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The Interaction Between Structural Transformation and the Environment: A Two-Sector General Equilibrium Analysis

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Abstract: Economic development is accompanied by sectoral reallocation from the goods (agriculture and industry) sector to the service sector. This structural change, in turn, can explain the emission intensity patterns in most regions of the world. Thus, this thesis develops a two-sector general equilibrium model taking the circular relationship between structural transformation and emissions into account. One direction of this relationship consists of the composition effect which captures the effect of a decreasing goods share on emissions. The other direction covers environmental policies such as exogenous CO_2 taxes or Pigouvian taxes. The latter taxes factor in the consequences of climate change by taking the accumulating character of CO_2 emissions into account. I find that the introduction of environmental policies leads to a considerable acceleration of structural transformation with lower emissions and higher per period utility than laissez-faire policies. Moreover, policies that are targeted against climate change, i.e. accounting for the accumulation of emissions, are even more stringent. The model is calibrated to the USA in 1950 which had a similar structural composition as many developing countries today. This implies that rigorous policies against climate change could have significant effects on developing countries' structural change.

Keywords: Structural Transformation, Composition Effect, Emissions, Climate Change, Economic Growth

JEL: H23, O13, O14, O41, O44

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1 Introduction

Within less than one and a half years, Greta Thunberg protesting on her own for political actions against climate change started the environmental movement *Fridays for Future* (FFF) which mobilized large demonstrations worldwide. The reason for the popularity of the topic and thus for the momentum of organizations like FFF, *Scientists for Future* or *Extinction Rebellion* are scientific publications such as more than 11,000 scientists around the world declaring that "clearly and unequivocally [...] planet Earth is facing a climate emergency" (Ripple et al. (2019)). To some extent, humans are perpetrators and victims of climate change. In fact, human influence on climate change is significant and there are negative effects of climate change on (not very far in the) future lives.

As a consequence of that, a wide range of policies has been proposed. The heterogeneity of these policy proposals stems from, among other things, their attitude towards the economy and specifically towards economic growth. On a more radical ecological side, there have been demands to stop economic growth (e.g. Jackson (2017)) or to pursue even *de-growth* since economic growth would inevitably lead to more and more severe environmental degradation. On the other side, though clearly not on the most extreme end of this side, are proponents of the so-called *Environmental Kuznets Curve*. Their arguments generally assert that the phase of increased pollution is only temporary and that, after some high level of income is achieved, pollution begins to decrease again. In other words, policies aimed at economic growth are environmental policies in the long-run: *grow now, clean later*.

Not surprisingly, economic scholars started to investigate the multilateral relationships between human behavior, the economy, and the environment. Clearly, a capstone in this context was William Nordhaus winning *The Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel* 2018 for his research on the effects of economic development on climate change and vice versa. Central to his and other environmental economists' work are so-called *Integrated Assessment Models* (IAM) which combine the neoclassical one-sector growth model with an environmental feedback. Even though the IAM are used to investigate the economy-environment cycle in the very long-run (decades or even centuries), the economic component disregards structural transformation. This omission, however, is problematic since, as an economy develops, the sectoral focus shifts from agriculture to industry to services. As a consequence, this structural change implies sizable differences in emissions while the overall economy experiences economic growth. The standard IAM fail to capture this variation which in turn also affect the economic policy analyses in this context.

The aim of this this thesis is to fill this gap in the literature by explicitly taking the interactions between structural change and the environment into account. For that reason, I develop a model of modern economic growth and the environment, capturing the effect of structural change on pollution and its influence on well-being. Moreover, my model allows for the introduction of environmental policies such as Pigouvian taxes. Thus, the contribution of this thesis is twofold: Investigating the effect of structural change on emissions and analyzing the effects of environmental policies, such as Pigouvian or exogenous taxes, on structural change. Figure 1 depicts a schematic overview of these research questions which aim to capture the circular causality from structural transformation to emissions, i.e. the so-called *composition effect*, and via environmental policies back to the economic structure.

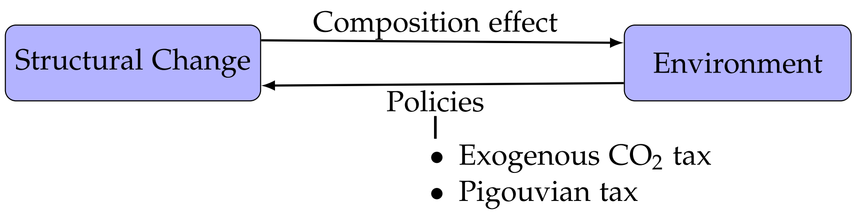

Figure 1: Schematic research questions

In the scope of this thesis, there are three main results. First, I find that the composition effect plays a considerable role in the explanation of emissions. Second, environmental policies such as carbon dioxide (CO_2) taxes accelerate structural transformation. Third, environmental policies which account for the accumulating aspect of CO_2 emissions for climate change, lead to an even further decrease in the labor share of the *goods sector*[1] than under a static setting.

The rest of this thesis is organized as follows: Section 2 presents the background, where 2.1 provides some empirical evidence and 2.2 presents the underlying research about structural change and environmental economics. Section 3 begins with an overview over the model and its components in 3.1. Thereafter, section 3.2 derives the equilibrium allocations. Then, 3.3 describes the baseline model and its implications and section 3.4 presents the baseline parameter calibration. Section 3.5 deals with the effects of environmental policies, where 3.5.1 explains the effect of exogenous taxes on structural change and ultimately on emissions, and 3.5.2 describes the structural change and emissions' setting under a planner's optimum. Finally section 4 discusses some short-comings of this thesis and section 5 concludes.

[1]The goods sector is the aggregate of the agricultural and industry sectors. In Definition 1 I describe it in more details.

2 Background

2.1 Empirical Motivation

Originally, the analysis of structural change focused on the transition from a mainly agricultural society to a non-agricultural (mainly industrial) economy. Historically and also from the point of development of the least developed countries, this is an important perspective. The canonical framework then implies that countries increase their manufacturing or industry share as they grow richer until this peaks and begins to fall again. During this process, development is accompanied by an increasing service sector such that the service sector dominates over the other two sectors in the long-run. The longevity of this structural transformation should be emphasized here, as the whole process can be observed over the last 200 years. Since the second half of the twentieth century, the movement out of agriculture has been advanced and, furthermore, manufacturing appears to have passed its peak. As a consequence of this later stage of development, modern structural transformation is characterized by an increasing service sector and a decreasing agriculture and industry sectors. The analysis of modern structural change (Definition 2) should take this into account, and Definition 1 is a straightforward implication of it:

Definition 1. *The goods sector is defined as the composite of the agricultural and manufacturing sectors. In terms of the United Nations (2008) "International Standard Industrial Classification of All Economic Activities" (ISIC) classification, this corresponds to section A through F. Complementary to the goods sector is the service sector that constitutes ISIC sections G through P.*

Definition 2. *Modern structural transformation or synonymously structural change is defined as the reallocation of labor from the goods sector to the service sector.*

Figure 2 shows the structural transformation over the last 70 years.[2] Specifically, it shows the median labor shares and median value added (VA) shares of the goods and service sector grouped by geographical regions. Abstracting for one moment from the levels and focusing on the employment shares, it is evident that the goods sector decreases while the service sector uniformly rises. The identical finding also holds for the value added shares, with the exception of Latin America. Finally, there are considerable level heterogeneities between different regions; for example, Europe reaches North America's 1960 services share level only in the mid-eighties. An implication of these regional differences, however, is that the last period's shares in Asia, Latin America, and roughly Sub-Saharan Africa are very similar to the first period's shares in North America. Empirical Fact 1 summarizes.

[2] Note that these graphs are not based on all countries within the specific geographic group but only the countries that are covered in the dataset by Timmer, G. J. d. Vries, and K. d. Vries (2015). Moreover, due to data scarcity, I ignore the entire Middle East and North Africa.

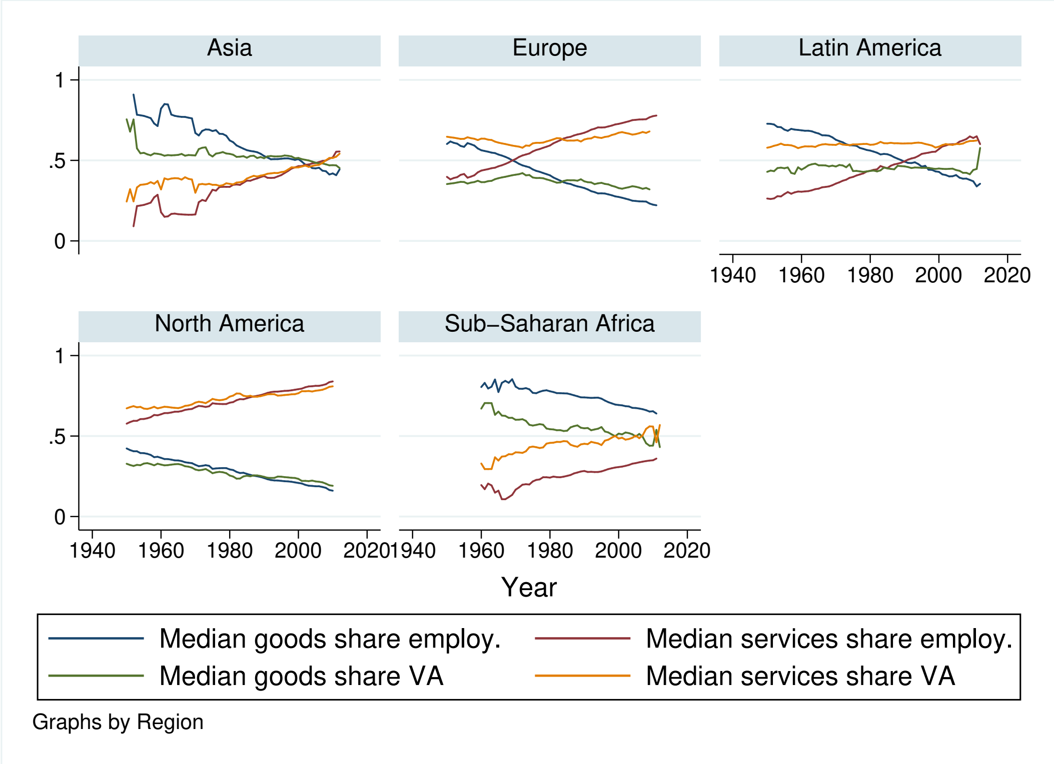

Figure 2: Employment shares and value added shares over time

Source: Timmer, G. J. d. Vries, and K. d. Vries (2015). Own calculations.

Empirical Fact 1. *There is a uniformly rising service sector share and a uniformly decreasing goods sector share over all regions in the world. This holds for employment and value added shares. Moreover, Asia, Latin America, and Sub-Saharan Africa have goods and services shares in 2010 that approximately correspond to North America's respective shares in 1950.*

In contrast to the relative point of view, a look at the absolute levels shows that there is an increase in absolute goods: Figure 3 depicts the amount of value added in constant prices of goods over the past 70 years, split by geographic regions. Clearly, there are considerable level differences, but the main idea is that the qualitative behavior is very similar across all of these regions: an overall steep (linear or partially exponential) increase in value added of the goods sector implying a multiplied real output over this period of time. Many economists and politicians would claim that this stems from overall economic growth and thus is symptomatic for economic development; in essence, a higher production in agriculture and industry implies a higher consumption of these goods, which in the end is associated with higher well-being of the people. Empirical Fact 2 summarizes the regularity:

Empirical Fact 2. *The absolute level of goods production increases over all regions in the world.*

From an environmental perspective, CO_2 emissions are of interest since they play a sizable role for climate change. Figure 4 shows the development of CO_2 emissions in kilotons over time, again grouped by

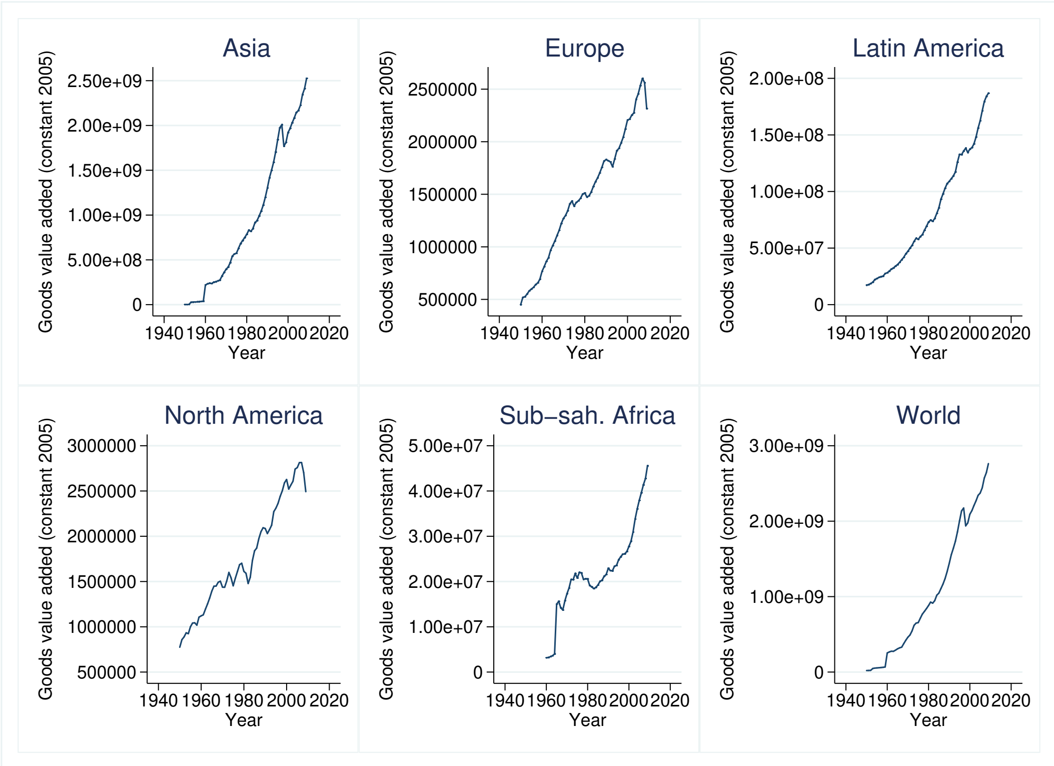

Figure 3: Goods (total) VA over time

Source: Timmer, G. J. d. Vries, and K. d. Vries (2015). Own calculations.

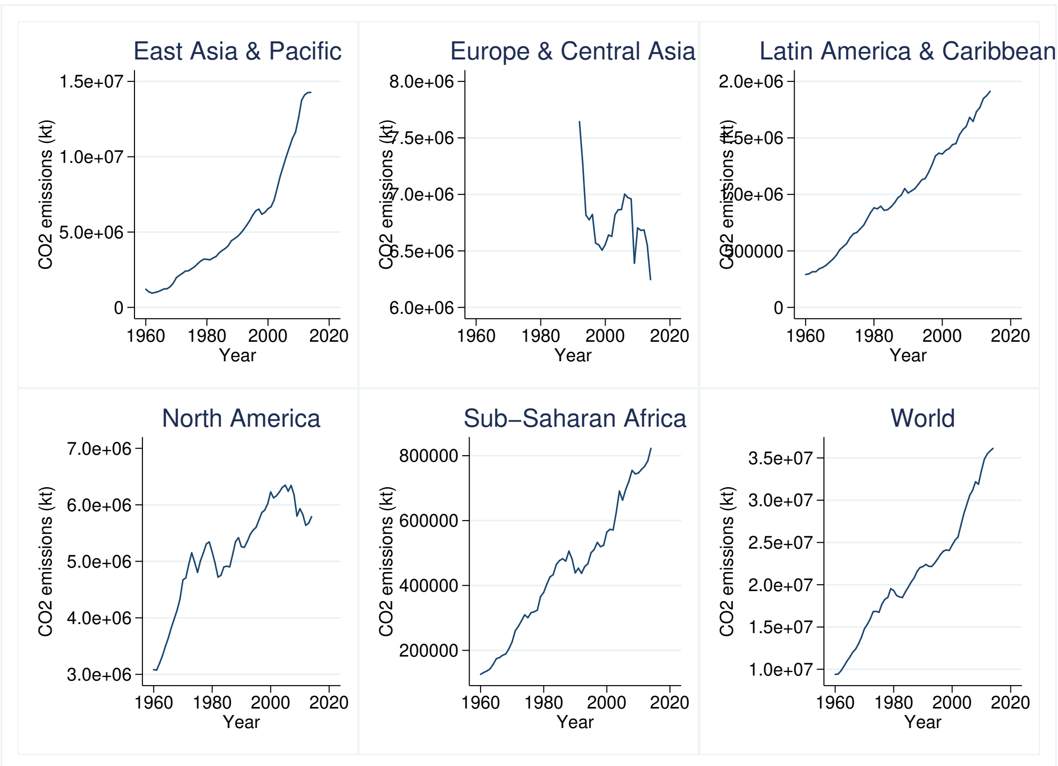

Figure 4: Total CO2 over time

Source: World Bank (2019). Own calculations.

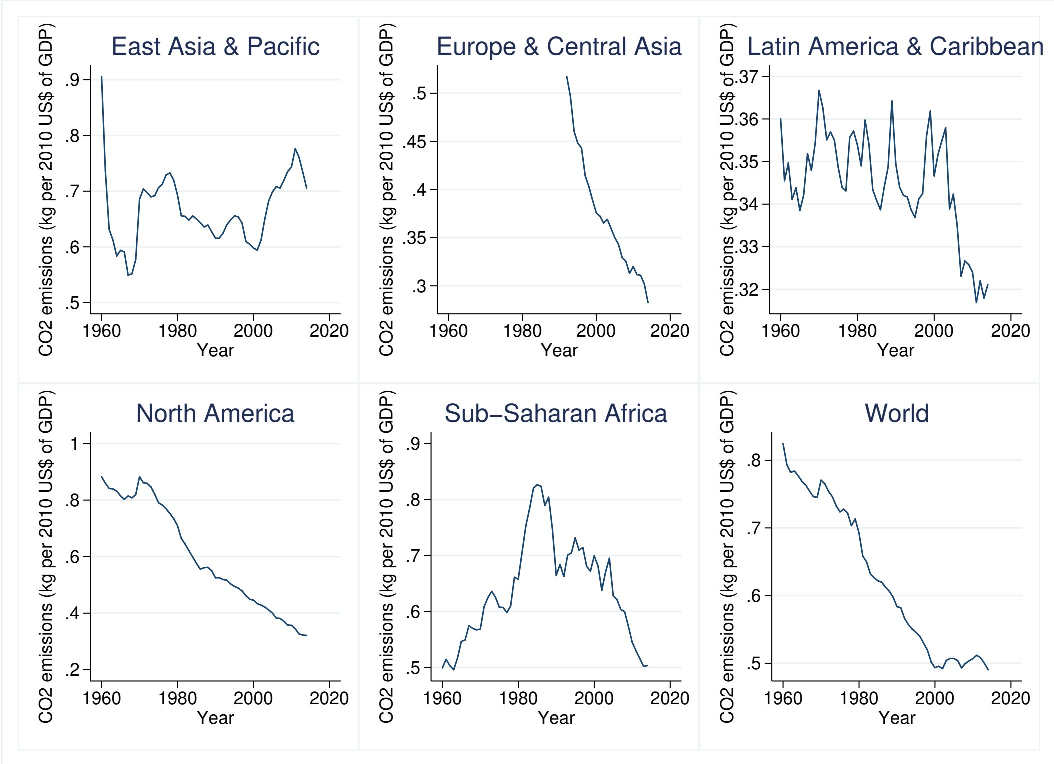

Figure 5: CO2 emissions per GDP (2010 US$)

Source: World Bank (2019). Own calculations.

geographical regions. Ignoring the scale difference, East Asia & Pacific, Latin America & Caribbean and Sub-Saharan Africa all exhibit increasing emissions over time. In a possibly more concave pattern, North America's total CO_2 emissions also increase, possibly levelling off around 2000. The only outlier is Europe & Central Asia, which shows falling emissions. For this region, however, data before 1990 is missing. All in all, with the exception of Europe & Central Asia, Empirical Fact 3 summarizes:

Empirical Fact 3. *Total CO_2 emissions rise over time.*

Considering the considerable heterogeneities in the levels of structural composition and the levels of absolute production, absolute levels of CO_2 emissions might be misleading. Thus, looking at CO_2 emissions per real GDP (*emission intensity*), gives insight into CO_2 emissions controlling for economic development. Figure 5 depicts the emission intensities for different geographical regions over the last 70 years. North America shows decreasing emissions per GDP over practically the whole time period. Sub-Saharan Africa, Europe & Central Asia as well as Latin America & Caribbean have falling emission intensities since about 1985, 1990, and 2000 respectively. Only East Asia & Pacific have an unclear pattern of emissions per GDP over the time period. A rough summary of these observations is Empirical Fact 4:

Empirical Fact 4. *CO_2 emissions per constant and real GDP (emission intensities) fall over time.*

As a combined example, Figure 6 shows the relationship of structural transformation and emissions for

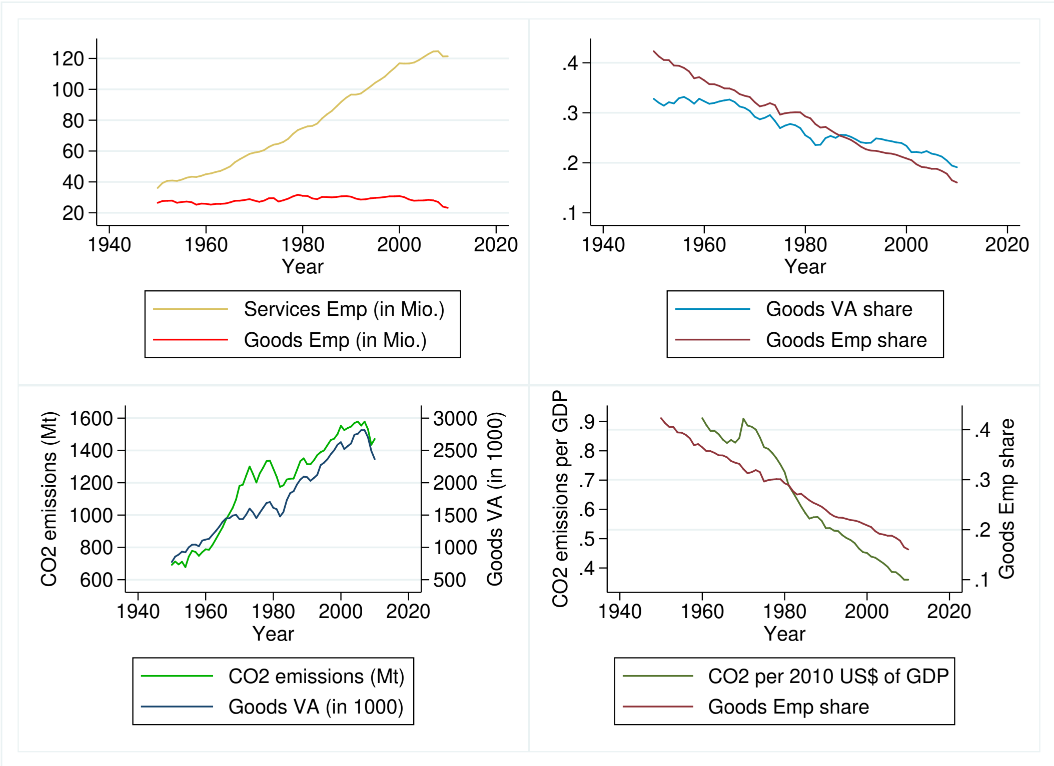

Figure 6: Structural change and emissions in the USA

Source: World Bank (2019); Timmer, G. J. d. Vries, and K. d. Vries (2015). Own calculations.

the USA. The left plot in the first line depicts the development of employment in the goods sector and the service sector from 1950 to 2010. Employment in the goods sector is relatively constant, but employment in the service sector increases dramatically. Consequently, the employment share of the goods sector falls, as is shown in the right plot in the first line. In this graph I also show the value added share of the goods sector, which also falls. Thus, the plots in the first line describe the effect of structural transformation since 1950. The left plot in the second line graphs CO_2 emissions in megatons ($1Mt = 1,000,000t$) and VA of the goods sector in thousands and constant prices over the same time period. Both time series increase in a quite parallel fashion. Finally, the right graph in the second line plots the employment share of the goods sector and CO_2 emission intensity over time. Similarly, these two time series develop in a correlated way, both falling (with possibly a structural break around 1970 for the emission intensity series).

In conclusion, the empirical evidence convey that total goods production and total CO_2 emissions increase. Combining these two findings, I claim that overall CO_2 emissions are proportional to overall goods production. Moreover, the Empirical Facts hint towards a sizable role of structural change, in the form of a falling goods share, for the explanation of emission intensities. Thus, the model I set up aims to capture a combination of increasing goods production and rising total emissions while the goods share falls and emission intensities decline. Finally, the uniform development across regions imply that the analyses of such a model, which is calibrated to North America in 1950, can be transferred to more developing regions today.

2.2 Literature Overview

This subsection first summarizes the historical and recent literature on structural change. Then, I present the foundations and newer findings in the realm of environmental economics. Finally, I provide an overview of research in the intersection between structural transformation and the environment.

2.2.1 Structural Change

The analysis of the role of sectoral composition and structural transformation for economic development has a long tradition. Historically, the focus on the economic structure has its roots in dividing an economy into stagnating traditional sectors versus productive and accumulating modern sectors (Lewis (1954); Ranis and Fei (1961)). Kuznets (1966) was one of the first scholars to describe the systematics that, while a country's income increases agriculture declines, services increase and manufacturing follows an inverse u-shaped behavior. Kaldor (1967) emphasized the role of manufacturing productivity for manufacturing's growth and its significance for overall growth. Chenery (1971) focused on the speed of structural transformation, Rostow (1977) conditioned economic progress on structural transformation, and Syrquin (1988) called structural change the center of modern economic growth.

The current models of structural change emphasize different drivers and causes of structural transformation.[3] Two of the most prominent explanations are income and price effects. The former stresses the demand side of an economy. Specifically, Echevarria (1997); Kongsamut, Rebelo, and Xie (2001); Foellmi and Zweimüller (2008)[4] incorporated non-homothetic preferences[5] as a reason for structural transformation. These preferences imply that as households become richer they shift their relative expenditure from agricultural goods to services which then also leads to labor reallocation. On the other side, Ngai and Pissarides (2007); Acemoglu and Guerrieri (2008) focus on the supply side of an economy and price effects. Precisely, relative price differences, which are caused by productivity growth differences or capital intensity differences, induce structural transformation. In this context, Herrendorf, Herrington, and Valentinyi (2015) find that differences in technological progress can explain the main technological forces of structural change.

A straightforward extension is the combination of income and price effects: Rogerson (2008); Duarte

[3]See Herrendorf, Rogerson, and Valentinyi (2014); Gabardo, Pereima, and Einloft (2017) for excellent review articles. Lin and Wang (2017) give a historical overview of structuralist versus neo-classical development policies and introduce the so-called "New Structural Economics".

[4]Note that the model by Foellmi and Zweimüller (2008) is more disaggregated than the canonical three-sector setup.

[5]Probably the most popular example of non-homothetic preferences is the so-called "Engel's (1857) Law" stating that as income increases, the expenditure share spent on food decreases. Technically, this implies a non-linear income expansion path.

and Restuccia (2010) set up static models with non-homothetic preferences and differential productivity growth to explain labor market and aggregate productivity differences, respectively. Finally, Boppart (2014) includes both income and price effects in an intertemporal setting with so-called "price independent generalized linearity" (PIGL) preferences (defined by Muellbauer (1975); Muellbauer (1976)) that fall in the class of non-Gorman preferences. Among other things, Boppart (2014) finds that the price and income effects seem to be of similar importance to explain structural change. In contrast to that, Comin, Lashkari, and Mestieri (2015) conclude that income effects play a larger role.

Similar to the origins of the analysis of structural transformation, there is a vast amount of literature focusing on the role of structural change in developing countries: Some authors (see e.g. Matsuyama (1992); Caselli and Coleman (2001); Gollin, Parente, and Rogerson (2002); Eckert and Peters (2018)) analyze the movement out of agriculture to a non-agricultural economy. On the other hand, Bah (2011); Rodrik (2016); McMillan, Rodrik, and Sepúlveda (2017); Diao, McMillan, and Rodrik (2019) find that developing countries follow different paths in their structural transformation than already developed countries and also exhibit sizable heterogeneities among their patterns of structural change.

2.2.2 Environmental Economics

One of the very first economic models introducing the environment into a neoclassical growth model was created by Forster (1973), who found that optimal allocations would differ when taking pollution into account. Shortly after this publication, Dasgupta and Heal (1974) published a growth model that included energy. The first economic analysis of environmental policies[6] against climate change was done by Nordhaus (1991), who then catalyzed the field of environmental macroeconomics with the formulation of *Dynamic Integrated Climate-Economy* (DICE) models (Nordhaus (1992)). These DICE and subsequent *Regional Integrated Climate-Economy* (RICE) models, which build on the model by Dasgupta and Heal (1974), have been enhanced and used extensively to this day. More recently, Golosov et al. (2014), building on the RICE model, specified the energy supply side completely, thus making it a general equilibrium model. In one of its applications, Hassler, Krusell, and Olovsson (2018) circumvent the issue of uncertainty and analyze the effects of policy errors under lower and upper limits of climate and economic sensitivity.[7]

On a more empirical research frontier, Grossman and Krueger (1993) were the first to describe that as a country's income increases, environmental quality first deteriorates which then, after a turning point at some high level of income, turns around. This inverted u-shape of pollution as a function of economic

[6] Already Pigou (1920) derived how market failures due to externalities could be solved with a tax that internalizes the otherwise social cost and thus induces a socially optimal solution.

[7] The handbook chapter by Hassler, Krusell, and Smith (2016) presents a comprehensive overview of environmental macroeconomics and Hassler and Krusell (2018) focus specifically on the macroeconomics of climate change.

growth was coined *Environmental Kuznets Curve* (EKC) with reference to Kuznets (1955)' discovery of a similar relationship between inequality and income. Following these footsteps, a vast amount of scholars empirically investigated the relationship between different environmental measures and income finding very ambiguous results.[8] In other words, the EKC is not robust and the relationship between economic growth and environmental quality is controversial.[9]

Nonetheless, the first model to create an EKC was Selden and Song (1994) who adapted the model by Forster (1973). Within a similar model Stokey (1998) also generates an EKC. Central to her model is the role of technology, which increases production and pollution. This, however, implies that sustained growth is not optimal. Andreoni and Levinson (2001) build another static model that generates an EKC: at low levels of income, agents do not invest in abatement; however, at high levels of income the disutility from pollution would get so high that agents begin to invest in pollution abatement. A dynamic version of this model is developed by Egli and Steger (2007), who also derive a Pigouvian tax in this context. With respect to the empirical ambiguity of the EKC, Kelly (2003) derives conditions for different forms of the income pollution relationship.[10]

In contrast to the result of unsustainable growth by Stokey (1998), Hartman and Kwon (2005) find sustainable economic growth in an endogenous growth setting with two goods. An earlier endogenous growth model with two goods is introduced by Bovenberg and Smulders (1995), who look for optimal environmental policy. Additionally, Acemoglu, Aghion, et al. (2012) present optimal policies for sustainable growth in an endogenous growth model with two goods. Both goods are inputs but one is clean and the other one is dirty. Among other results, the authors find that in the optimal scenario there would be a research subsidy and a carbon tax. However, a temporary implementation of them might be enough.[11] Similarly, R. E. López and Yoon (2013); R. E. López and Yoon (2014) develop models with a clean good and a dirty good. However, the goods are consumption complements. These papers focus on the difference between a closed versus open economy and the conditions for economic growth to be sustainable, respectively.

Another approach is taken by Brock and Taylor (2010), who incorporate pollution into the Solow Model, extending it to the so-called *Green Solow Model*, which stresses the role of convergence in emissions. Stefanski (2013) shows that the *Green Solow Model* overvalues GDP growth rates and undervalues the role

[8] See Kaika and Zervas (2013a) for a detailed literature survey on the EKC. Some more recent but not comprehensive list include the following articles: Ulucak and Bilgili (2018) find an EKC relationship when the environmental variable is the ecological footprint, Stern, Gerlagh, and Burke (2017)'s analysis does not provide evidence for an EKC of CO_2 and sulfur dioxide. Neither does Zoundi (2017) for CO_2. Apergis (2016) finds mixed support for an EKC behavior of CO_2 and Fujii and Managi (2016) find no EKC for individual industries but for total industry and on country level of eight (including CO_2) air pollutants.

[9] See Stern (2017) for an overall critical assessment of the EKC.

[10] See Kijima, Nishide, and Ohyama (2010) for a more elaborate literature review on models of the EKC.

[11] Fischer and Heutel (2013) review endogenous technological change models in the context of environmental policies.

of emission intensity growth rates. Moreover, he presents a model that captures the transformation from an agricultural economy to a non-agricultural economy which is able to generate an inverted u-shape in emission intensity. This directly leads me to models that focus on both structural transformation and the environment.

2.2.3 Structural Change and the Environment

A few research articles introduce the issue of structural transformation into an environmental context. R. E. López, Anríquez, and Gulati (2007); Kuralbayeva and Stefanski (2013) focus on natural resources in this context. The former authors set up a model with natural resources as production inputs and show how structural transformation can occur merely due to the constraint of non-increasing natural resources. On the other hand, Kuralbayeva and Stefanski (2013) concentrate on the effect of windfalls of revenues (of natural resources) on workers' specialization and consequently on relative productivity in the manufacturing sector. Finally, Stefanski (2014) analyzed the effect of structural transformation on oil demand and oil prices. Thus, all of these authors focus on a different aspect of the environment than emissions.

Closer to my research questions, R. López and Schiff (2013); Antoci et al. (2014) develop two-sector models with physical and natural capital as inputs. One of the sectors represents the agricultural sector, using natural capital, while the other corresponds to the manufacturing sector. The former authors analyze the effects of an over-exploiting agricultural sector under open access, resources versus under property rights, finding that under open access a resource curse or complete resource depletion can occur. The latter paper focuses on pollution generated by the manufacturing sector, which leads to endogenous industrialization and a reduction in welfare of the agricultural workers.

Finally, there is a working paper by Wolfersberger (2019), which is closest to my thesis. The author generates structural change through the model of Ngai and Pissarides (2007) and thus focuses on different productivity growth rates and the supply-side of the economy. My model, however, is oriented on structural transformation through the demand-side and also covers environmental policies which are omitted in Wolfersberger (2019).[12] A more detailed explanation is given in the next section.

[12] My model captures also supply-side factors. Though, I do not focus on them.

3 Model

3.1 Model setup

In this subsection I first present a general overview of my model. Thereafter, the household, firm, government, market clearing, and the environment are presented individually, including their functional forms.

3.1.1 Overview

My model set up builds extensively on Duarte and Restuccia (2010), which itself refers to Rogerson (2008) for the modelling of structural change. With this foundation, it incorporate price and income effects. The environmental part of the model is mainly based on Stefanski (2013), Bartz and Kelly (2008).

The model is kept simplistic on at least two dimensions: One, it is set up as a closed economy. This however, could be interpreted as the global economy. Especially in the context of effective climate policies and overall economic development, it is favorable to focus on a global setting instead of a national one. Moreover, as shown in section 2.1, the patterns I focus on seem to (roughly) hold in all world regions. Two, the model abstracts from inter-temporal household decisions.[13] Thus, in the decentralized setting, it is basically a sequence of static equilibria. Next to the analytic simplicity, this makes the problem absent of discounting more than one period. From a theoretical perspective this is an advantage since the topic of discounting is very controversial in the long-run climate change and economic growth literature. This controversy stems from the fact that classically, periods further in the future are discounted towards zero and the implications of climate change lose their grip (see e.g. Heal (2005); Colapinto, Liuzzi, and Marsiglio (2017)).

Figure 7 gives a general overview over my model. At the core of the analysis are the two blue boxes *Structural Change* and *Environment*. The effect of structural change on the environment is the so-called *composition effect*. This encompasses the economic transformation from the goods sector to the service sector. Methodologically, this transformation is measured in the change in labor shares. The effect of the environment on structural change is represented by environmental policies such as an exogenous CO_2 tax on consumption or a social planner's environmentally optimally implemented structural change. Thus, there is an evident two-way interaction between structural transformation and the environment. The environment also interacts with itself through pollution accumulation. This concludes the endogenous side of the model, which clearly focuses on the demand side of the economy.

[13] In section 4, I briefly explain why a more elaborate model with capital and thus with inter-temporal decisions should not imply major differences.

On the exogenous side of the model, there is *Economic Growth* and *Abatement Growth*. The former affects both the environment and structural change. The environment is detrimentally affected through goods productivity growth, inducing higher production and thus higher emissions. This is captured in the so-called *scale effect*. At the same time, however, economic growth induces structural change.[14] Both these aspects together, economic growth and structural change, can be interpreted as economic development when defining development from a broader perspective including the economic structure. Thus, an economy with a high goods share could, following this line of reasoning, be seen as less developed than an economy with a higher service sector share. Finally, there is also exogenous abatement growth which leads to less effective emissions per unit of goods output. This effect is called the *technique effect*.[15]

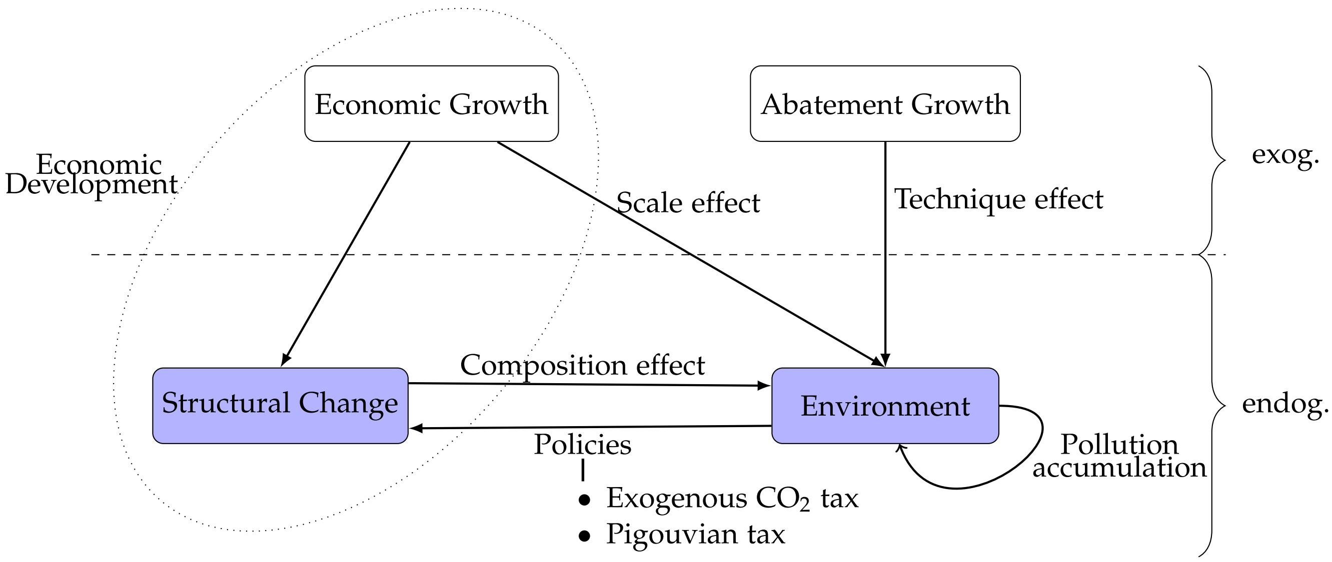

Figure 7: Schematic model overview

3.1.2 Household

The economy is populated by a representative household. Its size is constant at L. For simplicity, I assume that the household does not value leisure and therefore inelastically supplies its labor each period. Thus, the measure of total workers in the economy is identical to the household size. The household derives utility over a composite of consumption, i.e. consuming goods $c_{g,t}$ and consuming services $c_{s,t}$. At the same time the household has to meet subsistence consumption of goods $\bar{c}_g$ and has negative subsistence consumption of services $\bar{c}_s$. The former can be interpreted as having necessary food and basic goods (such as clothes, shelter, electricity, etc.) in order to "survive". Practically, this specification means that only goods consumption exceeding the subsistence level creates well-being. The latter can be seen as

[14]This one-way direction is a model simplification since the causality between economic growth and structural transformation is likely to go in both ways in reality. See Matsuyama (2008) for a brief analysis of this circular causality between structural change and economic growth. However, this is not the focus of this thesis.

[15]The terminology of *scale effect*, *composition effect* and *technique effect* in the context of the decomposition of emissions goes back to the seminal work by Grossman and Krueger (1993).

home production of services. In other words, only after a certain amount of wealth is achieved, does the household start to consume services provided by the market. Technically, this implies non-homothetic preferences, i.e. income expansion paths that do not go through the origin. Standard Stone-Geary utility achieves that.[16] Specifically, my utility function, following the Definition 1, includes goods and services. Thus, the instantaneous utility of the household takes the following form, where α is the weight on goods consumption with $\alpha \in (0, 1)$:

$$u(c_{g,t}, c_{s,t}) = \alpha \log(c_{g,t} - \bar{c}_g) + (1 - \alpha) \log(c_{s,t} + \bar{c}_s) \tag{1}$$

However, the overall welfare of the household is also affected by the state of the environment. It should be noted, though, that the household is not aware of its influence on the environment, thus *pollution* (P_t) is a pubic bad that generates disutility. *Pollution* is a catch-all term encompassing all sorts of climate change related damages.[17] I assume that composite consumption and the environmental aspect are additively separable and for simplicity I assume a constant marginal disutility of pollution $\chi > 0$[18]:

$$U(c_{g,t}, c_{s,t}, P_t) = u(c_{g,t}, c_{s,t}) - v(P_t) = \alpha \log(c_{g,t} - \bar{c}_g) + (1 - \alpha) \log(c_{s,t} + \bar{c}_s) - \chi P_t \tag{2}$$

Taking this together, the overall household's welfare is determined by the consumption bundles and the exposure to pollution from time $t = 0$ to infinity.[19] Future welfare is discounted with $\beta \in (0, 1)$:

$$\sum_{t=0}^{\infty} \beta^t U(c_{g,t}, c_{s,t}, P_t) = \sum_{t=0}^{\infty} \beta^t \left[\alpha \log(c_{g,t} - \bar{c}_g) + (1 - \alpha) \log(c_{s,t} + \bar{c}_s) - \chi P_t\right] \tag{3}$$

Finally, there is a period budget constraint the household faces. In addition to the market prices ($p_{g,t}$ is the goods price in period t and $p_{s,t}$ is the services price in period t), there is a government implementing environmental policies in the form of taxes on goods (e.g. taxes on CO_2 emissions), $\tau_{g,t} \geqslant 0$, which are rebated as lump-sum transfers (T_t). The left hand side of the budget constraint can be interpreted as the household's expenditure, whereas the right hand side expresses the household's total income (where w_t

[16] Geary (1950) was the first scholar to derive this functional form and Stone (1954) estimated the corresponding linear expenditure system for the first time.

[17] These adverse aspects of climate change are, for example, water and air pollution, extreme weather phenomena and their consequences, growing aridification and overall increasing uninhabitability of previously fertile regions, societal disruptions caused by climate change induced scarcity, and many more.

[18] Weitzman (2010) shows that my formulation of environmental pollution as a ”negative” amenity is isomorphic to multiplicative formulations with a damage function such as for example the DICE models. However, generally, damage function specifications imply a higher substitutability between consumption and the environment and therefore yield less stringent policies.

[19] Note that a majority of the analyses do not need the specific intertemporal dimension. However, the intertemporal specification will be needed in the context of a stock pollutant. Thus, I introduce the complete setup of the model already here.

is the wage rate in period t):

$$(p_{g,t} + \tau_{g,t})c_{g,t} + p_{s,t}c_{s,t} \leqslant w_t L + T_t \tag{4}$$

Note that I omit taxes on labor income. However, since this is a model of inelastic labor supply, taxes on labor are analogous to lump-sum taxes in their non-distorting effect. Thus, the lump-sum transfer (T_t) could be interpreted as a composite of wage tax/subsidy and purely lump-sum transfer. Equation (4) also shows that there are no taxes or subsidies on services consumption. There are two main reasons why I focus merely on goods consumption taxation: First, I assume that services production is completely clean, therefore there would never be an environmental tax on its consumption.[20] Second, the interactions between environmental policies and other fiscal policies would create another complexity.[21] However, this also implies that my model does not allow for a so-called *double dividend*, i.e. one dividend stemming from an environmental improvement and the other dividend from using the Pigouvian tax revenues to reduce distortionary taxes.

3.1.3 Firm

There are two firms in the economy, each producing its product (goods ($Y_{g,t}$) or services ($Y_{s,t}$)) with constant returns to scale and linear in the respectively deployed labor ($L_{i,t},\ i \in \{g, s\}$) and scaled by the particular productivity ($A_{i,t},\ i \in \{g, s\}$):

$$Y_{g,t} = A_{g,t}L_{g,t} \tag{5}$$

$$Y_{s,t} = A_{s,t}L_{s,t} \tag{6}$$

At this point, I define total (real) production (Y_t^r) as the sum of goods and services production:

$$Y_t^r = Y_{g,t} + Y_{s,t} = A_{g,t}L_{g,t} + A_{s,t}L_{s,t} \tag{7}$$

Moreover, I assume that there is a constant, positive, and exogenous (but not necessarily equal) growth

[20] Acemoglu, Aghion, et al. (2012) introduce subsidies for research of the clean sector. However, their overall model is a model of endogenous growth and thus these subsidies are needed to redirect innovation.
[21] See Goulder (2013) for a review article on this interaction.

rate of each productivity:

$$A_{g,t+1} = A_{g,t}(1 + \gamma_{Ag}) \tag{8}$$

$$A_{s,t+1} = A_{s,t}(1 + \gamma_{As}) \tag{9}$$

The economic structure is competitive, i.e. the firms are price takers. Moreover, labor is completely mobile across sectors leading to an equal wage rate across the two sectors. Hence, each firm's profit function is defined as:

$$\pi_{i,t} = p_{i,t}Y_{i,t} - w_t L_{i,t}, \quad i \in \{g, s\} \tag{10}$$

3.1.4 Government

As mentioned in the household's budget constraint, there is a government implementing goods taxes ($\tau_{g,t} \geqslant 0$) and a lump-sum transfer (T_t). I assume that the government budget constraint must hold each period, i.e. there is no governmental borrowing across time:

$$\tau_{g,t} c_{g,t} = T_t \tag{11}$$

3.1.5 Market Clearing

Finally, there is labor, goods, and services market clearing at each point in time. Labor market clearing implies that each period's supplied labor has to be allocated between the goods and the service sector. The goods (services) market clearing equation means that total goods (services) consumption is equal to total goods (services) supply:

$$L = L_{g,t} + L_{s,t} \tag{12}$$

$$Y_{g,t} = c_{g,t} \tag{13}$$

$$Y_{s,t} = c_{s,t} \tag{14}$$

3.1.6 Environment

CO_2 emission (E_t) is a byproduct of goods production but not of services production.[22] However, there is not necessarily a one-to-one correspondence since there is pollution abatement, usage of clean energy sources, and other technological factors exogenously reducing emissions per unit of goods output. Thus, the flow emissions in period t correspond to only a fraction (Ω_t) of the amount of produced goods. In other words, Ω_t corresponds to the emissions per unit of goods output:

$$E_t = \Omega_t Y_{g,t} = \frac{1}{(1+\gamma_C)^t} Y_{g,t} \tag{15}$$

The second equal sign in equation (15) implies that the CO_2 emission per unit of output (Ω_t) decreases over time. Namely, I assume that γ_C is the exogenous technological change leading to cleaner emissions and thereby effectively to less emissions, even for constant goods production.[23]

Besides the flow pollutant, I can also analyze the effect of environmental degradation and emissions in stock form. This, for example, is more reasonable for CO_2 emissions and their effect on public welfare. Specifically, the accumulation of CO_2 in the atmosphere drives global warming and climate change rather than a singular CO_2 emission. I capture this accumulation in the variable *pollution* (P_t). Moreover, a fraction ($\nu \in [0, 1]$) of the previously emitted pollution naturally decays.

$$P_t = E_t + \nu P_{t-1} \tag{16}$$

$$P_0 \geqslant 0$$

P_0 is the given level of pollution that is in the economy at time 0.[24] If $\nu = 0$, there is no accumulation of pollution and the overall pollution accumulation is identical to each period's emission (15), i.e. it corresponds to a flow pollutant. On the other hand, if $\nu = 1$, there is no natural degeneration and everything that is once effectively emitted, stays in the atmosphere forever. In later analyses it is sometimes helpful to first focus on the case of $\nu = 0$. I call this *static pollution* in contrast to a *dynamic pollution*. The reason for this terminology is the straightforward reason that under $\nu = 0$ the model becomes completely static: whereas the labor decisions and thus the economic part of my model always refer to the current period,

[22] A service sector being completely free of emissions is of course a simplification. In the caveats section I discuss this issue more in detail.

[23] Many models have abatement as a control variable and therefore also endogenous abatement growth. In section 4 I discuss the implications of setting up abatement exogenously.

[24] The value of this initial pollution level clearly depends on which time one assumes the economy to start with. Since the model assumes to start with a relatively high goods share and subsequently only decreases this, this should be seen as the time when the manufacturing share is at its peak.

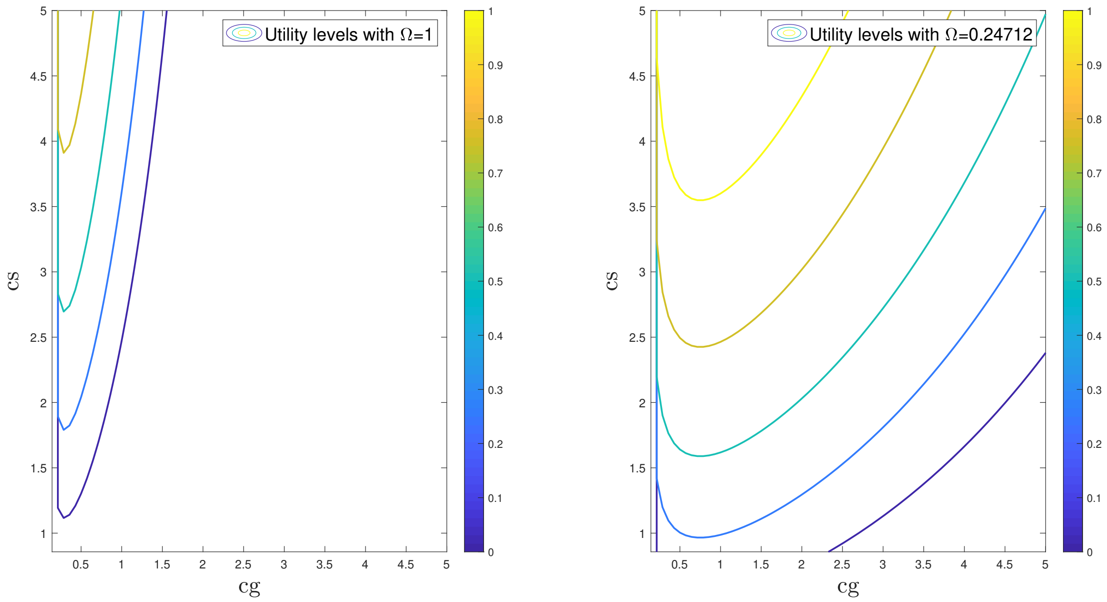

Figure 8: Welfare if pollution is only static emissions and $\chi = 1$

under $\nu = 0$, the pollution also has merely an instantaneous effect on the particular period's utility.

After introducing the environmental component, I am now equipped to give an overview over this model's instantaneous welfare equation (2). It is important, however, to keep in mind that the pollution disutility stems from an externality, and thus the household is not aware of this negative effect of goods consumption. Concretely, Figure 8 plots indifference curves on the c_g-c_s-plane for high and low Ω. High $\Omega = 1$ corresponds to the first period, i.e. when no growth in abatement technologies has yet happened (left plot). On the other hand, low $\Omega \approx 0.25$ corresponds to the last period in my baseline setup (right plot).[25] Note that for expositional reasons, I assume $\nu = 0$ in the figures. Ceteris paribus, $\nu > 0$ would just imply a shift in the utility levels. Finally, the disutility of emissions parameter is $\chi = 1$ in the figures and the lower boundaries of the graph are chosen to be $\bar{c}_g$ and $\bar{c}_s$.

The figure plots c_g-c_s-allocations for utility levels of 1 (yellow), 0.75 (yellow-green), 0.5 (turquoise), 0.25 (light blue), 0 (dark blue) if feasible in this range. Of course, I could have drawn many more indifference curves that yield negative values which would be situated to the (south-)east of the dark blue curve. Clearly, in the early period (left panel) the disutility through pollution is immanent when increasing goods consumption. In a less severe way, however, this holds also in the right panel. The overall implications can best be understood if I, for example, focus on the right panel and would fix services consumption levels to $c_s = 2.5$. For this level of services consumption, overall welfare is 0.5 at the lower boundary of goods consumption and then increases to 0.75 for goods consumption levels of around 0.5. Increasing goods

[25]See section 3.4 Calibration for detailed explanations of the baseline setup.

consumption further would lead to further increases in welfare, but not forever. In fact, for this fixed amount of services consumption, welfare would be again merely 0.75 (0.5) for goods consumption levels of around 1.4 (3). More generally, independent of high or low Ω, the indifference curves are u-shaped: This implies that there are two levels of goods consumption which induce the same overall welfare. In other words, for relatively low levels of goods consumption, the positive effect of consumption prevails and thus increasing goods consumption increases welfare (to the left and inside of the "u"). On the other hand, for higher levels of goods consumption, the negative effect through the pollution disutility dominates over the positive effects of consumption, and thus welfare decreases for even higher levels of goods consumption (to the right of the "u"). Finally, services consumption monotonically increases welfare, i.e. from south to north leads to higher welfare functions.

After introducing the individual agents and components with their respective constraints, it is now time to interact them. Specifically, in the next subsection I derive the allocations under a sequence of markets competitive equilibrium following Definition 3. From there, I deduce a decomposed form of emissions and emissions growth.

3.2 Equilibrium

Definition 3. *A sequence of markets competitive equilibrium is characterized by a vector of allocations* $\{L_{g,t}, L_{s,t}, Y_t, Y_{g,t}, Y_{s,t}, c_{g,t}, c_{s,t}, E_t, P_t\}_{t=0}^{\infty}$ *and a vector of prices* $\{w_t, p_{g,t}, p_{s,t}\}_{t=0}^{\infty}$ *such that for a given set of policies* $\{\tau_{g,t}, T_t\}_{t=0}^{\infty}$*, (i) the household maximizes its welfare (3) subject to its budget constraint (4), (ii) the firms maximize their respective profit functions (10), (iii) the government budget constraint binds (11), (iv) markets clear (12), (13), (14), and (v) the evolution of the environmental variables is given by (15) and (16).*

Necessary assumptions for the sequence of equilibria to be well defined and to be interior, i.e. positive consumption of goods and services, are:

$$\bar{c}_g < A_{g,0}L_{g,0} \tag{17}$$

$$\bar{c}_s \leqslant \frac{1-\alpha}{\alpha}A_{s,0}L_{s,0} \tag{18}$$

The corresponding mathematical proofs are in the Appendix A.1.1.

I take labor as the numeraire and normalize the wage rate (w_t) to one each period. Thus, the price of goods ($p_{g,t}$) at time t and the price of services ($p_{s,t}$) at time t are relative to wage. In other words, the prices of the consumption items are given in terms of labor. Then, the first-order conditions of the firm profit functions (10) directly imply that each consumption item's price is equal to the inverse of the respective productivity:

$$\frac{\partial \pi_{i,t}}{\partial L_{i,t}} = 0 \quad \Leftrightarrow \quad p_{i,t} = \frac{1}{A_{i,t}}, \quad i \in \{g, s\} \tag{19}$$

The household is a price taker and chooses each period's control variables (goods consumption and services consumption) in order to maximize its utility subject to a period budget constraint. Thus, for the household optimization I set up the Lagrangian, using $w_t = 1$:

$$\mathcal{L} = \sum_{t=0}^{\infty} \beta^t \left[\alpha \log(c_{g,t} - \bar{c}_g) + (1-\alpha) \log(c_{s,t} + \bar{c}_s) - \chi P_t \right] \\ - \lambda_t \left[(p_{g,t} + \tau_{g,t}) c_{g,t} + p_{s,t} c_{s,t} - L - T_t \right] \tag{20}$$

The associated first-order conditions are:

$$\frac{\partial \mathcal{L}}{\partial c_{g,t}} = 0 \quad \Leftrightarrow \quad \beta^t \frac{\alpha}{c_{g,t} - \bar{c}_g} = \lambda_t (p_{g,t} + \tau_{g,t}) \tag{21}$$

$$\frac{\partial \mathcal{L}}{\partial c_{s,t}} = 0 \quad \Leftrightarrow \quad \beta^t \frac{(1-\alpha)}{c_{s,t} + \bar{c}_s} = \lambda_t p_{s,t} \tag{22}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_t} = 0 \quad \Leftrightarrow \quad (p_{g,t} + \tau_{g,t}) c_{g,t} + p_{s,t} c_{s,t} = L + T_t \tag{23}$$

Dividing the respective first-order conditions of the consumption items by each other gives a familiar intra-temporal optimality condition: the marginal rate of substitution between *gross services consumption* and *gross goods consumption*[26] equals their price ratio (24). Plugging this into the first-order condition of the budget constraint (23) gives, after some simple Algebra, the Marshallian demand functions for the

[26] *Gross goods (services) consumption* refers to actual goods (services) consumption minus (plus) the subsistence term. This contrasts *net consumption*, which merely refers to the consumption item without the subsistence term.

Stone-Geary utility:

$$\frac{(21)}{(22)}: \quad \frac{\alpha}{(1-\alpha)}\frac{(c_{s,t}+\bar{c}_s)}{(c_{g,t}-\bar{c}_g)} = \frac{(p_{g,t}+\tau_{g,t})}{p_{s,t}} \tag{24}$$

$$\Leftrightarrow \quad c_{g,t} = \frac{\alpha}{(1-\alpha)}\frac{p_{s,t}}{(p_{g,t}+\tau_{g,t})}(c_{s,t}+\bar{c}_s)+\bar{c}_g \tag{25}$$

$$\Leftrightarrow \quad c_{s,t} = \frac{(1-\alpha)}{\alpha}\frac{(p_{g,t}+\tau_{g,t})}{p_{s,t}}(c_{g,t}-\bar{c}_g)-\bar{c}_s \tag{26}$$

$$(26) \text{ in } (23): \quad (p_{g,t}+\tau_{g,t})c_{g,t} + p_{s,t}\left[\frac{(1-\alpha)}{\alpha}\frac{(p_{g,t}+\tau_{g,t})}{p_{s,t}}(c_{g,t}-\bar{c}_g)-\bar{c}_s\right] = L + T_t$$

$$\Leftrightarrow \quad (p_{g,t}+\tau_{g,t})c_{g,t} = \alpha\left[L+T_t+p_{s,t}\bar{c}_s\right]+(1-\alpha)(p_{g,t}+\tau_{g,t})\bar{c}_g \tag{27}$$

$$\Leftrightarrow \quad c_{g,t} = \alpha\frac{1}{(p_{g,t}+\tau_{g,t})}\left[L+T_t+p_{s,t}\bar{c}_s-(p_{g,t}+\tau_{g,t})\bar{c}_g\right]+\bar{c}_g \tag{28}$$

$$(11) \text{ in } (28): \quad c_{g,t} = \alpha\frac{1}{(p_{g,t}+(1-\alpha)\tau_{g,t})}\left[L+p_{s,t}\bar{c}_s-p_{g,t}\bar{c}_g\right]+\bar{c}_g \tag{29}$$

Goods demand (28) has an intuitive interpretation: The last term on the right hand side is the subsistence consumption that is always consumed independent of its overall price. The term in the square brackets is the so-called supernumerary expenditure. This is the income the household has left after its subsistence consumption is fulfilled. Thus, the household will consume more goods if it values goods high (high α) relative to services and/or goods prices (including taxes) are low. In an analogous manner I can derive services expenditure and services demand:

$$(25) \text{ in } (23) \quad \Leftrightarrow \quad p_{s,t}c_{s,t} = (1-\alpha)\left[L+T_t-(p_{g,t}+\tau_{g,t})\bar{c}_g+p_{s,t}\bar{c}_s\right]-p_{s,t}\bar{c}_s \tag{30}$$

$$\Leftrightarrow \quad c_{s,t} = \frac{(1-\alpha)}{p_{s,t}}\left[L+T_t-(p_{g,t}+\tau_{g,t})\bar{c}_g+p_{s,t}\bar{c}_s\right]-\bar{c}_s \tag{31}$$

$$\Leftrightarrow \quad c_{s,t} = \frac{1}{p_{s,t}}\frac{(1-\alpha)(p_{g,t}+\tau_{g,t})}{(\alpha p_{g,t}+(1-\alpha)(p_{g,t}+\tau_{g,t}))}\left[L-p_{g,t}\bar{c}_g\right]-\frac{\alpha\bar{c}_s p_{g,t}}{(\alpha p_{g,t}+(1-\alpha)(p_{g,t}+\tau_{g,t}))} \tag{32}$$

For (32) I used (25) in (23) and used the government budget constraint (11). There it is apparent that even though taxes are only levied on goods consumption, they affect optimal services consumption: Via the substitution effect, increases in the goods tax lead to increased services consumption. Assuming for one moment that there are no taxes, i.e. $\tau_{g,t} = 0$, (32) would simplify to (31) without the transfers and taxes. The interpretation would be analogous to the goods demand interpretation, except for the negative services subsistence term which corresponds to the amount of home services. Finally, the two consumption expenditures ((27), (30)) constitute a linear expenditure system, which is typical for Stone-Geary preferences.

I can now plug the firm's first-order condition (19) in the goods (29) and services (32) demand equations, rewriting them again in expenditure form:

$$(19) \text{ in } (29): \quad c_{g,t}\left(\frac{1}{A_{g,t}}+(1-\alpha)\tau_{g,t}\right)=\alpha\left[L+\frac{\bar{c}_s}{A_{s,t}}\right]+(1-\alpha)\bar{c}_g\left(\frac{1}{A_{g,t}}+\tau_{g,t}\right) \tag{33}$$

$$(19) \text{ in } (30): \quad \frac{c_{s,t}}{A_{s,t}}=\frac{(1-\alpha)(\frac{1}{A_{g,t}}+\tau_{g,t})}{\left(\alpha\frac{1}{A_{g,t}}+(1-\alpha)(\frac{1}{A_{g,t}}+\tau_{g,t})\right)}\left[L-\frac{\bar{c}_g}{A_{g,t}}\right]-\alpha\frac{\bar{c}_s}{A_{s,t}}\frac{\frac{1}{A_{g,t}}}{\left(\alpha\frac{1}{A_{g,t}}+(1-\alpha)(\frac{1}{A_{g,t}}+\tau_{g,t})\right)} \tag{34}$$

In an application of Walras's law, I can derive the economy's resource constraint: plugging the government budget constraint (11) in the household budget constraint (23), then taking the normalized wage rate of $w_t = 1 \;\forall\; t$ as given and using firms' first-order conditions (19) for the prices, I just need goods market (13) and services market clearing conditions (14) to arrive at the resource constraint:

$$L = p_{g,t}c_{g,t}+p_{s,t}c_{s,t} = p_{g,t}Y_{g,t}+p_{s,t}Y_{s,t} = \frac{Y_{g,t}}{A_{g,t}}+\frac{Y_{s,t}}{A_{s,t}} = L_{g,t}+L_{s,t} \tag{35}$$

Generally, in this case of a simple linear production with only one input, I obtain that total output in wage units (the total goods and services supply) equals total labor input (the total goods sector labor and service sector labor demand by firms).

In the later analysis of emissions growth, I aim to decompose the different factors behind it: scale effect, technique effect, and composition effect. Since the overall interest lies in the analysis of the relationship between structural change and the environment, it is helpful to derive an explicit expression of structural composition, i.e. the share of labor in the goods sector over total labor (σ_t):

$$\sigma_t \equiv \frac{L_{g,t}}{L} = \frac{Y_{g,t}}{A_{g,t}L} \overset{(13)}{=} \frac{c_{g,t}}{A_{g,t}L} \overset{(33)}{=} \frac{1}{L}\left[\alpha\left(L+\frac{\bar{c}_s}{A_{s,t}}\right)+(1-\alpha)\frac{\bar{c}_g}{A_{g,t}}\right]-\frac{(1-\alpha)\tau_{g,t}\left(c_{g,t}-\bar{c}_g\right)}{L}$$

$$\Leftrightarrow \sigma_t = \frac{1}{\left(1+(1-\alpha)\tau_{g,t}A_{g,t}\right)L}\left[\alpha\left(L+\frac{\bar{c}_s}{A_{s,t}}\right)+(1-\alpha)\frac{\bar{c}_g}{A_{g,t}}\right]+\frac{(1-\alpha)\tau_{g,t}\bar{c}_g}{\left(1+(1-\alpha)\tau_{g,t}A_{g,t}\right)L} \tag{36}$$

I can use this now to rewrite the emission equation (15):

$$E_t = \Omega_t Y_{g,t} = \Omega_t A_{g,t}L_{g,t} = \Omega_t A_{g,t}\frac{L_{g,t}}{L}L = \Omega_t A_{g,t}L\sigma_t \tag{37}$$

From (37), I can look at the emission growth rate, where γ_X is the growth rate of the variable X, i.e. $\frac{X_{t+1}}{X_t}-1=\gamma_X$. Moreover, I use the approximation that the product of growth rates is zero:

$$\gamma_E \overset{(\approx)}{=} \gamma_\Omega + \gamma_{Ag} + \gamma_\sigma \tag{38}$$

In order to get the behavior of emissions over time, I need to characterize each of the growth rates on the right hand side of equation (38), where γ_Ω captures the *technique effect*, γ_{Ag} represents the *scale effect* and γ_σ encompasses the *composition effect*. Firstly, I notice that productivity growth is exogenously given and positive: $\gamma_{Ag} > 0$. Next, I look at the growth rate of the abatement growth: Recall that $\Omega_t = \frac{1}{(1+\gamma_C)^t}$ and thus, $(1+\gamma_\Omega) = \frac{1}{(1+\gamma_C)} \Leftrightarrow \gamma_\Omega \overset{(\approx)}{=} -\gamma_C < 0$.[27] Finally, in order to determine the emission growth rate, I need to characterize the remaining γ_σ. Note that in contrast to the other growth rates, the change rate of the goods share is not necessarily constant. Generally, it captures the effect of structural transformation on emissions but also the interaction of environmental policies and structural change on emissions.

In a very analogous manner, I can also derive an expression for emission intensity and for emission intensity growth:

$$\frac{E_t}{Y_t^r} = \frac{\Omega_t A_{g,t} L \sigma_t}{A_{g,t} L_{g,t} + A_{s,t} L_{s,t}} \tag{39}$$

$$\underbrace{\gamma_E - \gamma_Y}_{\equiv \gamma_{E/Y}} = \gamma_\Omega + \gamma_{Ag} + \gamma_\sigma - \gamma_Y \tag{40}$$

In the general case there is no further analytical simplification of emission intensity. In the special case of identical productivities, however, the emission intensity growth rate would be captured by $\gamma_\Omega + \gamma_\sigma$ and thus be independent of the scale effect (γ_{Ag}).

$$\gamma_{Ag} = \gamma_{As} \;\Rightarrow\; A_{g,t} = A_{s,t} \equiv A_t \overset{(12)}{\Rightarrow} Y_t^r = A_t L \;\Rightarrow\; \frac{E_t}{Y_t^r} = \Omega_t \sigma_t \tag{41}$$

As argued above and as can be seen in equation (36), structural transformation depends on environmental policies. I start by looking at the case of no government intervention (*laissez-faire*), my baseline model, to illustrate the different purely non-governmental effects on the environment. Thereafter, I calibrate the model parameters (section 3.4) such that the baseline model matches the empirical findings. This can then, finally, be used to analyze the effects of different policies (section 3.5).

3.3 Baseline Model: Laissez-faire

Straightforwardly, no government intervention implies no taxes on goods consumption and neither lump-sum transfers: $\tau_{g,t} = T_t = 0$. This simplifies the above-mentioned equations tremendously. Specifically, in a scenario without government intervention, the policy interaction with structural change disappears. Moreover, one can directly see that the goods share converges to the preference parameter associated

[27] I take the logarithm of both sides and use the approximation that $\log(1+x)^{-1} = -\log(1+x) \approx -x$ for small x.

with goods consumption relative to services consumption α, since the subsistence parameters lose their importance as the economy becomes richer (goods and services productivities grow). This is the effect of structural change:

$$\sigma_t = \frac{1}{L}\left[\alpha\left(L + \frac{\bar{c}_s}{A_{s,t}}\right) + (1-\alpha)\frac{\bar{c}_g}{A_{g,t}}\right] \tag{42}$$

$$\lim_{t\to\infty}\sigma_t = \lim_{t\to\infty}\frac{1}{L}\left[\alpha\left(L + \frac{\bar{c}_s}{A_{s,t}}\right) + (1-\alpha)\frac{\bar{c}_g}{A_{g,t}}\right] = \alpha \text{ as } A_{s,t}, A_{g,t} \to \infty \tag{43}$$

$$\gamma_\sigma < 0, \text{ but concave, i.e. } \gamma_\sigma \to 0 \text{ as } t \to \infty \text{ with } \gamma_{Ag}, \gamma_{As} > 0 \tag{44}$$

Less developed economies are characterized by higher goods shares. This implies that in the initial period, the goods share is larger than the preference parameter ($\sigma_0 = \frac{L_{g,0}}{L} > \alpha$) and thus there is negative growth of σ over time.

Moreover, note the corollary that in the laissez-faire scenario the relative goods expenditure share is identical to the relative labor allocation to the goods sector over total labor:

$$\frac{p_{g,t}c_{g,t}}{p_{g,t}c_{g,t} + p_{s,t}c_{s,t}} \overset{(19),(5)}{\underset{(35)}{=}} \frac{L_{g,t}}{L} = \sigma_t \tag{45}$$

I can use this case to decompose the different purely *economic* effects on emissions, namely the technique effect (γ_Ω), the composition effect (γ_σ), and the scale effect (γ_{Ag}). Clearly, the scale effect consists of the increase in production, i.e. productivity growth in the goods sector (γ_{Ag}). However, the composition effect also depends on productivity growth. In other words, without productivity growth, there is no reallocation of relative expenditure (and also labor) and thus no composition effect. This can be seen in Figure 9 which depicts the development of emissions and its growth rates for each effect individually without the others.

Specifically, an economy with only the scale effect and neither composition effect nor technique effect, leads to exponentially increasing emissions over time (panel (a) in Figure 9). On the other hand, a technique effect with no scale effect (and no composition effect) leads to decreasing emissions since the overall emissions growth rate is negative (panel (c) in Figure 9). Finally, as mentioned above, panel (b) of Figure 9 depicts the composition effect without the other two effects. However, as can be seen in equation (43), if there is no productivity growth, the labor share is constant, and thus the overall emissions growth rate is zero. This leads to emissions that stay on the initial level over time, never changing.

Clearly, it is more interesting to investigate cases of interactions between these effects. It is straightforward

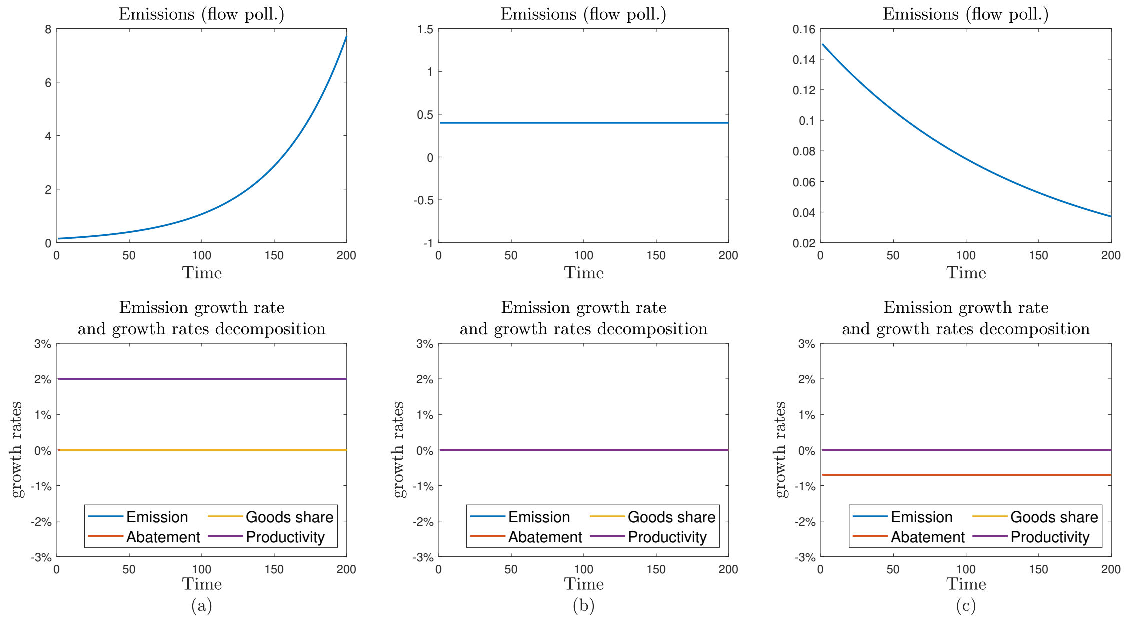

Figure 9: Individual economic effects on their own: (a) scale effect, (b) composition effect without scale effect, (c) technique effect

that if there is no composition effect ($\gamma_\sigma = 0$) but technique effect and scale effect, the emission path depends on the relation between the technique and scale effect: if $\gamma_{Ag} > |\gamma_\Omega|$ there is constant positive emission growth and thus exponential emission (congruent to panel (a) in Figure 9). On the other hand, if $\gamma_{Ag} < |\gamma_\Omega|$, emission growth is negative and emissions therefore converge to 0 (congruent to panel (c) in Figure 9). And finally, if $\gamma_{Ag} = |\gamma_\Omega|$, there is no emission growth and thus a constant emission on the initial emission level (congruent to panel (b) in Figure 9). Note that an economy without composition effect corresponds to the canonical analysis of one-sector models: If there is only one sector, there can be no structural change, and thus the influence on the environment has to stem from the scale and technique effect.

Therefore, the interesting cases include structural change and thus the composition effect. As argued above, (43), the goods share converges to the preference parameter α. However, the speed of this convergence is decreasing and thus the change rate of the composition effect is concave. In this case, there are three possible scenarios: (a) Emission growth is overall negative and emissions converge to 0, however with slower speed for later periods ($\gamma_{Ag} < |\gamma_\Omega + \gamma_\sigma| \ \forall\ t$). (b) Up until some time $t < t^*$ emission growth is negative ($\gamma_{Ag} < |\gamma_\Omega + \gamma_\sigma|$ for $t < t^*$), at this moment $t = t^*$ emission growth is 0 ($\gamma_{Ag} = |\gamma_\Omega + \gamma_\sigma|$ for $t = t^*$), and thereafter emission growth is positive ($\gamma_{Ag} > |\gamma_\Omega + \gamma_\sigma|$ for $t > t^*$). This induces u-shaped emissions. (c) The negative growth of structural change is, even at its beginning (which is its most negative value), not large enough (in absolute terms) to cause overall negative emission growth ($\gamma_{Ag} > |\gamma_\Omega + \gamma_\sigma| \ \forall\ t$). Here, emissions start moderately increasing but then grow exponentially. I document these three scenarios in the corresponding panels in Figure 10.[28]

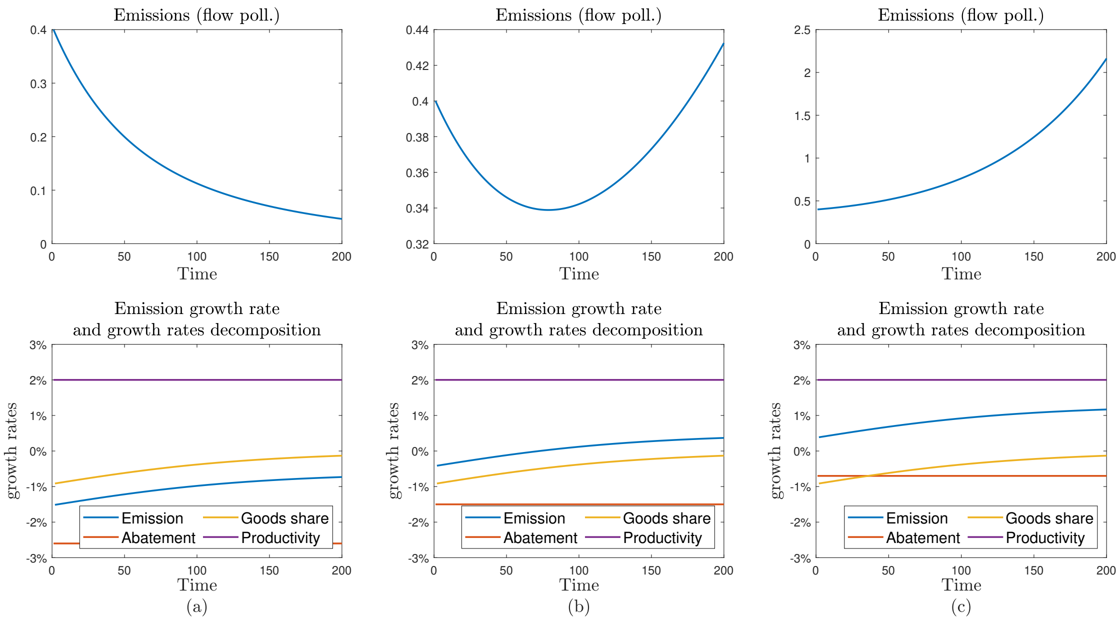

Figure 10: The role of structural change for emissions with no government

The analysis of emission intensity and emission intensity growth is very related. Comparing the right-hand sides of equation (38) and equation (40), emission intensity growth just includes real production growth as an additional subtrahend ($-\gamma_Y < 0$). Starting from situation (a) from above, i.e. when abatement growth and the growth rate of structural change are absolutely larger than productivity growth and therefore emission growth is negative, an additional negative expression would just imply an even more negative growth rate of emission intensity than of emissions. Correspondingly, both emissions and emission intensity would fall. On the other extreme, if productivity growth is so large that even subtracting the real production growth does not make emission intensity growth negative, i.e. $\gamma_{Ag} > |\gamma_\Omega + \gamma_\sigma| + \gamma_Y > |\gamma_\Omega + \gamma_\sigma| > 0$, then both emissions and emission intensity increase over the whole time. The interesting cases lie in between the extremes, especially the following scenario:

$$\gamma_E = \gamma_{Ag} + \gamma_\Omega + \gamma_\sigma > 0 \quad \Leftrightarrow \quad \gamma_{Ag} > |\gamma_\Omega + \gamma_\sigma| \tag{46}$$

$$\gamma_{E/Y} = \gamma_{Ag} + \gamma_\Omega + \gamma_\sigma - \gamma_Y < 0 \quad \Leftrightarrow \quad \gamma_{Ag} < |\gamma_\Omega + \gamma_\sigma| + \gamma_Y \tag{47}$$

In this case there is positive emission growth and thus increasing emissions over time. However, at the same time, emission intensity growth is negative and thus emission intensity falls. Figure 11 plots this: The overall economy is decentralized and there are no taxes, i.e. the laissez-faire allocations. Note that the

[28] In this example I achieve these different effects by manipulating the abatement growth rate. Clearly, one could also change productivity growth (as long as it is still larger than 0) or some mix of the two growth rates.

parameter constellation is identical to above's situation (c).[29] Thus, emissions increase over time (Figure 11: right panel, top row). The labor share in the goods sector (left panel, top row) falls over time and converges to $\alpha = 0.15$. Analogously, the emission intensity (right panel, bottom row) falls. Finally, the left panel in the bottom row depicts the decomposed growth rates of emission intensity, namely, constant goods productivity growth (green dotted), constant abatement growth (purple dotted), the concave labor goods share change rate (red, γ_σ), and the negative of real production growth rate (yellow, $-\gamma_Y$). The sum of these four constitutes the emission intensity growth rate (blue, $\gamma_{E/Y}$), which is smaller than zero and thereby induces the emission intensity behavior in the right panel, second row. Generally, since the negative of the real production growth is almost constant, the overall emission intensity growth rate has almost the same form as the labor goods share change rate. Finally, as shown above, the emissions (*not* emission intensity) growth rate corresponds to the sum without the negative real production growth rate, which is larger than zero.

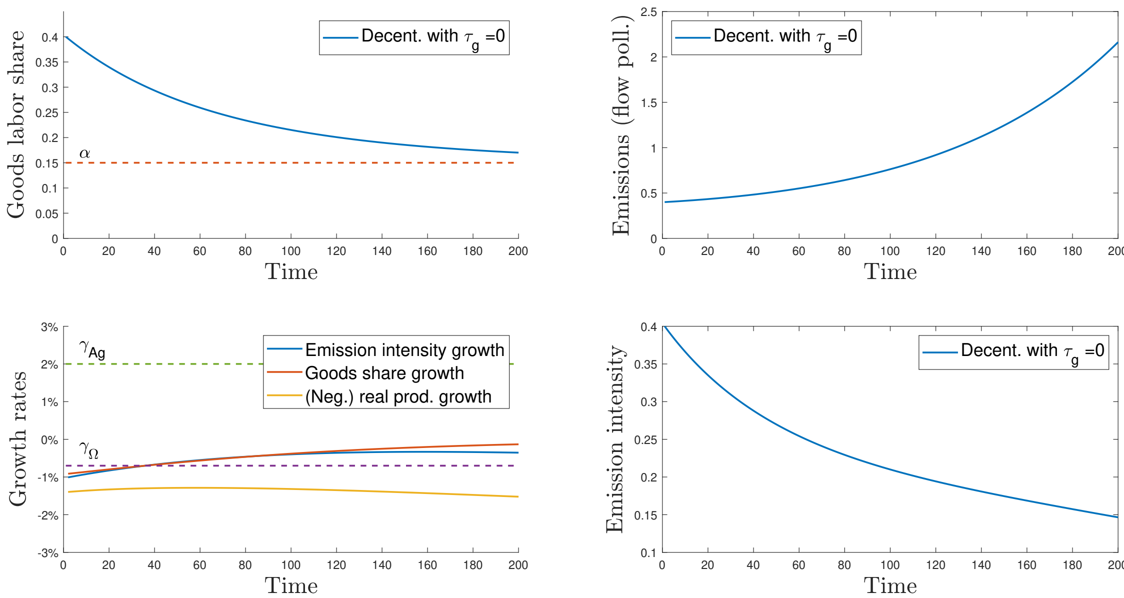

Figure 11: Structural change, emissions and emission intensity with no government

Another example of increasing emissions and falling emission intensity would be the simplifying assumption of uniform productivity ($A_{g,t} = A_{s,t} \Rightarrow \gamma_Y = \gamma_{Ag}$ with $\gamma_{Ag} > |\gamma_\Omega + \gamma_\sigma|$). Finally, there are of course also other scenarios in-between where emission growth and/or emission intensity growth are not positive/negative for the entire time but change sign at some time(s). This would give a more complex picture of emissions and emission intensity but I abstract from it for the major reason that the data does not seem to support such involved behavior. This leads directly to the issue of calibration of my model.

[29] The parameter choices are motivated in the next section.

3.4 Calibration

I chose the amount of time periods, $T = 200$, arbitrarily, to some extent. However, the first period corresponds to year 1950 and I have data until year 2010, so for 60 years or 240 quarters. Generally, the time horizon does not make a big difference, and the longer time setting brings out the behavior of the labor variables in a clearer way. The next three variables are calibrated (very similar as Rogerson (2008)) to match the data of the USA: α corresponds to the employment share of the goods sector in the last period (year 2010). The reason to do so, is the fact that, as shown, the goods sector of an economy without taxes would converge to α. Equation (33) is used to calibrate the subsistence consumption parameters $\bar{c}_g$ and $\bar{c}_s$ such that the labor shares in the first period (year 1950) are consistent with the data: $\frac{L_{g,0}}{L} \approx 0.4$ and $\frac{L_{s,0}}{L} \approx 0.6$. These imply that the goods subsistence consumption level of $\bar{c}_g = \frac{1}{7}$ corresponds to about one third of the household's goods consumption in 1950 which is very similar to what Rogerson (2008) gets for his calibrations. Since the household is of constant size, I normalize it to $L = 1$ without loss of generality.

Similarly, I also normalize the initial productivities in the goods sector ($A_{g,0}$) and the services sector ($A_{s,0}$) to 1. Their growth rates are oriented very closely at the values by Rogerson (2008), i.e. he gets $\gamma_{Ag} = 0.0248$ and $\gamma_{As} = 0.0144$. A discount factor of $\beta = 0.985$ is similar to discounting in DICE models and I trivially normalize the initial value of abatement to no abatement, i.e. $\Omega_0 = 1$. The different growth rates in clean/abatement technology, γ_C, are a bit more complicated: The values in parentheses were chosen arbitrarily to show emissions under different settings in the previous section (see Figure 10). The baseline value $\gamma_C = 0.007$, however, is chosen such that $\gamma_{Ag} > |\gamma_\Omega + \gamma_\sigma| \; \forall \, t$. This implies, as shown, that in the absence of structural transformation emissions would grow. This decision is motivated by Empirical Fact 3. Moreover, my parameter constellations also capture the emission intensity related Empirical Fact 4.

T	$\bar{c}_g$	$\bar{c}_s$	α	β	χ	ν	Ω_0	γ_C
200	1/7	6/7	0.15	0.985	1; (0.5); (0)	0.875	1	0.007; (0.015); (0.026)
$A_{g,0}$	$A_{s,0}$	γ_{Ag}	γ_{As}	L	L_{g0}	L_{s0}	P_0	$\tau_{g,t}$
1	1	0.02	0.01	1	0.4	0.6	0	$\{\cdot\}$

Table 1: Baseline parameters

The parameter for the share of pollution that remains from the previous period, ν, is taken from Bartz and Kelly (2008) who calculated the rate of decay of the stock of pollution ($1 - \nu = 0.125$) for different pollutants. The parameter for the disutility of pollution, χ, is taken from Andreoni and Levinson (2001). However, at several instances I show the implications of alternative values: $\chi = 0.5, \chi = 0$. I set the level of initial pollution, P_0 to zero. This is a very conservative guess considering that the economy starts around the time when the industry share is at its peak and thus has already emitted pollution until this moment. Table 1 presents these parameters in a compact way.

Finally, the tax rate is not calibrated but chosen exogenously or as part of the model solution. In fact, the previous section with laissez-faire policies ($\tau_{g,t} = 0$) implied that there was no channel from the environment back to structural change. In the next section, however, I look at the effects of environmental polices in the form of (sin) taxes on goods consumption. These effects influence the goods share σ_t and its change rate γ_σ and consequently constitute the channel from the environment to structural transformation.

3.5 Model with Environmental Policies

The first subsection presents the general implications of taxes on goods consumption, on structural transformation and consequently on emissions. In the following subsection 3.5.2 I concentrate on optimal allocations and corresponding Pigouvian taxes.

3.5.1 Exogenous taxes

I begin with exogenous (sub-optimal) taxes on goods consumption which are rebated back through lump-sum transfers: $\tau_{g,t} > 0, T_t = \tau_{g,t} c_{g,t}$. For expositional reasons I restate the intra-temporal optimality condition that was solved for goods consumption (25):

$$c_{g,t} = \frac{\alpha}{(1-\alpha)} \frac{p_{s,t}}{(p_{g,t} + \tau_{g,t})} (c_{s,t} + \bar{c}_s) + \bar{c}_g \tag{48}$$

Ceteris paribus, introducing (in contrary to a laissez-faire situation) or increasing taxes on goods consumption leads to a decrease in goods consumption. The household substitutes away from goods consumption to services consumption. Theoretically, the income effect through the rebated taxes could turn the overall effect around, i.e. taxes on goods consumption leading to an overall increase in goods consumption. However, this is not the case. In fact, going from a situation without taxes to a situation with taxes (or analogously increasing taxes) always decreases goods consumption: $c_{g,t}^{\text{tax}} < c_{g,t}^{\text{no tax}}$. The proof is in the Appendix A.1.2.

I look now at the goods labor share with taxes ($\tau_{g,t} > 0$):

$$\sigma_t = \frac{1}{(1 + (1-\alpha)\tau_{g,t} A_{g,t})} \left(\frac{1}{L} \left[\alpha \left(L + \frac{\bar{c}_s}{A_{s,t}} \right) + (1-\alpha) \frac{\bar{c}_g}{A_{g,t}} \right] + \frac{(1-\alpha)\tau_{g,t}\bar{c}_g}{L} \right) \tag{49}$$

$$\lim_{t\to\infty} \sigma_t = \lim_{t\to\infty} \underbrace{\frac{1}{(1 + (1-\alpha)\tau_{g,t} A_{g,t})}}_{=0 \text{ as } t\to\infty} \left(\underbrace{\frac{1}{L} \left[\alpha \left(L + \frac{\bar{c}_s}{A_{s,t}} \right) + (1-\alpha) \frac{\bar{c}_g}{A_{g,t}} \right]}_{=\alpha \text{ as } t\to\infty} + \frac{(1-\alpha)\tau_{g,t}\bar{c}_g}{L} \right) = 0 \tag{50}$$

The fact that increasing the price of goods consumption through the introduction of taxes, reduces goods demand is not very surprising. Concomitantly, with respect to the labor share, the introduction of taxes on goods consumption leads to a more and faster falling goods labor share compared to the no-tax situation. In fact, as the goods labor share in the laissez-faire economy converges to α, the labor share in the economy under environmental taxation converges to 0. The fact that this is introduced through the increasing productivity implies that even for very small tax rates, the goods share converges to 0 in the long-run.

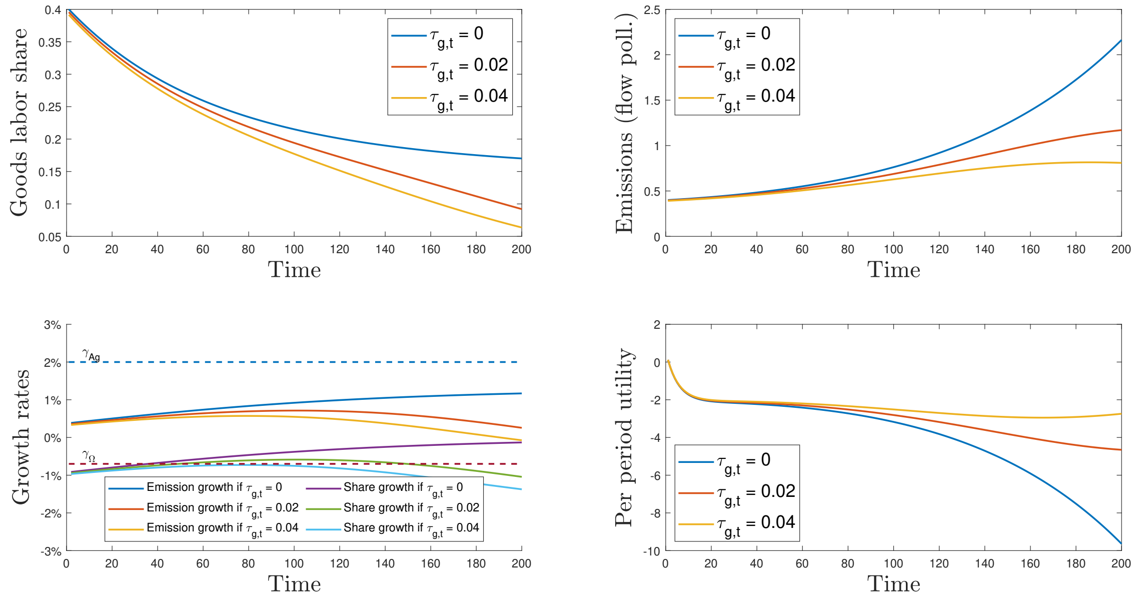

Figure 12: The evolution of emissions, the goods labor share and per period utility for different constant exogenous taxes

In Figure 12 I plot the effects of *constant* exogenous tax regimes on the goods labor share, emissions, emission growth (*not* emission intensity growth), and per period utility.[30] The blue line corresponds to the laissez-faire scenario. There, the goods share converges to α. Moreover, I imposed my baseline parameter constellation that without governmental interference would lead to emission growth in the

[30] In section A.2.1 I document the results under the same parameter constellation but instead of *constant* tax rates, the tax rate *increases* by 1% and 2% or 5% and 10% per period, respectively.

long-run. These increasing emissions lead in the long-run to very negative per-period utility. Comparing this scenario to a setup with constant exogenous taxes of 2% or 4% of the initial period's consumption yields one major finding: The growth rate of the goods labor share does not converge to zero but peaks and falls again inducing an inverted u-shape share growth rate. This reversal happens around period 100 (in this setting). After this, the goods share under taxes starts to considerably diverge from the goods share under laissez-faire. Specifically, the goods share under taxes decreases further and does not converge to α. Moreover, the structural transformation happens a bit quicker, i.e. a goods share level of around α is reached in an earlier period. Of course, the divergence in emissions and per-period utility also starts around the time the goods share diverges. Emissions under constant taxes still increase but not as fast as under laissez-faire. This behavior is reflected in the per-period utility that also falls in the tax scenarios but not as far as the utility under zero-tax.

Moreover, exogenous taxes give me another way to stress the role of structural transformation. In Figure 13 I plot the comparison between an economy without structural change and an economy with structural change. In the economy without structural change the goods labor share is constant over the whole time. On the other hand, as derived above, the goods labor share of an economy with structural change converges to α under no taxes. The two goods shares are shown in the left graph in the first line. Not surprisingly, a higher labor allocation to the goods sector implies higher production in the goods sector and consequently higher emissions if there is no structural transformation (second graph, first line).

The left plot in the second line shows a counterfactural scenario with hypothetical tax (blue line) that would induce the exact same goods consumption in an economy without structural change as in an economy with structural change but without taxes.[31] In this counterfactural economy the tax rate would first increase and then fall after around period 50. Its maximum is almost $\tau_{g,t} \approx 0.3$ which is quite high, considering the moderate tax rates 0.02 and 0.04 of Figure 12. In fact, as the red line (left graph, second line Figure 13) depicts, from around period 10 to period 60 this tax rate would correspond to at least 20% of the particular period's laissez-faire goods consumption, reaching a maximum of over 35%. This means that in order for an economy without "natural" structural change to have the same emissions (i.e. the same goods consumption) as a laissez-faire economy with structural transformation, extraordinarily high taxes would have to be imposed. This stresses the role of the composition effect in the determination of emissions. In a final step, in the right graph, second line, I plot the corresponding per period utility of such an economy without structural change where the blue line corresponds to an economy without this tax. The respective high emissions yield considerable disutilty. On the other hand, the red line corresponds to the same economy with this high hypothetical tax. Utility also decreases in this scenario but by far

[31] The mathematical derivation is done in Appendix A.1.3.

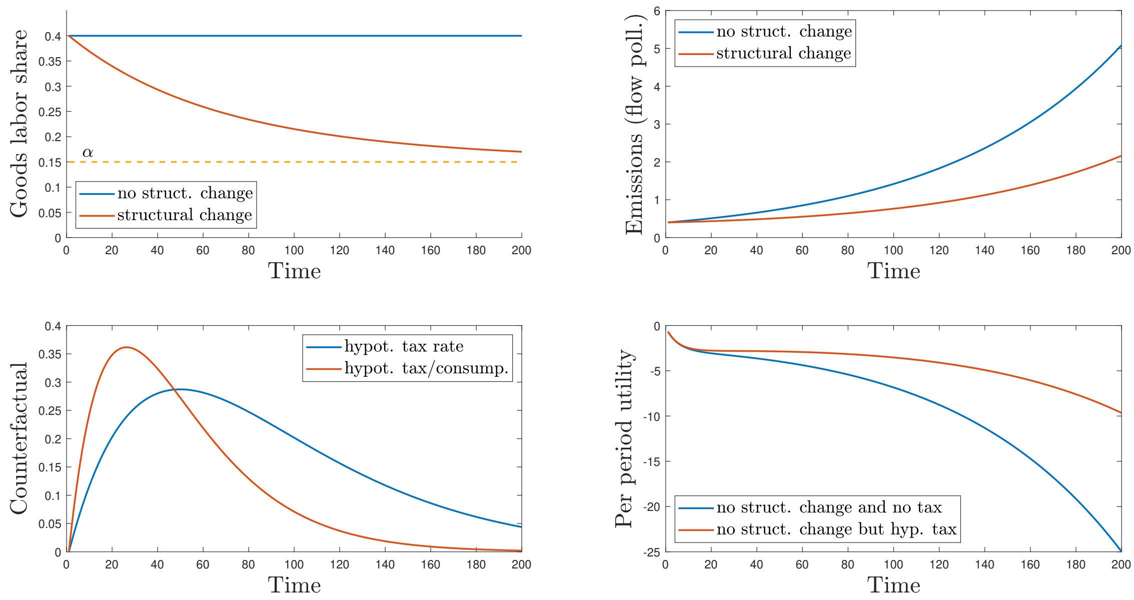

Figure 13: The effects of structural change

not as much as in the first case. Overall, Figure 13 underscores the role of structural transformation and corresponding changes in emissions.

All in all, the analysis of exogenous taxes yields two important findings: First, under taxes, the goods share growth rate loses its concave behavior. Therefore, the goods labor share decreases faster and further than under laissez-faire policies and converges to 0, which in turn leads to decreasing emissions. Second, when comparing economies with and without structural transformation, the role of the composition effect for the relative reduction in emissions is significant.

3.5.2 Pigouvian taxes

The motivation to include a government that imposes environmental policies in the first place is the negative externality from goods consumption. Intuitively, people consume but are not aware of their consumption's effects on the environment, and thus are likely to consume more than they optimally would. As a consequence of this inefficiency, the social planner would impose different allocations than the decentralized laissez-faire solution. Specifically, the government/social planner takes the negative externality of consumption into account when determining the amount of goods to be consumed and consequently produced. In a decentralized setting, the planner imposes a Pigouvian tax that internalizes the external effects and leads to the same allocations within the decentralized economy that the social planner would have implemented from its centralized and benevolent position.[32] In the most general

[32] In the Appendix A.1.4 I set up the planner problem and derive the Pigouvian tax.

case, I obtain the following expression for the Pigouvian tax (in real terms):

$$\frac{\tau_{g,t}}{p_{g,t}} = \frac{\Omega_t \chi - \nu \Omega_t \frac{\mu_{t+1}}{\beta^t}}{\frac{\alpha}{(c_{g,t}-\bar{c}_g)} + \nu \Omega_t \frac{\mu_{t+1}}{\beta^t} - \Omega_t \chi} = \frac{\Omega_t \chi - \nu \frac{\Omega_t}{\Omega_{t+1}} \beta \left[\frac{(1-\alpha)}{(c_{s,t+1}+\bar{c}_s)} \frac{A_{s,t+1}}{A_{g,t+1}} - \frac{\alpha}{(c_{g,t+1}-\bar{c}_g)} \right]}{\frac{\alpha}{(c_{g,t}-\bar{c}_g)} + \nu \frac{\Omega_t}{\Omega_{t+1}} \beta \left[\frac{(1-\alpha)}{(c_{s,t+1}+\bar{c}_s)} \frac{A_{s,t+1}}{A_{g,t+1}} - \frac{\alpha}{(c_{g,t+1}-\bar{c}_g)} \right] - \Omega_t \chi} \tag{51}$$

A straightforward way to interpret the Pigouvian tax is by looking at it from marginal utility and marginal distutility perspectives. The optimal real tax on goods consumption is the ratio between the negative external marginal goods consumption effect (through pollution) on utility and the overall marginal goods consumption effect on utility:

$$\frac{\tau_{g,t}}{p_{g,t}} = \frac{\frac{\partial v}{\partial P_t} \frac{\partial P_t}{\partial c_{g,t}}}{\frac{\partial u}{\partial c_{g,t}} - \frac{\partial v}{\partial P_t} \frac{\partial P_t}{\partial c_{g,t}}} \tag{52}$$

Specifically, the numerator corresponds to the marginal disutility per unit of goods consumption. In other words, a change in goods consumption leads to how much change in pollution ($\frac{\partial P_t}{\partial c_{g,t}}$) which in turn leads to how much change in overall welfare ($\frac{\partial v}{\partial P_t}$). Next to this effect, the denominator additionally captures the positive effect of a change in goods consumption on utility ($\frac{\partial u}{\partial c_{g,t}}$). The sum of these two changes is the total effect on welfare caused by a change in goods consumption, i.e. the marginal goods consumption effect ($\frac{\partial U}{\partial c_{g,t}}$). Thus, equation (52) implies that if there is a relatively high marginal disutility of goods consumption through pollution, the real Pigouvian tax will be higher, and if there is relatively high marginal utility of goods consumption, the real Pigouvian tax will be lower.

For ease of interpretation, I look at the two special cases *no disutility from pollution* and *flow pollutant externality* (static pollution) before analyzing the optimal solution under a *stock pollutant externality* (dynamic pollution). Note, however, that the Pigouvian tax is derived from the planner's perspective. Thus, $c_{g,t}$ refers to the goods consumption allocation the planner would have implemented under a centralized setting. Since the planner takes the particular externality into account, $c_{g,t}$ from the static setting is different than the $c_{g,t}$ in the dynamic setting. Therefore, the comparison of the different environmental policies is not possible in a purely analytical way.

No disutility from pollution

If the household does not value the environment and therefore does not experience disutility from environmental pollution, there is no externality. Thus, there is no need for a Pigouvian tax and the planner's solution should be identical to the unrestricted household optimization. Analytically, this implies that $\chi = 0$ (no disutility from pollution) and $\mu_t = 0 \ \forall \ t$ (a shadow price of 0 of the pollution dynamics equation, i.e. the pollution dynamics equation does not show up in the welfare maximization):

$$\mu_t = 0, \chi = 0 \quad \overset{(51)}{\Rightarrow} \quad \tau_{g,t}^{(\chi=0)} = 0 \tag{53}$$

$$\text{Moreover:} \quad \mu_t = 0 \quad \overset{(A.12)}{\Rightarrow} \quad \frac{\alpha}{(1-\alpha)} = \frac{p_{g,t}}{p_{s,t}} \frac{(c_{g,t} - \bar{c}_g)}{(c_{s,t} + \bar{c}_s)} \tag{54}$$

Equation (54) implies that the optimal relative *gross expenditures*[33] are equal to the relative preferences parameters. For example, a higher valuation of goods consumption (a higher α) implies higher gross expenditure on goods. Of course, this equation is the household's intra-temporal optimality condition absent of taxes (24). In conclusion, if the household is unaffected by the environment, it is optimal for the social planner to not impose a tax on goods consumption. Hence, no tax implies the laissez-faire scenario and above's analysis of the composition effect on the environment holds, though obviously without the disutility from pollution. Again, no taxation implies no feedback effect of the environment on structural change. Thus, in this case the goods share converges to the preference parameter α. This constitutes the optimal structural change under no disutility from pollution.

Flow pollutant externality

Another simplifying case is pollution being a flow pollutant. In this special case, there is no accumulation of pollution, and the pollution disutility stems merely from the effective emissions in this particular period. In other words, the problem is completely static. In my setup this translates to $\nu = 0 \overset{(16)}{\Rightarrow} P_t = \Omega_t E_t$:

$$\nu = 0 \quad \overset{(51)}{\Rightarrow} \quad \frac{\tau_{g,t}^{(\nu=0)}}{p_{g,t}} = \frac{\chi \Omega_t}{\frac{\alpha}{(c_{g,t} - \bar{c}_g)} - \chi \Omega_t} > 0 \tag{55}$$

The interpretation of the static Pigouvian tax is analogous to above's interpretation with the particularity that goods consumption has a mere instantaneous effect on marginal disutility. Specifically, the numerator corresponds to the disutility per unit of goods consumption, i.e. the disutility of effective emissions. The denominator includes the marginal utility of goods consumption in addition. Both numerator and denominator are positive.[34] Clearly, a positive tax on goods decreases the consumption. This implies that the (socially) optimal structural change and the structural change under the laissez-faire equilibrium

[33] *Gross expenditure* refers to the prices times *gross consumption*. The latter means actual goods (services) consumption minus (plus) the subsistence term. This contrasts *net consumption* which merely refers to the consumption item without the subsistence term.

[34] Since $\nu = 0$, (A.9) implies that $\mu_t = -\beta^t \chi_t$, I can replace this in (A.7). There, in the optimality conditions I can also see that the numerator and denominator of the Pigouvian tax are both larger than zero and thus, a social planner would impose a positive Pigouvian tax on goods.

differ.

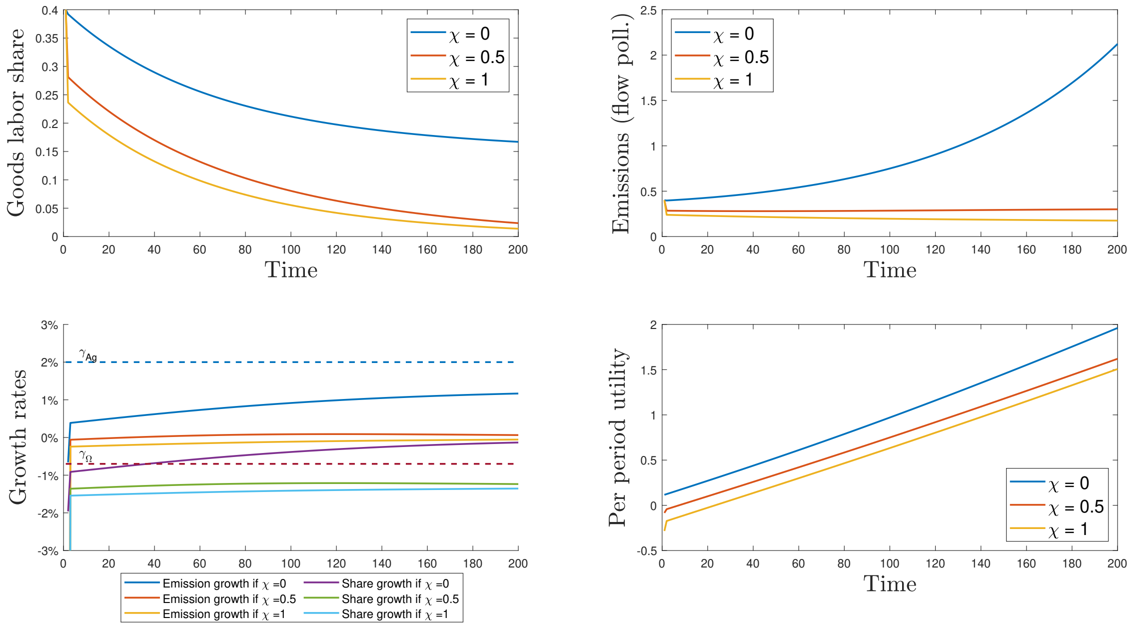

Figure 14: Optimal solutions for different levels of pollution disutility in a static setup

Figure 14 shows optimal solutions for this static setup, i.e. disutility stemming only from a flow pollutant.[35] Moreover, I plot different solutions for three different levels of disutility from emissions: $\chi = 0, \chi = 0.5, \chi = 1$. The former one implies that there is no disutility from emissions (this corresponds to the previous subsection) and the social planner would therefore impose the identical allocations than under a laissez-faire scenario. Thus, in this case, the goods share falls but converges "merely" to the preference parameter α and emissions increase over time. Moreover, since per period utility is only determined by consumption, the increase in emissions does not matter and per period utility rises.

On the other hand, the optimal solutions to a static emission disutility of $\chi = 0.5$ or $\chi = 1$ are fairly similar to each other. As established above, the goods share converges to zero and also emission levels stay around their initial level. Finally, per period utility increases linearly after the jump in the first period. It would be wrong, however, to associate the different utility levels to the different policies. In fact, the per period utility under the respective emission disutility would always be lower (equal for $\chi = 0$) in a laissez-faire scenario than in the social planner case.

Stock pollutant externality

Now, I am equipped to interpret the optimal solution with a dynamic aspect via the introduction of accumulating pollution that generates disutility. Note that whereas the static emission disutility setup could

[35]The jump in the first period's goods labor share and second period's growth rates stems from the imposed goods and services labor allocations in the first period. This corresponds to the goods labor share of a laissez-faire economy. In other words, the first period in the plots can be interpreted as an economy *before* the implementation of policies.

be solved by finding the root of a quadratic equation per period, the optimal solution under accumulating pollution is intertemporally linked. Specifically, the fact that the current level of pollution also depends on last period's pollution, requires that goods consumption is dynamically optimally chosen. I reach this solution with a non-linear least squares problem solver. In Appendix A.3 I present the equations that I use in the non-linear least squares solver.

In a similar fashion as under the static pollution equation, here it is also possible to induce the optimal solution under a decentralized setting with a Pigouvian tax. I restate the optimal Pigouvian tax (51):

$$\frac{\tau_{g,t}}{p_{g,t}} = \frac{\Omega_t \chi - \nu \frac{\Omega_t}{\Omega_{t+1}} \beta \left[\frac{(1-\alpha)}{(c_{s,t+1}+\bar{c}_s)} \frac{A_{s,t+1}}{A_{g,t+1}} - \frac{\alpha}{(c_{g,t+1}-\bar{c}_g)} \right]}{\frac{\alpha}{(c_{g,t}-\bar{c}_g)} + \nu \frac{\Omega_t}{\Omega_{t+1}} \beta \left[\frac{(1-\alpha)}{(c_{s,t+1}+\bar{c}_s)} \frac{A_{s,t+1}}{A_{g,t+1}} - \frac{\alpha}{(c_{g,t+1}-\bar{c}_g)} \right] - \Omega_t \chi} \tag{56}$$

The expression in the square brackets looks very similar to the intra-temporal optimality condition moved one period into the future. In fact, the term in the square brackets together with the division by Ω_{t+1} and this all discounted back to the current period via the discount factor β, corresponds to μ_{t+1}. Thus, it can be interpreted as the shadow price of one unit of pollution in period $t+1$. The natural degeneration ν implies that it refers to the part of pollution that is inter-temporal, i.e. the remaining part of today's pollution that will affect tomorrow's utility. Finally this expression is multiplied with today's abatement, i.e. if the amount of goods output that will be produced tomorrow would have been produced today, to how much emission (with the abatement technology of today and not tomorrow) would this have led to. The marginal utility/disutility interpretation also works here with the property that marginal disutilty of consumption today has an additional temporal effect on future periods.

This implies that, as expected, if the social planner takes the dynamic nature of pollution into account, i.e. acknowledging that there will be future disutility from emissions today via the accumulation of pollution, the socially optimally implemented solution is different. Concretely, there will be even less goods consumed, thus produced, and therefore less emissions emitted than under a "merely" static pollution scenario. Of course, it does not matter whether the social planner implements these allocations from a centralized perspective or whether the planner levies Pigouvian taxes. In the end, in the optimal scenario the equilibrium outcome is identical between a centralized solution and a decentralized solution with optimal Pigouvian taxes.

The findings with respect to stock pollution are shown in Figure 15 and Figure 16 with $\chi = 1$.[36] The former one compares the economy under a laissez-faire economy (blue line) to an optimal solution in the case of a stock pollutant. The laissez-faire economy has already been interpreted, except for its stock

[36] In the Appendix A.2.2 I document the the same graphs with pollution disutility of $\chi = 0.5$ and $\chi = 0.1$. The results are very similar.

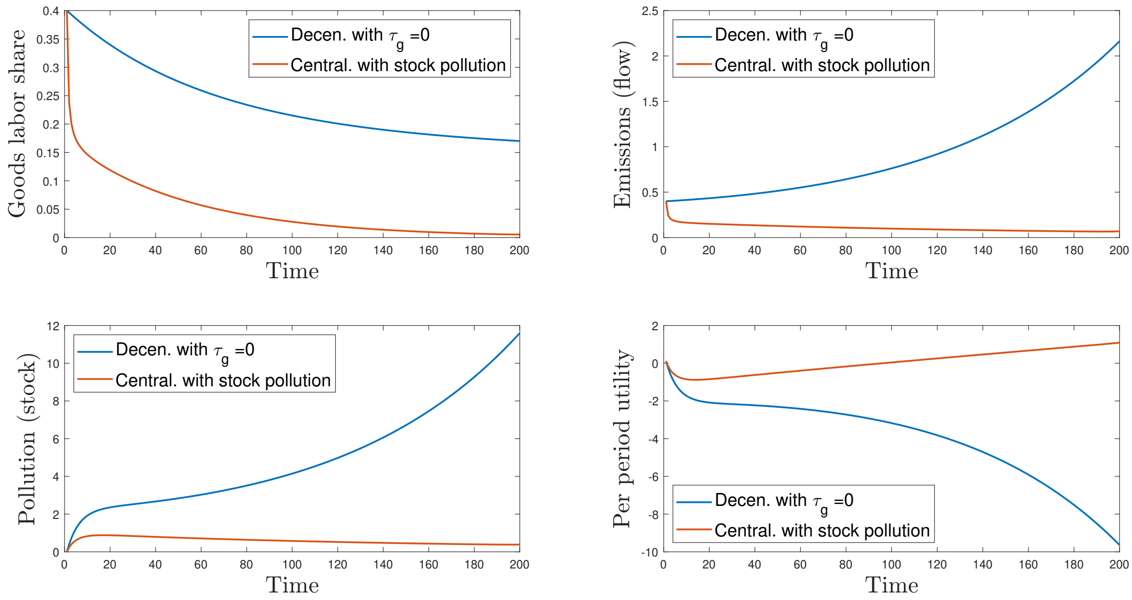

Figure 15: Decentralized vs. centralized solution to stock pollution

pollution, which I depict in the left plot in the second line. This clearly accumulates as emissions increase. Over time the increasing pollution leads to strongly falling per-period utility. On the other hand, the centralized optimal solution under a dynamic pollution setting exhibits a quickly falling goods labor share. In fact, already around the tenth period, the goods share is smaller than α and thus smaller than the goods share ever gets in the decentralized economy. Moreover, the overall emissions are very close to zero. Nonetheless, the stock pollution increases a little and then falls (this is clearer in Figure 16). In conclusion, Figure 15 implies increasing per-period utility under an optimal environmental policy, whereas no policy leads to immense disutility.[37]

Another interesting comparison is given by Figure 16. Specifically, these graphs show the difference between a centralized economy in response to static pollution disutility (previous subsection) and a centralized economy in response to dynamic pollution disutility. I assume that there is disutility from accumulating (stock) pollution; however, under one scenario (blue line) the government mistakenly imposes the polices that would have been optimal under a flow pollutant. In the other scenario (red line), the government implements the optimal policy for this pollution setting. Specifically, the left plot in the first line shows that if the planner takes the dynamic nature of accumulating pollution into account, the governmental reaction is more extreme. Concretely, the goods labor share shrinks faster than under a static setting. This of course implies lower emissions (even though the emissions in a static setting are also falling over time) and less stock pollution. The associated per-period utility is also higher, though the per period utility rises in both scenarios. Interestingly, the stock pollution exhibits for both cases an

[37] In the Appendix A.2.3 I present the corresponding goods tax in a similar manner as in Figure 13.

EKC, where the falling part stems from the increased degeneration and smaller emissions over time.

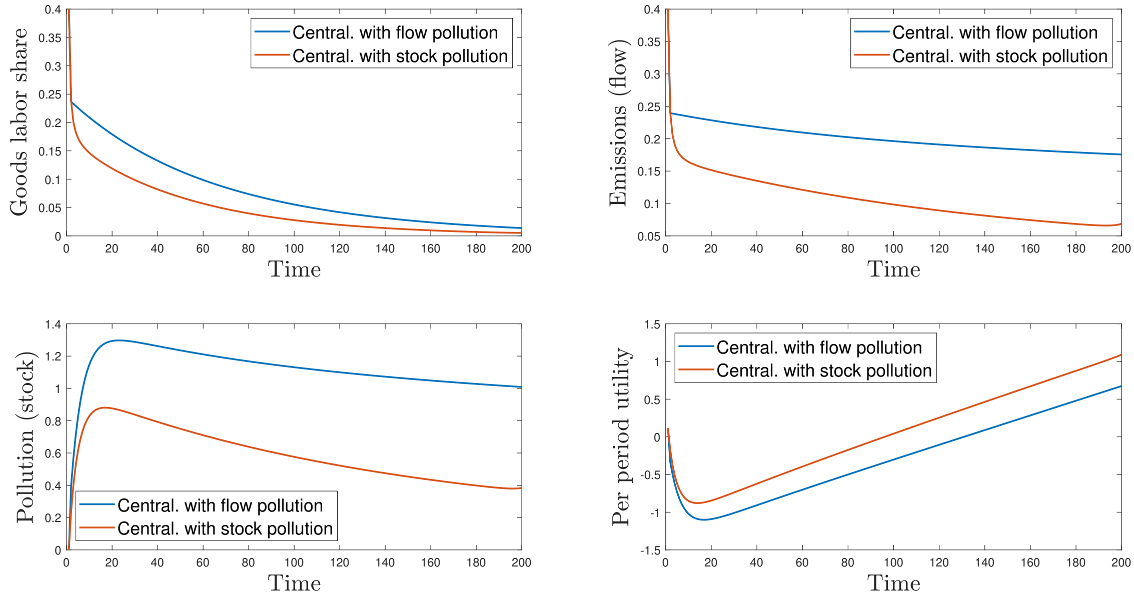

Figure 16: Solution to centralized flow vs. stock pollution

To sum up, I have shown that under both exogenous and optimal environmental policies structural transformation accelerates and the goods share converges to zero instead of converging to the preference parameter α. A government taking the dynamic nature of pollution, i.e. the role of CO_2 accumulation for climate change, into account, imposes very quickly a very low goods share. The implications of the different policies for utility are summarized as follows: A complete laissez-faire situation (assuming no negative effects of climate change) has by far the gravest per-period utility. Mistakenly imposing polices for a static pollution yield higher pollution and consequently lower utility levels than when taking the intertemporal effects of CO_2 emissions into account. Finally, policies for the dynamic pollution setting are most stringent but thereby induce the highest per period utility of the three scenarios.

Recall that my parameters were calibrated to match the USA in 1950. In section 2.1 I showed that this structural composition is very similar to regions with developing countries today. Therefore, the analyses of taxes do not only correspond to a theoretical or counterfactural scenario of what would have happened if the USA would have imposed environmental policies in 1950. In fact, these analyses can be transferred to (some) developing countries today and their reactions to possible global CO_2 taxes. In line with this reasoning, CO_2 taxes generally increase the speed of structural transformation in developing regions. More stringent policies, which account for the accumulating effects of emissions for climate change, would induce an even more quickly falling goods share. The economic and social costs of such quick transformation are outside of this thesis' scope and are left for future research. Other model related areas for future research and a discussion of central assumptions are given in the next section.

4 Caveats and Areas for Further Research

In this section I discuss the implications of some central assumptions of my model and argue how I would expect these discussion points to influence my results. Generally, they constitute promising areas for future research.

Clean service sector

My model assumes that the service sector is completely clean. This assumption, of course, generates the analytical simplicity that CO_2 taxes would only be levied on goods consumption and not on services consumption. From an empirical perspective, however, this is a stretch. For example, Kaika and Zervas (2013b) mention that the emissions intensive transport (sub)sector falls into the service sector and that high-end services occupations rely heavily on IT and infrastructure. Therefore, a split into *clean* and *dirty* along aggregate services and goods is debatable. Nonetheless, there are two reasons supporting my model's assumption in this context: First, from a developmental perspective, lower-end services production is much more human dependent and thus less energy intensive than goods production. In fact, since my model refers to the overall structural transformation, the lower-end, less emission intensive services, play a considerable role.

The other reason builds on ignored spill-over effects from increased wealth on preferences. In fact, some scholars of the EKC literature argue that the disutility of pollution increases with income (see e.g. Di Vita (2004)). If the disutility parameter increases as income rises, the social planner would impose allocations with even less goods consumption over time. Hence, since economic growth and increases in services consumption coincide, the effect of this higher disutility can be, for simplicity reasons, attributed to the increasing services share (becoming richer). This way, the ignored spill-over effect leading to less goods consumption could be, in a very simplistic manner, associated to my service sector being clean. Nonetheless, a more disaggregated approach of the overall sectors or maybe of clean and dirty services could generate a more involved pattern.

Intertemporal household decisions

A relatively straightforward way to incorporate dynamic household decisions would be to use the model of Herrendorf, Rogerson, and Valentinyi (2014) who present the model by Kongsamut, Rebelo, and Xie (2001). It would not make a difference to stick to my two consumption items, goods and services, instead of agriculture, industry, and services. The main distinction in their setup is that the production functions are not linear in labor anymore but also have capital as an input. Capital itself follows the canonical law of motion of capital, and therefore the household decisions are not static anymore. However, a central point is the derivation that the overall household's maximization problem can be split into an *intertemporal* and an *intratemporal* problem (see section 6.3.2 in Herrendorf, Rogerson, and Valentinyi (2014)). Thus, after allocating total income among composite consumption and future capital (the *intertemporal problem*), the subsequent analysis of splitting the total per period expenditure among goods and services consumption (the *intratemporal problem*) is analogous to my main section's analysis. Therefore, the incorporation of the environment into a model of structural change which includes capital would probably not induce major differences in the findings. Nonetheless, it would still be of interest to test this hypothesis.

Population dynamics

In my model I set population size to be constant. However, introducing population growth could have intriguing implications. Sticking to the assumption of inelastic labor supply, the population size would be equal to the labor force. Therefore, the market clearing conditions would become $Y_{i,t} = L_t c_{i,t},\ i \in \{g, s\}$ and the lowercase letters should be interpreted as per-capita variables. Generally, an exogenous positive growth rate of population would not alter the analysis. In this case, the scale effect should be seen as the the composite of the two growth rates population growth and productivity growth. This way, positive population growth would just introduce another variable but not affect the analysis in any major way.

A more promising setup would be to endogenize the population growth rate. In doing so, the falling population growth rate could be linked to the effects of structural change which in itself affects the environment. Considering that richer countries and regions tend to have decreasing population growth rates, the qualitative behavior of population growth seems related to the development of the goods share over time. In other words, endogenous population growth could be modeled as the inverse of the goods share growth rate, maybe with some lag. This would constitute a model with a falling goods share, i.e. negative growth that converges to 0 and, on the other hand, leveling out population, i.e positive growth that converges to 0. Generally, analyses taking population growth into account could lead to a less clear relationship between the economic structural transformation and emissions. Therefore, this could be a very promising future endeavor.

Abatement

In contrast to many models in environmental macroeconomics, I set up abatement as exogenous. Though, on a very superficial level, my model implicitly takes abatement into account when the social planner optimizes over optimal pollution. Generally, Bartz and Kelly (2008) show how a setup with endogenous abatement is isomorphic to a setup with pollution as an input in production. Since the focus of my thesis is on the effect of structural change on emissions and because the modelling of structural transformation relies on my simple production functions, I restrained from endogenous abatement. Possibly, in an analogous manner as capital in the production function, endogenous abatement could be modeled here. Moreover, modeling abatement as an endogenous control variable would put a stronger emphasis on the intra-household trade-off between goods consumption and the environment. In doing so, the pollution disutility would have to lose its externality character to some extent. Nonetheless, setting up abatement as a control variable, could affect the results in either direction.

Calibration

On a related note, calibrating the abatement growth rate closer to some actual data would locate my model closer to reality. More generally, the overall issue of calibration plays a particular role in the context of whether developing countries develop similarly as developed countries. Even though my data references convey a largely homogeneous development, in section 2.2 I mentioned several studies emphasizing the heterogeneity between developing and developed countries' structural transformation. One relevant reason might be the difference that I looked at geographical aggregates, whereas other authors focused on specific countries. Thus, using my model on more disaggregated data could shed some light on this controversy.

Policies

My analysis of optimal environmental policies in a decentralized setting referred to the use of Pigouvian taxes. However, in order to derive an optimal Pigouvian tax the social planner would need to know the optimal allocations and uncertain, possibly heterogeneous parameters such as the disutility of pollution. As a consequence of that, the theoretical optimal Pigouvian tax has only limited use in practical policy making. This issue, however, is not unique to my analysis. Some scholars, e.g. Golosov et al. (2014) impose some rather strong assumptions, which in turn allow them to derive a Pigouvian tax that does merely depend on a few parameters. Possibly, a similar approach could be used in my model.

Moreover, the introduction of other taxes and/or subsidies and thus the role of second-best taxation could influence the interaction of structural change and emissions. Another omitted area in the aspect of goods taxation is the issue of heterogeneous consumers. Specifically, poorer households consume more goods and are therefore more affected by environmental taxes. Therefore, environmental policies act like regressive taxation (Klenert et al. (2018)). This is, to some extent, another dimension but still of high relevance, especially in a setting with developing and developed countries and global CO_2 taxes.

5 Conclusion

This thesis developed a model capturing the circular relationship between structural transformation and the environment. The structural component is widely neglected by standard one-sector IAM. Thus, this model can account for the differing CO_2 emissions stemming from the sectoral shift of the goods sector to the service sector. The composition effect captures this relationship. In addition to this effect, the model also includes the scale effect, i.e. increasing emissions due to increased production, and the technique effect, which exogenously decreases effective emissions per unit of goods output. Finally, the emissions accumulate to pollution which itself induces disutility, however, in the form of an externality.

The analysis of exogenous taxes yields two findings. First, under CO_2 taxes, the goods share falls faster and converges to zero instead of converging to the preference parameter $\alpha > 0$. Second, the considerable role of the composition effect is illustrated in the comparison between an economy without structural transformation but with a hypothetical tax and an economy with structural change. In fact, to achieve the same structural transformation in both economies, the former one would need tax rates of up to 35 percent of laissez-faire consumption.

Taking the disutility caused by pollution into account, an optimal planner's solution, or analogously, Pigouvian taxes can be derived. The Pigouvian tax scenarios stress the role of the accumulation of emissions to pollution by conveying that optimal structural transformation is considerably quicker than laissez-faire structural change. Moreover, the difference between optimal allocations of a static pollution setting and optimal allocations of a dynamic pollution setting underscore that policies which take the intertemporal dimension of CO_2 emissions for climate change into account are more stringent. In a more real world related context, these findings imply that imposing global CO_2 taxes would lead to increases in the speed of structural transformation of developing countries. Moreover, structural change would accelerate even more if policies are targeted more rigorously against climate change.

Finally, there are issues which are not covered in this model or that are kept very simplistic. Examples of these topics are the completely clean service sector, no capital in the production function, abstraction from population growth, exogenous abatement, calibration to geographical aggregates, and that there are no other policies apart from the environmental taxation. These and many other areas are left for future research. Nonetheless, this model intended to bring structural transformation into the center of an economic growth model with accumulating emissions. Consequently, the composition effect and its interaction with environmental policies should be taken into account, especially in models analyzing the nexus between economic development and climate change.

6 Bibliography

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous (2012). “The Environment and Directed Technical Change”. *American Economic Review* 102(1), pp. 131–166.

Acemoglu, Daron and Veronica Guerrieri (2008). “Capital Deepening and Nonbalanced Economic Growth”. *Journal of Political Economy* 116(3), pp. 467–498.

Andreoni, James and Arik Levinson (2001). “The Simple Analytics of the Environmental Kuznets Curve”. *Journal of Public Economics* 80(2), pp. 269–286.

Antoci, Angelo, Paolo Russu, Serena Sordi, and Elisa Ticci (2014). “Industrialization and Environmental Externalities in a Solow-Type Model”. *Journal of Economic Dynamics and Control* 47, pp. 211–224.

Apergis, Nicholas (2016). “Environmental Kuznets Curves: New Evidence on Both Panel and Country-Level CO2 Emissions”. *Energy Economics* 54, pp. 263–271.

Bah, El Hadj (2011). “Structural Transformation Paths Across Countries”. *Emerging Markets Finance and Trade* 47(5), pp. 5–19.

Bartz, Sherry and David L Kelly (2008). “Economic Growth and the Environment: Theory and Facts”. *Resource and Energy Economics* 30(2), pp. 115–149.

Boppart, Timo (2014). “Structural Change and the Kaldor Facts in a Growth Model With Relative Price Effects and Non-Gorman Preferences”. *Econometrica* 82(6), pp. 2167–2196.

Bovenberg, A. Lans and Sjak Smulders (1995). “Environmental Quality and Pollution-Saving Technological Change in a Two-Sector Endogenous Growth Model”. *Journal of Public Economics* 57(9321), pp. 369–391.

Brock, William A and M Scott Taylor (2010). “The Green Solow Model”. *Journal of Economic Growth* 15(2), pp. 127–153.

Caselli, Francesco and Wilbur John Coleman (2001). “The U.S. Structural Transformation and Regional Convergence: A Reinterpretation”. *Journal of Political Economy* 109(3), pp. 584–616.

Chenery, Hollis B (1971). “Growth and Structural Change”. *Finance and Development* 8(3), pp. 16–27.

Colapinto, Cinzia, Danilo Liuzzi, and Simone Marsiglio (2017). “Sustainability and Intertemporal Equity: A Multicriteria Approach”. *Annals of Operations Research* 251(1-2), pp. 271–284.

Comin, Diego A, Danial Lashkari, and Martí Mestieri (2015). “Structural Change with Long-run Income and Price Effects”. *National Bureau of Economic Research Working Paper Series* No. 21595.

Dasgupta, Partha and Geoffrey Heal (1974). “The Optimal Depletion of Exhaustible Resources”. *Review of Economic Studies* 41, pp. 3–28.

Di Vita, Guiseppe (2004). “Another Explanation of Pollution–Income Patterns”. *International journal of environment and pollution* 21(6), pp. 588–592.

Diao, Xinshen, Margaret McMillan, and Dani Rodrik (2019). "The Recent Growth Boom in Developing Economies: A Structural-Change Perspective". In: *The Palgrave Handbook of Development Economics*. Ed. by M. Nissanke and J. A. Ocampo. Palgrave Macmillan, Cham, pp. 281–334.

Duarte, Margarida and Diego Restuccia (2010). "The Role of Structural Transformation in Aggregate Productivity". *Quarterly Journal of Economics* 125, pp. 129–173.

Echevarria, Cristina (1997). "Changes in Sectoral Composition Associated with Economic Growth". *International Economic Review* 38(2), pp. 431–452.

Eckert, Fabian and Michael Peters (2018). "Spatial Structural Change". *2018 Meeting Papers 98, Society for Economic Dynamics*.

Egli, Hannes and Thomas M. Steger (2007). "A Dynamic Model of the Environmental Kuznets Curve: Turning Point and Public Policy". *Environmental and Resource Economics* 36(1), pp. 15–34.

Engel, Ernst (1857). "Die Productions-und Consumtionsverhältnisse des Königreichs Sachsen". *Zeitschrift des Statistischen Bureaus des Königlich Sächsischen Ministeriums des Innern* 8, pp. 1–54.

Fischer, Carolyn and Garth Heutel (2013). "Environmental Macroeconomics: Environmental Policy, Business Cycles, and Directed Technical Change". *Annual Review of Resource Economics* 5(1), pp. 197–210.

Foellmi, Reto and Josef Zweimüller (2008). "Structural Change, Engel's Consumption Cycles and Kaldor's Facts of Economic Growth". *Journal of Monetary Economics* 55(7), pp. 1317–1328.

Forster, Bruce A (1973). "Optimal Capital Accumulation in a Polluted Environment". *Southern Economic Journal* 39(4), pp. 544–547.

Fujii, Hidemichi and Shunsuke Managi (2016). "Economic Development and Multiple Air Pollutant Emissions from the Industrial Sector". *Environmental Science and Pollution Research* 23(3), pp. 2802–2812.

Gabardo, Francisco Adilson, João Basilio Pereima, and Pedro Einloft (2017). "The Incorporation of Structural Change into Growth Theory: A Historical Appraisal". *EconomiA* 18(3), pp. 392–410.

Geary, Roy C. (1950). "A Note on 'A Constant-Utility Index of the Cost of Living'". *Review of Economic Studies* 18(2), pp. 65–66.

Gollin, Douglas, Stephen Parente, and Richard Rogerson (2002). "The Role of Agriculture in Development". *American Economic Review* 92(2), pp. 160–164.

Golosov, Mikhail, John Hassler, Per Krusell, and Aleh Tsyvinski (2014). "Optimal Taxes on Fossil Fuel in General Equilibrium". *Econometrica* 82(1), pp. 41–88.

Goulder, Lawrence H. (2013). "Climate Change Policy's Interactions With the Tax System". *Energy Economics* 40, S3–S11.

Grossman, Gene M. and Alan B Krueger (1993). "Environmental Impacts of a North American Free Trade Agreement". In: *The US-Mexico Free Trade Agreement*. Ed. by Peter M. Garber. MIT Press: Cambridge, MA, pp. 13–56.

Hartman, Richard and O. Sung Kwon (2005). "Sustainable Growth and the Environmental Kuznets Curve". *Journal of Economic Dynamics and Control* 29(10), pp. 1701–1736.

Hassler, John and Per Krusell (2018). "Environmental Macroeconomics: The Case of Climate Change". In: *Handbook of Environmental Economics*. Ed. by Partha Dasgupta, Subhrendu K. Pattanayak, and V. Kerry Smith. 4th ed. Elsevier, pp. 333–394.

Hassler, John, Per Krusell, and Conny Olovsson (2018). "The Consequences of Uncertainty: Climate Sensitivity and Economic Sensitivity to the Climate". *Annual Review of Economics* 10(1), pp. 189–205.

Hassler, John, Per Krusell, and Anthony A. Smith (2016). "Environmental Macroeconomics". In: *Handbook of Macroeconomics*. Ed. by John B. Taylor and Harald Uhlig. 2nd ed. Elsevier, pp. 1893–2008.

Heal, Geoffrey (2005). "Chapter 21 Intertemporal Welfare Economics and the Environment". In: *Handbook of Environmental Economics*. Ed. by Karl-Göran Mäler and J.R. Vincent. 3rd ed. Elsevier, pp. 1105–1145.

Herrendorf, Berthold, Christopher Herrington, and Ákos Valentinyi (2015). "Sectoral Technology and Structural Transformation". *American Economic Journal: Macroeconomics* 7(4), pp. 104–133.

Herrendorf, Berthold, Richard Rogerson, and Ákos Valentinyi (2014). "Growth and Structural Transformation". In: *Handbook of Economic Growth*. Ed. by Philippe Aghion and Steven N. Durlauf. 2nd ed. Elsevier, pp. 855–941.

Jackson, Tim (2017). *Prosperity without Growth: Foundations for the Economy of Tomorrow*. Routledge: New York, NY.

Kaika, Dimitra and Efthimios Zervas (2013a). "The Environmental Kuznets Curve (EKC) Theory-Part A: Concept, Causes and the CO2 Emissions Case". *Energy Policy* 62, pp. 1392–1402.

Kaika, Dimitra and Efthimios Zervas (2013b). "The environmental Kuznets Curve (EKC) Theory. Part B: Critical Issues". *Energy Policy* 62, pp. 1403–1411.

Kaldor, Nicholas (1967). *Strategic Factors in Economic Development*. Cornell University Press: Ithaca, N.Y.

Kelly, David L (2003). "On Environmental Kuznets Curves Arising from Stock Externalities". *Journal of Economic Dynamics and Control* 27, pp. 1367–1390.

Kijima, Masaaki, Katsumasa Nishide, and Atsuyuki Ohyama (2010). "Economic Models for the Environmental Kuznets Curve: A Survey". *Journal of Economic Dynamics and Control* 34(7), pp. 1187–1201.

Klenert, David, Gregor Schwerhoff, Ottmar Edenhofer, and Linus Mattauch (2018). "Environmental Taxation, Inequality and Engel's Law: The Double Dividend of Redistribution". *Environmental and Resource Economics* 71(3), pp. 605–624.

Kongsamut, Piyabha, Sergio Rebelo, and Danyang Xie (2001). "Beyond Balanced Growth". *Review of Economic Studies* 68(4), pp. 869–882.

Kuralbayeva, Karlygash and Radoslaw Stefanski (2013). "Windfalls, Structural Transformation and Specialization". *Journal of International Economics* 90(2), pp. 273–301.

Kuznets, Simon (1955). "Economic Growth and Income Inequality". *American Economic Review* 45(1), pp. 1–28.

Kuznets, Simon (1966). *Modern Economic Growth*. Yale University Press: New Haven, CT.

Lewis, W. Arthur (1954). "Economic Development with Unlimited Supplies of Labour". *Manchester School* 22(2), pp. 139–191.

Lin, Justin Yifu and Yong Wang (2017). "Remodeling Structural Change". *China Center for Economic Research Working Paper Series* E2017005.

López, Ramón E., Gustavo Anríquez, and Sumeet Gulati (2007). "Structural Change and Sustainable Development". *Journal of Environmental Economics and Management* 53(3), pp. 307–322.

López, Ramón E. and Sang W. Yoon (2013). ""Sustainable" Economic Growth: The Ominous Potency of Structural Change". *International Review of Environmental and Resource Economics* 7(2), pp. 179–203.

López, Ramón E. and Sang W. Yoon (2014). "Pollution-Income Dynamics". *Economics Letters* 124(3), pp. 504–507.

López, Ramón and Maurice Schiff (2013). "Interactive Dynamics Between Natural and Man-Made Assets: The Impact of External Shocks". *Journal of Development Economics* 104, pp. 1–15.

Matsuyama, Kiminori (1992). "Agricultural Productivity, Comparative Advantage, and Economic Growth". *Journal of Economic Theory* 58(2), pp. 317–334.

Matsuyama, Kiminori (2008). "Structural Change". In: *The New Palgrave Dictionary of Economics*. Ed. by Steven N. Durlauf and Lawrence E. Blume. 2nd ed. Palgrave Macmillan.

McMillan, Margaret, Dani Rodrik, and Claudia Sepúlveda (2017). *Structural Change, Fundamentals, and Growth*. International Food Policy Research Institue (IFPRI): Washington, D.C.

Muellbauer, John (1975). "Aggregation, Income Distribution and Consumer Demand". *Review of Economic Studies* 42(4), pp. 525–543.

Muellbauer, John (1976). "Community Preferences and the Representative Consumer". *Econometrica*, pp. 979–999.

Ngai, L. Rachel and Christopher A. Pissarides (2007). "Structural Change in a Multisector Model of Growth". *American Economic Review* 97(1), pp. 429–443.

Nordhaus, William D. (1991). "To Slow or Not to Slow: The Economics of The Greenhouse Effect". *Economic Journal* 101(407), pp. 920–937.

Nordhaus, William D. (1992). “An Optimal Transition Path for Controlling Greenhouse Gases”. *Science* 258(5086), pp. 1315–1319.

Pigou, Arthur (1920). *The Economics of Welfare*. Macmillan: London.

Ranis, Gustav and John C. H. Fei (1961). “A Theory of Economic Development”. *American Economic Review* 51(4), pp. 533–565.

Ripple, William J, Christopher Wolf, Thomas M Newsome, Phoebe Barnard, and William R Moomaw (2019). “World Scientists’ Warning of a Climate Emergency”. *BioScience* Viewpoint(biz088).

Rodrik, Dani (2016). “Premature Deindustrialization”. *Journal of Economic Growth* 21(1), pp. 1–33.

Rogerson, Richard (2008). “Structural Transformation and the Deterioration of European Labor Market Outcomes”. *Journal of Political Economy* 116(2), pp. 235–259.

Rostow, Walt Whitman (1977). *The Stages of Economic Growth: A Non-Communist Manifesto*. 2. ed. Cambridge University Press.

Selden, Thomas M. and Daqing Song (1994). “Environmental Quality and Development: Is there a Kuznets Curve for Air Pollution Emissions?” *Journal of Environmental Economics and Management* 27(2), pp. 147–162.

Stefanski, Radoslaw (2013). “On the Mechanics of the Green Solow Model”. *OxCarre Research Papers* 47.

Stefanski, Radoslaw (2014). “Structural Transformation and the Oil Price”. *Review of Economic Dynamics* 17(3), pp. 484–504.

Stern, David I. (2017). “The Environmental Kuznets Curve after 25 Years”. *Journal of Bioeconomics* 19(1), pp. 7–28.

Stern, David I., Reyer Gerlagh, and Paul J. Burke (2017). “Modeling the Emissions–Income Relationship Using Long-Run Growth Rates”. *Environment and Development Economics* 22(6), pp. 699–724.

Stokey, Nancy L (1998). “Are There Limits to Growth?” *International Economic Review* 39(1), pp. 1–31.

Stone, Richard (1954). “Linear Expenditure Systems and Demand Analysis: An Application to the Pattern of British Demand”. *Economic Journal* 64(255), pp. 511–527.

Syrquin, Moshe (1988). “Patterns of Structural Change”. In: *Handbook of Development Economics*. Ed. by H. Chenery and T. N. Srinivasan. Elsevier, pp. 203–273.

Timmer, Marcel P., Gaaitzen J. de Vries, and Klaas de Vries (2015). “Patterns of Structural Change in Developing Countries”. In: *Routledge Handbook of Industry and Development*. Ed. by J. Weiss and M. Tribe. Routledge. https://www.rug.nl/research/portal/datasets/ggdc-10sector-database(8e8fcc0d-3c13-424a-88be-7b87a31672fd).html, pp. 65–83.

Ulucak, Recep and Faik Bilgili (2018). “A Reinvestigation of EKC Model by Ecological Footprint Measurement for High, Middle and Low Income Countries”. *Journal of Cleaner Production* 188, pp. 144–157.

United Nations (2008). "International Standard Industrial Classification of All Econoimc Activities (ISIC), Rev.4". *Statistica Papers* Series M N.

Weitzman, Martin L. (2010). "What Is the "Damages Function" for Global Warming — and What Difference Might It Make?" *Climate Change Economics* 1(1), pp. 57–69.

Wolfersberger, Julien (2019). "Growth and the Environment: Taking into Account Structural Transformation". *Working Paper hal* 02156298.

World Bank (2019). "World Development Indicators DataBank". *https://datacatalog.worldbank.org/dataset/world-development-indicators*(accessed October 29, 2019).

Zoundi, Zakaria (2017). "CO2 Emissions, Renewable Energy and the Environmental Kuznets Curve, a Panel Cointegration Approach". *Renewable and Sustainable Energy Reviews* 72, pp. 1067–1075.

A Appendix

A.1 Mathematical Derivations

A.1.1 Derivation of assumptions about subsistence terms

Here, I derive how the assumption about the goods subsistence term (17) implies positive *gross* goods consumption for all periods and the assumption about the services subsistence term (18) implies positive *net* consumption of services for all periods.[38] In other words, these assumptions make sure that the maximization problem is well defined ($c_{g,t} > \bar{c}_g \Rightarrow \log(c_{g,t} - \bar{c}_g)$ exists) and the solution is interior ($c_{s,t} > 0 \Rightarrow Y_{s,t} > 0\ \forall t$). Recall that taxes on goods are $\tau_{g,t} \geqslant 0$ and the transfer is used to rebate these tax revenues $T_t = \tau_{g,t} c_{g,t}$:

$$\bar{c}_g < A_{g,0} L_{g,0} = c_{g,0} \leqslant c_{g,t}\ \forall t \quad \square \tag{A.1}$$

$$\begin{aligned}
\bar{c}_s &\leqslant \frac{1-\alpha}{\alpha} A_{s,0} L_{s,0} = \frac{1-\alpha}{\alpha} A_{s,0} \left[L - L_{g,0}\right] = \frac{1-\alpha}{\alpha} A_{s,0} \left[L - \frac{c_{g,0}}{A_{g,0}}\right] \overset{(A.1)}{<} \frac{1-\alpha}{\alpha} A_{s,0} \left[L - \frac{\bar{c}_g}{A_{g,0}}\right] \\
&\leqslant \frac{1-\alpha}{\alpha} A_{s,t} \left[L - \frac{\bar{c}_g}{A_{g,t}}\right] \leqslant \frac{1-\alpha}{\alpha} A_{s,t} \left[L + \tau_{g,t} \underbrace{\left(c_{g,t} - \bar{c}_g\right)}_{\geqslant 0\ (A.1)} - \frac{\bar{c}_g}{A_{g,t}}\right] \\
&= \frac{1-\alpha}{\alpha} A_{s,t} \left[L + T_t - \left(\frac{1}{A_{s,t}} + \tau_{g,t}\right) \bar{c}_g\right] \\
&\overset{(31)}{\Leftrightarrow} \quad c_{s,t} > 0\ \forall t \quad \square
\end{aligned} \tag{A.2}$$

[38] *Gross* consumption refers to the aggregate of consumption item and the corresponding subsistence term, whereas *net* consumption refers to the consumption item without the subsistence term.

A.1.2 Derivation of less goods consumption under taxes

Here, I show that goods consumption with taxes is always smaller than goods consumption without taxes. Thus, the substitution effect prevails over the income effect:

$$
\begin{aligned}
& 0 < L_{s,t} + \frac{\bar{c}_s}{A_{s,t}} \\
\Leftrightarrow \quad & L_{g,t} < L + \frac{\bar{c}_s}{A_{s,t}} \\
\Leftrightarrow \quad & \frac{A_{g,t}L_{g,t}}{A_{g,t}} - \frac{\bar{c}_g}{A_{g,t}} < L + \frac{\bar{c}_s}{A_{s,t}} - \frac{\bar{c}_g}{A_{g,t}} \\
\Leftrightarrow \quad & p_{g,t}\left(c_{g,t} - \bar{c}_g\right) < L + p_{s,t}\bar{c}_s - p_{g,t}\bar{c}_g \\
\Leftrightarrow \quad & p_{g,t}\tau_{g,t}\left(c_{g,t} - \bar{c}_g\right) + p_{g,t}\left[L + p_{s,t}\bar{c}_s - p_{g,t}\bar{c}_g\right] < \tau_{g,t}\left[L + p_{s,t}\bar{c}_s - p_{g,t}\bar{c}_g\right] + p_{g,t}\left[L + p_{s,t}\bar{c}_s - p_{g,t}\bar{c}_g\right] \\
\Leftrightarrow \quad & p_{g,t}\left[L + T_t + p_{s,t}\bar{c}_s - (p_{g,t} + \tau_{g,t})\bar{c}_g\right] < (p_{g,t} + \tau_{g,t})\left[L + p_{s,t}\bar{c}_s - p_{g,t}\bar{c}_g\right] \\
\Leftrightarrow \quad & \frac{\alpha}{(p_{g,t} + \tau_{g,t})}\left[L + T_t + p_{s,t}\bar{c}_s - (p_{g,t} + \tau_{g,t})\bar{c}_g\right] + \bar{c}_g < \frac{\alpha}{p_{g,t}}\left[L + p_{s,t}\bar{c}_s - p_{g,t}\bar{c}_g\right] + \bar{c}_g \\
\Leftrightarrow \quad & c_{g,t}^{\text{tax}} < c_{g,t}^{\text{no tax}} \quad \square
\end{aligned} \tag{A.3}
$$

A.1.3 Derivation tax rate under no structural change

The goods demand of an economy without structural transformation can be derived from equation (33) with $\bar{c}_s = \bar{c}_g = 0$. Practically, without the subsistence terms the utility function becomes homothetic and thus goods and services consumption and labor allocation correspond to a constant share. Starting from this equation, the derivation of the tax rate that leads to the same goods consumption under an economy without structural change as in an economy with structural change but without taxes, is straightforward: First, I use the equation to derive the goods consumption with structural change but with no taxes: $c_{g,t}^{\text{struct.},\tau_g=0}$. From this value I subtract the equilibrium goods consumption with no structural change but with taxes: $c_{g,t}^{\text{no struct.},\tau_g\neq 0}$. Since this difference is zero if both economies demand the same amount of goods, I can use this new equation to get and expression for the per period tax rate. In other words, applying this tax rate to an economy without structural change would induce the exact same goods consumption than for an economy with structural change (but no taxes):

$$
\begin{aligned}
& c_{g,t}^{\text{struct.},\tau_{g,t}=0} - c_{g,t}^{\text{no struct.},\tau_{g,t}\neq 0} = 0 \quad \Leftrightarrow \quad c_{g,t}^{\text{struct.},\tau_{g,t}=0} - \frac{\tilde{\alpha}L}{\frac{1}{A_{g,t}} + (1-\tilde{\alpha})\tau_{g,t}} = 0 \\
\Leftrightarrow \quad & \tau_{g,t} = \frac{\tilde{\alpha}L}{(1-\tilde{\alpha})c_{g,t}^{\text{struct.},\tau_{g,t}=0}} - \frac{1}{(1-\tilde{\alpha})A_{g,t}}
\end{aligned} \tag{A.4}
$$

The replacement for $c_{g,t}^{\text{no struct.},\tau_g \neq 0}$ in the first line stems from equation (33) under the condition that the subsistence terms are zero: $\bar{c}_g = \bar{c}_s = 0$. Moreover the constant goods share of the economy without structural change, corresponds to the first period's goods share of the economy with structural transformation. Theoretically, this implies a different parameter for the valuation of goods over services consumption: $\tilde{\alpha} = \frac{L_{g,0}}{L}$.

A.1.4 Derivation of Pigouvian tax

Here, I set up the planner problem that internalizes the external effects. Comparing the solution of this centralized setup with the obtained solution to the decentralized setup allows me to derive the Pigouvian tax which induces the optimal solution even in a decentralized economy. Generally, this approach is closely related to Egli and Steger (2007). The social planner chooses a sequence of goods and services consumption to maximize household's utility. However, the planner is aware of the pollution disutility and thus can internalize it:

$$U^{\text{Planner}}(c_{g,t}, c_{s,t}, P_t) = \left[\alpha \log(c_{g,t} - \bar{c}_g) + (1-\alpha)\log(c_{s,t} + \bar{c}_s) - \chi P_t\right] \tag{A.5}$$

The associated Lagrangian of this social planner welfare function subject to the resource constraint (35) and the environmental evolution equation (16) is given by:

$$\begin{aligned} \mathcal{L}^{SP} = \sum_{t=0}^{\infty} \beta^t & \left[\alpha \log(c_{g,t} - \bar{c}_g) + (1-\alpha)\log(c_{s,t} + \bar{c}_s) - \chi P_t\right] \\ & - \lambda_t \left[\frac{c_{g,t}}{A_{g,t}} + \frac{c_{s,t}}{A_{s,t}} - L\right] \\ & - \mu_t \left[P_t - \Omega_t c_{g,t} - \nu P_{t-1}\right] \end{aligned} \tag{A.6}$$

The associated first order conditions are:

$$\frac{\partial \mathcal{L}^{SP}}{\partial c_{g,t}} = 0 \quad \Leftrightarrow \quad \beta^t \frac{\alpha}{(c_{g,t} - \bar{c}_g)} + \mu_t \Omega_t = \lambda_t \frac{1}{A_{g,t}} \tag{A.7}$$

$$\frac{\partial \mathcal{L}^{SP}}{\partial c_{s,t}} = 0 \quad \Leftrightarrow \quad \beta^t \frac{(1-\alpha)}{(c_{s,t} + \bar{c}_s)} = \lambda_t \frac{1}{A_{s,t}} \tag{A.8}$$

$$\frac{\partial \mathcal{L}^{SP}}{\partial P_t} = 0 \quad \Leftrightarrow \quad \mu_{t+1}\nu - \beta^t \chi = \mu_t \tag{A.9}$$

$$\frac{\partial \mathcal{L}^{SP}}{\partial \lambda_t} = 0 \quad \Leftrightarrow \quad \frac{c_{g,t}}{A_{g,t}} + \frac{c_{s,t}}{A_{s,t}} = L \tag{A.10}$$

$$\frac{\partial \mathcal{L}^{SP}}{\partial \mu_t} = 0 \quad \Leftrightarrow \quad P_t = \Omega_t c_{g,t} + \nu P_{t-1} \tag{A.11}$$

In order to get rid of the Lagrange multipliers, (1), I plug (A.8) solved for λ_t in (A.7) which I then can solve for μ_t. (2), I plug this solution for μ_t and the same solution evaluated at $t+1$ in (A.9) which I will use in the final step. Then, (3), I insert (A.9) into (A.7). (4), I solve the result of (3) for λ_t, which I can then set equal to the decentralized household's optimization ((21), which I solved for λ_t and where I replaced the goods price with $\frac{1}{A_{g,t}}$). I solve this for the tax rate which gives me the externality internalizing Pigouvian tax rate. Finally, (5) I insert the detailed solution obtained in (2) into the tax rate equation:

$$(1): \quad \beta^t \frac{\alpha}{(c_{g,t} - \bar{c}_g)} + \mu_t \Omega_t = \beta^t \frac{(1-\alpha)}{(c_{s,t} + \bar{c}_s)} \frac{A_{s,t}}{A_{g,t}}$$

$$\Leftrightarrow \quad \mu_t = \frac{1}{\Omega_t} \beta^t \left[\frac{(1-\alpha)}{(c_{s,t} + \bar{c}_s)} \frac{A_{s,t}}{A_{g,t}} - \frac{\alpha}{(c_{g,t} - \bar{c}_g)} \right] \tag{A.12}$$

$$(2): \quad \frac{\nu}{\Omega_{t+1}} \beta^{t+1} \left[\frac{(1-\alpha)}{(c_{s,t+1} + \bar{c}_s)} \frac{A_{s,t+1}}{A_{g,t+1}} - \frac{\alpha}{(c_{g,t+1} - \bar{c}_g)} \right] - \beta^t \chi = \frac{1}{\Omega_t} \beta^t \left[\frac{(1-\alpha)}{(c_{s,t} + \bar{c}_s)} \frac{A_{s,t}}{A_{g,t}} - \frac{\alpha}{(c_{g,t} - \bar{c}_g)} \right] \tag{A.13}$$

$$(3): \quad \beta^t \frac{\alpha}{(c_{g,t} - \bar{c}_g)} + \Omega_t \left(\mu_{t+1}\nu - \beta^t \chi \right) = \lambda_t \frac{1}{A_{g,t}} \tag{A.14}$$

$$(4): \quad A_{g,t} \left[\beta^t \frac{\alpha}{(c_{g,t} - \bar{c}_g)} + \Omega_t \left(\mu_{t+1}\nu - \beta^t \chi \right) \right] = \beta^t \frac{\alpha}{c_{g,t} - \bar{c}_g} \frac{1}{\frac{1}{A_{g,t}} + \tau_{g,t}}$$

$$\Leftrightarrow \beta^t \frac{\alpha}{(c_{g,t} - \bar{c}_g)} + \Omega_t \left(\mu_{t+1}\nu - \beta^t \chi \right) + \tau_{g,t} A_{g,t} \left[\beta^t \frac{\alpha}{(c_{g,t} - \bar{c}_g)} + \Omega_t \left(\mu_{t+1}\nu - \beta^t \chi \right) \right] = \beta^t \frac{\alpha}{c_{g,t} - \bar{c}_g}$$

$$\Leftrightarrow \tau_{g,t} = \frac{-\Omega_t \left(\mu_{t+1}\nu - \beta^t \chi \right)}{A_{g,t} \left[\beta^t \frac{\alpha}{(c_{g,t} - \bar{c}_g)} + \Omega_t \left(\mu_{t+1}\nu - \beta^t \chi \right) \right]} \tag{A.15}$$

$$(5): \quad \tau_{g,t} = \frac{-\Omega_t \left(\frac{\nu}{\Omega_{t+1}} \beta^{t+1} \left[\frac{(1-\alpha)}{(c_{s,t+1} + \bar{c}_s)} \frac{A_{s,t+1}}{A_{g,t+1}} - \frac{\alpha}{(c_{g,t+1} - \bar{c}_g)} \right] - \beta^t \chi \right)}{A_{g,t} \left[\beta^t \frac{\alpha}{(c_{g,t} - \bar{c}_g)} + \Omega_t \left(\frac{\nu}{\Omega_{t+1}} \beta^{t+1} \left[\frac{(1-\alpha)}{(c_{s,t+1} + \bar{c}_s)} \frac{A_{s,t+1}}{A_{g,t+1}} - \frac{\alpha}{(c_{g,t+1} - \bar{c}_g)} \right] - \beta^t \chi \right) \right]}$$

$$\Leftrightarrow \underbrace{\tau_{g,t} A_{g,t}}_{= \frac{\tau_{g,t}}{p_{g,t}}} = \frac{\Omega_t \chi - \nu \frac{\Omega_t}{\Omega_{t+1}} \beta \left[\frac{(1-\alpha)}{(c_{s,t+1} + \bar{c}_s)} \frac{A_{s,t+1}}{A_{g,t+1}} - \frac{\alpha}{(c_{g,t+1} - \bar{c}_g)} \right]}{\frac{\alpha}{(c_{g,t} - \bar{c}_g)} + \nu \frac{\Omega_t}{\Omega_{t+1}} \beta \left[\frac{(1-\alpha)}{(c_{s,t+1} + \bar{c}_s)} \frac{A_{s,t+1}}{A_{g,t+1}} - \frac{\alpha}{(c_{g,t+1} - \bar{c}_g)} \right] - \Omega_t \chi} \tag{A.16}$$

A.2 Robustness

A.2.1 Increasing exogenous taxes

In this subsection I present the findings for exogenous *increasing* taxes instead of exogenous *constant* taxes. The general findings do not differ dramatically, though the scale is larger than the results in section 3.5.1.

Overall, increasing taxes (Figure 17) lead to a faster decline in the goods share than under constant taxes. Thus, emissions also increase less before tipping and then falling again (in other words, representing an environmental Kuznets curve). This tipping point happens when overall emissions growth gets negative, which is the case when the governmental affected goods share growth rate together with the abatement growth rate exceed (in absolute terms) the goods productivity growth rate. Since abatement growth is constant, this behavior is entirely driven by the goods share growth rate. This increases, falls, and for later period increases again, converging. The final increase stems from the periods when the goods share has reached almost zero. Overall utility falls and then increases again. Interestingly, the per-period utilities under a tax regime of 2% are higher than under a tax regime of 1%. Most clearly, this is based on the higher tax scenario leading to less emissions and thus less disutility that enter linearly in the utility function.

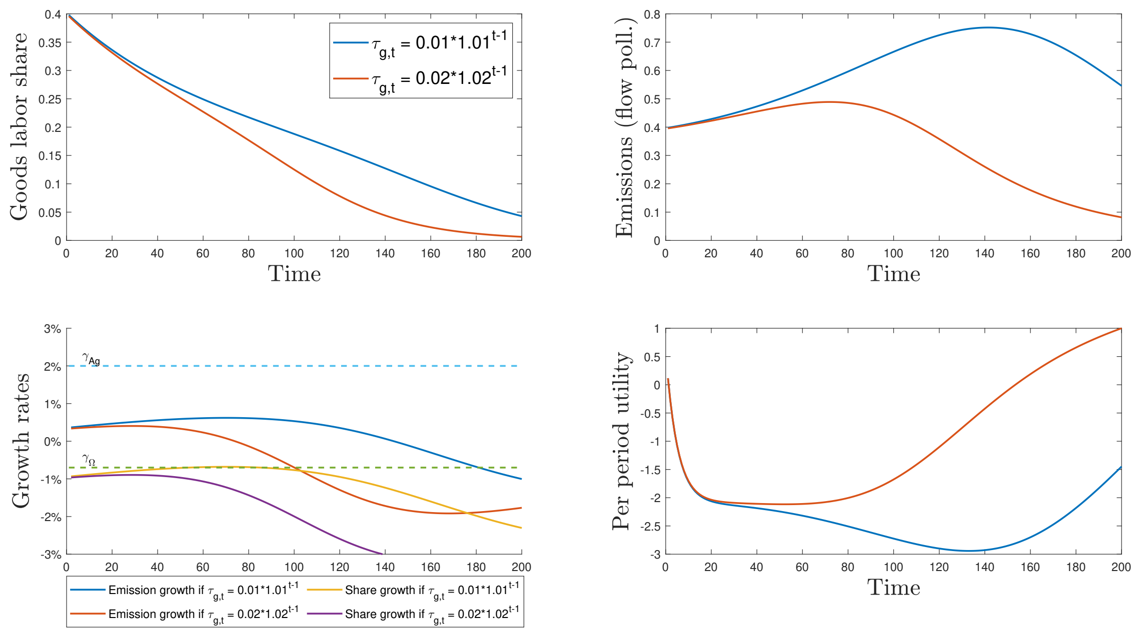

Figure 17: The evolution of emissions, the goods labor share and per period utility for different increasing exogenous taxes: 1%, 2%

In Figure 18, I present the same graphs for tax increases of 5% or 10% per period, respectively. Very straighforwardly, the goods share decreases even faster and also converges to zero. Similarly, the emissions converge to zero. In contrast to Figure 17, the emission growth rate reaches zero in an earlier period and thus the emissions begin to decrease from an earlier period on. The per period utility shows an interesting pattern: For the 5% per period increase, the per period utility first falls but then increases in a concave way. The per period utility for the 10% tax increase, however, first diminishes, then increases, and finally falls again. Since the emissions are very similar to the emissions in the "5% per period increase" scenario, the fall in per period utility is most likely coming from a severe decrease in income and thus overall consumption, and not from the disutility of pollution. Finally, the comparison between the respective growth rates of the goods labor share show a u-shaped behavior. This implies, that these high increasing taxes skip the increasing goods growth rate and directly decrease until the tipping point is reached, after which the goods share increases again but is still negative for all periods.

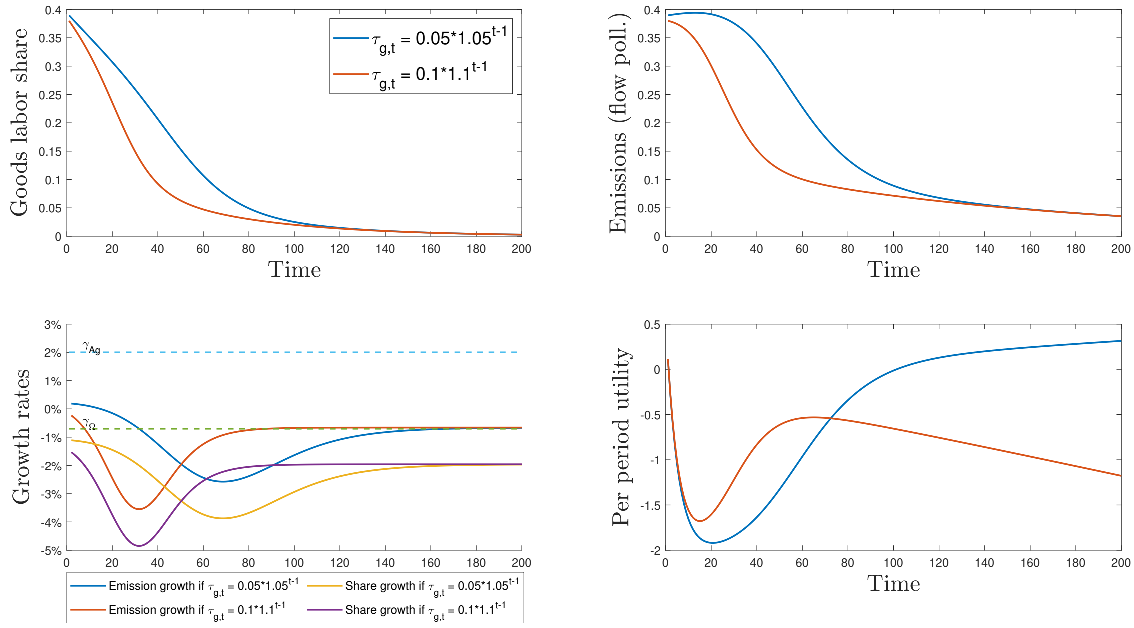

Figure 18: The evolution of emissions, the goods labor share and per period utility for different increasing exogenous taxes: 5%, 10%

A.2.2 Stock pollutant analysis with different pollution disutility

In Figure 19 and Figure 20 I display the same graphs as in Figure 15 and in Figure 21 and Figure 22 I report the same graphs as in Figure 16 with the only difference that the disutility of pollution is merely $\chi = 0.5$ and $\chi = 0.1$, respectively. The planner's solution are very similar, namely even for relatively low disutility of pollution, structural transformation accelerates. The major exception is the planner's solution that does only account for a static pollutant with a very low disutility of pollution ($\chi = 0.1$). Here, emissions increase over time. Another bigger difference is the utility graphs of the laissez-faire scenarios: obviously, the experienced disutility from pollution is not as severe as under $\chi = 1$.

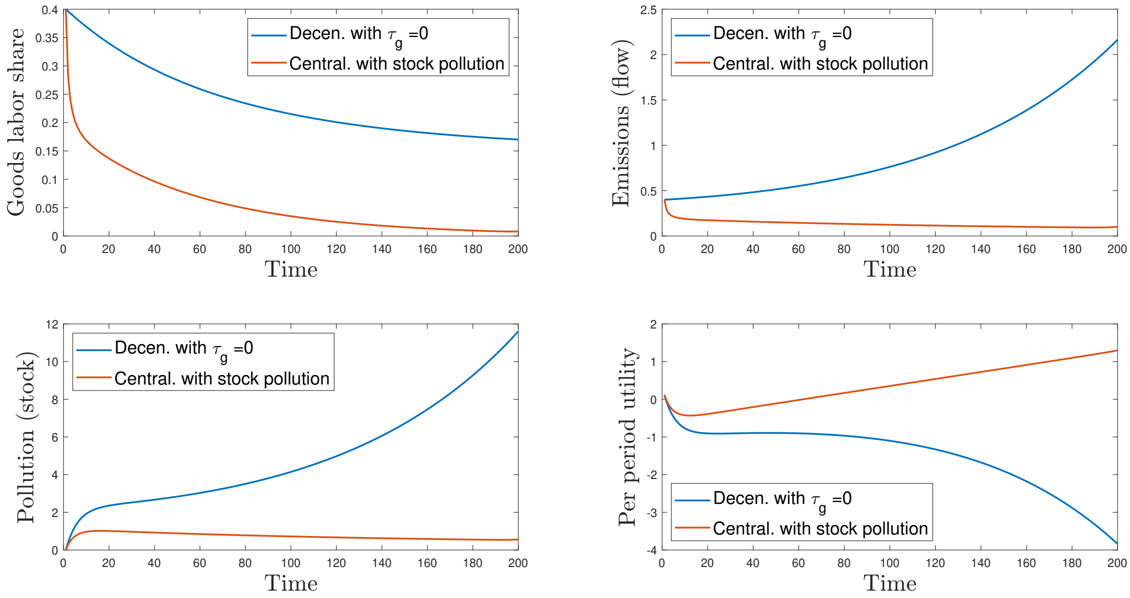

Figure 19: Decentralized vs. centralized solution to stock pollution with $\chi = 0.5$

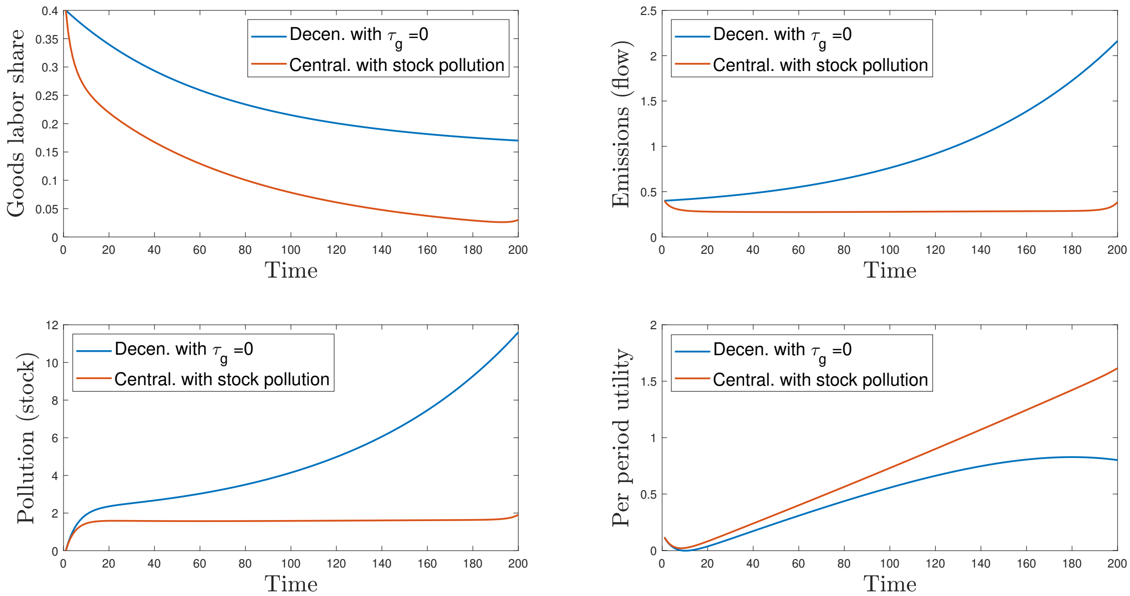

Figure 20: Decentralized vs. centralized solution to stock pollution with $\chi = 0.1$

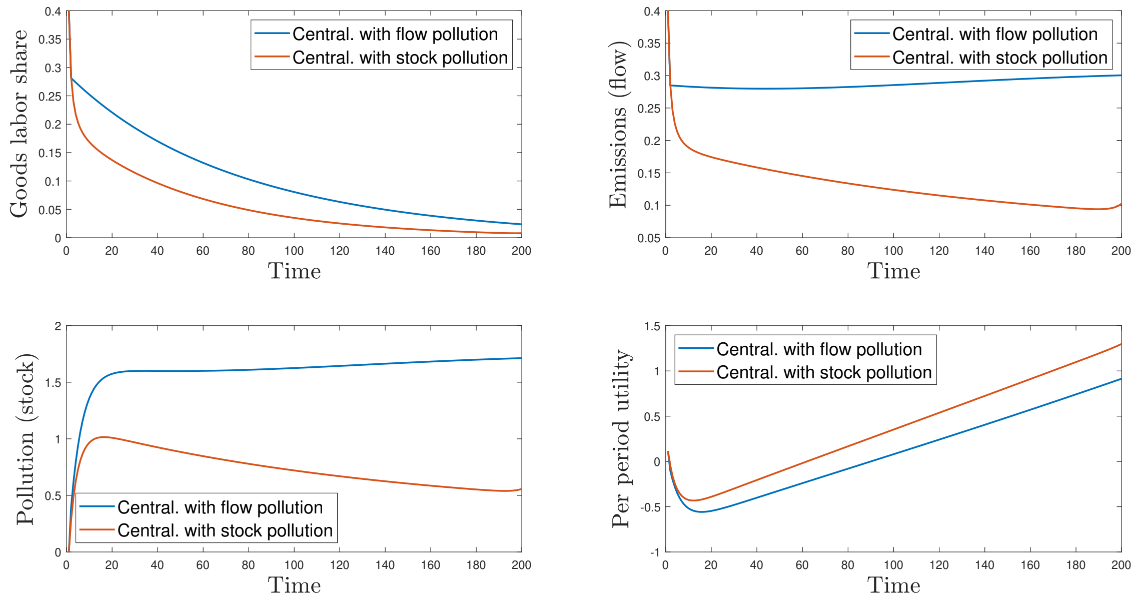

Figure 21: Solution to centralized flow vs. stock pollution with $\chi = 0.5$

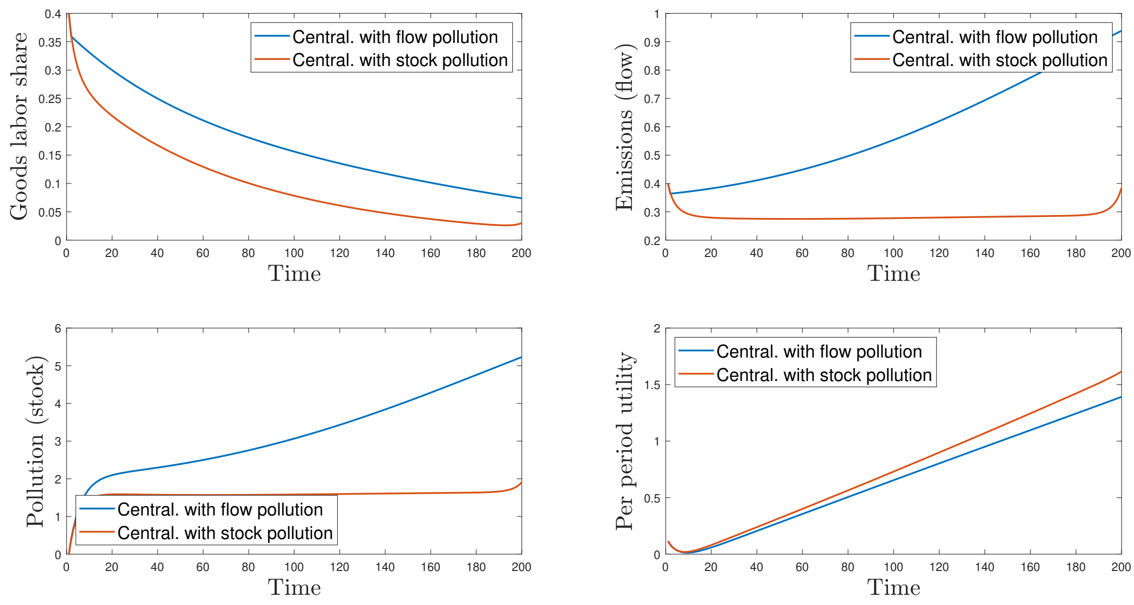

Figure 22: Solution to centralized flow vs. stock pollution with $\chi = 0.1$

A.2.3 Tax rate for stock pollutant

This subsection emphasizes the comparison between a laissez-faire scenario and a scenario with optimal goods tax against stock pollution. Thus, it builds on the subsection *Stock pollutant externality* in section 3.5.2, however, here the focus is on the corresponding goods tax rate. Proportional to the differences in emission, the left plot in Figure 23 graphs the highly differing goods consumption under a laissez-faire scenario and under an optimal tax scenario. As analyzed previously, this plot underlines that without taxation goods consumption increases exponentially, whereas under optimal tax it decreases and then stays relatively constant. The right graph in this Figure shows how high the corresponding tax would have to be to induce the optimal outcome. In fact, the maximum of the goods tax would be higher than 8 and thus, this tax rate would correspond to almost 20 times the laissez-faire goods consumption. This is, of course, extraordinary high. However, this stems from the accumulating nature of emissions and the concomitant need for reduced emissions from early on.

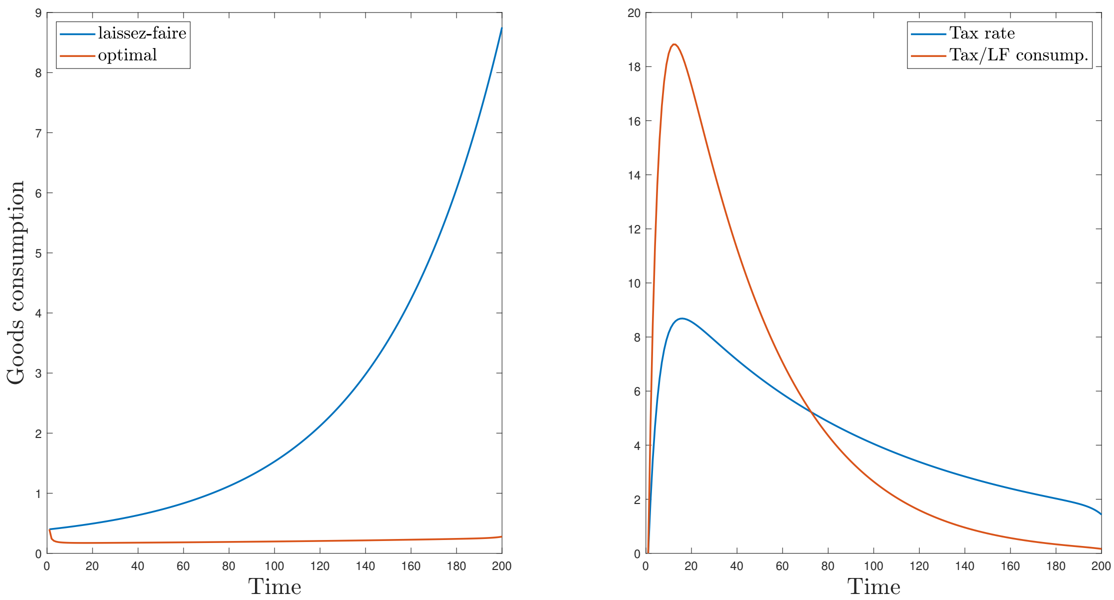

Figure 23: Tax in stock pollution scenario with $\chi = 1$

A.3 Dynamic Equations Setup for Numerical Solver

I set up the problem with both labor lead allocations ($\mathbf{L_{g,t+1}}, \mathbf{L_{s,t+1}}$) as control variables, where $\mathbf{L_{i,t+1}} = [L_{i,1} \cdots L_{i,T}]'$, $i \in \{g,s\}$. This constitutes a set of $2 \times T$ unknowns: $L_{g,1},...,L_{g,T}, L_{s,1},...,L_{s,T}$. Moreover, I take $L_{g,0}$ and $L_{s,0}$ as given and thus have from the combination with the labor lead vectors directly vectors for the current labor allocations ($\mathbf{L_{g,t}}, \mathbf{L_{s,t}}$). The $2 \times T$ unknowns are solved with the following system of $2 \times T$ equations:

$$\begin{aligned} M_t = & \frac{\nu}{\Omega_{t+1}}\beta\left[\frac{(1-\alpha)}{(A_{s,t+1}L_{s,t+1}+\bar{c}_s)}\frac{A_{s,t+1}}{A_{g,t+1}} - \frac{\alpha}{(A_{g,t+1}L_{g,t+1}-\bar{c}_g)}\right] \\ & -\chi - \frac{1}{\Omega_t}\left[\frac{(1-\alpha)}{(A_{s,t}L_{s,t}+\bar{c}_s)}\frac{A_{s,t}}{A_{g,t}} - \frac{\alpha}{(A_{g,t}L_{g,t}-\bar{c}_g)}\right] \end{aligned} \tag{A.17}$$

$$\Lambda_t = L - L_{g,t+1} - L_{s,t+1} \tag{A.18}$$

Note that equation (A.17) is equation (A.13) with the right-hand side brought to the left-hand side and using $c_{i,t} = Y_{i,t} = A_{i,t}L_{i,t}$, $i \in \{g,s\}$. This equation states intra- and inter-temporal optimality conditions. Clearly, in equilibrium M_t should be zero. Similarly, also Λ_t (stemming from equation (A.10) and using $\frac{c_{i,t}}{A_{i,t}} = \frac{Y_{i,t}}{A_{i,t}} = L_{i,t}$, $i \in \{g,s\}$) should be zero in equilibrium. This equation ensures that goods and services labor add up to total labor each period. I use the non-linear least squares solver "lsqnonlin.m" in MATLAB which allows me to impose the further conditions that both labor allocations are between zero (strictly speaking larger than zero) and (smaller than) L in all allocations: $L_{i,t} \in (0, L)$, $i \in \{g,s\}$.