting $p_{Rt} = p_{R0}e^{\int_0^t r_s ds}$, from (3.15), and $C_t = C_0 e^{\int_0^t (r_s-\rho)ds}$, from (3.14), gives $R_t^o = (1-\alpha)\left(\frac{p_{R0}}{C_0}e^{\rho t} + \frac{\tau_t^o}{C_t}\right)^{-1}$. Now consider a different tax $\tau_t^o + \Delta e^{\int_0^t r_s ds}$ with $\Delta > -p_{R0}$. It is straightforward to verify that in this case $R_t^o = (1-\alpha)\left(\frac{p_{R0}+\Delta}{C_0}e^{\rho t} + \frac{\tau_t^o}{C_t}\right)^{-1}$. Since τ_t^o/C_t is constant, and the resource is essential, we can use the feasibility constraint $\int_0^\infty R_t dt = S_0$

to calculate in both cases the same optimal resource extraction path as $R_t^o = (1-\alpha)\left[\frac{\tau_t^o}{C_t}\left(1+e^{\rho t}\left(e^{\frac{S_0\rho}{1-\alpha}\frac{\tau_t^o}{C_t}}-1\right)^{-1}\right)\right]^{-1}$.

5.2.7 Social optimum with non-logarithmic utility

This part of the Appendix provides the dynamic system used in the simulation for section 3.6, i.e. we treat the asymptotic balanced growth path and stability in the general case of $\sigma \neq 1$. It will be convenient to modify the dynamic system of the social planner in variables that converge to a constant at the limit. In Appendix 5.2.3 we proved asymptotic constancy of ϵ, and $u = R/S$. Moreover, we showed that $\tilde{\tau}_t^o = \frac{\tau_t^o}{C_t} = -\phi\kappa\frac{\lambda_{Zt}}{\lambda_{Ct}C_t}$ reaches also a constant value at the limit. From (5.51) and (5.39) with $\lim_{t\to\infty}\widehat{\lambda_{Kt}K_t} = -B\epsilon_\infty + \rho$ same holds for $\tilde{\gamma}_t = \frac{\lambda_{Pt}}{\lambda_{Ct}C_t}$. Furthermore, we define, as in Appendix 5.2.5, $\psi_t \equiv p_{Rt}/(p_{Rt} + \tau_t^o) = (\lambda_{St}/\lambda_{Ct})/(\lambda_{St}/\lambda_{Ct} - \kappa\phi\lambda_{Zt}/\lambda_{Ct})$, the fraction of the producers' price in the total price paid by consumers. It follows from the asymptotic constancy of τ_t^o/C_t, the Hotelling rule, $\hat{p}_{Rt} = r_t$, and the Keynes-Ramsey rule, $\sigma\hat{C}_t = r_t - \rho$, that the term τ_t^o/p_{Rt} grows at $-((\sigma-1)r_t+\rho)/\sigma < 0$, for $\sigma \geq 1$, which we conventionally assume, so that $\lim_{t\to\infty}\psi_t = 1$. To get the dynamic system in $\{\epsilon_t, u_t, \tilde{\tau}_t, \tilde{\gamma}_t, \psi_t, S_t, P_t, Z_t\}$ we proceed as follows.[1] By log-differentiating (3.3) with $u_t = R_t/S_t$, using (3.5) we get

$$\hat{C}_t - \alpha(\hat{\epsilon}_t + B(1-\epsilon_t) - \eta(\delta + \chi P_t)) - (1-\alpha)(\hat{u}_t - u_t) = 0. \tag{5.56}$$

With our definitions, equation (5.40) can be written as $(1-\alpha)C_t/(u_tS_t) = p_{Rt} + \tau_t^o$. We log-differentiate this expression with $\hat{p}_{Rt} = \hat{\lambda}_{St} - \hat{\lambda}_{Ct} = \rho + \sigma\hat{C}_t$ from (5.38), the Hotelling rule $\hat{\lambda}_S = \rho$, and $\tilde{\tau}_t = \tau_t^o/C_t$, to get

$$\hat{u}_t - u_t + \psi_t(\rho + (\sigma-1)\hat{C}_t) + (1-\psi_t)\hat{\tilde{\tau}}_t = 0. \tag{5.57}$$

[1] For convenience we will drop in this section the "^{o}" upper script, having however in mind that all results refer to the social optimum solution.

Furthermore, we log-differentiate the definition for ψ_t which gives

$$\hat{\psi}_t - (1-\psi_t)(\rho + (\sigma-1)\hat{C}_t - \hat{\tilde{\tau}}_t) = 0. \tag{5.58}$$

From (5.38), (5.39) and (5.41) we get

$$\hat{\epsilon}_t + (\sigma-1)\hat{C}_t + \rho - \epsilon_t B = 0. \tag{5.59}$$

Finally, we substitute the growth rate of the shadow prices in the log-differentiated version of the definitions for $\tilde{\tau}_t = \frac{\tau_t^o}{C_t} = -\kappa\phi\frac{\lambda_{Zt}}{\lambda_{Ct}C_t}$ and $\tilde{\gamma}_t = \frac{\lambda_{Pt}}{\lambda_{Ct}C_t}$ from (5.38), (5.43), and (5.44) to get

$$\hat{\tilde{\tau}}_t - (\sigma-1)\hat{C}_t - \kappa\left(1+\phi\frac{\tilde{\gamma}_t}{\tilde{\tau}_t}\right) - \rho = 0, \tag{5.60}$$

$$\hat{\tilde{\gamma}}_t - (\sigma-1)\hat{C}_t - \frac{\alpha\eta\chi}{B\epsilon_t\,\tilde{\gamma}_t} - \theta - \rho = 0. \tag{5.61}$$

We then combine equations (5.56)-(5.61) to get the relevant dynamic system in $\{\epsilon_t, u_t, \tilde{\tau}_t, \tilde{\gamma}_t, \psi_t, S_t, P_t, Z_t\}$, as

$$\dot{\epsilon}_t = \epsilon_t\left(\kappa\frac{(\sigma-1)(1-\alpha)(1-\psi_t)}{\sigma}\left(1+\phi\frac{\tilde{\gamma}_t}{\tilde{\tau}_t}\right) - \frac{(\sigma-1)\alpha\Theta_t+\rho}{\sigma} + B\epsilon_t\right), \tag{5.62}$$

$$\dot{u}_t = u_t\left(-\frac{(\sigma-1)\alpha\Theta_t+\rho}{\sigma} - \kappa\frac{(1+\alpha(\sigma-1))(1-\psi_t)}{\sigma}\left(1+\phi\frac{\tilde{\gamma}_t}{\tilde{\tau}_t}\right) + u_t\right), \tag{5.63}$$

$$\dot{\tilde{\tau}}_t = \tilde{\tau}_t\left(\kappa\frac{(1+\alpha(\sigma-1))(1-\psi_t)+\sigma\psi_t}{\sigma}\left(1+\phi\frac{\tilde{\gamma}_t}{\tilde{\tau}_t}\right) + \frac{(\sigma-1)\alpha\Theta_t+\rho}{\sigma}\right), \tag{5.64}$$

$$\dot{\tilde{\gamma}}_t = \tilde{\gamma}_t\left(-\kappa\frac{(\sigma-1)(1-\alpha)(1-\psi_t)}{\sigma}\left(1+\phi\frac{\tilde{\gamma}_t}{\tilde{\tau}_t}\right) + \frac{\alpha\eta\chi}{B\epsilon_t\,\tilde{\gamma}_t} + \frac{(\sigma-1)\alpha\Theta_t+\rho}{\sigma} + \theta\right), \tag{5.65}$$

$$\dot{\psi}_t = \psi_t(\psi_t-1)\kappa\left(1+\phi\frac{\tilde{\gamma}_t}{\tilde{\tau}_t}\right), \tag{5.66}$$

along with (3.1) and (3.6), with $\Theta_t = B - \eta(\delta + \chi P_t)$, and $R_t = u_t S_t$. The steady state values read

$$\epsilon_\infty = \frac{\rho + \alpha(\sigma - 1)(B - \eta(\delta + \chi P_\infty))}{B\sigma}, \tag{5.67}$$

$$u_\infty = B\epsilon_\infty, \tag{5.68}$$

$$\tilde{\tau}_\infty = \kappa \frac{\alpha\eta\phi\chi}{B\epsilon_\infty(B\epsilon_\infty + \theta)(B\epsilon_\infty + \kappa)}, \tag{5.69}$$

$$\tilde{\gamma}_\infty = -\frac{\alpha\eta\chi}{B\epsilon_\infty(B\epsilon_\infty + \theta)}, \tag{5.70}$$

$$\psi_\infty = 1, \tag{5.71}$$

$$S_\infty = 0, \tag{5.72}$$

$$P_\infty = P_0, \text{ if } \theta > 0 \text{ and } P_0 + \phi S_0, \text{ if } \theta = 0, \tag{5.73}$$

$$Z_\infty = 0. \tag{5.74}$$

The eigenvalues of the jacobian matrix of the corresponding system, calculated at the steady state values, are $\{-\theta, -\kappa, -\frac{\rho+\alpha(\sigma-1)\Theta_\infty}{\sigma}, -\frac{\rho+\alpha(\sigma-1)\Theta_\infty}{\sigma}, \frac{\rho+\alpha(\sigma-1)\Theta_\infty}{\sigma}, \frac{\rho+\alpha(\sigma-1)\Theta_\infty}{\sigma}, \frac{\rho+\theta\sigma+\alpha(\sigma-1)\Theta_\infty}{\sigma}, \frac{\rho+\kappa\sigma+\alpha(\sigma-1)\Theta_\infty}{\sigma}\}$, with $\Theta_\infty = B - \eta(\delta + \chi P_\infty)$, and $P_\infty = P_0 + \phi S_0$, if $\theta = 0$, or $\bar{P} = P_0$, if $\theta > 0$, i.e. four negative and four positive eigenvalues, implying a saddle-path stability around the steady state. The growth rate of consumption can be calculated by (5.56) to be

$$g_{Ct} = \frac{\alpha\Theta_t - \rho}{\sigma} - \frac{\kappa(1-\alpha)(1-\psi_t)}{\sigma}\left(1 + \phi\frac{\tilde{\gamma}_t}{\tilde{\tau}_t}\right), \tag{5.75}$$

with a steady state value of

$$g_{C\infty} = \frac{\alpha(B - \eta(\delta + \chi P\infty)) - \rho}{\sigma}. \tag{5.76}$$

Linearized Version of the Model for $\sigma \neq 1$

In order to simulate the model we use the standard linearization technique: the linearized version of our autonomous dynamic system in $\mathbf{x}_t = \{\epsilon_t, u_t, \tilde{\tau}_t, \tilde{\gamma}_t, \psi_t, S_t, P_t, Z_t\}^\top$ can be obtained by using the jacobian matrix $\mathbf{J}$ evaluated at the steady states presented above as $d(\mathbf{x}_t - \mathbf{x}_\infty)/dt \approx \mathbf{J}(\mathbf{x}_t - \mathbf{x}_\infty)$, with $\mathbf{x}_\infty = \{\epsilon_\infty, u_\infty, \tilde{\tau}_\infty, \tilde{\gamma}_\infty, \psi_\infty, S_\infty, P_\infty, Z_\infty\}^\top$, which allows for an easy solution of the system of linear homogenous equations. For the simulation we use as initial conditions $\{\psi_0 = 0.65, S_0 = 6000\text{GtC}, P_0 = 830\text{GtC}, Z_0 = 0\}$, while we calculate the initial level of the control variables $\{\epsilon_0, u_0, \tau_0, \gamma_0\}$ such that the constants of integration associated with the unstable roots (positive eigenvalues) are zero. The parameters chosen are $\{\rho = 0.015, \sigma = 1.5, \alpha = 0.9, \theta = 0, \delta = 0.05, B = 0.106, \chi = 1.7 \times 10^6\$/\text{GtC}, \phi = 1, \eta = 1, \kappa_{\text{low}} = 0.02, \kappa_{\text{high}} = 0.04\}$. Below we justify our choices for the numerical exercise.

Choice of initial conditions and parameters

We choose 2010 to be our $t = 0$. An approximation for ψ_0, the share of the before tax price to the total price paid by consumers, can be taken from the IEA Monthly Oil Statistics, IEA (2015), to be around 0.65 as an average for the period 2006-2015. $S_0 = 6000\text{GtC}$ follows estimates from the 2010 version of the DICE model. $P_0 = 830GtC$ was retrieved by data from the European Environmental Agency.[2] $Z_0 = 0$ is chosen according to our discussion in Appendix A. The values of ρ, σ and δ are standard in the literature of endogenous growth. We normalize $\phi = 1$, so that a unit of resource use equals a unit of emissions; we also set $\eta = 1$ in the numerical exercise. In this model real GDP equals to $C_t + p_{It}I_t$. Worldwide gross capital formation, $p_{It}I_t/GDP_t$, is on average 0.24 for the period 1960-2014, World Bank Indicators, 2015. Accordingly $C_t/GDP_t = 0.76$. Energy expenditure as share of GDP in the US for the period 1949-2011 is in the range of $0.04 - 0.1$, EIA (2015). We choose then a value of 0.08. Using now the FOC (3.10) for energy we can calculate $\alpha = 1 - \frac{(p_{Rt}+\phi\tau_t)R_t/GDP_t}{C_t/GDP_t} \approx 0.9$. The value of natural disasters reported in the period 2005-2015 amounts on average to 139×10^9 \$/year (EM-DAT The International Disasters Database 2015). Using the value for the stock of capital from the 2010 version of the DICE model (DICE2010) and $P_0 = 830\text{GtC}$, we get that $\chi = 1.7 \times 10^6$ \$/GtC. B was chosen so that the initial level of the interest rate is about 5% (as in DICE2010) and that it satisfies the condition

[2] http://www.eea.europa.eu

$\alpha(B - \eta(\delta + \chi(P_0 + \phi S_0)) > \rho$, from (5.76), equivalent to the one assumed in section 4.2. Parameter κ is the reciprocal of the mean time lag. We choose a low value to reflect a time lag of 50 years, and a high value to reflect a time lag of 25 years.

5.3 Appendix for Chapter 4

5.3.1 Decentralized equilibrium

From (4.3) using $w = (1-\beta)Q$, $Y = QL_Y$ and $g = \dot{Y}/Y$, we get $\hat{\lambda}_j = g - \hat{L}_Y - \omega\hat{q}_{jt} - (1-\omega)\hat{K}_t$. Dividing (4.4) by λ_j, substituting $r = g + \rho$ from the Keynes-Ramsey rule, $w = (1-\beta)Q$, and assuming symmetry (i.e. $L_{Sj} = L_S$ and $q_j = Q$), the growth rate of non-scientific labor employment in the final good sector follows as in (4.5).

5.3.2 Social Optimum

The associated Hamiltonian of the social planner reads

$$H_t = \ln(Q_t L_{Yt}) + \lambda_t \eta Q_t^{\omega} K_t^{1-\omega}(L - L_{Yt}) + \mu_t \kappa (Q_t - K_t). \tag{5.77}$$

The first order conditions with respect to L_Y, Q and K are respectively

$$L_{Yt}^{-1} = \eta(\lambda_t Q_t)\left(\frac{K_t}{Q_t}\right)^{1-\omega}, \tag{5.78}$$

$$Q_t^{-1} + \lambda_t \omega \eta \left(\frac{K_t}{Q_t}\right)^{1-\omega}(L - L_{Yt}) + \mu_t \kappa = \rho\lambda_t - \dot{\lambda}_t, \tag{5.79}$$

$$\lambda_t(1-\omega)\eta\left(\frac{K_t}{Q_t}\right)^{-\omega}(L - L_{Yt}) - \mu_t\kappa = \rho\mu_t - \dot{\mu}_t. \tag{5.80}$$

Variables λ and μ are the shadow prices for the two dynamic equations. By substituting L_Y from (5.78) to the other two equations, after dividing (5.79) with λ and (5.80) with μ, and using (4.7) and (4.8), we have a system of differential equations in the $\{Q, K, \lambda, \mu\}$-space. We can then redefine the variables $\chi = \lambda Q$, $\xi = \mu K$ and $\gamma = K/Q$ to get the following autonomous system of dynamic equations for the social planner (in growth rates)

$$\hat{\chi}_t = \rho - \frac{1}{\chi_t}\left(1 + (1-\omega) + \kappa\frac{\xi_t}{\gamma_t}\right) + (1-\omega)\eta L \gamma_t^{1-\omega}, \tag{5.81}$$

$$\hat{\xi}_t = \rho + \kappa + \frac{1-\omega}{\xi_t}(1 - \chi_t \eta L \gamma_t^{1-\omega}) + \kappa\left(\frac{1}{\gamma_t} - 1\right), \tag{5.82}$$

$$\hat{\gamma}_t = \kappa\left(\frac{1}{\gamma_t} - 1\right) - \eta L \gamma_t^{1-\omega} + \frac{1}{\chi_t}. \tag{5.83}$$

Furthermore the transversality conditions $\lim_{t\to\infty} \chi_t e^{-\rho t} = 0$ and $\lim_{t\to\infty} \xi_t e^{-\rho t} = 0$ apply. In the steady state $\hat{\gamma}_t = 0$. so that $\hat{Q} = \hat{K} = g$. It follows as a necessary condition from (5.81)-(5.83) that $\hat{\chi}_t = 0$ and $\hat{\xi}_t = 0$ as well. Solving (5.81) and (5.82) for χ in the steady state and substituting the solution in (5.83) while noting that $g = \kappa(1/\gamma - 1)$ from (4.11) gives equation (4.13) of the main text.

5.3.3 Comparative statics

Suppose that using (4.11), (4.12) and (4.13) the steady state level of the vector $\mathbf{z}$ of the endogenous variables g^*, γ^*, ϕ^* in the first best allocation is given by the system of implicit functions $\mathbf{f}(\mathbf{z}, \mathbf{a}) = 0$, with vector $\mathbf{a}$ containing the relevant parameters κ and ω, as defined in the main text. Then, to a first approximation, sufficiently small changes in the exogenous parameters $d\mathbf{a}$ will result in changes in the endogenous variables $d\mathbf{z}$ according to

$$d\mathbf{z} = -\mathbf{J_z}^{-1}\mathbf{J_a} d\mathbf{a} = 0, \tag{5.84}$$

with $\mathbf{J_z}$ the 3x3 matrix of partial derivatives of the $\mathbf{f}$ functions w.r.t. the elements of the vector $\mathbf{z}$ and $\mathbf{J_a}$ the 3x2 matrix of partial derivatives of $\mathbf{f}$ w.r.t. the elements of $\mathbf{a}$, both evaluated at the optimal steady state values g^*, γ^*, ϕ^* for the specific parameters κ and ω. We can then get the static effect of each of the exogenous parameters on each of the endogenous variables by having the relevant parameter varying and the other constant.

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