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Structural Economic Change and the Environment

Decoupling Economic Growth from Natural Resource Use

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Abstract

The core question of this thesis is whether economic growth can be decoupled from natural resource use and ongoing environmental pollution. It contains three chapters which contribute with theoretical and empirical methods to shed light on this issue from different perspectives. In the first part I investigate the effect of human capital accumulation on the direction of technical change extending the paper "The Environment and Directed Technical Change" by Acemoglu et al. (2012). My model simulates that an increasing knowledge stock of workers tends to direct technical change in favour of intangible goods under some mild economic conditions. If tangible and intangible goods are just weak substitutes the paper further shows that economic growth in the clean sector cannot be too strong when absolute decoupling of economic growth from natural resources is to be achieved. The second part contains an analysis of recent energy intensity trends for 40 major economies using a structural decomposition analysis. The focus lies on the question whether improvements in energy intensity were caused by structural change towards a greener economy or by technological improvements. We account for intersectoral trade by using the World Input-Output database and adjust sectoral energy use via the environmentally extended input-output analysis. The results show strong differences between a consumption- and production-based accounting approach across sectors, particularly in the construction and electricity industries. Using the Three Factor Logarithmic Mean Divisia Index method, the decomposition analysis shows that recent energy intensity reductions were mostly driven by technological advances. Structural changes within countries played only a minor role, whereas international trade by itself even increased global energy intensity. Compared to a previous study using only production-based sectoral energy data, we find structural effects on energy intensity reductions to be systematically weaker by using consumption-based data. In the last part, I study global CO2 emissions of the service sector with a high share of college-educated workers by using an Input-Output Subsystem Analysis for the years 1995-2009. While the share of production-based emissions of high-skilled service sectors is rather small, a footprint analysis reveals that the emission share of those sectors is considerably higher by using consumption-based accounting (about 17.7% of total emissions). The subsystem analysis offers a closer look at the origins of carbon intensive goods necessary to meet consumption in high-skilled service sectors by disentangling the supply chain into various channels. I find that the emissions embodied in intermediate inputs from the electricity sector are the most important component of the CO2 footprint in those branches. Manufacturing and transport also play an important role for the carbon content of the supply chain. In addition to the global analysis, this paper extents the analysis to region-specific subsystems with a case study of the European Union. Finally, I conduct a structural decomposition analysis (SDA) in order to obtain major drivers of changes

in emissions of input factors. I find that increasing global demand of such services is the main driver of emission growth in those sectors. Interestingly, also the structure of intermediate inputs plays an important role for an increasing environmental footprint.

Kurzfassung

Diese Doktorarbeit behandelt im Kern die Frage ob immer weiter gehendes Wirtschaftswachstum von steigendem Ressourcenverbrauch und Umweltverschmutzung entkoppelt werden kann. Sie enthält drei Kapitel, die diese Frage mit theoretischen und empirischen Methoden aus verschiedenen Perspektiven beleuchten. Im ersten Teil wird die Auswirkung von Humankapital-Akkumulation auf die Richtung des technischen Wandels untersucht. Diese Arbeit ist eine Erweiterung des bekannten Artikels "The Environment and Directed Technical Change"von Acemoglu et al. (2012). Das Modell simuliert, unter welchen Bedingungen wachsendes Wissen dazu führt, dass der technische Wandel mehr und mehr intangible Güter hervorbringt, die keine starke Umweltbelastung verursachen. Falls tangible und intantible Güter nur schwer ersetzbar sind, kann es kein schnelles Wirtschaftswachstum geben, ohne dass immer mehr Ressourcen eingesetzt werden, selbst wenn es nur noch technischen Fortschritt im sauberen Sektor gibt. Der zweite Teil enthält eine sogenannte Strukturelle Dekompositionsanalyse der Entwicklung von Energieintensität von 40 großen Volkswirtschaften. Der Fokus liegt hier auf der Frage, ob Verbesserungen in der Energieintensität entweder auf strukturellen Wandel hin zu einer saubereren Wirtschaft oder auf technische Verbesserung zurückzuführen ist. Hierbei wird auf Basis der World Input-Output Database der Handel innerhalb von Branchen und zwischen Ländern miteinbezogen. Die Resultate zeigen starke Unterschiede zwischen einer produktions- und konsumbasierten Berechnungsmethode, vor allem im Baugewerbe und bei der Stromerzeugung. Unter der Benutzung der sogenannten "Three Factor Logarithmic Mean Divisia Index" Analyse wird gezeigt, dass die Entwicklung der Energieintensität zwischen 1995 und 2009 in den meisten Volkswirtschaften hauptsächlich auf technische Verbesserung zurückzuführen ist. Strukturwandel innerhalb eines Landes spielte nur eine kleine Rolle, allerdings vergrößerte die zunehmende Handelsvernetzung zwischen den Ländern die Energieintensität. Im Vergleich zu einer ähnlichen Studie, die nur produktionsbasierte Daten benutzt, zeigt sich, dass der strukturelle Wandel eine deutlich geringere Auswirkung auf die Energieintensität hat, als wenn konsumbasierte Daten untersucht werden. Im letzten Teil werden mittels einer Input-Output Subsystem Analyse die globalen CO_2-Emissionen der hochtechnologischen Dienstleistungssektoren für die Jahre 1995 bis 2009 untersucht. Während der Anteil dieser Sektoren an den globalen CO_2 Emissionen relativ gering ist, wenn man nur die direkten Emissionen berechnet, zeigt eine Fußabdruck-Analyse, dass diese einen bemerkenswert größeren Einfluss haben wenn man eine konsumbasierte Perspektive einnimmt. Die Subsystem Analyse ermöglicht einen genaueren Blick auf die CO_2 Emissionen, die entstehen, um diese Dienstleistungen anzubieten indem sie die Zulieferketten in einzelne Komponenten zerlegt. Es zeigt sich, dass die Emissionen, die in der Stromerzeugung entstehen, die wichtigste Komponente des CO_2 Fußabdrucks für diese Sektoren ist. Das produzierende Gewerbe sowie der Transportsektor haben ebenfalls großen Einfluss auf den Fußabdruck. Zusätzlich zu der globalen Analyse wird in dieser Arbeit auch ein regionenspezifische Subsystem Analyse mit einer Fallstudie zur Europäischen Union durchgeführt. Eine Strukturelle Dekompositions Analyse (SDA) wird durchgeführt, um die Entwicklungen in den Zulieferketten zu erklären und in einen Intensitäts-, einen Struktur- und einen Endnachfrageeffekt zu zerlegen. Die steigende Endnachfrage in diesen Sektoren ist der Hauptverursacher für die Zunahme der Emissionen in den Zulieferketten. Interessanterweise spielt auch die Struktur der Vorleistungen eine wichtige Rolle für die Vergrößerung des ökologischen Fußabdruckes.

Declaration

I hereby certify that no other than the sources and aids referred to were used in this thesis. All parts which have been adopted either literally or in a general manner from other sources have been indicated accordingly.

I certify that this thesis is my own work.

Vienna, October 2017
Daniel Croner

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CHAPTER 1

Introduction

The opposing impact of economic growth on the wealth of nations on the one hand and on the planet's ecological system on the other hand has been widely discussed in politics, science and society. While standards of living, health, nutrition, mortality and other socio-economic indicators increased persistently in most regions in the last 200 years, the impact on the environment exhibits more and more dramatic consequences. Resource scarcity and climate change challenge the way of thinking about economic growth established in the last centuries. Since the 1970s concerns about the disruptive effects of economic growth raised strongly.[1] While former major economic concerns dealt with questions of unemployment, material well-being or the avoidance of economic crises, environmental economics became a major part of growth theory during the last decades. Discussions tend towards the question whether green growth is possible. Green growth is a widely used term and generally means decoupling of economic growth from increasing environmental impact. The report UNEP (2011) from the United Nations Environmental Program distinguishes between two concepts of decoupling, absolute and relative. The term absolute decoupling of economic growth from CO2 emissions denotes that the GDP is growing but CO2 emissions are declining on the same time. With relative decoupling, in contrast, CO2 emissions are increasing but with a lower growth-rate than economic growth. During the last 15 years we observe relative decoupling of the world economy [2], still leading to tremendous increase in CO2 emissions. However, during the last two years there was absolute decoupling from CO2 emissions (see The World Bank (2016)).[3]

The question how to achieve absolute decoupling of economic growth from environmental pollution is the key motivation of this thesis. The relationship between emissions and growth can be decomposed in the factors emission intensity and energy intensity. The former term gi-

[1] One of the most famous work from this time is the report on the limits to growth from the Club of Rome (see Meadows and Meadows (1972)) which inspired the debate on future growth.

[2] Except 2009, the year of the global financial crisis. where global GDP declined.

[3] See `https://data.worldbank.org/indicator/EN.ATM.CO2E.PC` for the development of CO2 emissions and `https://data.worldbank.org/indicator/NY.GDP.MKTP.CD` for the GDP trend.

ves the amount of emissions which is emitted when using a given amount of energy. The latter denotes the energy which is needed for producing economic output. Emission intensity can be improved by introducing renewable energy technologies or when electricity utilities shift from carbon-intensive inputs like coal to less carbon-intensive inputs like natural-gas. Energy intensity improves when new innovations allow for more efficient production or if more and more firms adopt the most efficient technology on the market. Deutsch (2017) presents data for the period 2008-2015 and finds that global emission intensity declined by only 0.3% in average per year while global energy intensity was reduced by 3.3 % per year. Furthermore he provides forecasts for the years 2015-2040 which show similar trends with an 1.9 % average decrease of energy intensity and a 0.4 % decrease of carbon intensity. Hence, while there is some scope of improvement in carbon intensity, the main contribution has to come from the more efficient use of energy.

The technology related improvements in electricity intensity mentioned above can be complemented by demand shifts towards less energy intensive goods. I refer to the first path as technological change and to the second as structural change. It is important for several reasons to distinguish between those two effects, even though they are usually hard to disentangle as new technology often also induces structural upheavals. First, decoupling is an important goal, not only for firms or politicians but also for the whole society around the globe, as everyone is affected by climate change and, equally important, everyone affects the climate with his behaviour. For example, the focus of the debate could lie on the consumption behaviour of people in developed countries, which is not sustainable. Changing this behaviour would induce structural transformations towards a cleaner economy. Therefore it is important to monitor whether such a behaviour already takes place, whether we observe a positive structural trend as economies become more mature and how policy suggestions or society movements could further encourage this behaviour. Second, policy affects the technological and structural effects in a different way. Improvement of technology is often considered to be addressed easier by policy than structural transformation as the latter is also strongly embedded in cultural and behavioural norms of people or institutional structures. Technology can be affected by resource and environmental taxes as this provides an incentives for firms to invest in better manufacturing processes. However, there are technical limits regarding the extent improvements are possible. A car cannot drive without fuel or electricity which has to be produced. Therefore the limits and pace of technology improvements could be a major obstacle for sustainable economic growth. On the other hand, policies which aim to change structural patterns of an economy often face considerably resistance from industry and population and are therefore hard to implement in the short run.

The methods chosen in this thesis to shed light on the issues mentioned above give a broad picture on the process of decoupling. This cumulative thesis contains three papers: First, a theoretical growth model is developed in order to examine general conditions which have to be fulfilled for sustained economic growth. Second, an empirical study reveals structural and technological contributions for relative decoupling of economic activities from energy use in 40 major countries. Third, I show the inter-linkage of sectors which are assumed to be relatively green.

In the first paper, I describe a Directed Technical Change (DTC) framework with human capital, natural resources and environmental externalities. In general, Directed Technical Change models, which were first prominently introduced by Acemoglu (2002), offer an elegant way of depicting long-term structural developments by endogenizing the decision of investing in specialised technologies. While the early models focus mainly on the structural change in the labour market towards college educated workers, recent papers increasingly apply DTC to environmental issues. As future technologies play a crucial role for efficiency and the structural development of the economy, they have to be incorporated in any long-term contemplation about growth and the environment. The influence from policy on development of technology as described above is, of course, very complex in a competitive market environment. Many factors contribute to the innovation decision of a firm, not only the current price and tax of natural resources. Companies must expect a proper profit in the future before they start to invest in risky research as outcomes are often not assured. There are various determinants of this expected future profit; one of them is the market size effect. To illustrate this, consider a pharmaceutical firm doing research on a new drug. Usually it focuses its research effort on those diseases which are quite common as this promises many customers, whereas rare diseases are often not sufficiently investigated.[4] Another important effect is the direct productivity effect which favours those research which takes part in relatively further developed technologies as they are already well established and benefit from various network effects as for example the combustion engine. Neglecting those endogenous incentives of investing in certain technologies would distort forecasts and lead to misleading policy suggestions. The contribution of this paper is the introduction of human capital as an alternative source of wealth creation besides natural resources. Scarcity and increasing knowledge determine the direction of economic development. Whether this leads to absolute decoupling depends on the efficiency of knowledge accumulation, the price development of natural resources and the ease of substitution between clean and dirty goods.

Besides the chapter on growth theory, this dissertation also contributes to the issue on green growth with two empirical analyses. It is important to reveal the environmental burden that is associated with consumption. Doing so, is challenging because accounting for the environmental load of a consumption good is far from trivial. As production of a commodity is a complex task with many intermediate inputs one must not only account for the direct emissions occurring in production of this good. If for example a car is produced, there are direct emissions in the factory where the cars are produced but also emissions which occur in the production of intermediate inputs as electricity, robots, the factory building and so on. The Input-Output Analysis is the method which deals with this issue. This models were first introduced by the famous economist Wassily Leontief, a work for which he was honoured with the Nobel Memorial Prize in Economic Science in 1973. An Input-Output model represents the interdependencies between different economic branches in an economy.

Each column of the input–output matrix contains the monetary value of inputs from all sec-

[4] For example, Acemoglu and Linn (2004) found a large effect of market size on innovation in the pharmaceutical industry of the USA.

tors. Therefore the columns give a complete picture of the requirements of production in each sector. The rows depict the output of each sector and for what purposes it is used, mostly input to other sectors or final demand. Those monetary data are available in all national statistic accounts and therefore deliver a broad and well known data basis. With some assumptions it can also be linked to environmental accounts. The national environmental agencies collect data of various environmental accounts, for example energy use, CO2 emissions and land use and provide it on a sectoral level. The input-output analyst can conclude how much emissions are embodied in the input of one sector for production in another sector. We connect the average emissions occurring in the production of one unit of output in each sector and multiply it with the monetary value delivered to another sector. Hence, we obtain a fairly good measure for the upstream emissions which are necessary in each sector.

The construction of input-output tables requires considerable effort in collecting data. In recent decades growing attention was brought to the inter-linkage of economic entities and therefore governments strongly supported the improvement of input-output tables in all industrialised countries. In the mid 20th century Input-Output tables were only available for a few years in some countries, making it a challenging task to analyse time trends. Another obstacle was the inconsistence between the tables in different countries which often used divergent sector aggregations and definitions. Especially for pollution accounting, this posed a huge problem as environmental externalities, for example climate change, might affect everyone on the globe and supply chains become more and more diversified among different countries in the course of globalization. For instance, it is important to account for carbon leakage when new environmental regulations are introduced. Therefore, one must know the trade flows from each country to each other country as well as the environmental accounts in comparable aggregations. Since the 1990s, tremendous efforts have been made to deal with those problems and now there are several Multi-Region Input-Output (MRIO) models available. The most important ones are the World Input-Output Database (WIOD), Eora, the Global Trade Analysis Project (GTAP) and Exiobase. All of those databases are designed for different purposes, each of them exhibiting various advantages and disadvantages. For example, Eora offers a rich database of environmental accounts for almost every nation and estimates input-output tables back in the 1970s. Exiobase provides a broad picture of global resource flows. In this thesis, the WIOD is chosen, as it fulfills various important features: First, it accounts for emissions in all major countries plus a rest of the world model for all countries not included. All countries are split in the same 35 sectors and are therefore perfectly comparable. Comparability is not only possible between countries but also between years, the WIOD offers previous-year tables which enable the analysis of time trends.

In this framework, we can account for the emissions which are associated with the consumption of the products of economic sectors. Therefore, input-output analysis is an important part of this thesis. More in detail, in the second paper a so called Index Decomposition Analysis (IDA) is applied in order to study time trends of energy intensity. This work contributes to the debate on green growth by disentangling the trends in energy intensity in structural, technological and trade factors. Distinguishing those factors offers a clear picture how economies tend towards a more sustainable way of production. Hereby, the technology effect captures the efficiency gains in a sector which occur due to new innovation or adoption of best technologies by more and more firms. But it could also be the case, that there is a natural structural shift towards a more sustainable service economy as economies grow and become more mature. However, structural shifts can also be reached by outsourcing heavy industry in other countries and therefore obscure the real development of an economy.

The assumption that the service sector could be a clean sector is already challenged in the second paper. The third paper focuses explicitly on the service sector, or more exactly, on the high-skilled service sector as it seems to be a candidate for green growth. High-skilled sectors are those which demand a high share of college educated workers and therefore use brain power and knowledge as a major input instead of natural resources. The connection to the first paper is obvious as it is an empirical analysis about the reciprocal cross-linkage of human capital and natural resources. I found out that those sectors are by far not as clean as it seems because they are strongly dependent on electricity, manufactured goods and transport. The method chosen in this chapter is a so called subsystem analysis, a subcategory of input-output analysis. It is useful for analysing specific parts of the economy which are characterised with some conmen properties as knowledge intensity of recent growth patterns. Those subsystems can only contribute to green growth if they are not too strongly connected with other heavily polluting sectors.

All three articles of this thesis provide important new, theoretical or empirical, insights under which conditions decoupling of economic activities and environmental pollution takes place. All papers suggest that the strong cross-linkage of all parts in the economy exacerbate clean economic growth and sustainable development. New technologies which seem to be clean might induce rebound effects in other parts of the economy and increase the environmental burden. This thesis shows, that even in a very favourable setting, absolute decoupling is only possible if heavily polluting commodities can be substituted by clean goods which do not have a carbon-intensive supply chain. Empirically, on a sectoral level, this is hard to find. The second article also shows that there is no strong structural change towards a low carbon world. Even when economies become richer and invest more in environmental goods, the overall high level of consumption is still a burden and it could turn out that it will further be. In general, policy measures have to support both, better technologies and incentives to change consumption and production patterns. A global view including all supply chains is necessary to evaluate economic activities in terms of their environmental footprint. Green supply chains have to be found and a shift of consumption towards those commodities should be supported. If this is not possible, more and more destruction of the environment will lead to resource conflicts and will challenge the growth-favourable attitude of the last centuries.

This thesis is organized as follows: Chapter 2 contains the Directed Technical Change model. This model is the content of a paper which has been resubmitted to *Mathematical Social Science*, a highly ranked peer-review journal with a focus on mathematical modelling in social science. The choice of this journal was motivated by the strong technical character of the model. This paper is purely analytical and therefore no software was used. In Chapter 3 I continue with the analysis of energy intensities in 40 major economies. This chapter is a slightly modified version of the paper by Croner and Frankovic (2016) which has been accepted in *The Energy Journal*. It is joined work with my colleague Ivan Frankovic from the Vienna Institute of Demography. I contributed equally shared to all parts of this paper including the algorithm necessary to organize the data in Stata, Matlab and Excel. The journal was chosen because it is one of the most important journals in energy economics world wide and already focused on trends in energy intensity in previous issues. Chapter 4 is the article about the subsystem analysis. I will submit this paper to *Ecological Economics*, one of the most important journals in environmental economics. As each chapter contains its own conclusion I do not discuss them again in the end of the thesis.

CHAPTER 2

Directed Technical Change with Human Capital and Natural Resources

2.1 Introduction

In recent decades the literature on sustainability of economic growth in view of climate change has been increasing persistently.[1] The urgency of climate change suggest that the main problem for sustainability is the excessive use of fossil fuels. The effect of carbon dioxide emissions on global warming is well known (IPCC (2014)). Most economic goods are made out of natural resources which cause emissions in production and consumption. In order to pursue a more preserved path of growth several different approaches are suggested (see e.g. Gans (2012)): Development of better abatement technologies, more energy efficient production methods, advancement towards less environmental damaging materials or transformation to intangible products. All approaches aim at decoupling the economic activities from increasing environmental damage or physical resource use. This paper is concerned with the substitution of natural resource intensive goods with intangible goods. Empirical evidence shows that the GDP per unit of natural resources is growing and therefore resource use is relatively decoupling from economic growth but still increasing in absolute numbers.[2]

One example of decoupling is the emergence of the new economy. It has made intangible capital more important. One could regard software as a final good which has low natural resource input in production but massive knowledge input of skilled workers. The same applies for pharmaceuticals products. The costs of material used in production is relatively small compared to the time expenditure of researchers and we can, for instance, observe a steadily increasing share of expenses on medical products in the US (Hall and Jones (2007)). Although this pattern

[1] See e.g. Nordhaus (2014), Stern (2008), Smulders and Di Maria (2012), Acemoglu et al. (2012), Gerlagh and van der Zwaan (2003), Pezzy and Toman (2002)

[2] See (UNEP (2011).

extenuated after the financial crises (OECD (2015)), long term trends are quite stable and are predicted to hold in future.

Modern economies in the OECD countries shift to an economy which is more and more dominated by the service sector. Thereby knowledge and high-skilled labour plays an important role (Buera and Kaboski (2012)). Eichengreen and Gupta (2011) identifies two waves of growth of the service sector industry where the most current waves has been ongoing since the beginning of the 90s. It is preliminary driven by an increasing share of computer-, legal-, technical- and advertising-, financial intermediation- and post and telecommunication services, all of which are highly skill intensive.

For modelling those considerations one can describe a economy where every product is a result of the combination of labour, knowledge, raw material, technology and machines. Hereby knowledge is the intangible input which doesn't cause negative externalities. This knowledge can be treated as human capital which is accumulated via time allocation towards education. The fundamental question of this paper is, to which degree and under what economic circumstances the supply of human capital by the households gives rise to endogenous incentives for R&D and therefore changes the composition of a final good which is crucial for environmental quality.

This paper is an extension of Acemoglu et al. (2012). The general structure is very similar, however, in order to introduce a microfoundation of human capital accumulation, some important changes are made. The model simulates the accumulation of human capital by individual time allocation towards education, and therefore I distinguish between three different types of households. Unskilled worker household, skilled worker household, both working in production, and scientists which are employed in the R&D sector. There is no mobility between these sectors because we want to focus on human capital as a substitute for natural resources in production and not on the competition between the research and the production sector for educated workers. Skilled households distribute a certain fraction of their human capital stock to education and the remaining fraction to production. Thus, they face a dynamic optimization problem between producing and earning now or educating and earning more later. Scientists cannot improve their personal skill level. Their increasing knowledge is manifested in patents which drive technological change.

As in Acemoglu et al. (2012), the economy exhibits a dirty and a clean intermediate sector. Intermediate goods constitute the final good which can be consumed and invested. Dirty input production uses labour and physical capital as well as natural resources, while clean input production uses human capital instead of natural resources. Non-monopolistic firms own natural resources and extract those following the Hotelling Rule. The production of dirty intermediates has negative externalities on the environment. The introduction of physical capital in production follows Romer (1990). The resulting interest rate, makes the trade-off between education and saving visible.

Human capital changes the strength of the market size and the price effect. Due to the asymptotically growing human capital stock, the market size effect of the clean sector is increasing which can lead research effort away from the dirty sector. However, despite of these tendency of directed technical change, the results show that fast human capital accumulation leads to an environmental disaster if dirty and clean inputs are no strong substitutes.

Summarizing, this paper has two main results: First, long term research can be directed to clean research without policy intervention if human capital accumulation is fast enough. Whether this switch to clean research comes early enough in order to prevent an environmental disaster depends on the initial state of the environment. Second, even if all research takes only place in the clean sector, the dirty sector will still grow if the elasticity of substitution is not high enough. This is due to external effects of clean research which also increases production of the dirty output. Therefore, the pace of human capital accumulation has to lie in between a certain interval, predetermined by the condition of the economy.

The paper is related to two strands of literature. First, it builds on the growing Directed Technical Change (DTC) literature of the last decade. Di Maria and Valente (2008) introduces natural resources as a complement to physical capital in a directed technical change framework and addresses the problem of resource scarcity. Pittel and Bretschger (2010) add an investigation of worker dynamics between research and production sector. Acemoglu et al. (2014) calibrate a DTC model to show how important policy instruments are in the transition to a green growth path and how fast the transition should be under optimal policy. Aghion et al. (2016) analyse the direction of technical change in the automotive industry and found empirical evidence for the 'standing on the shoulder of giants effect' in clean research. There are several more papers which analyse the effect of fuel prices and technology gaps and the respective policy instruments on the direction of technological change. For instance Popp (2002) shows that energy prices and the existing knowledge has a strong impact on innovation.

The second body of literature, which is important to this paper, is the literature on human capital accumulation and skill biased technical change (Lucas Jr. (1988), Acemoglu (2002) and Acemoglu (2003)). Fagnart and Germain (2015) distinguish between quantitative growth and non-quantitative growth in a model with product complexity and non-renewable energy. They point out that sustainable quantitative growth is only possible if energy intensity converges to zero. The notion of non-quantitative growth is related to a increasing product variety or quality. If intermediates and R&D are not energy intensive this kind of growth is possible, even if energy intensity of final production is bounded from below. Strulik (2005) extends the growth models of Romer (1990) and Li (2000) by introducing human capital accumulation by households to derive an endogenous growth model with declining returns to scale in the research sector. We use similar dynamics of human capital accumulation for the clean sector.

The paper is organized as follows. In chapter 2 the basic model is introduced. While the production side is standard for Directed Technical Change models, we introduce three heterogeneous households. In chapter 3 we derive the economic equilibrium and the growth path of the economy. In chapter 4, a short policy implication is examined and chapter 5 concludes.

2.2 The Model

Overview

The production side of the model has the following structure. First, it has a complete competitive sector which produces the final good in the economy. Inputs of this sector are produced in the first intermediate good sector which is also competitive. Machines for intermediate goods are produced by monopolists which receive patents from the $R\&D$ sector.

The households are split into three different types: Unskilled households providing labour L, skilled households providing skilled labour H and scientists S. The amount of worker and scientists are exogenously given. There is no population growth. We assume that there is no mobility between the three sectors. The only endogenous decision of unskilled households and scientists is the familiar investment-saving decision. Additionally, the skilled households decide whether to allocate their knowledge to the production sector or to invest it in the education sector to increase their skill level in order to be more productive in future. Therefore there exist three different forms of wages for each type of household and there is no arbitrage between those sectors. For simplicity we normalize the size of each household to one.

Households

We follow the approach from Böhm et al. (2014) by introducing heterogeneous households without mobility between low skilled workers, high skilled workers and scientists.

The households can save money by buying property rights of natural resources or by investing in assets which are made out of physical capital. Thus we have the following optimal control problem of the **unskilled households** (see also Appendix A1 for derivation of the budget condition):

$$\max_{C_L} \sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} \log C_L(t) \tag{2.1}$$

$$s.t. \quad A_L(t+1) = (r(t)+1)A_L(t) + \omega_L(t)L + q(t)R_L(t) - C_L(t) \tag{2.2}$$

We consider a representative **skilled household** and do not distinguish between skill levels of individual households. Hence there is just one skill level H(t) in each period t (see Lucas Jr. (1988)). This household can decide whether to allocate its time to increase its education level or to use its already obtained skills in production. Note that t denotes a certain period. We denote as $u(t)H(t)$ the fraction of time which is used for production at period t and $(1-u(t))H(t)$ time which is devoted to the education sector. Thus the skilled consumer optimization problem is

$$\max_{C_H,u} \sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} \log C_H(t) \tag{2.3}$$

$$s.t.\ \ A_H(t+1) = (r(t)+1)A_H(t) + \omega_H(t)u(t)H(t) + q(t)R_H(t) - C_H(t) \tag{2.4}$$

$$H(t+1) - H(t) = D(1-u(t))H(t) \tag{2.5}$$

where $\omega_H(t)$ is the wage of skilled workers in production at time t.

Scientists maximize

$$\max_{C} \sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} \log C_S(t) \tag{2.6}$$

$$s.t. \quad A_S(t+1) = (r(t)+1)A_S(t) + \omega_S(t)S + q(t)R_S(t) - C_S(t) \tag{2.7}$$

where S is the (constant) amount of scientists and ω_S is the wage of the scientists. In equilibrium $\omega_S S$ must equal the total profits of monopolists Π. Patents in this model hold only for one period. Hence the value of the patent is no discounted profit stream like in the Romer-Model (Romer (1990)). The number of scientists is normalized to one.[3] Note that scientists cannot accumulate new knowledge like the skilled household. The innovation input of scientists is fully captured by the innovation possibility frontier introduced below.

We add up assets, resource stocks and depletion rates of the individual households and obtain the stocks for the whole economy:

$$Q = Q_H + Q_L + Q_S$$
$$R = R_H + R_L + R_S$$
$$A = A_H + A_L + A_S$$

Households can only save in terms of physical capital. Hence, in equilibrium, it must hold that A=K. R and K must equal the input values used in production. We denote aggregate consumption in the economy as $C = C_L + C_H + C_S$. The resource constraint of the whole economy

[3]Scientists are the agents which decide the direction of technical change. The assumption that they have the same population share like unskilled labour and skilled labour does not change the result because the magnitude of technology improvement can also be controlled by the research efficiency ξ as shown below. Scientists cannot increase their personal knowledge stock. Improvements of research manifests itself in new patents for higher product quality. This paper does not focus on the competition for skilled worker between the research and production sector. Therefore skilled workers and scientists are strictly separated even though the names indicate a relationship between both groups.

is

$$Y = I + C,$$

where

$$I = A(t+1) - A(t),$$

and Y is the output of the economy. On the other hand, the income of all households together must be equal to the economy's output:

$$\begin{aligned} Y =& rA_L + rA_H + rA_S \\ &+ \omega L + \omega_H uH + \omega_S S + \Pi + qR_L + qR_H + qR_S \end{aligned}$$

The budget constraint of the whole economy is therefore

$$\begin{aligned} &A(t+1) - A(t) \\ &= r(t)A_L(t) + r(t)A_H(t) + r(t)A_S(t) + \omega_L(t)L + \omega_H(t)u(t)H(t) \\ &+ \omega_S(t)S + q(t)R_L(t) + q(t)R_H(t) + q(t)R_S(t) - C_L(t) - C_H(t) - C_S(t) \end{aligned} \tag{2.8}$$

If the three heterogeneous households satisfy their budget constraint, (2.8) is also satisfied.

The Environment

Like in Acemoglu et al. (2012) an environmental function is introduced:

$$\begin{aligned} E(t+1) &= -\varrho Y_R(t) + (1+\delta)E(t) \\ E(t) &< EOpt \\ 0 < E_0 &\leq EOpt \end{aligned} \tag{2.9}$$

ϱ measures the rate of pollution which is caused by dirty production Y_R and δ measures environmental self regeneration, E_0 is the initial and EOpt is the optimal condition of the environment (there is no further regeneration possible at this threshold). An environmental disaster occurs if there is a t for which $E_t = 0$.[4] In this model, the role of the environment is restricted to the question whether there occurs a environmental disaster or not. In order to isolate the effect of human capital on the structure on the environment does not occur in the preferences of the household.

Alternatively to the formula above, we can also write the environment path dependent on the use of natural resource $R(t)$ instead of $Y_R(t)$. We add this change in the appendix.

Production

Now the production side of the economy will be explained:

Final good sector: In this paper it is assumed that there is a unique final good which is produced in a perfectly competitive market:

$$Y = \left[Y_R^{\frac{\epsilon-1}{\epsilon}} + Y_H^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}} \tag{2.10}$$

For the production of these goods, the firms need two intermediate goods Y_R and Y_H. Y_R refers to the dirty sector in Acemoglu et al. (2012) and uses natural resources R as an essential production factor. Via the use of Y_R, environmental damage occurs. Y_H uses skilled workers as production factor and is called the clean sector.

$\epsilon \in (0, +\infty)$ is the elasticity of substitution between the two goods. The two goods are *substitutes* if $\epsilon > 1$. They are *complements* if $\epsilon < 1$. Whether the elasticity of substitution between green and dirty technology is below or above one is still a very intensively discussed topic in research. Hourcade et al. (2011) for instance link the elasticity of substitution with price elasticity and derive a elasticity of substitution significantly below one. On the other hand Papageorgiou et al. (2013) estimate an elasticity of substitution between clean and dirty energy input of about 1.8. We follow the assumption of Acemoglu et al. (2012) and set $\epsilon > 1$.

Intermediate Good Sector: Formally the intermediate sector is very similar to the Acemoglu's model:

[4]Note that the damage to environment is done purely from the output of the dirty sector not from the inputs. This way of modelling is carried over from the Acemoglu et al. (2012) model. However, with this approach, we cannot capture efficiency gains in the polluting sector. If Y_R growth without using more and more natural resource R, it should a positive decoupling effect. Therefore we add an analogous case with R as the pollution source in the appendix.

$$Y_R = R^{\alpha_2} L_R^{1-\alpha} \int_0^1 B_{Ri}^{1-\alpha_1} x_{Ri}^{\alpha_1} di \qquad Y_H = (uH)^{\beta_2} L_H^{1-\beta} \int_0^1 B_{Hi}^{1-\beta_1} x_{Hi}^{\beta_1} di \tag{2.11}$$

where $\alpha,\ \alpha_1,\ \alpha_2, \beta, \beta_1, \beta_2 \in (0,1)$ with $\alpha_1 + \alpha_2 = \alpha$ and $\beta_1 + \beta_2 = \beta$ are the output elasticities between the inputs in the clean and in the dirty intermediate sector respectively. For simplicity we assume that $\alpha_1 = \beta_1, \alpha_2 = \beta_2$ and hence $\alpha = \beta$.[5] The firms need unskilled worker L_j ($j = R, H$), different kinds of machines x_{ji} ($i \in (0,1)$) with quality B_{ji} and dependent on the sector natural resources (R) or human capital (uH). We assume all input factors to be essential in production. Technical change in this model can only occur due to quality improvements.

Market clearing requires labour demand to be less than labour supply which is normalized to one:

$$L_{Ht} + L_{Rt} \leq 1 \tag{2.12}$$

Resource extraction: As already stated above, the natural non-renewable resource can be extracted by a rate R from the resource stock Q:

$$Q(t+1) - Q(t) = -R(t)$$

with the initial resource stock denoted by

$$Q_0 = Q(0)$$

We abstract from extraction costs. Households own shares of the resource extraction firms which maximize their profit by using the Hotelling Rule which indicates that the growth rate of natural resource prices equals the interest rate:

$$\frac{q(t+1)}{q(t)} = 1 + r(t) \tag{2.13}$$

Monopolist Sector: The monopoly sector produces the machines $x_{ji},\ j \in \{R, H\}$. For each machine to be produced the firms need one unit of physical capital and a patent (see e.g. Di Maria and Valente (2008), Acemoglu (2003)):

[5] With this assumption it is easier to focus on the particular influence of human capital accumulation. The general outcome of the model does not change with this strong assumption.

$$x_{Ri} = K_{Ri} \qquad\qquad x_{Hi} = K_{Hi} \tag{2.14}$$

$\psi_{ji}(t)$ is the price that monopolists charges for a machine i in sector $j \in (R, H)$

All capital which is available in the economy is used by the monopolists. Thus we have the market clearing condition:

$$\int_0^1 K_{Ri} di + \int_0^1 K_{Hi} di = K \tag{2.15}$$

R&D Sector: The number of scientists is normalized to 1. They decide whether to do research in the R or in the H sector and are denoted by $s_R(t)$ and $s_H(t)$ respectively. Thus we have $s_R + s_H \leq 1$.

Both sectors differ in their probability of success. We denote the probability of a scientist being successful with η_j, $j \in \{R, H\}$. The quality of the products increases by the rate $\xi > 0$ if research was successful. Scientists who invent a new patent sell it to the monopoly sector and it lasts for one period. Thus, if scientists are successful, their wage ω_S is equal to the monopolistic profit π_j in their sector. If they cannot develop a better quality design the wage is zero. Hence there is no credit market for patents. Scientists take the risk of not being successful. Whether they go in the R or in the H sector therefore depends on the relative expected profitability in both sectors.

We define the aggregated quality level of a sector is defined as:

$$B_R = \int_0^1 B_{Ri} di \qquad\qquad B_H = \int_0^1 B_{Hi} di \tag{2.16}$$

The innovation possibility frontier is as follows:

$$B_R(t+1) = (1 + \xi \eta_R s_R(t)) B_R(t) \qquad B_H(t+1) = (1 + \xi \eta_H s_H(t)) B_H(t) \tag{2.17}$$

Equation (2.17) implies that there is state dependence in each sector: The more advanced a sector is, the higher is the increment.

2.3 Equilibrium

We define an equilibrium in the economy as follows: An equilibrium is given by a sequence of prices $\{\omega_H(t),\, q(t),\, \omega(t),\, P_H(t),\, P_R(t),\, \psi_R(t),\, \psi_H(t),\, r(t),\, \omega_S(t)\}_{t\in[0,\infty)}$, demands for inputs $\{Y_R, Y_H\}_{t\in[0,\infty)}$, demand for labour $\{L_R,\, L_H\}_{t\in[0,\infty)}$ in the intermediate sector, demand for capital $\{K_L,\, K_H\}_{t\in[0,\infty)}$ to build machines in the monopolistic sector, demand for natural resources R and human capital uH in the intermediate R and H sector respectively, allocation of scientists $\{s_R(t),\, s_H(t)\}_{t\in[0,\infty)}$ such that

- Y_R, Y_H maximize profit of the final good producer.
- R, L_R maximize profit of the intermediate good producer in the R-Sector.
- uH, L_H maximize profit of the intermediate good producer in the H-Sector.
- (ψ_{Ri}, x_{Ri}) and (ψ_{uHi}, x_{Hi}) maximize profits of monopolists.
- s_{Rt}, s_{Ht} maximize expected profits of researchers at date t
- $\omega(t)$ clears labour market.
- $r(t)$ clears capital market.
- P_R, P_H clear input market.
- The evolution of E_t is given by (2.9).
- Households maximize utility.

Maximization of each household leads to the familiar Keynes-Ramsey rule which gives the growth rate of consumption (see Appendix A2):

$$\frac{C_H(t)}{C_H(t-1)} = \frac{1+r(t)}{1+\rho}$$

$$\frac{C_L(t)}{C_L(t-1)} = \frac{1+r(t)}{1+\rho}$$

$$\frac{C_S(t)}{C_S(t-1)} = \frac{1+r(t)}{1+\rho}$$

Additionally we derive a no-arbitrage equation for the skilled workers which face the time allocation decision:

$$\frac{\omega_H(t)}{\omega_H(t-1)} = \frac{1+r(t)}{1+D} \tag{2.18}$$

The interpretation of (2.18) is as follows: If $(1+D)\omega_H(t) < (1+r(t))\omega_H(t-1)$ the increase of future earnings is too small. It is rational for the household to use more skills for production because it is more profitable to earn more now and receive the interest rate r until the next period, then using skills for education with a low efficiency rate D and provide the higher skill level in the next period. If $(1+D)\omega_H(t) > (1+r(t))\omega_H(t-1)$ it is the other way around. Hence, in equilibrium the growth rate of wages has to offset the differences between the efficiency rates of the two types of capital.

Next, we explain the optimization of the production side. Final good producers maximize their output by choosing Y_R, Y_H optimally:

$$\max_{Y_R, Y_H} Y - P_R Y_R - P_H Y_H$$

where P_R and P_H are prices of Y_R and Y_H respectively. First order conditions are derived in Appendix A3.

As usually, we set the final good price as numeraire:

$$\left[(P_R)^{1-\epsilon} + (P_H)^{1-\epsilon}\right]^{\frac{1}{\epsilon-1}} = 1 \tag{2.19}$$

Intermediate good producers maximize their output by choosing R, L_R, x_{Ri} and uH, L_H, x_{Hi} respectively, where they face the prices of machines ψ_j.

R-Sector:

$$\max_{R, L_R, x_{Ri}} P_R Y_R - \int_0^1 \psi_R x_{Ri} di - qR - \omega L_R$$

H-Sector:

$$\max_{uH, L_H, x_{Hi}} Y_H - \int_0^1 \psi_{Hi} x_{Hi} di - \omega_H uH - \omega L_H$$

Machine producing firms need to buy a patent from the research sector. After they obtained it, those firms are monopolists for the special variety they produce. They face a given market interest rate r and also take machine demand (2.41) and (2.44) as given. Hence the profit function is

$$\max_{\psi_{Ri}} \pi_{Ri} = \psi_{Ri} x_{Ri} - r x_{Ri} \tag{2.20}$$

and

$$\max_{\psi_{Hi}} \pi_{Hi} = \psi_{Hi} x_{Hi} - r x_{Hi} \tag{2.21}$$

respectively. Maximization of all sectors leads to the following expected profit ratio for scientists (see Appendix A3 and A4 for details):

$$\frac{\Pi_R(t)}{\Pi_H(t)} = \frac{\eta_R}{\eta_H} \underbrace{\left(\frac{L_R(t)}{L_H(t)}\right)^{\frac{1-\alpha}{1-\alpha_1}} \left(\frac{R(t)}{uH(t)}\right)^{\frac{\alpha_2}{1-\alpha_1}}}_{\substack{market\ size \\ effect}} \underbrace{\left(\frac{P_R(t)}{P_H(t)}\right)^{\frac{1}{1-\alpha_1}}}_{\substack{price \\ effect}} \underbrace{\frac{B_R(t-1)}{B_H(t-1)}}_{\substack{direct \\ productivity \\ effect}} \tag{2.22}$$

Natural resources and human capital together with the labor force determine the market size effect. The larger the market for a technology the more profitable is research in this field. The price effect often has the opposite direction: If there is less supply of an input factor the price might be higher which positively influences research incentives. What effect prevails depends on the degree of substitutability (see Acemoglu (2002)). Finally there is the direct productivity effect of past research. This effect indicates that an initially more developed technology is mostly more profitable. The ratio can be rewritten to depict it just dependent on research status and prices of R and uH (see Appendix A5):

$$\frac{\Pi_R(t)}{\Pi_H(t)} = \frac{\eta_R}{\eta_H} \left(\frac{\omega_H(t)}{q(t)}\right)^{(\epsilon-1)\alpha_2} \left(\frac{1+\xi\eta_R s_R(t)}{1+\xi\eta_H s_H(t)}\right)^{-\varphi_1-1} \left(\frac{B_R(t-1)}{B_H(t-1)}\right)^{-\varphi_1} \tag{2.23}$$

where $\varphi_1 := (1-\epsilon)(1-\alpha_1)$.

This ratio determines in which sector research will take place and is therefore crucial for directed technical change. It also depicts the meaning of input prices for human capital and natural resources. The higher the price of natural resources is, the more profitable is research in the clean sector. We analyse the equilibrium tendency of this ratio:

Proposition 1

If the research level in the H-Sector is initially sufficiently more developed, research will be directed to the clean sector forever. If the research level in the R-sector is initially sufficiently more developed, research will take place in the dirty sector forever, if

$$1 + D < (1 + \xi\eta_R)^{\frac{1-\alpha_1}{\alpha_2}} \tag{2.24}$$

It will switch to the clean sector after some time and stay there forever, if

$$1 + D > (1 + \xi\eta_R)^{\frac{1-\alpha_1}{\alpha_2}} \tag{2.25}$$

The proof is shown in the Appendix A6.

This result states, what is intuitively plausible: If there is research in the dirty sector only, growth of human capital must offset growth in research. Note, that the result is also dependent on scarcity of the natural resource but this effect is cancelled out due to the similliarity of no-arbitrage conditions for resource extractors and skilled households.[6] $1 - \alpha_1$ and α_2 are weights for the importance of research and human capital/natural resources respectively.

We now want to investigate the consequences of research taking place only in the clean sector. In Appendix A.7 we derive a more narrow form for the sectoral and overall output:

$$Y_R = \frac{\left(\frac{\alpha_1^2}{r}\right)^{\frac{\alpha_1}{1-\alpha}} \alpha_2^{\frac{\alpha_2}{1-\alpha}} q^{-\epsilon\alpha_2} B_R^{\frac{1-\alpha_1}{1-\alpha}} B_H^{\varphi_1 \frac{\alpha+\varphi}{\varphi}}}{\left[\omega_H^{\alpha_2(1-\epsilon)} B_R^{\varphi_1} + q^{\alpha_2(1-\epsilon)} B_H^{\varphi_1}\right]^{\frac{\alpha+\varphi}{\varphi}}} \tag{2.26}$$

Analogously one derives

$$Y_H = \frac{\left(\frac{\alpha_1^2}{r}\right)^{\frac{\alpha_1}{1-\alpha}} \alpha_2^{\frac{\alpha_2}{1-\alpha}} \omega_H^{-\epsilon\alpha_2} B_H^{\frac{1-\alpha_1}{1-\alpha}} B_R^{\varphi_1 \frac{\alpha+\varphi}{\varphi}}}{\left[\omega_H^{\alpha_2(1-\epsilon)} B_R^{\varphi_1} + q^{\alpha_2(1-\epsilon)} B_H^{\varphi_1}\right]^{\frac{\alpha+\varphi}{\varphi}}} \tag{2.27}$$

Using (2.10) overall output writes as

[6] As $\frac{\omega_{H(t+1)}}{\omega_{Ht}} = 1 + r_t$ and $\frac{q_{(t+1)}}{q_t} = 1 + r_t$ the interest rate r does not appear in the above formula if $\alpha_2 = \beta_2$.

$$Y = \left(\frac{\alpha_1^2}{r}\right)^{\frac{\alpha_1}{1-\alpha}} \alpha_2^{\frac{\alpha_2}{1-\alpha}} \frac{\left[\omega_H^{-(\epsilon-1)\alpha_2} B_H^{\frac{\epsilon-1}{\epsilon}\frac{1-\alpha_1}{1-\alpha}} B_R^{\frac{\epsilon-1}{\epsilon}\varphi_1\frac{\alpha+\varphi}{\varphi}} + q^{-(\epsilon-1)\alpha_2} B_R^{\frac{\epsilon-1}{\epsilon}\frac{1-\alpha_1}{1-\alpha}} B_H^{\frac{\epsilon-1}{\epsilon}\varphi_1\frac{\alpha+\varphi}{\varphi}}\right]^{\frac{\epsilon}{\epsilon-1}}}{\left[\omega_H^{\alpha_2(1-\epsilon)} B_R^{\varphi_1} + q^{\alpha_2(1-\epsilon)} B_H^{\varphi_1}\right]^{\frac{\alpha+\varphi}{\varphi}}} \tag{2.28}$$

Note that Y_R also depends on the level of research in the clean sector B_H and Y_H on the level of research in the dirty sector B_R. Whether we have positive or negative externalities depends on the substitution parameter ϵ.

If $\alpha + \varphi < 0$ ($\epsilon > \frac{1}{1-\alpha}$), Y_R and Y_H are *strong substitutes*.

If $\alpha + \varphi > 0$ ($\epsilon < \frac{1}{1-\alpha}$), Y_R and Y_H are *weak substitutes*

In the case of strong substitutes, the research in the opposed sector has negative externalities on the output. In the case of weak substitutes positive externalities arise.

Like in Acemoglu (2003), we define the Balanced Growth Path (BGP) as follows:

Definition 1:
The economy is on a BGP if the following two conditions both hold:

- Consumption and Output grow with the same rate in the long run. Thus $g := \lim_{t\to\infty} \frac{Y(t+1)}{Y(t)} = \lim_{t\to\infty} \frac{C(t+1)}{C(t)}$
- There is a time T where $\frac{\Pi_R}{\Pi_H}$ is either above 1, below 1 or equal to 1 for all $t > T$.

The economy is said to be on a green BGP if it holds additionally that $\frac{\Pi_R}{\Pi_H} < 1$ for all $t > T$.

Now we investigate the consequences for the long run growth rate of Y and Y_R.

Theorem 1
If innovation in the long run only occurs in the clean sector the growth rate in the dirty sector is

- negative if
  - Y_R and Y_H are strong substitutes.
  - Y_R and Y_H are weak substitutes and additionally it holds that

$$\left(\frac{q(t+1)}{q(t)}\right)^{\epsilon\alpha_2}\left(\frac{\omega_H(t+1)}{\omega_H(t)}\right)^{\frac{\alpha_2}{1-\alpha}(\alpha+\varphi)} > \left(\frac{B_H(t+1)}{B_H(t)}\right)^{\frac{\alpha+\varphi}{\varphi}\varphi_1} \tag{2.29}$$

asymptotically.

- positive (non-negative resp.) if
  - Y_R and Y_H are weak substitutes and additionally it holds that

$$\left(\frac{q(t+1)}{q(t)}\right)^{\epsilon\alpha_2}\left(\frac{\omega_H(t+1)}{\omega_H(t)}\right)^{\frac{\alpha_2}{1-\alpha}(\alpha+\varphi)} \leq \left(\frac{B_H(t+1)}{B_H(t)}\right)^{\frac{\alpha+\varphi}{\varphi}\varphi_1} \tag{2.30}$$

asymptotically.

For the proof see Appendix A8.

Corollary 1
In case of strong substitutes overall long term output is

$$\frac{Y(t+1)}{Y(t)} = (1+\xi\eta_H)\left(\frac{1+D}{1+\rho}\right)^{\frac{\alpha_2}{1-\alpha}} \tag{2.31}$$

In case of weak substitutes and an negative growth rate of dirty output the overall output growth of the economy is in the long run

$$\frac{Y(t+1)}{Y(t)} = \frac{Y_H(t+1)}{Y_H(t)} = (1+\xi\eta_H)^{\alpha+\varphi}\left(\frac{1+D}{1+\rho}\right)^{\frac{\alpha_2}{1-\alpha_1}} \tag{2.32}$$

Proof:

See also Appendix A.8.

□

Comparing the growth rates in the case of strong substitutes and in the case of weak substitutes, we can see that the latter is always lower than the former because $\frac{\alpha_2}{1-\alpha_1} < \frac{\alpha_2}{1-\alpha}$ and $\alpha + \varphi < 1$.

As indicated in (2.26) the output in the polluting sector also depends on the activity in the clean sector. Clearly, the lower the elasticity of substitution between this two sectors is, the greater is the dependency of Y_R on B_H. We also found that there is a threshold of substitutability above which decoupling takes place for sure, no matter whether equation (2.29) holds.

We can interpret (2.29) as follows: The equation contains a growth restriction for the polluting sector (the growth rate of resource prices q), a growth restriction for the green sector (the growth rate of high skilled worker wages ω_H) and a growth accelerating factor for the green sector (the growth rate of quality improvement B_H). High resource prices impede growth in the dirty sector because the resource is essential in it. High wages for skilled worker in the clean sector would prevent the clean sector to grow too fast. On the other hand, a fast increase in machine quality of the clean sector could accelerate the growth in the green sector so fast that it goes along with growth in the dirty sector. Hence the threshold for sustainable growth is defined by the constraint (2.29).

The next theorem summarizes under which conditions we have actually a decoupling effect. For sustained economic growth we need Y_H to grow in the long run and Y_R to approach zero.

Theorem 2:

In case of strong substitutes, sustained economic growth will take place and an environmental disaster will be avoided if and only if

- The initial environmental quality is sufficiently high.
- $1 + D > (1 + \xi\eta_R)^{\frac{1-\alpha_1}{\alpha_2}}$
- $1 + D > (1 + \xi\eta_H)^{-\frac{1-\alpha}{\alpha_2}}(1 + \rho)$

In the case of weak substitutes, sustained economic growth will take place and an environmental disaster will be avoided if and only if

- The initial environmental quality is sufficiently high.
- $1 + D > (1 + \xi\eta_R)^{\frac{1-\alpha_1}{\alpha_2}}$
- $\left(\frac{q(t+1)}{q(t)}\right)^{\epsilon\alpha_2} \left(\frac{\omega_H(t+1)}{\omega_H(t)}\right)^{\frac{\alpha_2}{1-\alpha}(\alpha+\varphi)} > \left(\frac{B_H(t+1)}{B_H(t)}\right)^{\frac{\alpha+\varphi}{\varphi}\varphi_1}$
- $1 + D > (1 + \xi\eta_H)^{\frac{(1-\alpha_1)(\alpha+\varphi)}{\alpha_2}}(1 + \rho)$

Proof:

This Theorem summarizes (2.24) (2.25), (2.29), (2.30), (2.31) and (2.32)

□

In the case of strong substitutes, there are two condition for absolute decoupling. The first is necessary to obtain a green research path. If the knowledge stock doesn't increase fast enough, it cannot surpass the increasing gap between clean and dirty research. The second condition is obligatory for economic growth in case of an economy with only clean research activities. The two drivers of growth, human capital and clean research must offset the growth stemming effect of high impatience which is indicated by a high discount rate.

Besides these two effects, we need additionally condition (2.29) in order to avoid growth in Y_R in the case of weak substitutes. With respect to climate change, the first condition, an initial sufficient high environmental quality is crucial. Empirical data suggest clearly that this condition is not fulfilled and any climate policy has to increase the pace of transition to clean technology.

2.4 Policy

Acemoglu et al. (2012) suggested subsidies for clean research as a measure to reach a clean research path and subsidies for clean research plus taxes for the polluting factor as an social optimal policy.

In this chapter, we examine the effect of subsidies on clean research. We introduce a subsidie f_t, financed via lump-sum transfers from the households, in the profit ratio:

$$\frac{\Pi_R(t)}{\Pi_H(t)} = \frac{1}{1+f(t)} \frac{\eta_R}{\eta_H} \left(\frac{\omega_H(t)}{q(t)}\right)^{(\epsilon-1)\alpha_2} \left(\frac{1+\xi\eta_R s_R(t)}{1+\xi\eta_H s_H(t)}\right)^{-\varphi_1-1} \left(\frac{B_R(t-1)}{B_H(t-1)}\right)^{-\varphi_1} \quad (2.33)$$

The subsidies which are necessary to push the economy towards a clean research path depend on the technology gap between dirty and clean research and, in this model, on the prices of natural resources and human capital. The next theorem established the threshold for this subsidies in order to be sufficient for a switch to green research if initial research takes place in the dirty sector only.

Theorem 3:

If all scientist initially work in the dirty sector, then research can be directed towards the clean sector in period t if

$$1 + f(t) > \frac{\eta_R}{\eta_H} \left(\frac{\omega_H(t)}{q(t)}\right)^{(\epsilon-1)\alpha_2} (1+\xi\eta_R)^{-\varphi_1-1} \left(\frac{B_R(t-1)}{B_H(t-1)}\right)^{-\varphi_1} \quad (2.34)$$

Proof:

Follows from (2.33). □

Imposing those subsidies implies that, after some time, research in the clean sector is sufficiently developed, such that a subsidy is not necessary any more as stated in proposition 1. This is equivalently to Acemoglu et al. (2012) with the only difference that the price of human capital also influences the threshold. The higher the wages for high skilled worker, the lower the incentive to direct research towards the clean sector. Therefore, the subsidies would have to compensate for this. On the other hand, a high price of the natural resource would have an impeding effect on the dirty sector and therefore lowers the threshold for the subsidy.

2.5 Conclusion

This paper is an extension of the Directed Technical Change Paper on the Environment from Acemoglu et al. (2012). It differs by introducing heterogeneous households and human capital accumulation. The availability of human capital and natural resources drive the sectoral transformation of the economy via the market size and price effect. Hereby, human capital accumulation exhibits constant scale effects leading to an advantage for the clean sector in the long run. We assume an elasticity greater than one which is a precondition for deep structural change.

The model demonstrates first, the accumulation of human capital leads to skill biased technical change if the growth rate of human capital is high enough. This is simply due to the scarcity of natural resources and the possibly unlimited accumulation of knowledge. The acquisition of skills drives technological change in favour of skilled workers more than technological change favouring natural resources. The initial technology gap can be closed if efficiency of education, learning by doing and other skill acquisition is greater than the productivity, adjusted for the output elasticities, of the dirty research sector. All results are under the condition that the initial environmental quality is high enough to prevent an environmental disaster.

More important, we found that even if there is zero technological progress in the dirty sector after some point in time, a limitation of growth in dirty good production is not secured. External effects from the clean sector are dangerous, if clean and dirty goods are just weak substitutes. Therefore the most important finding of this paper is, that in case of weak substitutes there is also an upper threshold for the efficiency of knowledge accumulation. If it is too easy to acquire new knowledge the clean sector will grow too fast and therefore carry along the dirty sector. Therefore fast economic growth contradicts with a sustainable development.

Future research could alter the exact form of human capital accumulation. For example, we could examine the case of human capital with diminishing returns in both sectors or relax the assumption of fixed proportions of worker and scientists. Crucial for empirical calibration would be the elasticity of substitution between high technology sectors in the new economy which produce rather intangible goods and classical manufacturing industries. It would also be interesting to analyse whether the introduction of human capital offers new perspective for structural policies.

2.6 Appendix

Budget restriction

Formally the wealth of the **unskilled household** is (see also Di Maria and Valente (2008)):

$$W_L(t) = A_L(t) + q(t)Q_L(t)$$

where q(t) is the price of the (non-renewable, natural) resource and Q_L is the fraction of the resource stock which is owned by the unskilled households. The total stock which belongs to the unskilled household is depleted by a rate $R_L(t)$:

$$Q_L(t+1) = Q_L(t) - R_L(t)$$

Wealth W_L increases according to:

$$W_L(t+1) - W_L(t) = A_L(t+1) - A_L(t) + q(t+1)Q_L(t+1) - q(t)Q_L(t)$$

where A_L denotes the assets held by the household. On the other hand households face the following budget constraint:

$$W_L(t+1) - W_L(t) = r(t)A_L(t) + \omega_L(t)L + (q(t+1) - q(t))Q_L(t+1) - C_L(t)$$

where L is the supply of unskilled workers and ω_L is the wage. We assume that there is no population growth and hence L is constant. Setting those two equations equal and using $Q_L(t+1) = Q_L(t) - R_L(t)$ we get the following budget restriction:

$$A_L(t+1) = (r(t)+1)A_L(t) + \omega_L(t)L + q(t)R_L(t) - C_L(t)$$

where C_L is the consumption of the unskilled worker. To keep the analysis simple, one can assume that there is no possibility to receive a loan for each household. Therefore $A_L \geq 0$ for each t.

Household Optimization

We follow the methods introduced in Feichtinger and Hartl (1986) Appendix A to apply the discrete maxima principle. The Hamiltonian for skilled workers is:

$$\begin{aligned}
&\mathcal{H}(C_H, A_H, u, H, \lambda, \mu) \\
&= \log C_H(t) + \lambda(t)((1 + r(t))A_H(t-1) + \omega_H(t)u(t)H(t-1) \\
&+ q(t)R_H(t) - C_H(t)) + \mu(t)(D(1 - u(t+1))H(t-1) + H(t-1))
\end{aligned}$$

First order conditions give:

$$\mathcal{H}_{C_H} = \frac{1}{C_H(t)} - \lambda(t) \tag{2.35}$$

$$\mathcal{H}_u = \lambda(t)\omega_H(t)H(t-1) - \mu(t)DH(t-1) \tag{2.36}$$

$$\mathcal{H}_{A_H} = \lambda(t)(1 + r(t))$$

$$\mathcal{H}_H = \lambda(t)\omega_H(t)u(t) + \mu(t)D(1 - u(t))$$

$$\lambda(t-1) = \frac{\lambda(t)(1 + r(t))}{1 + \rho} \tag{2.37}$$

$$\mu(t \dot{-} 1) = \frac{\lambda(t)\omega_H(t)u(t) + \mu(t)(D(1 - u(t)) + 1)}{1 + \rho} \tag{2.38}$$

With (2.35) and (2.37) we get the familiar Ramsey Rule:

$$\frac{C_H(t)}{C_H(t-1)} = \frac{1 + r(t)}{1 + \rho}$$

Consider (2.36):

$$\mu(t) = \frac{\omega_H}{DC_H}$$

set in (2.38)

$$\frac{\omega_H(t-1)}{DC_H(t-1)} = \frac{\frac{1}{C_H(t)}\omega_H(t)u(t) + \frac{\omega_H(t)}{DC_H(t)}(D(1 - u(t)) + 1)}{1 + \rho}$$

Hence we get

$$\frac{\omega_H(t-1)}{\omega_H(t)} = \frac{\frac{C_H(t-1)}{C_H(t)} Du(t) + \frac{C_H(t-1)}{C_H(t)}(D(1-u(t))+1)}{1+\rho}$$

It follows by using the Rasmey rule:

$$\frac{\omega_H(t)}{\omega_H(t-1)} = \frac{1+\rho}{\frac{C_H(t-1)}{C_H(t)}(D+1)} = \frac{C_H(t)}{C_H(t-1)} \frac{1+\rho}{D+1} = \frac{1+r(t)}{1+D}$$

The Hamiltonian of the unskilled households:

$$\begin{aligned}&\mathcal{H}(C_L, A_L, \lambda) \\ &\quad = \log C_L(t) + \lambda(t)((1+r(t))A_L(t-1) + \omega_L(t)L + q(t)R_L(t) - C_L(t))\end{aligned}$$

which leads to the Keynes-Ramsey rule

$$\frac{C_L(t)}{C_L(t-1)} = \frac{1+r(t)}{1+\rho}$$

Finally we have the Hamiltonian of the scientists:

$$\begin{aligned}&\mathcal{H}(C_S, A_S, \lambda) \\ &\quad = \log C_S(t) + \lambda(t)((1+r(t))A_S(t-1) + \omega_S(t)S + q(t)R_S(t) - C_S(t))\end{aligned}$$

Hence,

$$\frac{C_S(t)}{C_S(t-1)} = \frac{1+r(t)}{1+\rho}$$

First Order Conditions

First order conditions in the final good sector:

$$\begin{aligned}P_R = \frac{\partial}{\partial Y_R} Y &= \frac{\epsilon}{\epsilon-1}\left[Y_R^{\frac{\epsilon-1}{\epsilon}} + Y_H^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}-1} \frac{\epsilon-1}{\epsilon} Y_R^{(\frac{\epsilon-1}{\epsilon})} \\ &= Y^{\frac{1}{\epsilon}} Y_R^{-\frac{1}{\epsilon}} = \left(\frac{Y}{Y_R}\right)^{\frac{1}{\epsilon}}\end{aligned}$$

and similar:

$$P_H = \left(\frac{Y}{Y_H}\right)^{\frac{1}{\epsilon}} \tag{2.39}$$

Therefore the input price ratio is obtained:

$$\frac{P_H}{P_R} = \left(\frac{Y_H}{Y_R}\right)^{-\frac{1}{\epsilon}} \tag{2.40}$$

Intermediate R-Sector:

$$x_{Rit} = L_{Rt}^{\frac{1-\alpha}{1-\alpha_1}} B_{Rt} \left(P_R R^{\alpha_2} \alpha_1 \frac{1}{\psi_{Ri}}\right)^{\frac{1}{1-\alpha_1}} \tag{2.41}$$

$$q = \frac{\alpha_2}{R} P_R R^{\alpha_2} L_R^{1-\alpha} \int_0^1 B_{Ri}^{1-\alpha_1} x_{Ri}^{\alpha_1} di \tag{2.42}$$

$$\omega_L = \frac{1-\alpha}{L_R} P_R R^{\alpha_2} L_R^{1-\alpha} \int_0^1 B_{Ri}^{1-\alpha_1} x_{Ri}^{\alpha_1} di \tag{2.43}$$

Intermediate H-Sector:

$$x_{Hi} = L_H^{\frac{1-\alpha}{1-\alpha_1}} B_H \left(P_H (uH)^{\alpha_2} \alpha_1 \frac{1}{\psi_{Hi}}\right)^{\frac{1}{1-\alpha_1}} \tag{2.44}$$

$$\omega_H = \frac{\alpha_2}{uH} P_H (uH)^{\alpha_2} L_H^{1-\alpha} \int_0^1 B_{Hi}^{1-\alpha_1} x_{Hi}^{\alpha_1} di \tag{2.45}$$

$$\omega_L = \frac{1-\alpha}{L_H} P_H (uH)^{\alpha_2} L_H^{1-\alpha} \int_0^1 B_{Hi}^{1-\alpha_1} x_{Hi}^{\alpha_1} di \tag{2.46}$$

Profit-ratio

Maximization of (2.20) with respect to ψ_{Ri} gives

$$\psi_{Ri} = \frac{r}{\alpha_1}$$

Hence, the price of the machine does not depend on the specific machine i. So we can also write machine demand independent of the index i:

$$x_R = L_R^{\frac{1-\alpha}{1-\alpha_1}} B_R \left(P_R R^{\alpha_2} \alpha_1^2 \frac{1}{r} \right)^{\frac{1}{1-\alpha_1}} \tag{2.47}$$

Thus, profit of monopolists is

$$\pi_R = \left(\frac{1-\alpha_1}{\alpha_1} \right) r^{\frac{2-\alpha_1}{1-\alpha_1}} L_R^{\frac{1-\alpha}{1-\alpha_1}} B_R \left(P_R R^{\alpha_2} \alpha_1^2 \right)^{\frac{1}{1-\alpha_1}} \tag{2.48}$$

For the clean sector one obtains analogously:

$$\psi_{Hi} = \frac{r}{\alpha_1}$$

$$x_H = L_{Ht}^{\frac{1-\alpha}{1-\alpha_1}} B_H \left(P_H (uH)^{\alpha_2} \alpha_1^2 \frac{1}{r} \right)^{\frac{1}{1-\alpha_1}} \tag{2.49}$$

$$\pi_H = \left(\frac{1-\alpha_1}{\alpha_1} \right) r^{\frac{2-\alpha_1}{1-\alpha_1}} L_H^{\frac{1-\alpha}{1-\alpha_1}} B_H \left(P_H (uH)^{\alpha_2} \alpha_1^2 \right)^{\frac{1}{1-\alpha_1}} \tag{2.50}$$

(2.50) together with (2.48) gives the equilibrium profit ratio:

$$\frac{\pi_R}{\pi_H} = \left(\frac{L_{Rt}}{L_{Ht}} \right)^{\frac{1-\alpha}{1-\alpha_1}} \frac{B_R}{B_H} \left(\frac{P_R}{P_H} \right)^{\frac{1}{1-\alpha_1}} \left(\frac{R}{uH} \right)^{\frac{\alpha_2}{1-\alpha_1}}$$

Expected Profit Ratio

We want to write (2.22) such that it only depends on machine quality and prices of R and uH.

Set (2.47) into (2.42) to get:

$$q = \frac{\alpha_2}{R} P_R R^{\alpha_2} L_R^{1-\alpha} \int_0^1 B_{Ri}^{1-\alpha_1} L_{Rt}^{\frac{(1-\alpha)\alpha_1}{1-\alpha_1}} B_{Rit}^{\alpha_1} \left(P_R R^{\alpha_2} \alpha_1^2 \frac{1}{r} \right)^{\frac{\alpha_1}{1-\alpha_1}} di$$

Therefore,

$$R = \left(\frac{1}{q}\right)^{\frac{1-\alpha_1}{1-\alpha}} L_R B_R^{\frac{1-\alpha_1}{1-\alpha}} \left(\frac{1}{\alpha_2}\right)^{\frac{1-\alpha_1}{1-\alpha}} \left(\frac{\alpha_1^2}{r}\right)^{\frac{\alpha_1}{1-\alpha}} P_R^{\frac{1}{1-\alpha}} \tag{2.51}$$

The same result is obtained in the H-Sector with (2.49) and (2.45):

$$uH = \left(\frac{1}{\omega_H}\right)^{\frac{1-\alpha_1}{1-\alpha}} L_H B_H^{\frac{1-\alpha_1}{1-\alpha}} \left(\frac{1}{\alpha_2}\right)^{\frac{1-\alpha_1}{1-\alpha}} \left(\frac{\alpha_1^2}{r}\right)^{\frac{\alpha_1}{1-\alpha}} P_H^{\frac{1}{1-\alpha}} \tag{2.52}$$

Use (2.47) and (2.49) to get

$$Y_R = \left(\frac{\alpha_1^2}{r}\right)^{\frac{\alpha_1}{1-\alpha_1}} R^{\frac{\alpha_2}{1-\alpha_1}} L_R^{\frac{1-\alpha}{1-\alpha_1}} B_{Rt} P_R^{\frac{\alpha_1}{1-\alpha_1}}$$

$$Y_H = \left(\frac{\alpha_1^2}{r}\right)^{\frac{\alpha_1}{1-\alpha_1}} uH^{\frac{\alpha_2}{1-\alpha_1}} L_H^{\frac{1-\alpha}{1-\alpha_1}} B_{Ht} P_H^{\frac{\alpha_1}{1-\alpha_1}}$$

(2.51) and (2.52) leads to:

$$Y_R = \left(\frac{\alpha_1^2}{r}\right)^{\frac{\alpha_1}{1-\alpha}} \left(\frac{\alpha_2 B_R}{q}\right)^{\frac{\alpha_2}{1-\alpha}} L_R B_R P_R^{\frac{\alpha}{1-\alpha}} \tag{2.53}$$

$$Y_H = \left(\frac{\alpha_1^2}{r}\right)^{\frac{\alpha_1}{1-\alpha}} \left(\frac{\alpha_2 B_H}{\omega_H}\right)^{\frac{\alpha_2}{1-\alpha}} L_H B_H P_H^{\frac{\alpha}{1-\alpha}} \tag{2.54}$$

Now using (2.43) and (2.46) together with the labour market arbitrage condition one gets:

$$\frac{P_H}{P_R} = \left(\frac{\omega_H}{q}\right) \left(\frac{B_H}{B_R}\right)^{\alpha-1+\alpha_2} \tag{2.55}$$

Now using (2.55), (2.46), (2.43), (2.54), (2.53) and (2.40) one obtains the labour ratio

$$\frac{L_H}{L_R} = \left(\frac{\omega_H}{q}\right)^{-\alpha_2(\epsilon-1)} \left(\frac{B_H}{B_R}\right)^{-(\alpha-1+\alpha_2)(\epsilon-1)} \tag{2.56}$$

Now plug (2.51), (2.52), (2.55) and (2.56) in (2.22) to get the expected profit ratio dependent only on prices of R and H and on research levels (we denote $\varphi_1 := (1-\epsilon)(1-\alpha_1)$).

$$\frac{\Pi_R(t)}{\Pi_H(t)} = \frac{\eta_R}{\eta_H} \left(\frac{\omega_H(t)}{q(t)}\right)^{(\epsilon-1)\alpha_2} \left(\frac{1+\xi\eta_R s_R(t)}{1+\xi\eta_H s_H(t)}\right)^{-\varphi_1-1} \left(\frac{B_R(t-1)}{B_H(t-1)}\right)^{-\varphi_1}$$

Proof of Proposition 1

Set

$$\tilde{g} := \frac{\Pi_R(t+1)}{\Pi_H(t+1)} - \frac{\Pi_R(t)}{\Pi_H(t)}$$

According to (2.23) we have

$$\begin{aligned}
\tilde{g} = {} & \frac{\eta_R}{\eta_H} \\
& \left[\left(\frac{\omega_H(t+1)}{q(t+1)}\right)^{(\epsilon-1)\alpha_2} \left(\frac{1+\xi\eta_R s_R(t+1)}{1+\xi\eta_H s_H(t+1)}\right)^{-\varphi_1-1} \left(\frac{B_R(t)}{B_H(t)}\right)^{(\epsilon-1)(1-\alpha_1)} \right. \\
& \left. - \left(\frac{\omega_H(t)}{q(t)}\right)^{(\epsilon-1)\alpha_2} \left(\frac{1+\xi\eta_R s_R(t)}{1+\xi\eta_H s_H(t)}\right)^{-\varphi_1-1} \left(\frac{B_R(t-1)}{B_H(t-1)}\right)^{(\epsilon-1)(1-\alpha_1)} \right]
\end{aligned}$$

Now using (2.13), (2.17), and (2.18) we have

$$\begin{aligned}
\tilde{g} = {} & \frac{\eta_R}{\eta_H} \\
& \left[\left(\frac{\omega_H(t)(1+r(t+1))\frac{1}{1+D}}{q(t)(1+r(t+1))}\right)^{(\epsilon-1)\alpha_2} \left(\frac{1+\xi\eta_R s_R(t+1)}{1+\xi\eta_H s_H(t+1)}\right)^{-\varphi_1-1} \right. \\
& \left(\frac{(1+\xi\eta_R s_R(t))B_R(t-1)}{(1+\xi\eta_H s_H(t))B_H(t-1)}\right)^{-\varphi_1} \\
& \left. - \left(\frac{\omega_H(t)}{q(t)}\right)^{(\epsilon-1)\alpha_2} \left(\frac{1+\xi\eta_R s_R(t)}{1+\xi\eta_H s_H(t)}\right)^{-\varphi_1-1} \left(\frac{B_R(t-1)}{B_H(t-1)}\right)^{(\epsilon-1)(1-\alpha_1)} \right]
\end{aligned}$$

Hence

$$
\tilde{g} = \frac{\eta_R}{\eta_H}
\left[\left(\frac{1}{1+D}\right)^{(\epsilon-1)\alpha_2} \left(\frac{(1+\xi\eta_R s_R(t+1))}{(1+\xi\eta_H s_H(t+1))}\right)^{-\varphi_1-1} - \left(\frac{1+\xi\eta_R s_R(t)}{1+\xi\eta_H s_H(t)}\right)^{-1} \right]
\left(\frac{\omega_H(t)}{q(t)}\right)^{(\epsilon-1)\alpha_2} \left(\frac{B_R(t-1)}{B_H(t-1)}\right)^{(\epsilon-1)(1-\alpha_1)} \left(\frac{1+\xi\eta_R s_R(t)}{1+\xi\eta_H s_H(t)}\right)^{-\varphi_1} \tag{2.57}
$$

Case 1: If we assume that the research level in the H-Sector is initially sufficiently more developed than in the R-Sector, or more formally if we assume that

$$
\frac{B_H(0)}{B_R(0)} > \left(\frac{\eta_R}{\eta_H}\right)^{\frac{1}{(1-\alpha_1)(\epsilon-1)}} \left(\frac{\omega_H(1)}{q(1)}\right)^{\frac{\alpha_2}{1-\alpha_1}}
$$

and

$$
\frac{B_H(1)}{B_R(1)} > \left(\frac{\eta_R}{\eta_H}\right)^{\frac{1}{(1-\alpha_1)(\epsilon-1)}} \left(\frac{\omega_H(2)}{q(2)}\right)^{\frac{\alpha_2}{1-\alpha_1}} \tag{2.58}
$$

then we have $\Pi_{H0} > \Pi_{R0} \Rightarrow s_{H0} = 1, s_{R0} = 0, s_{H1} = 1, s_{R1} = 0$[7]. We know that

$$
\left(\frac{1}{1+D}\right)^{(\epsilon-1)\alpha_2} \left(\frac{1}{1+\xi\eta_H}\right)^{-\varphi_1}
$$

is always lower than 1 ($1+D > 1, \epsilon > 1, \varphi < 0, \xi > 0, \eta_H > 0$), therefore $\tilde{g} < 0$ and thus

$$
\left(\frac{1}{1+D}\right)^{(\epsilon-1)\alpha_2} \left(\frac{1}{1+\xi\eta_H}\right)^{-\varphi_1-1} - \left(\frac{1}{1+\xi\eta_H}\right)^{-1}
$$

is lower than 0. Hence, research in H gets gradually even more profitable and thus innovation only occurs in the H-sector.

[7] (2.58) is needed to ensure $s_{H1} = 1,\ s_{R1} = 0$. If this condition does not hold, hence if we get $s_{H1} = 0, s_{R1} = 1$, $\tilde{g}$ would be greater than zero and that can lead to a dirty sector being more profitable than the clean sector. In this case we just would jump to case 2, thus there is no loss of generality.

Case 2: On the other hand, if we assume that the research level in the R-Sector is initially sufficiently more developed than in the H-Sector, more exactly if we assume that

$$\frac{B_H(0)}{B_R(0)} < \left(\frac{\eta_R}{\eta_H}\right)^{\frac{1}{(1-\alpha_1)(\epsilon-1)}} \left(\frac{\omega_H(1)}{q(1)}\right)^{\frac{\alpha_2}{1-\alpha_1}}$$

$$\frac{B_H(1)}{B_R(1)} < \left(\frac{\eta_R}{\eta_H}\right)^{\frac{1}{(1-\alpha_1)(\epsilon-1)}} \left(\frac{\omega_H(2)}{q(2)}\right)^{\frac{\alpha_2}{1-\alpha_1}}$$

then we get $\Pi_{H0} < \Pi_{R0} \Rightarrow s_{H0} = 0,\ s_{R0} = 1\ s_{H1} = 0,\ s_{R1} = 1:$

Consider

$$\begin{aligned}&\left(\frac{1}{1+D}\right)^{(\epsilon-1)\alpha_2} (1+\xi\eta_R)^{-\varphi_1-1} - (1+\xi\eta_R)^{-1} \\ &= \left[\left(\frac{1}{1+D}\right)^{(\epsilon-1)\alpha_2} (1+\xi\eta_R)^{-\varphi_1} - 1\right](1+\xi\eta_R)^{-1}\end{aligned}$$

in (2.57). If

<u>Case 2a:</u>

$$D < (1+\xi\eta_R)^{\frac{1-\alpha_1}{\alpha_2}} - 1$$

it follows that $\tilde{g} > 0$ and therefore innovation occurs in the R-sector only. If

<u>Case 2b:</u>

$$D > (1+\xi\eta_R)^{\frac{1-\alpha_1}{\alpha_2}} - 1$$

we have $\tilde{g} < 0$ for all t. Hence, research will only take place in sector H after some time[8].

Proof of Case 2b:

[8] This condition is the analogon to Proposition 9 in Acemoglu et al. (2012) where here the no-arbitrage condition of the Euler equation is translated into the no arbitrage condition of the education-work decision.

If $\tilde{g} < 0$ in the beginning, there exists a $T > 0$ such that $\Pi_H(T) > \Pi_R(T)$[9]. Therefore we have that $s_R(T-1) = 1,\ s_H(T-1) = 0,\ s_R(T) = 0,\ s_H(T) = 1$. Thus we consider

$$\left(\frac{1}{1+D}\right)^{(\epsilon-1)\alpha_2} (1+\xi\eta_H)^{\varphi_1+1} - (1+\xi\eta_R)^{-1} \tag{2.59}$$

If

1. $\epsilon > \frac{2-\alpha_1}{1-\alpha_1} \Rightarrow \varphi_1 < -1$: (2.59) is lower than 0 for all possible parameter settings and thus research will only take place in the clean sector from time T on as well, in this case.
2. $\epsilon < \frac{2-\alpha_1}{1-\alpha_1} \Rightarrow \varphi_1 > -1$: In this case we argue as follows:

   If

   a) $D > (1+\xi\eta_R)^{\frac{1}{(\epsilon-1)\alpha_2}}(1+\xi\eta_H)^{\frac{(1-\epsilon)(1-\alpha_1)-1}{(\epsilon-1)\alpha_2}} - 1 \Rightarrow \tilde{g} < 0 \Rightarrow$ Future research stays in the H-sector.

   b) $D < (1+\xi\eta_R)^{\frac{1}{(\epsilon-1)\alpha_2}}(1+\xi\eta_H)^{\frac{(1-\epsilon)(1-\alpha_1)-1}{(\epsilon-1)\alpha_2}} - 1$ we need to show that this parameter setting contradicts with (2.25).
   Putting (2.25) and condition (b) together we see that

   $$(1+\xi\eta_R)^{-\frac{\varphi_1-1}{(\epsilon-1)\alpha_2}} < (1+\xi\eta_H)^{\frac{\varphi_1-1}{(\epsilon-1)\alpha_2}}$$

   has to be fulfilled. But this is not possible, because ($\varphi_1 > -1$)

   $$\begin{aligned}&(1+\xi\eta_R)^{-\frac{\varphi_1-1}{(\epsilon-1)\alpha_2}} < (1+\xi\eta_H)^{\frac{\varphi_1-1}{(\epsilon-1)\alpha_2}}\\ &\Leftrightarrow (1+\xi\eta_R) < (1+\xi\eta_H)^{-1}\\ &\Leftrightarrow (1+\xi\eta_R)(1+\xi\eta_H) < 1\end{aligned}$$

   $(1+\xi\eta_R)$ and $(1+\xi\eta_H)$ are both greater than 1, thus this parameter setting is impossible.

$\square$

Case 3: If

$$\frac{B_H(0)}{B_R(0)} = \left(\frac{\eta_R}{\eta_H}\right)^{\frac{1}{(1-\alpha_1)(\epsilon-1)}} \left(\frac{\omega_H(1)}{q(1)}\right)^{\frac{\alpha_2}{1-\alpha_1}}$$

[9] if the case $\Pi_H(T) = \Pi_R(T)$ occurs, case 3 applies.

we have $\Pi_{H0} = \Pi_{R0}$. Then scientists are active in both sectors. If the allocation is such that

$$\left[\left(\frac{1}{1+D}\right)^{(\epsilon-1)\alpha_2}\left(\frac{(1+\xi\eta_R s_R(t+1))}{(1+\xi\eta_H s_H(t+1))}\right)^{-\varphi_1-1} - \left(\frac{1+\xi\eta_R s_R(t)}{1+\xi\eta_H s_H(t)}\right)^{-1}\right] = 0$$

then $\tilde{g} = 0$ and hence the above allocation is an equilibrium. If

$$\left[\left(\frac{1}{1+D}\right)^{(\epsilon-1)\alpha_2}\left(\frac{(1+\xi\eta_R s_R(t+1))}{(1+\xi\eta_H s_H(t+1))}\right)^{-\varphi_1-1} - \left(\frac{1+\xi\eta_R s_R(t)}{1+\xi\eta_H s_H(t)}\right)^{-1}\right] < 0$$

$\tilde{g}$ will be below zero, and therefore we can switch to case 1 for the next round. If

$$\left[\left(\frac{1}{1+D}\right)^{(\epsilon-1)\alpha_2}\left(\frac{(1+\xi\eta_R s_R(t+1))}{(1+\xi\eta_H s_H(t+1))}\right)^{-\varphi_1-1} - \left(\frac{1+\xi\eta_R s_R(t)}{1+\xi\eta_H s_H(t)}\right)^{-1}\right] > 0$$

$\tilde{g}$ will be above zero, and we switch to case number 2 in the next round.

Derivation of Y_R, Y_H and Y

In order to calculate Y_R we transform (2.12) into

$$L_H = 1 - L_R$$

and (2.19) to

$$P_R^{1-\epsilon} = 1 - P_H^{1-\epsilon}$$

With (2.55), (2.56), (2.19) and (2.12) we get

$$P_R = \left[\left(\frac{\omega_H}{q} \right)^{\alpha_2(1-\epsilon)} \left(\frac{B_H}{B_R} \right)^{-(1-\alpha_1)(1-\epsilon)} + 1 \right]^{\frac{-1}{1-\epsilon}} \tag{2.60}$$

and

$$L_R = \left[\left(\frac{\omega_H}{q} \right)^{-\alpha_2(1-\epsilon)} \left(\frac{B_H}{B_R} \right)^{-(1-\alpha_1)(1-\epsilon)} + 1 \right]^{-1} \tag{2.61}$$

Via (2.53) we derive (2.26). Analogously we derive Y_H and Y.

Proof of Theorem 1

The proofs proceeds as follows. In Part 1 it is shown that the growth rate of Y_R is below zero in the long run if the economy is in a clean BGP ($\frac{\Pi_R}{\Pi_H} < 1$) and exhibits strongly substitutable intermediates. In Part 2 we investigate the case of an clean BGP and weak substitutes.

First note, that due to the Euler equation, the interest rate r is constant in the long run.

Part1: Assume the economy is on a green BGP and the intermediates are strong substitutes. Consider (2.26). If innovation in the long run occurs only in the clean sector B_R is constant in the long run. We know that $\varphi_1 < 0$. Hence $\lim_{t\to\infty} B_H^{\varphi_1} = 0$. q does not tend to zero due to the Hotelling rule (assuming positive interest rates). Therefore $q^{\alpha_2(1-\epsilon)} B_H^{\varphi_1} \to 0 \; for \; t \to \infty$ which simplifies the numerator. Therefore we have

$$Y_R = \frac{\left(\frac{\alpha_1^2}{r} \right)^{\frac{\alpha_1}{1-\alpha}} \alpha_2^{\frac{\alpha_2}{1-\alpha}} q^{-\epsilon\alpha_2} B_R^{\frac{1-\alpha_1}{1-\alpha}} B_H^{\varphi_1 \frac{\alpha+\varphi}{\varphi}}}{\left[\omega_H^{\alpha_2(1-\epsilon)} B_R^{\varphi_1} \right]^{\frac{\alpha+\varphi}{\varphi}}}$$

in the long run.

The growth factor of Y_R is

$$\frac{Y_R(t+1)}{Y_R(t)} = \left(\frac{q(t+1)}{q(t)} \right)^{-\epsilon\alpha_2} \left(\frac{B_H(t+1)}{B_H(t)} \right)^{\frac{\alpha+\varphi}{\varphi}\varphi_1} \left(\frac{\omega_H(t+1)}{\omega_H(t)} \right)^{-\frac{\alpha_2}{1-\alpha}(\alpha+\varphi)}$$

We can substitute the growth rates of ω_H, B_H and q:

$$\frac{Y_R(t+1)}{Y_R(t)} = \left[(1+r(t))^{-\alpha_2} (1+\xi\eta_H)^{(1-\alpha_1)(\alpha+\varphi)} (1+D)^{\alpha_2(\alpha+\varphi)} \right]^{\frac{1}{1-\alpha}} \tag{2.62}$$

for $t \to \infty$.

Next, in order to calculate r(t) in the BGP we need to obtain the growth rate of Y first: If we look to the second term in the enumerator of (2.28) we can argue similarly. Due to strong substitutes the power term of B_H: $\frac{\epsilon-1}{\epsilon}\varphi_1\frac{\alpha+\varphi}{\varphi}$ is negative as well. Thus output in the long run is

$$Y(t) = \left(\frac{\alpha_1^2}{r}\right)^{\frac{\alpha_1}{1-\alpha}} \alpha_2^{\frac{\alpha_2}{1-\alpha}} \omega_H^{-\alpha_2(1-\epsilon)\frac{\alpha+\varphi}{\varphi}-\alpha_2\epsilon} B_H^{\frac{1-\alpha_1}{1-\alpha}}$$

Thus the growth factor of Y is

$$\frac{Y(t+1)}{Y(t)} = \left(\frac{\omega_H(t+1)}{\omega_H(t)}\right)^{-\alpha_2(1-\epsilon)\frac{\alpha+\varphi}{\varphi}} \left(\frac{B_H(t+1)}{B_H(t)}\right)^{\frac{1-\alpha_1}{1-\alpha}}$$

Hence,

$$\frac{Y(t+1)}{Y(t)} = \left(\frac{1+r}{1+D}\right)^{\frac{-\alpha_2}{1-\alpha}} (1+\xi\eta_H)^{\frac{1-\alpha_1}{1-\alpha}}$$

This is intuitive: The growth rate is a composition of the efficiency parameter of the two constant return to scale functions - human capital and technology - which drive economic growth.

Now we can make use of the BGP property of equal growth rates in consumption and output to obtain the interest rate:

$$\frac{1+r}{1+\rho} = \left(\frac{1+r}{1+D}\right)^{\frac{-\alpha_2}{1-\alpha}} (1+\xi\eta_H)^{\frac{1-\alpha_1}{1-\alpha}}$$

Hence

$$1+r = (1+D)^{\frac{\alpha_2}{1-\alpha}}(1+\xi\eta_H)(1+\rho)^{\frac{1-\alpha}{1-\alpha_1}} \tag{2.63}$$

This leads to the growth factor

$$\frac{Y(t+1)}{Y(t)} = \left(\frac{1+D}{1+\rho}\right)^{\frac{\alpha_2}{1-\alpha}} (1+\xi\eta_H)$$

Using (2.63) we get

$$\frac{Y_R(t)}{Y_R(t-1)} = (1+\xi\eta_H)^{\alpha_1-\alpha_1(1-\epsilon)+(1-\epsilon)}(1+D)^{\frac{\alpha_2}{1-\alpha_1}(\alpha_1-\alpha_1(1-\epsilon)+(1-\epsilon))}(1+\rho)^{\frac{-\alpha_2}{1-\alpha_1}} \tag{2.64}$$

It is easy to see, that under the case of strong substitutes, all powers are below zero. $\xi\eta_H$, D, and ρ are all above zero. Therefore the growth factor of dirty goods is below one which implies decreasing dirty output.

Part 2: Now we assume that the economy is on a green BGP and exhibits weak substitutes ($\alpha + \varphi > 0$).

As in the first part we get

$$\frac{Y_R(t+1)}{Y_R(t)} = \left(\frac{q(t+1)}{q(t)}\right)^{-\epsilon\alpha_2} \left(\frac{B_H(t+1)}{B_H(t)}\right)^{\frac{\alpha+\varphi}{\varphi}\varphi_1} \left(\frac{\omega_H(t+1)}{\omega_H(t)}\right)^{-\frac{\alpha_2}{1-\alpha}(\alpha+\varphi)}$$

and therefore

$$\frac{Y_R(t+1)}{Y_R(t)} = \left[(1+r(t))^{-\alpha_2}(1+\xi\eta_H)^{(1-\alpha_1)(\alpha+\varphi)}(1+D)^{\alpha_2(\alpha+\varphi)}\right]^{\frac{1}{1-\alpha}}$$

Here we have cannot argue like in the first part. (2.28) has a different asymptotic behaviour due to the small elasticity of substitution. The second part of the denominator can not be cancelled out. Therefore we have to impose the condition

$$\left(\frac{q(t+1)}{q(t)}\right)^{-\epsilon\alpha_2}\left(\frac{B_H(t+1)}{B_H(t)}\right)^{\frac{\alpha+\varphi}{\varphi}\varphi_1}\left(\frac{\omega_H(t+1)}{\omega_H(t)}\right)^{-\frac{\alpha_2}{1-\alpha}(\alpha+\varphi)} < 1$$

in order to avoid long term growth in the dirty sector. Given this condition we can derive Y for this case:

If $\frac{Y_R(t+1)}{Y_R(t)} < 1$ in the long run Y_R will converge to zero. Under those circumstances we have $\frac{Y(t+1)}{Y(t)} = \frac{Y_H(t+1)}{Y_H(t)} = \frac{C(t+1)}{C(t)}$. We can derive that

$$\frac{Y_H(t+1)}{Y_H(t)} = (1+\xi\eta_H)^{\varphi_1\frac{\alpha+\varphi}{\varphi}}\left(\frac{1+r}{1+D}\right)^{-\frac{\alpha_2}{1-\alpha}}$$

Equating this with the Euler equation gives the interest rate in this particular case of weak substitutes and decreasing dirty output (denoted by r_{wf}):

$$1+r_{wf} = (1+\xi\eta_H)^{\alpha+\varphi}(1+D)^{\frac{\alpha_2}{1-\alpha_1}}(1+\rho)^{\frac{1-\alpha}{1-\alpha_1}} \tag{2.65}$$

and therefore we can write the overall output growth in the BGP as

$$\frac{Y(t+1)}{Y(t)} = \frac{Y_H(t+1)}{Y_H(t)} = (1+\xi\eta_H)^{\alpha+\varphi}\left(\frac{1+D}{1+\rho}\right)^{\frac{\alpha_2}{1-\alpha_1}}$$

$\square$

R as polluting source

In this chapter we examine the case of an alternative environmental function. We replace Y_R with R in (2.9) and obtain the equation for the environment:

$$\begin{aligned} E(t+1) &= -\varrho R(t) + (1+\delta)E(t) \\ E(t) &< EOpt \\ 0 < E_0 &\leq EOpt \end{aligned} \tag{2.66}$$

Hence, the environmental disaster can be avoided if the growth rate of R is below one in the long term. The following theorem summarizes the necessary and sufficient conditions.

Theorem A10:

In case of strong substitutes, sustained economic growth will take place and an environmental disaster will be avoided if and only if

- The initial environmental quality is sufficiently high.
- $1 + D > (1 + \xi\eta_R)^{\frac{1-\alpha_1}{\alpha_2}}$
- $1 + D > (1 + \xi\eta_H)^{-\frac{1-\alpha}{\alpha_2}}(1 + \rho)$

In the case of weak substitutes, sustained economic growth will take place and an environmental disaster will be avoided if and only if

- The initial environmental quality is sufficiently high.
- $1 + D > (1 + \xi\eta_R)^{\frac{1-\alpha_1}{\alpha_2}}$
- $\left(\frac{q(t+1)}{q(t)}\right)^{1-\alpha_2(1-\epsilon)} \left(\frac{\omega_H(t+1)}{\omega_H(t)}\right)^{\frac{\alpha_2}{1-\alpha}(1+\varphi)} > \left(\frac{B_H(t+1)}{B_H(t)}\right)^{\frac{1+\varphi}{\varphi}\varphi_1}$
- $1 + D > (1 + \xi\eta_H)^{\frac{(1-\alpha_1)(\alpha+\varphi)}{\alpha_2}}(1 + \rho)$

Proof:

The following equation is the equivalent of equation (2.26) for R:

$$R = \frac{\left(\frac{\alpha_1^2}{r}\right)^{\frac{\alpha_1}{1-\alpha}} \alpha_2^{\frac{-(1-\alpha_1)}{1-\alpha}} q^{\frac{\alpha_2(\varphi+1)-(1-\alpha_1)}{(1-\alpha)}} B_R^{\frac{1-\alpha_1}{1-\alpha}} B_H^{\varphi_1 \frac{1+\varphi}{\varphi}}}{\left[\omega_H^{\alpha_2(1-\epsilon)} B_R^{\varphi_1} + q^{\alpha_2(1-\epsilon)} B_H^{\varphi_1}\right]^{\frac{1+\varphi}{\varphi}}}$$

Equivalently to the proof in theorem 1 we obtain the growth rate of R:

$$\frac{R(t+1)}{R(t)} = \left(\frac{q(t+1)}{q(t)}\right)^{\frac{\alpha_2(\varphi+1)-(1-\alpha_1)}{(1-\alpha)}} \left(\frac{B_H(t+1)}{B_H(t)}\right)^{\frac{1+\varphi}{\varphi}\varphi_1} \left(\frac{\omega_H(t+1)}{\omega_H(t)}\right)^{-\frac{\alpha_2}{1-\alpha}(1+\varphi)}$$

It can easily be shown that this is always below one in the long run in case of strong substitutes. In case of weak substitutes, condition

$$\left(\frac{q(t+1)}{q(t)}\right)^{\epsilon\alpha_2}\left(\frac{\omega_H(t+1)}{\omega_H(t)}\right)^{\frac{\alpha_2}{1-\alpha}(\alpha+\varphi)} > \left(\frac{B_H(t+1)}{B_H(t)}\right)^{\frac{\alpha+\varphi}{\varphi}\varphi_1}$$

has to hold additionally.

$\square$

If the economy exhibits strong substitutes, we obtain the same result as with Y_R. The economy reaches absolute decoupling after some time. In case of weak substitutes we obtain a slightly different condition as in theorem 1. The weights for the resource price q are higher and for ω_H and B_H they are lower.

CHAPTER 3

A Structural Decomposition Analysis of Global and National Energy Intensity Trends

3.1 Introduction

In the last decades, climate change caused by anthropogenic emissions of green house gases, particularly CO_2, has become a major concern for the world community. To a large extent, CO_2 emissions are caused by the global energy use. While ever increasing living standards lead to continuously rising energy consumption, it has also been an inevitable ingredient for economic growth, see e.g. Ayres et al. (2013). However, in order to meet the 2 degree Celsius target of the Copenhagen Accord 2009 and to avoid the possibly catastrophic consequences of even stronger global warming, countries have to reduce their carbon emissions significantly, see Chappe (2015). This requires, as we argue further below, also a substantial reduction of energy consumption. Considering the increasing energy demand that, so far, has come along with economic growth, such climate change targets and continued growth seem to be an insuperable contradiction. Nevertheless, a large body of literature on green growth suggests a way to harmonize both goals, and thus, to achieve a sustainable path of economic growth.[1]

Following the literature on green growth, there are at least two ways to achieve economic growth and simultaneously limit global warming. First, policy can aim at decoupling energy consumption from CO_2 emissions via the use of renewable energy. This approach has, however, so far failed on a global scale and has its limits even when taking into account future technological improvements, see Wirl and Yegorov (2015). Second, one can attempt to decouple economic growth from energy consumption and, hence, reduce the energy intensity (the ratio of energy use

[1]For a discussion and introduction to green growth, see Bowen and Fankhauser (2011). Furthermore, OECD (2013) provides an overview of green growth policies.

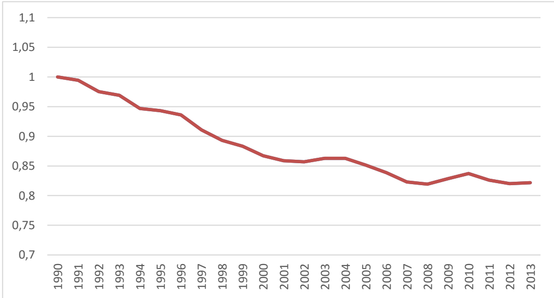

Figure 3.1: Development of energy intensity (ratio of global energy use to world GDP) since 1990 (base year)

to output). Over the course of the last decades, the global energy intensity has been constantly decreasing (see Figure 3.1),[2] giving rise to some scope for this second path of green growth.

In our paper we investigate three different pathways of how the energy intensity of an economy can be reduced. First, technological progress can render production more efficient with respect to energy use. Second, the production of relatively energy intensive goods and services can be outsourced to other countries. This approach, however, only decreases the domestic energy-intensity but not necessarily global energy intensity.[3] Third, structural change within a country towards sectors with a relatively low energy use per unit of output can lower the energy intensity of the economy. In this paper we want to shed light on the question, to which extent changes in these three factors explain the decreasing global energy intensity. We do so by following an empirical approach exploiting the World Input-Output Database (WIOD), providing information about intersectoral trade within and across countries alongside with WIOD environmental accounts which entail data on sector-specific energy use. However, we adjust energy use as provided in the WIOD with respect to intersectoral trade using the environmentally extended input-output analysis (EEIOA). This enables us to determine the magnitude of energy use that a sector ultimately causes through its final demand by also considering energy consumption embodied in trade. We analyze the role of changes of structural shifts within economies and the world using the consumption-based approach and apply the Logarithmic Mean Divisia Index (LMDI), as proposed by Ang and Choi (1997). Additionally, we contrast our results to a decomposition using production-based energy consumption.

Our work is most importantly related to Voigt et al. (2014) who investigate to which extent energy intensity developments have been due to structural and technological change, based on an analysis of WIOD environmental accounts.[4] They find that, while structural change has played an important role in explaining energy efficiency trends in some countries, in particular

[2]The data in Figure 3.1 stems from the World Bank Indicators "GDP at market prices (constant 2010 USD)" and "Energy use (kg of oil equivalent)", available at *http://data.worldbank.org/indicator*.

[3]In fact, trade can increase global energy intensity, if production is outsourced to countries with a higher energy use per output. This problematic aspect of international trade has been called Carbon Leakage in the context of CO_2 emissions. Peters et al. (2011) study the extent of international Carbon Leakage. Jakob and Marschinski (2013) discuss the implications of Carbon Leakage with respect to trade policies.

[4]We are able to completely reproduce the results of Voigt et al. (2014) and use them for comparison of our findings further below.

in the U.S., global energy intensity has improved largely due to technological advancements. The study does not, however, adjust for energy use embodied in trade by using trade information from the WIOD and, thus, only considers the production-based perspective. Consequently, Voigt et al. (2014), solely implement an index decomposition analysis (IDA). In contrast, this paper employs a structural decomposition analysis (SDA) and uses information on intersectoral trade relationships.[5] By employing the LMDI method within a SDA framework, we are following an approach that was only recently established as traditionally LMDI is used in the context of IDAs (see Su and Ang (2012)). For example, Wachsmann et al. (2009) apply an SDA to energy use in Brazil using national input-output tables. Furthermore, Wood (2009) conducts a structural decomposition of greenhouse gas emissions in the Australian economy. Both studies use an additive LMDI decomposition method, while we resort to a multiplicative version of the LMDI to obtain a better comparability of our results to Voigt et al. (2014). An emerging literature applies the SDA to WIOD data, but differs to this paper with respect to the used decomposition method and the focus of analysis. For example, Zhong (2016) applies an averaging technique of perfect decomposition methods[6] to study emission and energy use trends. Xu and Dietzenbacher (2014) analyze global emission trends instead of energy use by employing an SDA using the WIOD. Finally, Peters et al. (2011) study CO_2 emissions embodied in trade and focus on a country-level analysis and on identifying the extent of carbon leakage. To our knowledge, a structural decomposition analysis on global energy intensity trends using the LMDI method has not been conducted yet.
More generally our analysis is based on the growing literature of structural change. A recent article from Mulder (2015) highlights the importance of structural effects in manufacturing sectors for OECD countries in the period from 1980 to 2005. He focuses particularly on the reasons of cross-country differences in energy intensity and finds that structural change is a diverging force. Metcalf (2008) investigates energy intensity trends on U.S. national and state level. At the national level he finds that roughly 75% of the reduction in energy intensity between 1970 and 2003 can be attributed to the technology effect. He also estimates that per capita income and energy prices have a significant impact on the energy efficiency within a sector but do not influence the structural composition of the economy considerably. Huntingtion (2010) uses a less aggregated sector structure of the U.S. economy for the period 1997 to 2006. His results indicate a much stronger structural effect: Almost 40% of energy intensity reduction are due to structural shifts. Cole et al. (2005) even find, that the technology effect within a sector led to an increase of CO2 intensity in four European countries between 1990 and 1998. On the other hand Sun (1999) investigates CO2 intensity trends in the OECD countries for a long time series between 1960 and 1995 and finds that increasing energy efficiency is a main driver for declining CO2 intensity.

Our results show that energy intensity in a number of sectors change dramatically, if we consider consumption-based data (in particularly for the construction and electricity sector). Nonetheless, the global decomposition results exhibit qualitatively similar trends as under production-based data. We find, however, that structural effects are systematically overestimated when

[5] See Hoekstra and van den Bergh (2003) as well as Su and Ang (2012) for a discussion and comparison of IDA and SDA studies.

[6] See Su and Ang (2012) for a discussion of differences with respect to the LMDI method.

using production-based energy data. Moreover, our analysis shows that technological improvements within the sectors are the most important factors of decreasing global energy intensity and that these primarily occurred during the times of increasing oil prices from 2004 to 2008, while structural changes within countries only modestly contributed to falling energy intensities. International trade even led to an increasing global energy intensity, indicating that production was outsourced to relatively more energy-intensive regions. On a country level, we find that the structural effect is strongly overestimated in a range of countries when using production-based data, particularly in Japan and Turkey. Our result for the U.S. indicates that the structural effect accounts for about 32% of the energy intensity decline. This result is in line with Huntingtion (2010), but strongly contrasts with Voigt et al. (2014) who find that structural change explains almost 80% of energy intensity decline in the U.S. between 1995 and 2007.[7] Our result, that structural change seems to be a weaker driving force of reductions in the energy intensity than previously assumed, has rather positive implications for environmental policy. As Huntingtion (2010) notes, such policy is more likely to have an effect on within sector efficiency than on the structural composition of the economy as the latter is often determined by other forces not easily to be influenced by policy-makers. Thus, a strong importance of technological factors in energy efficiency trends creates a possibly large role of policy interventions.

The remainder of the paper is structured as follows: In the following section the data as well as the EEIOA are introduced in detail, followed by a comparison of consumption- and production-based energy use in Section 3. Section 4 and 5 introduce the decomposition algorithm and present the main results of this study before Section 6 concludes.

3.2 Data and Methods

Our analysis is based on the World Input-Output Database (WIOD), a public database providing time-series (covering the period from 1995 to 2011) of intersectoral input-output tables for 40 countries including a model estimation of the rest of the world. It features 35 standardized sectors, that can be further aggregated into agriculture, construction, manufacturing, electricity, transport, and service industry. The 40 countries covered in the database entail 27 member states of the European Union[8], the BRIC nations as well as other major economies such as the U.S., Canada, Australia and Japan. Together, these nations comprised more than 80 % of the world GDP in 2009.

The WIOD has been widely used in trade economics. Data from various national sources have been harmonized in order to enable comparability of data across countries. Moreover, the accompanying WIOD previous-year-prices dataset provides information on price developments on sectoral level, enabling us to deflate each sector independently instead of using aggregate nati-

[7] The rather large difference between the result of Voigt et al. (2014) and Huntingtion (2010) is quite surprising considering the large overlap in the considered time period. While Huntington uses the North American Industry Classification System (NAICS) rather than the NACE classifcation applied in Voigt et al. (2014), this should nevertheless not produce such strongly differing results. As Huntingtion (2010) is employing the more refined NAICS sectoral structure, he should, if at all, be able to detect a stronger structural change.

[8] As the WIOD was released in 2012, Croatia as the 28th member state is not included.

onal price deflators which lack important information on the heterogeneity of inflation in each sector.
In addition to the input-output tables, the WIOD is accompanied by environmental satellite accounts providing information about sector-specific gross energy use in terajoule (TJ), that encompasses the total energy requirements in the industry. Importantly, energy use only includes energy consumed in the production process of a given sector, while ignoring indirect energy consumption through trade of goods and services with other sectors.[9] We only use data on energy use from production and do not include household energy consumption as our main focus lies on structural effects and technology improvements within sectors.[10]
As international supply chains have been integrated to an increasing extent during the last decades (see Timmer et al. (2014)), it is necessary to account for energy transfers embodied in intersectoral and international trade to obtain a realistic picture of the energy use of a given sector. As an example, we consider the construction sector. In the WIOD environmental accounts, the energy use of the construction sector would be comprised mostly of electricity and fossil fuel consumption by vehicles and machinery deployed in construction works. While this direct energy demand by the construction sector is certainly not negligible, one would grossly underestimate the extent of energy consumption that is required for the final demand this sector is supplying if only this direct energy demand is considered. Obviously, the construction sector is heavily dependent on inputs from other sectors, such as materials from the mining and quarrying sector as well as the wood sector. Moreover, it requires heavy machinery, vehicles, and technical equipment from various manufacturing subsectors. Conversely, the output produced by the construction sector does not only satisfy final demand but also intermediate demand by other sectors. Consider as an example the manufacturing or service sector that require factories and office space for their production processes.
In our globalized economies, the interdependencies between sectors within and between countries through trade are highly developed, such that tracking indirect energy use for each sector would be a very cumbersome, if not impossible task. However, Wassily Leontief has developed a convenient method to calculate direct and indirect inputs required in the production processes of sectors, the Input-Output Analysis.[11] Moreover, he extended this method to study material and pollution flows across sectors in his seminal paper "Environmental Repercussions and the Economic Structure" (Leontief (1970)), laying the groundwork for what was later called the environmentally extended input-output analysis. This method allows us to determine the total energy use of a sector, based not only on its direct but also on the indirect energy consumption. The method translates production-based sectoral energy use as given in the WIOD environmental accounts, denoted by the vector e, into consumption-based energy use ($\tilde{e}$) and is described by

[9] The WIOD and its accompanying environmental accounts are freely available at http://www.wiod.org. While this paper provides a short introduction on the use of input-output tables, detailed information on the database is provided in Timmer et al. (2015). Extensive documentation about the construction of the WIOD is compiled in Dietzenbacher et al. (2013). A technical report on the environmental accounts is provided by Genty (2012).

[10] Here, we follow Xu and Dietzenbacher (2014) who took a similar approach in their analysis of global CO_2 emissions trends.

[11] Leontief (1936) introduced the Input-Output Analysis for the first time.

$$\tilde{e} = c(I - A)^{-1}\hat{y}, \tag{3.1}$$

where $\hat{y}$ is the diagonal matrix of the consumption vector y, x is industry-specific output, $c = e \oslash x$ is the energy coefficient, which indicates how much energy is needed for one unit of output ($\oslash$ denotes element-wise division) and A is the matrix of technological coefficients carrying information on the intersectoral trade structure.[12] Energy use is, hence, merely reallocated across sectors according to trade flows such that double-counting is avoided. In Croner and Frankovic (2016), we provide an extensive introduction to the EEIOA and its application to the WIOD-Tables as employed here. Moreover we therein provide a two sector, two country example of how production-based sectoral energy use is transformed into consumption-based accounting.

3.3 Consumption- vs. Production-Based Energy Use

This section compares energy use data from the WIOD environmental accounts (production-based energy use) with the measure of trade-adjusted energy consumption introduced in the previous section (consumption-based energy use). Table 3.1 provides summarized country and sector statistics for three selected years, where energy use is reported in terajoule. Consumption-based accounting reduces the variance across countries and, in particular, across sectors. We analyse general differences between consumption and production-based energy use for the year 2007 on an aggregated national and sectoral level. Lastly, we examine time trends of these differences across countries and sectors.

Year	Mean	Std.dev	Min	Max	Mean	Std.dev	Min	Max
	Production Based Energy Use - Country Statistic				**Production Based Energy Use - Sector Statistic**			
1995	1.25e+07	2.48e+07	60551.79	1.21e+08	1.46e+07	3.46e+07	11011.24	1.62e+08
2002	1.40e+07	2.77e+07	67056.23	1.32e+08	1.64e+07	3.97e+07	12362.28	1.81e+08
2009	1.61e+07	3.22e+07	65405.9	1.35e+08	1.88e+07	4.53e+07	0	2.00e+08
	Consumption Based Energy Use - Country Statistic				**Consumption Based Energy Use - Sector Statistic**			
1995	1.25e+07	2.44e+07	80958.86	1.23e+08	1.46e+07	1.56e+07	38843.94	6.41e+07
2002	1.40e+07	2.76e+07	89722.68	1.42e+08	1.64e+07	1.79e+07	28062.52	7.39e+07
2009	1.61e+07	3.15e+07	89200.38	1.30e+08	1.88e+07	2.27e+07	10872.13	1.10e+08

Table 3.1: Summarized Country and Sector Statistic

Country-level analysis

We begin with a country-level analysis where sectoral energy consumption is aggregated nationally. Figure 3.2 shows the world largest energy users consisting of the USA, China, Japan, Russia, and India in the year 2007.[13] In the U.S., consumption-based energy use exceeds the production-based value provided in the WIOD environmental accounts by 8.5 %. Hence, final

[12] This model is based on direct impact coefficients, that is the energy used in a sector is associated with the monetary value flow from each sectors to the other sectors. It is well know that this approach has some important drawbacks because changes in physical energy flows might not correspondent with monetary flows. For instance the price of the intermediate inputs from the electricity sector might change due to service improvements where as the physical energy flow is not changing. This case might not be complete captured by the sectoral deflation. However, given the data availability it still seems the most accurate assumption.

[13] We use the year 2007 as the last year before the global crisis after which large declines in international trade created an exception to the overall pattern of strong adjustment effects.

consumption in the U.S. is associated with a larger energy consumption than required for the production of total output in the USA. While, to our knowledge, this result has not yet been established in the context of energy consumption, Peters et al. (2011) have shown that the USA is a net-importer of CO_2 emission considering the carbon-intensity of internationally traded goods and services. Considering that energy use and CO_2 emissions are highly correlated; i.e., high energy use in a given sector implies large CO_2 emissions[14], our results are consistent with these findings.

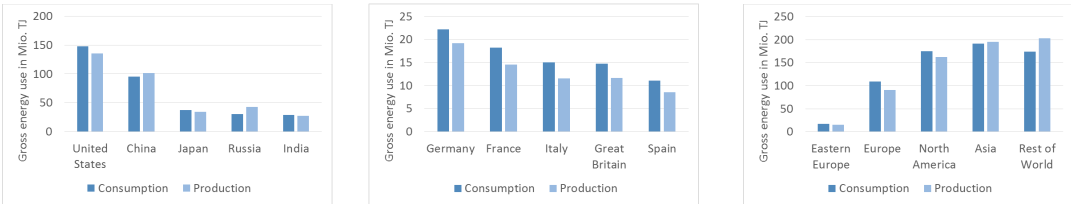

Figure 3.2: Consumption and production-based gross energy use in 2007 in various world regions and countries

China, the second largest energy user in the world, exhibits the exact opposite pattern. Here, consumption-based energy use lies below the production-based value, a difference of 6.7 %. To a large part, the results of the USA and China reflect the trade patterns in each country; while the U.S. runs a large trade deficit, China is net exporter of goods and services.[15] In fact, across the 40 countries national trade deficits are strongly and negatively correlated with net energy imports.[16] In other words, the larger the net imports of goods in services in a given country are, the larger are the net imports of energy across our sample of 40 countries. Nonetheless, this pattern does not hold for all countries. For example, Japan, which exhibits a trade surplus, shows a relatively higher consumption-based energy use. Apparently, Japan's imports are heavily energy-intensive relative to its exports. In the case of Russia we observe the largest differences of consumption to production-based energy use, namely by 40.9 %. This is due to the rather energy-intensive exports in Russia, dominated by petroleum and gas production as well as the mineral resource industry. Interestingly, Russia's consumption-based energy use lies below Japan's while in terms of production-based energy consumption they would be ranked in the opposite way. Lastly, India is a net-importer of energy, a likely consequence of its trade deficit.

Figure 3.2 also shows energy use among the five largest European economies, consisting of Germany, France, Italy, Great Britain and Spain, in the year 2007. Considering that the latter four countries were running a trade deficit in 2007, it is not surprising that their consumption-based energy use exceeds the production-based values. The degree to which energy is implicitly imported through trade is remarkably stable across countries: In these countries, consumption-based exceeds production-based energy use by about 20%-23%. In contrast to this similarity across large European economies, Germany shows a different pattern. Despite its immense trade surplus (approx 5% of GDP in 2007), Germany nevertheless exhibits net energy imports. This

[14]This correlation, of course, depends on the mix of energy sources used in the production.
[15]Here and in the following, data on trade patterns for 2007 is based on the indicator "Net trade in goods and services (BoP, current US$)" from The World Bank (2016).
[16]The correlation coefficient is -0.62.

indicates that the outputs produced in Germany for the use in foreign industries are distinctly less energy-intensive than those goods and services that are imported from foreign sources. However, and due to the large trade surplus, Germany's consumption-production gap in energy use amounts to only 13.7 % in 2007 and thus is considerably lower than in the other considered European countries.

The far-right plot in figure 3.2 depicts consumption and production-based energy consumption in world regions.[17] Most interestingly, the Asian region is almost net-neutral with respect to trade-related energy imports and exports.

Sector-level analysis

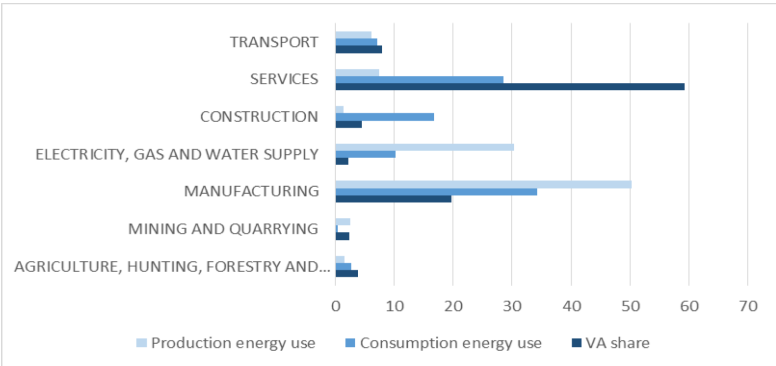

Figure 3.3: Gross energy use and value added shares in 2007 of 7 sectors aggregated to a global level

We now focus on seven sectors[18] aggregated to a global level for the year 2007. Figure 3.3 shows consumption and production-based energy use share of the global energy consumption together with information on the industry-specific value added share of the world's GDP. This allows us to compare the energy use of a given sector relative to its market size. Due to their dominance, we focus on the service as well as on the manufacturing sector. While the former contributes nearly 60 % of the world GDP, it is responsible for only 8 % to the total energy use. In contrast, the manufacturing sector, with a market share of approximately 20 %, is responsible for about 50 % of global energy use. However, when considering the extent of energy use associated with the final demand that these sectors ultimately satisfy as measured by consumption-based energy use, this strong difference in sector-specific energy use narrows dramatically. From this consumption-based perspective, the service sector requires close to 30 % of world energy use, whereas the share of the manufacturing industry shrinks to about 35 %. The adjustment of energy use towards the service sector can be explained by its strong reliance on inputs from

[17] Eastern Europe = Bulgaria, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Poland, Romania, Slovakia, Slovenia; Europe = Austria, Belgium, Cyprus, Germany, Denmark, Spain, Finland, France, Great Britain, Greece, Ireland, Italy, Luxembourg, Malta, Netherlands, Portugal, Sweden; North America = Canada, Mexiko, USA; Asia = China, India, Indonesia, Japan, Korea, Taiwan.

[18] In order to make the analysis more concise, we have aggregated the 35 sectors into seven more broadly defined sectors in this section. In the subsequent sections of the paper the more detailed sector disaggregation is used again.

other sectors, whereas manufactures deliver a larger share of their outputs for the use of other sectors rather than for final demand.

The electricity, gas, and water supply sector as well as the mining and quarrying industry show a similar pattern as the manufacturers, being predominantly producers of intermediate inputs into other sectors. The construction industry, on the other side, exhibits a qualitatively similar adjustment as the service industry. Notably, it shows the strongest reallocation of energy use across all sectors which indicates a strong reliance on energy-intensive inputs from other sectors.

Time trends

So far, we have focused only on the differences between production and consumption-based energy use for the year 2007. In this section, however, we analyze time trends in these differences across selected countries and global sectors. First we refer to Figure 3.4, that displays energy use trends for USA and China over the period from 1995 to 2009 with 1995 as the baseline.[19] Independent from the measure we apply, we observe an increase of energy use in the U.S. until the Great Recession in 2008 and a subsequent strong reduction. The gap between consumption and production-based energy consumption was widening until the recession and only declined slightly due to the slump in trade caused by the recession.[20] By contrast, China exhibits increases in energy use throughout the whole time period. The gap between consumption and production-based energy use was initially narrowing and later on remained fairly stable.

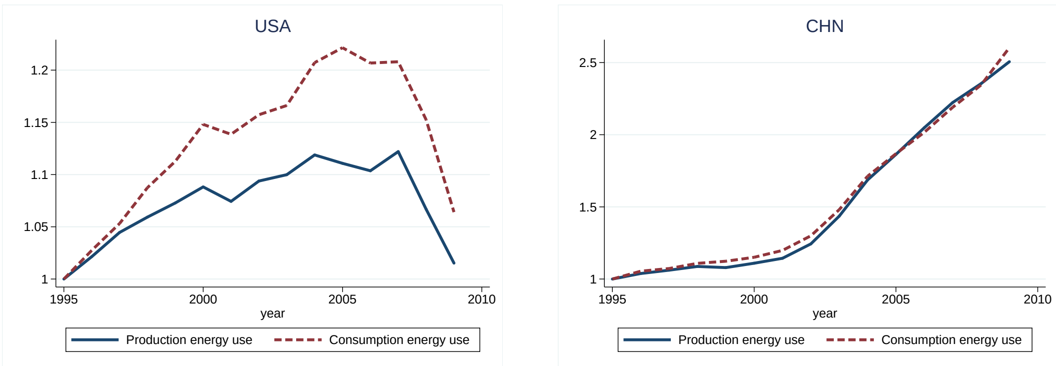

Figure 3.4: Energy use trends in the USA (left) and China, base=1995

We extend the same time trend analysis on the global construction and energy sector. Figure 3.5 shows the evolution of consumption and production-based energy use (in each case relative to the level in 1995) for both sectors. We observe, that the difference between both measures has considerably increased over the considered time period. This becomes most evident when

[19] While this is not shown in Figure 3.4, it is important to know how large the absolute levels of consumption and production-based energy use were in each country: In the U.S., consumption-based energy use exceeded the energy use in production in all years. In China, however, more energy was used in production than was associated with the country's consumption throughout the whole time-horizon that we consider.

[20] See "Trade (% of GDP)" indicator for the U.S. and the world in The World Bank (2016)

looking at the construction sector, which exhibits relatively stable production energy use since the mid 2000s but dramatically increasing consumption-based energy use in the same period. The rising integration of global supply chains, see Timmer et al. (2014) has, thus, likely resulted in larger transfer of energy embodied in trade.

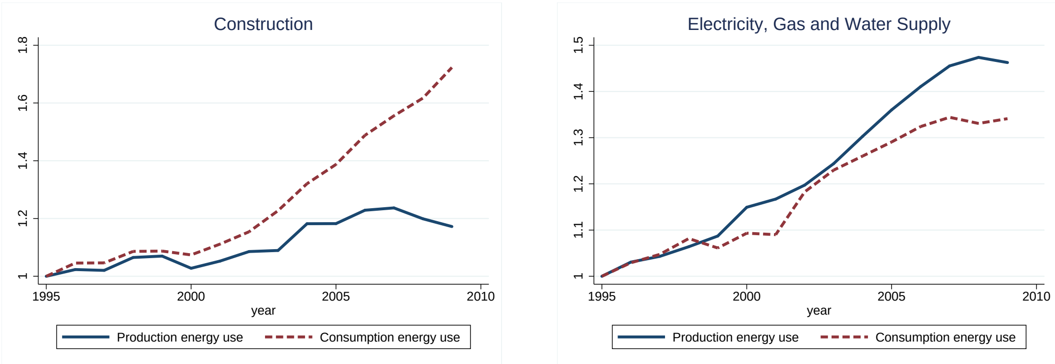

Figure 3.5: Energy use trends in the construction (left) and electricity, gas and water supply sector, base = 1995

3.4 Decomposition

Our main focus in this paper lies on the question whether structural, trade or technological factors drive the overall trend of global and national energy intensity.[21] First, we clarify these terms: "Structural effects" denote sectoral shifts within a country whereas trade effects denote structural changes between countries. "Technological effects" represent any changes within a specific sector such as those relating to production technology and processes or intrasectoral market share shifts between companies. Using this definition, note that technological effects encompass a broad range of factors. Anything that influences the ratio of energy input to consumption within a sector is captured herein. For example, if a manufacturer employs modern machinery instead of workers, it might lead to an increase of the energy intensity within a sector as the machine requires electricity to produce the same amount of output for final consumption. Moreover, consumption shifts from less energy efficient firms to more energy efficient firms that occur within one single sector would fall into the category of technological effects.
For decomposing the trend in energy intensity into the effects of trade, sectoral shifts within a country and technology, we use the Log-Mean Divisia Method II (LMDI II) introduced by Ang and Choi (1997). This method has the advantage that it leaves no residual term and therefore

[21]Contrary to Voigt et al. (2014) we define global (national) energy intensity as the ratio of global (national) energy use to global (national) consumption when using the consumption-based energy use. Equivalently, sectoral energy intensity is defined as the ratio of sectoral consumption-based energy use to its consumption level. In view of an appropriate measure of sectoral responsibility of energy consumption, it is, however, important how much energy is needed for final consumption rather than for total output. The production-based measure, thus, overestimates the advances in energy intensity reductions as it also attributes increases in intermediate inputs as contributors to a lower energy intensity where the consumption-based approach only considers energy use relative to consumption.

completely decomposes the trends in its components. Its original version is applied as a two factor decomposition method for specific countries.[22]
In order to obtain results on a global level we additionally use the three factor LMDI II introduced by Voigt et al. (2014) and apply it to our consumption-based energy use data to separate the effect of technological improvement as well as structural change within and between countries. But first we introduce the two factor LMDI II which decomposes the trend of energy intensity into technological improvements and structural change between sectors within a country.

Two factor LMDI II

The energy intensity of a country is defined as the sum of energy use of all its economic sectors divided by the sum of the overall final consumption levels of these sectors[23]. Hence we can write energy intensity as:

$$I_{j,t} = \sum_i \frac{E_{i,j,t}}{C_{j,t}} = \sum_i \frac{C_{i,j,t}}{C_{j,t}} \frac{E_{i,j,t}}{C_{i,j,t}} = \sum_i S_{i,j,t} I_{i,j,t} \tag{3.2}$$

where $t \in (1995, 2009)$ is the time period, $i = 1, ..., 35$ is the sector index, $j = 1, ..., 40$ indicates the country, $E_{i,j,t}$ is the energy use of sector i in economy j, $E_{j,t} = \sum_i E_{i,j,t}$ is the energy use of economy j, $C_{i,j,t}$ is final consumption of sector i in economy j, $C_{j,t} = \sum_i C_{i,j,t}$ is the consumption of the whole economy, $S_{i,j,t} = \frac{C_{i,j,t}}{C_{j,t}}$ is the consumption share of sector i in total consumption of the country, $I_{i,j,t} = \frac{E_{i,j,t}}{C_{i,j,t}}$ is the energy intensity of sector i in economy j and $I_{j,t} = \frac{E_{j,t}}{C_{j,t}}$ is total energy intensity of economy j. Note that in the definition by Voigt et al. (2014) energy use is divided by gross output rather than consumption to obtain the energy intensity. In the subsequent sections we juxtapose results of the decomposition of the consumption and production-based energy use, where the former method is using the approach by Voigt et al. (2014) and the latter the approach presented here. As proven in Ang and Choi (1997), changes in energy intensity between period t and t+1 can be expressed as

$$D_{Tot,j,t+1} = \frac{I_{j,t+1}}{I_{j,t}} = D_{Str,j,t+1} D_{Int,j,t+1}. \tag{3.3}$$

The components are

$$D_{Str,j,t+1} = \exp\left[\sum_i \frac{L(\omega_{i,j,t+1}, \omega_{i,j,t})}{\sum_i L(\omega_{i,j,t+1}, \omega_{i,j,t})} \ln\left(\frac{S_{i,j,t+1}}{S_{i,j,t}}\right)\right] \tag{3.4}$$

$$D_{Int,j,t+1} = \exp\left[\sum_i \frac{L(\omega_{i,j,t+1}, \omega_{i,j,t})}{\sum_i L(\omega_{i,j,t+1}, \omega_{i,j,t})} \ln\left(\frac{I_{i,j,t+1}}{I_{i,j,t}}\right)\right] \tag{3.5}$$

[22] The more recent method LMDI I proposed by Ang and Lui (2001) would have the additional advantage of consistency in aggregation which allows for consistent estimation of sub-groups. However, we do not apply further analysis of sub-groups in this paper. The focus of this article is rather to compare our results with Voigt et al. (2014) who used production-based data. For this reason we resort to the LMDI II method in this paper.

[23] All foreign consumption of domestic produced goods is included.

where

$$L(\omega_{i,j,t+1}, \omega_{i,j,t}) = \frac{\omega_{i,j,t+1} - \omega_{i,j,t}}{\ln\left(\frac{\omega_{i,j,t+1}}{\omega_{i,j,t}}\right)} \tag{3.6}$$

and

$$\omega_{i,j,t} = \frac{E_{i,j,t}}{E_{j,t}} \tag{3.7}$$

is the share of energy use from a specific sector in the overall energy use of the economy in a country. $L(\omega_{i,j,t+1}, \omega_{i,j,t})$ is a logarithmic weight function for country j which is normalized in (3.4) and (3.5) by dividing it through the sum of each country's weight function. $D_{Str,j,t+1}$ describes how much structural change within a country contributes to the change in overall energy intensity between period t and t+1. The higher the share of a sector is, the higher is its weight for total energy intensity. $D_{Int,j,t+1}$ shows to which extent technological improvements in a sector contribute to the change in overall energy intensity between t and $t+1$ (with "Int" standing for sectoral energy intensity). The lower $I_{i,j,t}$ is, the more efficient is the use of energy in a particular sector. While it is evident that D_{Tot} denotes the total change in energy intensity between two periods, the values of D_{Str} and D_{Int} can be interpreted counter-factually: D_{Str} represents the change in energy intensity caused by structural changes within the economy if technology had remained constant throughout the considered period. Conversely, D_{Int} denotes the change in energy intensity associated with technological progress if sectoral market shares had stayed unchanged.

In order to obtain a decomposed time series from 1995 to 2009 the results are chained as in Ang and Lui (2007). All indices are set to 1 for the baseline year 1995. The chained factors indicate the percentage change of each factor as compared to 1995.

3.5 Results

In this section, we present the results of the decomposition of consumption-based energy use data. First we focus on the decomposition results on a country level and discuss patterns in efficiency gains across countries. Second, we analyze and decompose global energy intensity trends. Finally, we juxtapose the difference in decomposition results between consumption and production-based data.

Decomposition on a country level

The country level results are summarized in table 3.2. We see that the average energy intensity across the 40 considered countries in 2009 is about 77.6% of the intensity in 1995. The structural component is associated with a decline in energy intensity of about 5.8% and the technological effect of about 17.4% in 2009 compared to 1995. We identify strong technological improvements of up to 54% in some countries. The structural effect is generally weaker than the technological effect, which was especially strong in the years from 2004 to 2008, most likely driven by the increasing oil and energy prices during that time.

Figure 3.6 shows three scatter plots that depict the relationship between energy intensity improvements (y-axis) and GDP per capita, GDP growth as well as initial energy intensity (on

Year	Mean	Std.dev	Min	Max
Total				
1995	1	0	1	1
2,002	.878323	.1148429	.6547465	1,247,129
2009	.7755952	.145933	.4846849	1,111,699
Structural Effect				
1995	1	0	1	1
2002	.9713212	.0821956	.6606359	1,197,197
2009	.941888	.0876902	.650878	1,105,566
Technological Effect				
1995	1	0	1	1
2002	.9058169	.0997229	.6566586	1,112,162
2009	.8258537	.1454902	.4648073	1,128,145

Table 3.2: Summarized Country Statistic

the x-axis) across the 40 countries and the period 1995-2009 considered in the WIOD. The first graph shows that less developed countries tend to have more success in reducing energy intensity than countries with a higher development status, measured by the average GDP per capita (PPP).[24] Hence, poorer countries exhibit on average higher relative gains in energy efficiency. In fact, this association is driven by the technological effect on energy efficiency that were most pronounced in poorer countries. By contrast, structural changes tended to be stronger in richer countries.[25]. Moreover, average GDP growth appears to be correlated with efficiency gains (center graph). Economies that grew at higher rates also exhibited large efficiency gains. Again, the association is shaped by the technological component, while the impact of structural changes seem to be independent of GDP growth. Finally and as shown in the right plot, countries with larger initial energy intensities also tended to improve their energy efficiency much stronger as seen in the graph at the right of Figure 3.6. Hence, we observe a global convergence of energy-intensities in the considered period.

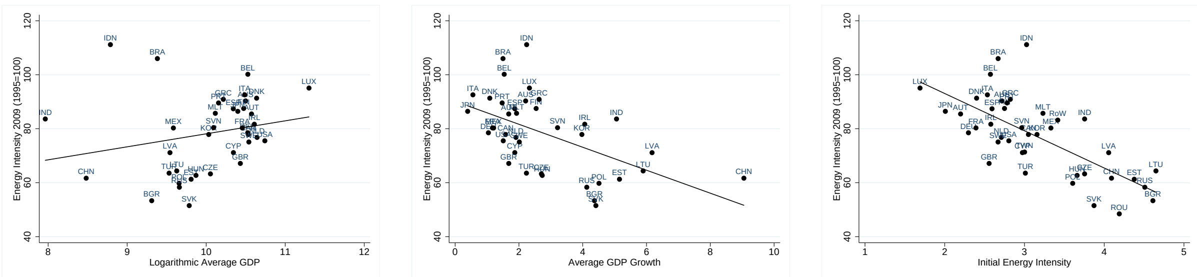

Figure 3.6: Relationship between energy intensity improvement and GDP per capita (left), average GDP growth (center) and initial energy intensity (right)

In the following, we highlight the results of some selected countries of interest, namely USA, India, China, Japan and Turkey. Our choice of the USA and China is motivated by their large share in global energy consumption. The structure of the Indian economy has an increasing impact on global energy use as well. In addition we discuss decomposition results of

[24]Here we use GDP per capita (PPP) in constant 2011 international Dollar from the The World Bank (2016).

[25]See Appendix A2 for a decomposition of energy efficiency gains in a structural and technological component and their relationship to GDP per capita, GDP growth and initial energy intensity.

Japan and Turkey because the differences to production-based data are most pronounced for these countries. In the Appendix A1, we provide the results for all nations. Figure 3.7 shows the development of energy use in the USA with consumption-based energy data (left graph) and production-based energy data (right graph). While the trends in energy intensity are quite similar, we can observe a dramatic difference in the contribution of structural and technological effects on overall energy intensity. For production-based data we see, starting at 2002, a strong trend towards the structural effect, contributing by about 80% to the overall energy intensity decline. In contrast, the consumption-based approach suggests a much weaker structural effect, being only responsible for about 32% of the total reduction in energy-intensity.

We observe no differences across the production-based and consumption-based approach for China and India in the decomposition. Both approaches indicate that the structural effect played almost no role.[26] Therefore we just depict the consumption-based decomposition for this countries. In both countries, the structural effect was even resulting in a more energy-intensive economy during some years.

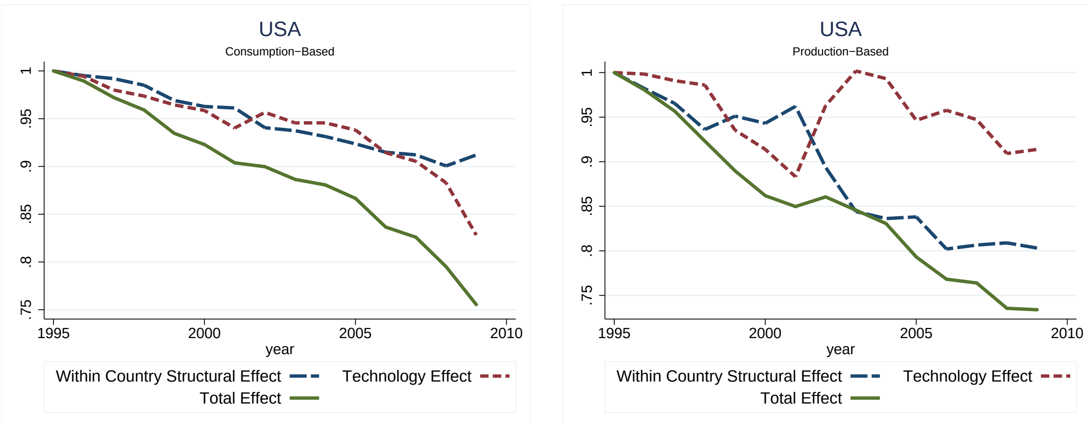

Figure 3.7: Decomposition trends for the USA

The outcome for Turkey shows strong differences, in particular for the last two years of the time period considered. When decomposing production-based data, the technological effect is underestimated by about 10% while the structural effect appears to be strongly exaggerated. Note that the time trend of the total effect also differs across consumption and production-based data. This gap reflects the higher energy consumption of Turkey compared to its production-based energy use.

In Japan, structural changes seem responsible for all improvements in national energy efficiency under production-based energy consumption data, while the pattern dramatically changes if we look at consumption-based data. These differences are an indicator of the importance of an environmental extended input-output analysis in evaluating energy intensity trends.

[26]This result might seem surprising considering the strong structural transformations in these countries during this time interval. However, by having a closer look at the data we find that sectors with increasing share of overall domestic consumption have similar energy intensity than sectors which where declining in their consumption share.

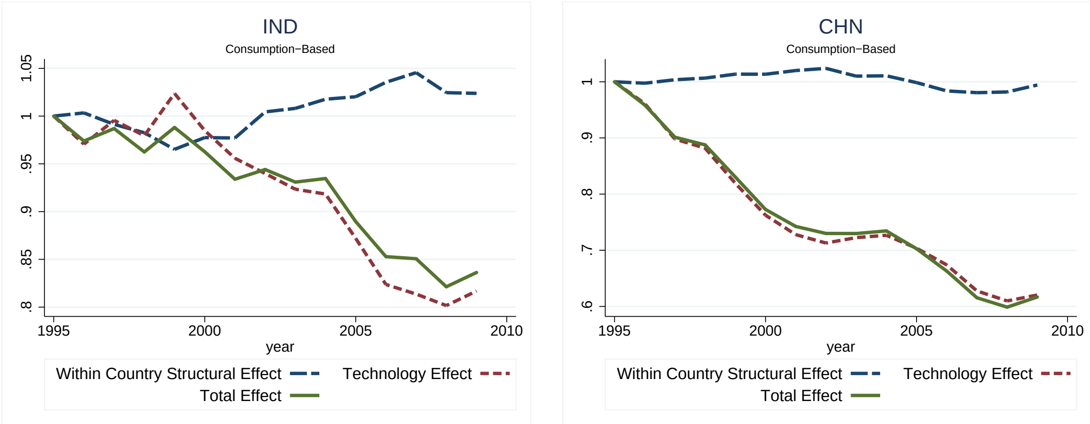

Figure 3.8: Decomposition trends for USA and China

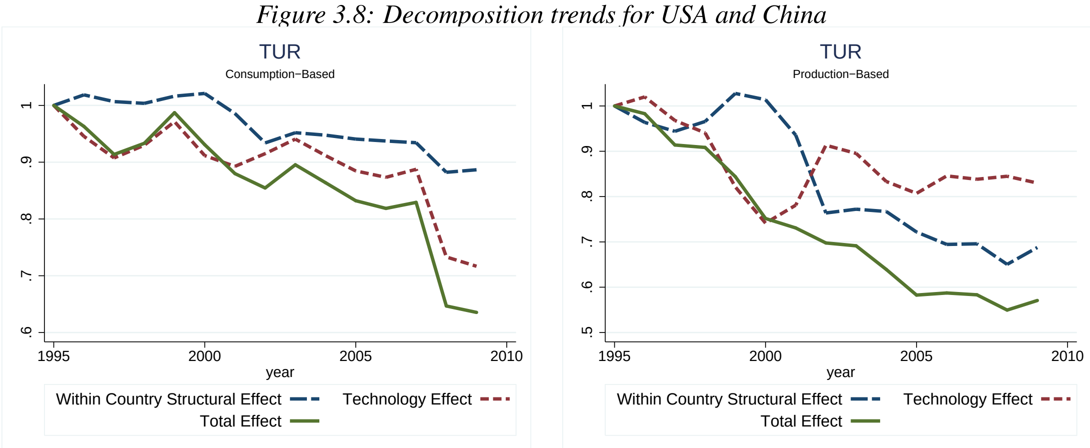

Figure 3.9: Decomposition trends for Turkey

Decomposition on a global level

In addition to the two factors considered in the country analysis, we also have to account for a third factor on a global level, namely the structural effect between countries, also called the trade effect. It is a well known concern that industrial countries, by tightening their environmental laws, create incentives for heavily polluting industries to move to less-regulated countries.[27] We therefore decompose the global energy intensity trend into a technological effect, structural effect within a country and a structural effect between countries (trade effect). We apply a three factor decomposition analysis, described by Voigt et al. (2014).[28]

On a global scale, consumption and production-based results show similar patterns. It is evident in both approaches that the trade effect between countries, illustrated by the orange line in Figure 3.11, is associated with an increasing global energy intensity. This implies, that if everything else had remained unchanged, the shifts in the global trade structure from 1995 to 2009 would have driven up the global energy intensity by about 15%. As Voigt et al. (2014)

[27] See e.g. Babiker (2005).

[28] This method is also explained in the Appendix of Croner and Frankovic (2016).

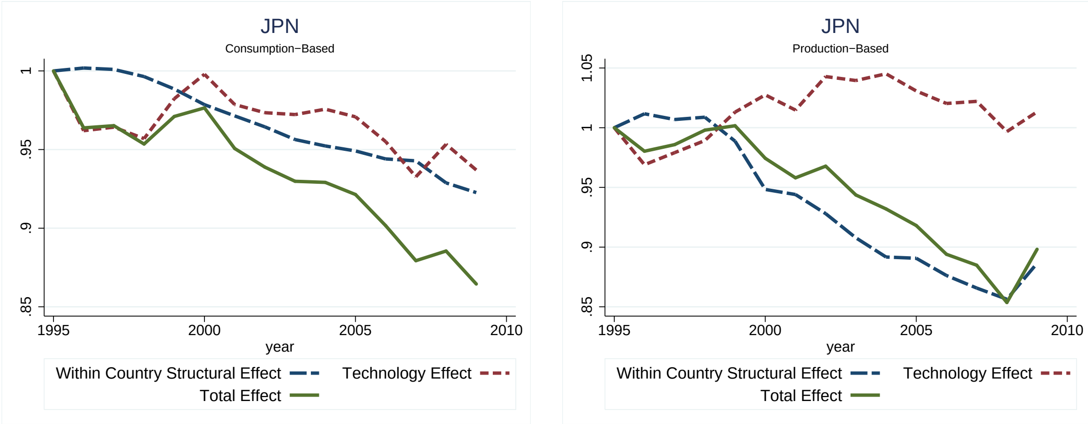

Figure 3.10: Decomposition trends for Japan

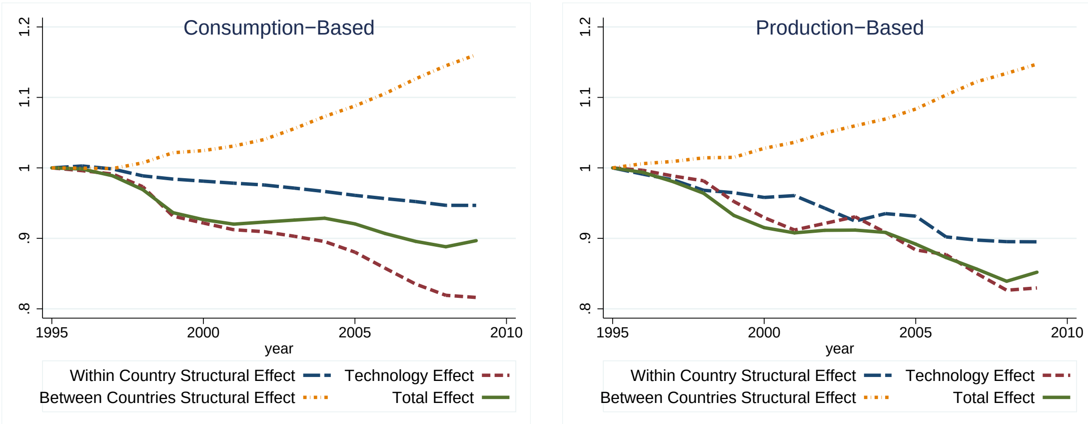

Figure 3.11: Global Decomposition Results

note, this was due to the shift of the global economy towards countries like China and India that have relatively high energy intensities.

Both approaches imply that the structural effect within a country, shown by the blue line in Figure 3.11, lead to a reduction of global energy intensities.

Both approaches also have in common that the technology effect was the main driving force for energy efficiency gains. In particular we can see by examining the red line in Figure 3.11, that the increasing energy prices between 2004 and 2008 coincided with a strong global improvement due to technology.

To highlight some differences in results of both approaches we calculate the structural and technological effects relative to the total efficiency gains.[29] Figure (3.12) depicts the relative contribution of trade, between country and within country structural effect relative to normalized

[29]We have to calculate the relative contributions because the total levels of energy intensity are different. This is due to the use of consumption data for measuring energy intensity in the consumption-based approach.

total effects for both approaches.

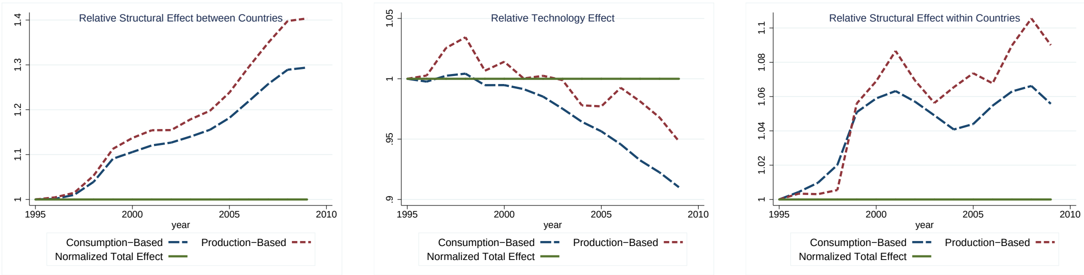

Figure 3.12: Comparison of Decomposition Results

The trade effect appears to be weaker over the considered period using consumption-based data as can be inferred from the left hand graph of Figure 3.12. The overestimation of the trade effect under production-based data is due to the missing reallocation of energy embodied in trade away from energy-intensive countries such as China and India. In fact, a significant part of energy use in these countries is linked to final demand in less energy-intensive countries, see Section 3. Thus, the global shift in energy use is less pronounced when considering consumption-based rather than production-based energy use.

In addition, production-based data overestimate the importance of structural effect within a country, as seen in the second graph in Figure 3.12. We thus observe, once again, that, when energy-embodied trade is accounted for, structural changes appear to have a weaker effect on the global energy intensity.

The overestimation of structural effects using production-based data necessarily results in an underestimation of the technology effect. The contribution of the technology effect trend on overall energy intensity trends is almost double in the case of consumption-based data.

3.6 Conclusion

The fundamental question posed in the green growth literature is whether it is possible to reconcile economic growth with environmental sustainability. This question hinges most importantly on the feasibility of decreasing the emission of greenhouse gases and the exploitation of natural resources in global production processes. Apart from the utilization of renewable energy, widespread and significant reductions in energy intensities can contribute to achieving sustainable growth in the future. This can not only be achieved by technological but also by structural changes. Moreover, international trade can affect the global energy intensity. In this paper, we have attempted to shed some light on the importance of these three factors by analyzing recent developments in global and national energy intensities.

Our key contribution lies in the utilization of the World Input-Output database in combination with the accompanying environmental accounts to arrive at a consumption-based measure of energy use on a sectoral level. In contrast to Voigt et al. (2014), we are thus able to take into account the energy use of intermediate goods that contribute to the satisfaction of sectoral final demand. Only by doing so can we meaningfully study the ultimate effect of changes in consumption patterns on national or global energy intensities.

We find large effects of energy use adjustments according to the EEIOA. In particular, the energy use associated with final demand in the construction and service sector exceeds by far the energy consumption in their production processes. This indicates a strong reliance on energy-intensive inputs from other sectors. Conversely, the manufacturing industry as well as the electricity, water and gas sector that, to a large degree, deliver intermediate inputs to other sectors, show lower energy use when consumption-based for energy embodied in trade. Overall, we find that the global energy intensity from 1995 to 2009 was declining, predominantly due to more efficient technology used within sectors than due to a structural change in the economy. Nevertheless, structural change within countries played a sizable role in the reduction of energy consumption. Furthermore, our analysis shows that international trade by itself led to a higher energy intensity level. This is likely a result of outsourcing production processes to countries with lower levels of energy intensities.

Decomposing consumption and production-based energy use reveals that the role of structural change is systematically overestimated in previous studies. This is because, after adjusting sectoral energy use according to intersectoral trade, changes in structural composition, both within and between countries, appear to have a smaller impact on global energy intensities. Nevertheless, also the production-based decomposition identifies technological change as the main driver of reducing energy intensity. However, this qualitative similarity on a global level does not hold for each country. For instance, we show that, in some countries, like USA, Japan and Turkey, the technological effect is strongly underestimated. While structural change seems to be the driving factor of energy intensity reductions using production-based data, technology plays the dominant role using consumption-based energy use. Hence, our adjusted measure of energy use indicates that these countries are not exceptions from the general global pattern in which the main force of increasing energy efficiency is technological progress.

Our analysis implies that green growth policy has to take into account the adjustment of sectoral data in order to obtain a correct picture of what can be considered a "green" or "dirty" sector. This is particularly relevant for the theoretical literature on directed technical change and the environment that usually features such a stylized distinction between industries.[30] The interdependencies of sectors through trade of intermediate goods might even give rise to doubts whether such a classification of sectors can be meaningfully applied. More importantly for policy-makers is the fact that technological advances seem to play the largest role in the energy intensity trends. Given that environmental policy mostly affects within-sector efficiency and structural change itself is rather difficult to influence (Huntingtion (2010)), such policy is likely able to play a strong role in achieving efficiency goals.

There are several ways to build on this emerging literature analyzing environmental impacts of global production processes based on WIOD and its accompanying environmental accounts. First, past global trends have shown little evidence of a strong structural break towards relatively cleaner sectors. China has become the largest energy consumer in 2010 and is, therefore, of particular importance for future global energy intensities. In fact, China itself practically did not experience any effect from structural change, and its energy intensity decrease is explained

[30] See e.g. Acemoglu et al. (2012)

completely by technological progress. More recent literature argues, however, that energy intensity gains in China during the 2010s might be mostly driven by structural change (see Jos et al. (2015)). Thus, it would be an interesting and important field for future research, once the data are available, to analyze whether there is a potential for structural transformation of economies beyond the magnitude shown in this paper for the period up to 2009.[31] Second, this work and numerous other papers have documented the large extent of emissions and energy embodied in international trade. In fact, we show that increasing outsourcing of energy-intensive production has by itself increased global energy intensities. Thus, an analysis of the effects of carbon border taxation on overall global energy and emission intensities poses another important further research challenge. Finally, technological improvements were identified as the main driver of decreasing energy intensities. WIOD accounts can be used to identify sectors and countries that would benefit most strongly from technology transfers and those that can provide the technology to do so. Considering the large differences in sectoral energy-intensities across countries, there is certainly scope for global energy intensity reductions through technology-transfers to less efficient countries. Following this reasoning, it would be an interesting field of future research to go more deeply into the details of technology change, e.g. the effect of energy prices or policies on global energy efficiency.

[31] Su and Ang (2012) point out that the construction of input-output tables are rather time-intensive such that there is a large time lag between publication and data used.

3.7 Appendix

In the following, we present scatter plots of the relationship between the average GDP, average GDP growth and initial energy intensity and the overall energy intensity change (first row), the structural component of this change (second row) and technology component (third row). Furthermore, we provide consumption-based decomposition results for all countries not displayed in the main part of this paper.

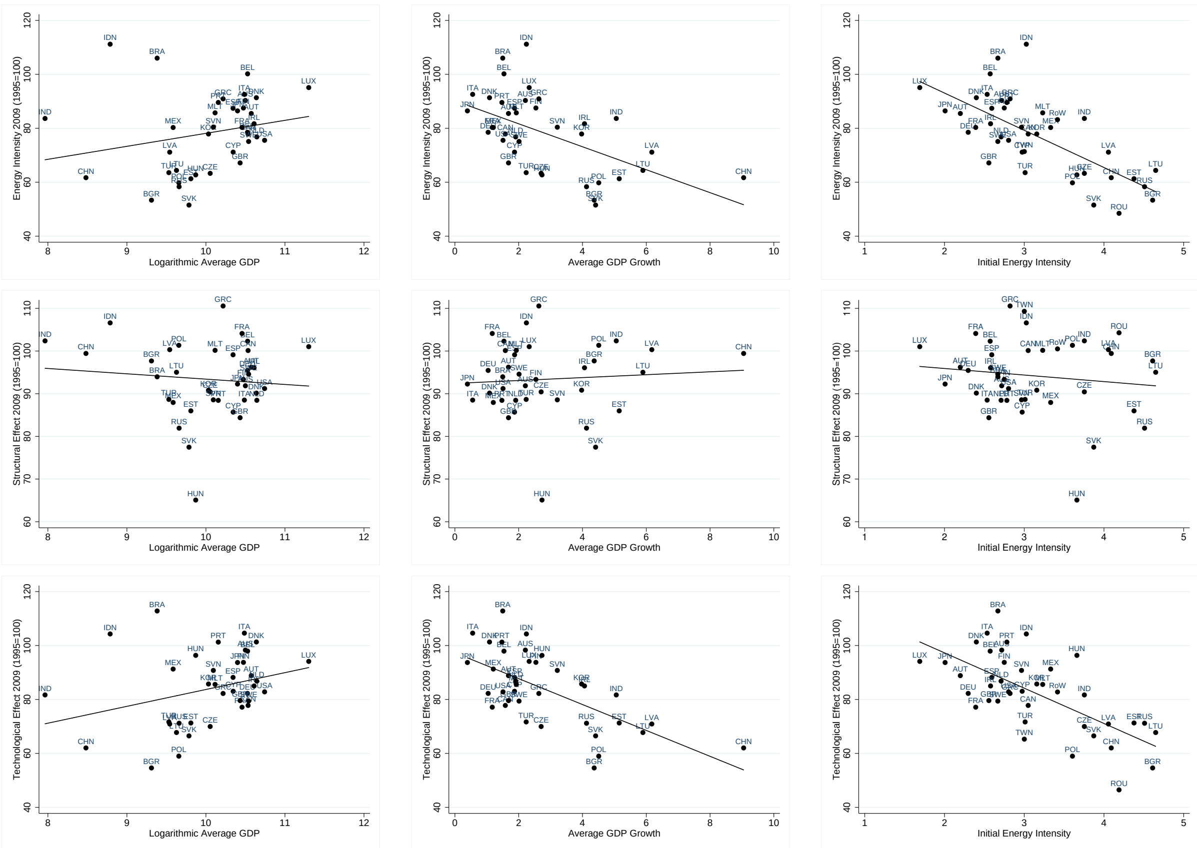

Figure 3.13: Regression of Energy Intensity, Structural Effect and Technological Effect

Country	Country Abbr.	Structural Effect	Technology Effect	Total	Country	Country Abbr.	Structural Effect	Technology Effect	Total
Australia	AUS	90	107	96	Italiy	ITA	92	99	92
Austria	AUT	95	79	75	Japan	JPN	93	91	84
Belgium	BEL	96	99	95	Korea	KOR	83	76	64
Bulgaria	BGR	113	43	48	Lithuenia	LTU	83	82	67
Brasilia	BRA	98	109	107	Luxembourg	LUX	78	105	82
Canada	CAN	96	85	81	Latvia	LVA	96	70	67
China	CHN	100	51	51	Mexico	MEX	86	94	81
Cyprus	CYP	88	64	56	Malta	MLT	111	74	82
Czech Rep.	CZE	78	80	62	Netherlands	NLD	89	87	77
Germany	DEU	100	74	74	Poland	POL	93	66	62
Denmark	DNK	91	91	82	Portugal	PRT	89	95	85
Spain	ESP	101	91	92	Romenia	ROU	88	65	57
Estonia	EST	68	81	55	Russia	RUS	93	62	58
Finland	FIN	90	85	77	Rest of World	RoW	102	75	77
France	FRA	93	87	81	Slovakia	SVK	66	89	59
UK	GBR	86	86	74	Slovenia	SVN	89	83	74
Greece	GRC	97	99	97	Sweden	SWE	91	83	75
Hungary	HUN	57	102	58	Turkey	TUR	86	80	69
Indonesia	IDN	104	101	104	Taiwan	TWN	100	52	52
India	IND	102	82	84	United States	USA	87	95	82
Ireland	IRL	89	82	73					

Table 3.3: Decomposition Results for the period 1995-2007 in percent with baseline year 1995 = 100

CHAPTER 4

Decoupling or Upstream Dispersion of CO2 Emissions? A Subsystem Analysis of Global High-Skilled Service Sectors for the Years 1995 to 2009

4.1 Introduction

By tackling global warming, many nations focus on emission reduction of electricity and manufacturing sectors.[1] However, as the value added share of the service sector was increasing steadily during the last years and adds up to 68% of global GDP in 2014,[2] it is important to monitor and investigate emission trends of these branches as well. The common view that the service sector is considered as a clean sector does not withstand a closer look. Emissions directly emitted from services might be relatively small (except for transportation); however, they contribute strongly to global emissions if we account also for intermediate goods which are delivered to the service sector in order to run its business (see e.g. Zhang et al. (2015)). Figure 1 shows both the share of emissions of the service sector in global CO_2 emissions with a production-based approach, and the share including the emissions embodied in the supply chain of the sectors - the consumption-based approach. In the former case, the ratio of CO_2 emissions

[1] For example the Emission Trading System (ETS), which is the key tool of mitigating greenhouse gas emissions in the European Union, targets only the power, the industry and the aviation sector (https://ec.europa.eu/clima/policies/strategies/2020_en).

[2] World Bank: http://data.worldbank.org/indicator/NV.SRV.TETC.ZS?end=2015&start=2000

from the service sector to overall CO_2 emissions is nearly 18% whereas it culminates to 34% in the latter case.[3].

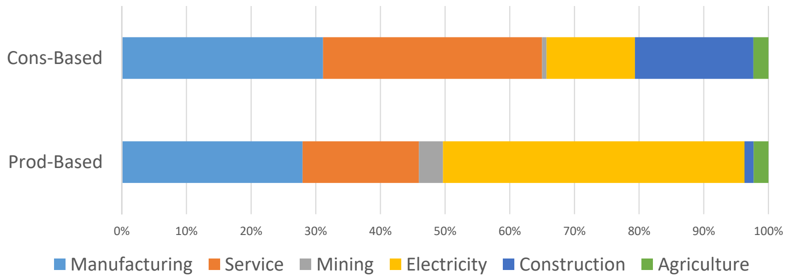

Figure 4.1: Global CO_2 Emission Share in 2007
Source: WIOD

As Figure 1 shows the huge difference of production and consumption-based accounting we can see in Figure 2 that this difference is even growing with time due to a stronger nesting of economic structures. Long-term trends show different tendencies between production- and consumption-based CO_2 emissions of the service sector, excluding transport.[4] Hence, while the service sector is improving in its direct emission balance, the supply chain of the service sector leads to increasing emissions.

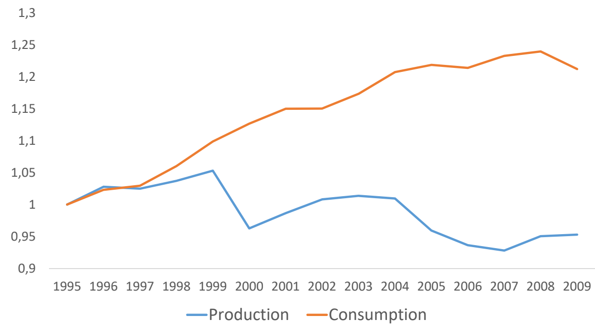

Figure 4.2: Production-Based vs. Consumption-Based CO_2 Emission Trends for the Service Sector excluding Transport

The difference of the results of those two accounting methods are striking. Which approach is to be preferred depends on the specific policy question under consideration. If the purpose of the policy is to introduce specific technology or emission standards for industries, the production-based approach is appropriated. For discussing the influence of consumption patterns, international trade or decoupling of the world economy from carbon emissions, the consumption-based approach should be preferred. The underlying motivation of this paper is

[3]Data are from the World Input-Output Database (see Dietzenbacher et al. (2013))

[4]I treat transport as a special sector because it shows strong differences to other services with respect to CO_2 emissions.

the question whether growth in the service sector leads to absolute decoupling of economic growth from environmental pollution. Therefore it is important to monitor the whole supply chain of a sectors final demand. Hence, this paper applies a consumption-based analysis.

However, the service sector considered in Figure 4.1 is a rather broad category with a high heterogeneity with respect to carbon emissions, education attainment, and growth patterns. For instance, the transport sector, which is highly emission intensive, is usually subsumed under the service sector. At the same time, health, education, and information technology are also services but exhibit less direct emissions and are mainly characterized by a high share of college-educated employees. By investigating the service sectors in detail, Eichengreen and Gupta (2011) find that especially branches with a large share of high-skilled workers exhibited a strong growth in GDP share between 1970 and 2005. While there is a broad literature studying the effect of this pattern for the labour market, the effect of this structural transformation on CO_2 emissions is less well known. Summarizing, there are two distinct properties why high-skilled services are of special interest in this paper: First, the aforementioned growth pattern, and second, the low intensity of direct CO_2 emissions.

The main questions to be addressed in this paper are, first, how strong does the demand of high-skilled services drive CO_2 emissions. Second, through what channels does this demand contribute to those emissions and whether the development of this contributions suggest a trend towards “cleaning” of the supply chains of high-skilled services. Furthermore, I want to examine whether the emissions embodied in the supply chain of high-skilled services increase/decrease due to changes in sector-specific CO_2 intensity, a different structure of intermediate inputs, or due to increased final demand. These questions are also posed for a more detailed country and subsector level.

The service sector can be split into three parts: Transport, high- and low-skilled services. I trace back emissions embodied in intermediate inputs for the high-skilled service sector and categorize these according to 10 different components: The Agriculture Component (AGC), the Mining and Quarrying Component (CC), the Electricity Component (ELC), the Low-skilled Service Component (LSC), the Manufacturing Component (MC), the Construction Component (FC), and the Transport Component (TRC). Three components stem from the high-skilled service sector itself: The Direct Volume Component (DVC), the Intra Spillover Component (IC) and the Feedback Component (FBC). The results show that the contribution of those factors change strongly over time, which motivates a structural decomposition analysis (SDA) in order to clarify reasons for the trends. This analysis is done for each year between 1995 and 2009 and covers 40 countries plus a rest-of-the-world model using the World Input-Output Database (WIOD). Results of the SDA identify the rise of final demand and structural change as the main force behind increasing emissions and, opposed to that, improvement of CO_2 intensity as the "greening force" among all components.

This paper is based on four strands of literature. First, it is motivated by the literature on the rise and the structure of the service sector (see e.g. Eichengreen and Gupta (2011) or Buera and Kaboski (2012). Second, it contributes to the emerging literature of sector-specific CO_2 footprint analysis (see Lenzen (2016) for an overview of decomposition analyses of energy and CO_2 footprints).[5] Third, this paper builds on Dietzenbacher et al. (2000), Xu and Dietzenbacher (2014) and Zhong (2016) by conducting a multiplicative structural decomposition analysis. And fourth, it is methodological based on the literature of subsystem analysis of Zhang et al. (2015), Alcantara and Padilla (2009) and Butnar and Llop (2011). The last two paper analyse the service sector in Spain and find strong dependency on carbon emissions which occur in the manufacturing sector. Both categorize the economy in two subsystems, services and manufacturing. Zhang et al. (2015) introduces a international perspective and analyses the supply chain of the service sector according to its international linkage by also distinguishing between emissions from services and non-service activities. My paper is concerned about the cross-linkage of the service sector in more detail, e.g. whether services depend mainly on the electricity generating sector, whether they rely heavily on transport or they need considerable inputs from the construction sector.

This paper contributes in six ways to the existing literature. First, it offers a global subsystem analysis of specific sectors, where former subsystem analyses focus on a country level. Second, it is a generalization of the method introduced in Alcantara and Padilla (2009) to more than two subsystems. Third, it examines the influence of structural change towards a high-skilled economy on CO_2 emissions, and therefore categorizes the service sector into skill levels which offers a more detailed view. Fourth, this analysis is specified for all 40 economies provided in the World Input-Output Database (WIOD),[6] providing a broad picture of country-specific supply chains for high-skilled services. Fifth, it offers time trends of this analysis which reveals the development of the inter-dependencies between sectors. Finally, these time trends are decomposed into intensity, structure and demand effect, which offers a more detailed insight into the reasons behind diverging carbon content of supply chains.

The paper is organized as follows: In Chapter 2 I explain briefly the method of subsystem analysis in general. In Chapter 3 I introduce the underlying data sources, characterize the service sector into two categories according to its skill level and also divide the rest of the economy in meaningful sectors. In Chapter 4 I present descriptive results concerning CO_2 emissions resulting from this categorization as well as the empirical results of the subsystem analysis and the structural decomposition analysis. Chapter 5 concludes.

[5] E.g., Croner and Frankovic (2016) analyse production- and consumption-based energy use for 40 major economies and show that the energy footprint of the service sector contributes 28% to the global energy use. In addition, there is especially strong attention in research on the emissions and energy use in the ICT sector. For example, see Schulte et al. (2016), Malmodin et al. (2010), Fehske et al. (2011) and Van Heddeghem et al. (2014). Rivera et al. (2014) discuss positive and negative environmental impacts of ICT. For instance, ICT can contribute to a more sustainable economy by optimizing processes and making production more energy efficient. It also substitutes other, more energy intensive consumption goods. On the other hand, there are direct and indirect effects which lead to higher energy use as, for example, the electricity used in production of ICT goods and the development of new products which might have strong environmental impact.

[6] A brief explanation of the database is provided below in Chapter 4.3.

4.2 Method

In this section I generalize the subsystem model of Alcantara and Padilla (2009) by allowing for multiple subsystems in order to obtain a more refined picture of supply chains. I assume a closed economy and use the common notation of Input-Output Analysis:

From the well known relationship $Z + Y = x$ we receive

$$Ax + Y = x \tag{4.1}$$

where Z is the flow matrix of intermediate trade between the sectors, Y is the final demand vector,[7] x is the total output vector and $A = Z \otimes diag(x^{-1})$ is the matrix of technical coefficients.[8] We can reformulate (4.1) to

$$(Id - A)^{-1}Y = LY = x \tag{4.2}$$

where $L = (Id - A)^{-1}$ is the Leontief Inverse and Id the identity matrix. The matrices Z,A,L are quadratic $n \times n$ matrices, and n is the number of sectors in the economy. In order to obtain a subsystem I, these matrices are further divided into $N < n$ subcategories.[9] Let Matrix A_{IJ} be the matrix of technical coefficients between system I and system J. That is, A_{IJ} contains the technical coefficient of goods and services delivered from all sectors $i \in I$ to each sector $j \in J$.[10] The distinction between a subsector (indexed by small letters i) and a subsystem (indexed by capital letters I) is important through out the paper.

Therefore,I write A and L as a composition of all its subsystem matrices :

$$A = \begin{bmatrix} A_{11} & . & . & . & A_{1N} \\ . & & & & . \\ . & & & & . \\ . & & & & . \\ A_{N1} & . & . & . & A_{NN} \end{bmatrix} \qquad L = \begin{bmatrix} L_{11} & . & . & . & L_{1N} \\ . & & & & . \\ . & & & & . \\ . & & & & . \\ L_{N1} & . & . & . & L_{NN} \end{bmatrix} \tag{4.3}$$

Setting x from equation (4.2) into the left hand side of (4.1) yields

$$ALY + Y = x \tag{4.4}$$

The term ALY indicates the intermediate inputs needed to obtain the final demand.[11] The reason for this reshaping of the Leontief model is to separate the direct effect of increasing con-

[7] In the global analysis, the elements of Y are the sum of demand from all regions for the product of one specific sector in one specific region.

[8] $\otimes$ is the Hadamard product and indicates element-wise multiplication.

[9] In the literature, usually N=2 and the two categories are the service sector and the manufacturing sector (see Alcantara and Padilla (2009), Butnar and Llop (2011).

[10] All indices of subsystems are denoted with capital letters and indices of subsectors are denoted with lower-case letters.

[11] It is helpful to write down the development of the potential series of L to gain a better understanding of this formula. Note that $L = A^0 + A^1 + A^2 + ...$ and therefore $AL = A^1 + A^2 + ...$ Hence $ALY + Y = LY$ splits the Leontief formula into the first order effect and the effects of higher order.

sumption of the subsystem under consideration as shown further below.

When investigating a subsystem I, the demand vector Y in this formula is

$$Y_I = \begin{bmatrix} 0 \\ . \\ y_I \\ . \\ 0 \end{bmatrix}, \tag{4.5}$$

where $y_I = (y_1, ..., y_i, ..., y_m)^T$ is the global demand vector of all m subsectors of I, denoted by y_i. Equation (4.4) can be spelled in full as:

$$\begin{aligned}
&x_1 = A_{11}L_{1I}y_I + ... + A_{1N}L_{NI}y_I \\
&. \\
&x_I = A_{I1}L_{1I}y_I + ... + A_{IN}L_{NI}y_I + y_I \\
&. \\
&x_N = A_{N1}L_{1I}y_I + ... + A_{NN}L_{NI}y_I
\end{aligned}$$

or equivalently

$$x_K = \sum_{J=1}^{N} A_{KJ}L_{JI}y_I \quad if\ K \neq I \tag{4.6}$$

$$x_K = \sum_{J=1}^{N} A_{KJ}L_{JI}y_I + y_I \quad if\ K = I \tag{4.7}$$

Let e_K be the vector of CO_2 emissions divided by unit of output of each subsector of subsystem K. In order to obtain emissions associated with the economic activity in each component I add e_K to the equation. I call

$$SOC_K = e_K^T \left(\sum_{J=1}^{N} A_{KJ}L_{JI} \right) y_I \quad if\ K \neq I \tag{4.8}$$

the *Spillover Component from system* K. This component contains all emissions which are associated with the production in system K in order to meet final demand in system I. It also includes emissions which emerge in system K as a by-product of intermediate goods delivered to other systems $J \neq K, I$ and then are finally delivered to I from J. The term

$$DVC_I = e_I^T y_I \tag{4.9}$$

indicates the *Direct Volume Component*, that is, the emissions from system I which are directly associated with its consumption.

$$FBC_I = e_I^T \sum_{\substack{J=1 \\ J \neq I}}^{N} A_{IJ} L_{JI} y_I \tag{4.10}$$

is the *Feedback Component* of system I. This element contains all emissions which occur in the production of intermediate goods in system I which are first delivered to any other system and are then provided from those systems to the final consumers of system I. Finally,

$$IC_I = e_I^T A_{II} L_{II} y_I \tag{4.11}$$

is the *Intra Spillover Component* of subsystem I. IC_I contains all emissions which are associated with the production within a specific subsector in I as an intermediate input for another subsector of services in I and then finally delivered to consumer in I.

So far, all components refer to the emissions associated with the consumption of the whole subsystem I. By using $\hat{Y}_I = diag(Y_I)$ in the above formulas one gets the result for each subsector of subsystem I.

It is also easily possible to extend this subsystem analysis by including region-specific components. For instant, the above derived Spillover Component can also be distinguished in the regions of origin. This changes (4.8) into

$$SOC_{K_\alpha} = e_{K_\alpha}^T \left(\sum_{\beta=1}^{\tau} \sum_{J=1}^{N} A_{K_\alpha J_\beta} L_{J_\beta I_\gamma} \right) y_{I_\gamma} \quad if\ K_\alpha \neq I_\gamma, \tag{4.12}$$

where α indicates the region of origin, β the transit region and γ the region where the subsystem is analysed and τ is the number of countries. According to this, $A_{K_\alpha J_\beta}$ indicates the technical coefficients for goods, delivered from subsystem K in region α to subsystem J in region β. Y_{I_γ} is the final demand of goods of subsystem I in region γ. I apply this analysis to the European Union below.

The above analysis is static. It can be done for any time period. In the case of data availability the construction of time trends of each component is also possible. With these trends we conduct a SDA as it is done by Butnar and Llop (2011). However, contrary to that paper I use the framework of Dietzenbacher et al. (2000) for a multiplicative SDA. I apply the method below on a global level for the factors carbon intensity, structural effect and the demand level effect. For example, if emissions from a spillover component strongly increase, it is interesting whether this is due to a change in the technology used in production or it is due to a structural shift of inputs, for example via changes in trade patterns. In order to conduct a SDA between the periods 0 and 1 we mark every variable with the time index (0) and (1). The change in the

Spillover Component can therefore be written as:

$$\frac{SOC_K^{(1)}}{SOC_K^{(0)}} = \frac{e_K^{T(1)}}{e_K^{T(0)}} \frac{\left(\sum_{J=1}^{N} A_{KJ}^{(1)} L_{KJ}^{(1)}\right)}{\left(\sum_{J=1}^{N} A_{KJ}^{(0)} L_{KJ}^{(0)}\right)} \frac{y_I^{(1)}}{y_I^{(0)}} \tag{4.13}$$

The three effects which we want to extract can now be obtained as follows:

$$Int = \frac{e_K^{T(1)}}{e_K^{T(0)}} \frac{\left(\sum_{J=1}^{N} A_{KJ}^{(0)} L_{KJ}^{(0)}\right)}{\left(\sum_{J=1}^{N} A_{KJ}^{(0)} L_{KJ}^{(0)}\right)} \frac{y_I^{(0)}}{y_I^{(0)}} \tag{4.14}$$

$$Struct = \frac{e_K^{T(1)}}{e_K^{T(1)}} \frac{\left(\sum_{J=1}^{N} A_{KJ}^{(1)} L_{KJ}^{(1)}\right)}{\left(\sum_{J=1}^{N} A_{KJ}^{(0)} L_{KJ}^{(0)}\right)} \frac{y_I^{(0)}}{y_I^{(0)}} \tag{4.15}$$

$$Demand = \frac{e_K^{T(1)}}{e_K^{T(1)}} \frac{\left(\sum_{J=1}^{N} A_{KJ}^{(1)} L_{KJ}^{(1)}\right)}{\left(\sum_{J=1}^{N} A_{KJ}^{(1)} L_{KJ}^{(1)}\right)} \frac{y_I^{(1)}}{y_I^{(0)}} \tag{4.16}$$

where *Int* denotes the intensity effect, *Struct* is the structural effect and *Demand* indicates the contribution of a rising final demand in system I. The Feedback Component and the Intra Spillover Component have an equivalent structure and are therefore decomposed in the same way. The Direct Volume Component consists of only two factors, intensity and demand. We can interpret each factor as follows: if all factors in the economy were equal, and only one sector in system K improves intensity, then the CO_2 emissions which are embodied in the inputs of system K for system I rise with *Int* percent. Note, that the time indices in factor $\sum_{J=1}^{N} A_{KJ} L_{KJ}$ always change for both factors A_{KJ} and L_{KJ} as a separation of these factors does not make any economic sense.

With these tools, we can analyse the dependency of carbon intermediates of subsystem I in detail.

4.3 Data and Application

This paper uses the World Input-Output Database (WIOD, Release 2013)[12] and its accompanied social and environmental accounts.[13] The WIOD consists of multi-region industry-by-industry

[12] In 2016 the WIOD was updated. However, this version cannot be used in this paper since it does not yet include environmental accounts, socioeconomic accounts and tables in previous year prices.

[13] For a detailed introduction to the WIOD tables and environmental accounts see Timmer et al. (2015), Dietzenbacher et al. (2013) and Genty (2012).

input-output tables for the years 1995-2011. It contains 40 major economies contributing more than 85% to the world GDP and therefore delivers a fairly detailed picture of the trade flows in the world economy. It includes the 27 member countries of the European Union,[14] the BRIC countries and other major economies like the USA, Canada, Mexico, Australia or Japan. In addition, WIOD provides an estimated model of the remaining countries in order to have a complete picture of the world economy. The economies of all countries are aggregated to 35 sectors. Therefore, trade flows from each industry in each country to any industry in all countries are reported. The unit of all cells is the current US Dollar of each year. Additionally, in order to obtain comparable times series, WIOD offers all tables in previous year prices. Most important for the analysis of pollution are the environmental accounts which are provided on detailed industry and sector level as well as for the years 1995 until 2009. They provide data on carbon dioxide emissions, energy use and other pollutants. In addition, WIOD provides data on employment categorized by level of educational attainment.[15]

As mentioned above, the question of this paper is, how strong knowledge intensive sectors depend on CO_2 emissions. Therefore I categorize all sectors in WIOD according to its skill structure. Figure 4.3 shows the mean global skill structure of all industries.[16]

Figure 4.3: Mean Global Sector-Specific Skill Structure

Hereby, the gray color shows the proportion of workers which have a maximum of lower secondary education (low-skilled), the orange part shows the percentage of employees with up

[14]Note that at time of the first release in 2013, Croatia was not yet member of the EU and is not included in the WIOD data (Release 2016 includes Croatia). On the other hand, the UK is a EU state at this time.

[15]The skill levels are classified according to the International Standard Classification of Education (ISCED 1997): low-skilled (ISCED categories 1 and 2), medium-skilled (ISCED 3 and 4) and high-skilled (ISCED 5 and 6).

[16]A detailed explanation of sector abbreviations is provided in the Appendix.

to post-secondary education (middle-skilled) and the green bar indicates the amount of workers with tertiary education (high-skilled).[17] Not surprising, Agriculture, Hunting, Forestry and Fishing (AtB) has the lowest skill share of all sectors. While the skill composition of most manufacturing sectors is similar, most service sectors demand a fairly far developed skill structure. The six most human capital intensive sectors are all service sectors: Financial Intermediation (J), Real Estate Activities (70), Renting of M&Eq and Other Business Activities (71t74), Public Admin and Defence; Compulsory Social Security (L), Education (M) and Health and Social Work (N). The subsystem analysis in this paper focuses on those high-skilled service sectors, rather than on the whole service sector like it is done in previous studies, e.g. Alcantara and Padilla (2009), Butnar and Llop (2011) or Zhang et al. (2015).

In order to obtain a detailed picture of CO_2 embodied in the supply chain of the high-skilled service sectors I categorize the economy in eight different subsystems: Beside the aforementioned high-skilled service sectors (HS), I also distinguish between manufacturing (M), mining and quarrying (C), electricity and water supply (EL), construction (F), agriculture (AG), low-skilled services (LS) and transport (TR). For each of those subsystems one obtains a spillover component as described in equation (4.8). Additionally, for a complete analysis one also needs to catch the feedback effect (FB), the emissions embodied in the goods of high-skilled services which are first delivered to other sectors where they are used for production of goods which are needed in the high-skilled sector again. Emissions which are produced in a high-skilled subsector for demand in another high-skilled subsector are part of a Intra Spillover Component (IC). Finally, emissions which are produced directly in a sector and also consumed in that sector form the Direct Volume Component (DVC).[18]

The exact stage at which one accounts for emissions during the supply chain is important. Therefore I give some intuition and examples for each component. For example the CO_2 emitted in production of electricity used by the service sector is contained in the production-based accounts of the electricity sector and not in the sector which uses this electricity for its business. Direct emissions of the service sector only occur if the actual ejection of CO_2 occurs in the service sector, that is for example emissions of a company car or direct emissions from a heating system in a service company itself. Those emissions are included in the Direct Volume Component (DVC). Emissions in IC are those which are directly emitted in one of the high-skilled services which are used as input in another HS sector, for example the emissions from a law company car which is needed for consulting clients in the IT branch. The Feedback Component (FBC) captures all emissions which occur directly as a byproduct of high-skilled services but only of that part which is first delivered to other subsystems and then used in the final demand of the HS system. An example are all emissions embodied in IT services which are necessary to run a manufacturing firm which produces goods for medical research. Finally, all spillover components work in the same way: For example, the Manufacturing Component only contains

[17] We present the skill levels as average of all 40 economies considered in this paper. For the Rest of the World categories, no skill data are available. For sector "50" (Sale, Maintance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel) and "P" (Private Households with Employed Persons) there are only skill shares for 38 and 33 countries, respectively. The results do not change remarkably if I weight skill shares with GDP level of countries.

[18] See Appendix Table 4.3 for an overview of that categorization and abbreviations.

the emissions directly associated with the manufacturing processes which are part of the supply chain of HS services. E.g. CO_2 emissions in the production of a crane which is delivered to the construction sector where it is used for the construction of a university building are part of the Manufacturing Component.

4.4 Results

Descriptive Results

In this subsection I present some descriptive results deduced solely from the categorization mentioned above and from the calculation of footprints.

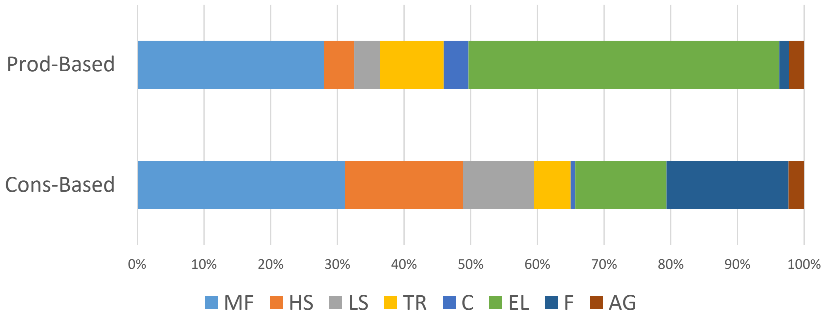

Figure 4.4: CO_2 Emissions Share of Subcategories 2007

If we direct our attention on the demand side of the economy, the carbon content of the whole supply chain has to be considered. Emissions in the high-skilled service sector are responsible for 4.6% of global CO_2 emissions. However, emissions embodied in the supply chain of this subsystem contribute with 17.7% to global CO_2 emissions.[19] Hence, it is responsible for more than half of the footprint in the service sector, much more important than the transport sector. The difference between production-based accounting for those emissions is striking and surprisingly high. Therefore, the supply chain of high-skilled services is highly carbon intensive. It is even more polluting than the construction sector, and the electricity generating sector.

Table 4.1 shows in more detail the contribution of each subsector to the emissions of the high-skilled service subsystem. We can see that "Public Admin and Defense" is by far the most polluting sector, no matter if we look at direct emissions or footprints.

Not surprisingly, all sectors have larger footprints than directly produced emissions. While the difference in "Renting of m&eq and other business activities" which also contains the IT industry, is rather small, the footprint is almost ten times higher than direct emissions for real estate activities which heavily rely on construction activities.

[19]Note that I consider only emissions associated with any business activity, not emissions of private households.

sector	Description	CO2 Production Based	CO2 Consumption Based
70	Real estate activities	51893	424453
71t74	Renting of m&eq and other business activities	215852	269221
J	FINANCIAL INTERMEDIATION	64750	229306
L	PUBLIC ADMIN AND DEFENCE; COMPULSORY SOCIAL SECURITY	364727	1405362
M	EDUCATION	84778	425213
N	HEALTH AND SOCIAL WORK	159045	914354

Table 4.1: Global CO_2 Emissions of Subsectors and Footprints in kt for 2007

Figure 4.5 shows the footprint of sectors in different groups of countries in 2007. The consumption-based emissions in 2009 were still the highest in the USA.[20] However, the composition of emissions associated with final demand is very heterogeneous. For example, even in a consumption-based approach, China has a much higher share of manufacturing pollutants than the USA where the consumption of high-skilled services and electricity causes the largest part of CO_2 emissions. The BRIC countries without China have a similar structure like China as well as the EU countries but with a higher share in CO_2 emissions associated with agricultural products. The patterns of the USA are quite different of those observed in other regions. The footprint of the high-skilled services is particular large in the USA. The next session analyses the footprint of the high-skilled service sectors in more detail.

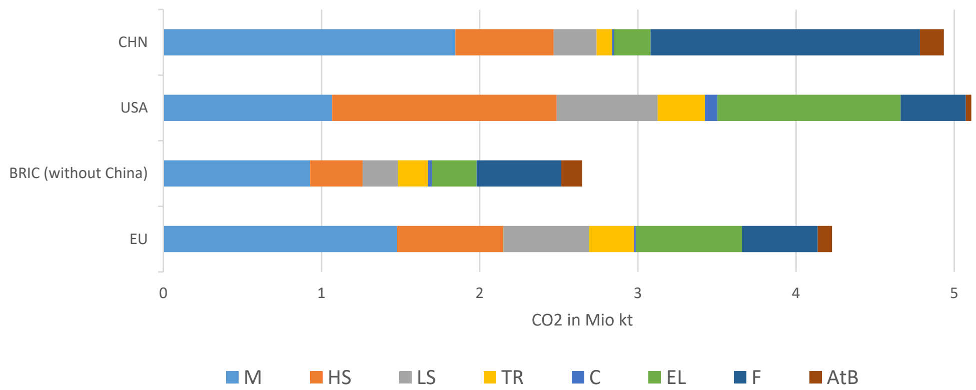

Figure 4.5: CO_2 Footprint 2007

Subsystem Analysis Results

Figure 4.6 shows the first main result of the paper. It contains all aforementioned components which contribute to the carbon footprint of global high-skilled service sectors for the years 1995 to 2009. In all periods, the production of electricity caused the most CO_2 emissions in the supply chain of high-skilled service sectors, almost 2 million kt in 2009. This is 7,69% compared to the overall global CO_2 emissions in 2009.[21] The Direct Volume Component is the second-largest

[20] This result is in line with previous studies like Peters et al. (2011).

[21] See Table 4.5 in the Appendix which depicts the percentage of each component in global CO_2 emissions.

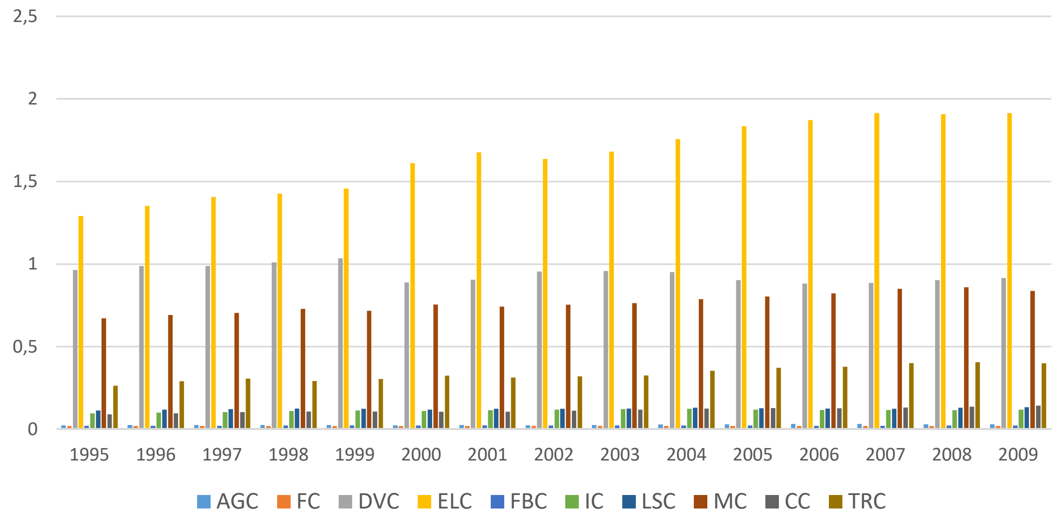

Figure 4.6: Results of the Subsystem Analysis in Million kt for 1995-2009

driver, far behind electricity in later years. Third important are the sum of manufacturing products which are used in the service industry. The relatively small role of manufacturing is rather surprising as many different economic sectors are contained in this subsystem as can be seen in Table 4.3 in the Appendix. Transportation is the fourth important sector with about 400.000 kt of CO_2 associated with the high-skilled services. This indicates that many service activities are linked to high travel efforts. The influence of mining and quarrying (CC) is far lower compared to the sectors mentioned above. The impact of the other two components from the high-skilled service sector, the Intra Spillover Component and the Feedback Component range rather low. Almost not important are agriculture and construction. Construction is important for services but by looking at Figure 4.4 one can see that the production-based emissions from construction (indicated with F) itself are very low and therefore are not accounted here as an important influence.

Besides those results, Figure 4.6 also offers information on the time trends of each component. Most strikingly, we see that the Electricity Component is growing sharply until 2007 and stays constant during the global financial crisis, ending up with an increase of 48%. The Manufacturing Component is also increasing by 24%, while the strongest relative increase happened in the transportation sector, with 52%. Surprisingly, this trend can not be seen in the Direct Volume Component which drops by 5%. That is, while the services itself get less polluting, even in total numbers, and not only relative to output, the carbon content in the supply chains, especially in electricity, rises sharply. Therefore, the increasing linkage of high-skilled services with other parts of the economy prevents this subsystem from absolute decoupling of economic growth from CO_2 emissions.

The global analysis above can be refined on a country and sectoral level:

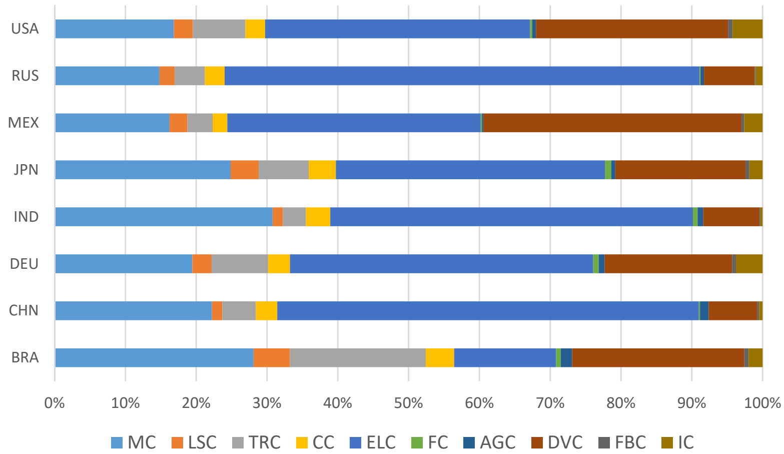

Figure 4.7: Share of Components for Selected Country in 2007

Figure 4.7 shows a more detailed picture of the contribution of each component for selected countries. It depicts the carbon footprints of high-skilled service sectors in some countries but does not distinguish between countries of origin. In most countries, the Electricity Component is by far the most dominant contributor to the CO_2 footprint of high-skilled services. However, there are several exceptions, for example Brazil and Mexico. Brazil exhibits a service sector which is more related to carbon intensive manufacturing goods. In Mexico, the direct emissions in the high-skilled services are particularly high. Direct emissions have also a strong impact in Brazil and the USA. Interestingly, services are strongly dependent on the transport sector in Brazil, a pattern which can not be observed in the other countries. Table 4.4 in the Appendix contains the complete country results.

Absolute

Sector	Sector Name	MC	LSC	TRC	CC	ELC	FC	AGC	DVC	FBC	IC
J	Financial Intermediation	43.817	13.980	38.103	7.493	115.544	1.034	1.629	33.433	1.775	21.310
70	Real Estate Activities	95.767	12.450	44.439	14.754	251.104	7.149	2.262	46.487	2.401	16.942
71t74	Renting of M&Eq etc.	75.041	13.444	44.441	10.780	146.456	761	2.506	63.285	1.891	12.394
L	Public Admin and Defence etc.	283.083	44.127	150.656	52.104	647.420	5.976	11.082	450.024	8.063	35.344
M	Education	75.878	11.726	44.410	13.036	296.622	1.251	5.080	100.276	1.683	7.268
N	Health and Social Work	275.989	28.003	78.978	33.217	456.737	2.302	8.940	191.107	5.441	22.727

Shares

Sector	Sector Name	MC	LSC	TRC	CC	ELC	FC	AGC	DVC	FBC	IC
J	Financial Intermediation	15,8	5,0	13,7	2,7	41,5	0,4	0,6	12,0	0,6	7,7
70	Real Estate Activities	19,4	2,5	9,0	3,0	50,9	1,4	0,5	9,4	0,5	3,4
71t74	Renting of M&Eq etc.	20,2	3,6	12,0	2,9	39,5	0,2	0,7	17,1	0,5	3,3
L	Public Admin and Defence etc.	16,8	2,6	8,9	3,1	38,4	0,4	0,7	26,7	0,5	2,1
M	Education	13,6	2,1	8,0	2,3	53,2	0,2	0,9	18,0	0,3	1,3
N	Health and Social Work	25,0	2,5	7,2	3,0	41,4	0,2	0,8	17,3	0,5	2,1

Table 4.2: Global Result for Subsectors in 2007

Finally, Table 4.2 shows the results on a subsector level, both, in absolute terms and as procentual share of each component. As already indicated in the footprint analysis in the descriptive chapter, "Public Admin and Defence" is the most polluting sector. Most of the pollution is due to the Electricity Component and the Direct Volume Component. Transport also plays a significant role. "Health and Social Work", which exhibits the second largest footprint according to Table 4.1, has a much larger share of manufacturing and the Direct Volume Component. Education exhibits the largest dependency on electricity, which makes 53.2% of its footprint. All in all, component shares in each sectors are similar.

Subsystem Analysis for the European Union

Contrary to the country specific depiction in Figure 4.7, the subsystem analysis of a specific region also distinguish the regions of origin of each component. The results for the region-specific subsystem analysis applied to the European Union is provided in the left panel of Figure 4.8 for the years 1995, 2002 and 2009 and for the most important components: ELC, TRC, MC, DVC. The world is divided in four regions, the European Union, Asia, the United States and the Rest of the World (see Appendix for a detailed country classification). Clearly, the carbon emitted in the European Union itself is the dominant factor in the composition of the high-skilled service sector footprint. The influence of U.S. emissions embodied in European high-skilled services is almost negligible.

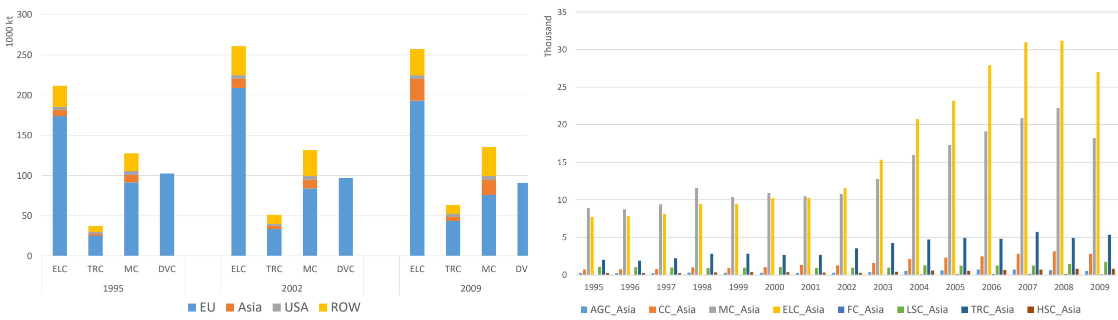

Figure 4.8: Left: Selected Components for the European High-Skilled Service Sector. Right: Emissions in Asia Embodied in EU High-Skilled Services Sectors

However, as the orange bar shows, there is some tendency towards a higher influence of emissions from Asia in the electricity and manufacturing components. This is confirmed in the right panel of Figure 4.8 which depicts all components for Asia. From the end of the 1990s on, the influence of the Asian economies (mainly China) on Europe grew sharply, affecting carbon footprints of the EU. Therefore, it is not surprising that there is a strong increase in all Asian components.

SDA Result

The global time trends motivate a structural decomposition analysis to investigate the reasons behind the changes in the components. Of special interest is the reason for diverging time trends between the Electricity Component and the Transport Component on the one hand, and the non-increasing Direct Volume Component on the other hand. We decompose all components (except

DVC which cannot have a structural effect by definition[22]) into the factors intensity, structure and demand as described in Chapter 2.

The results are shown in Figure 4.9: All components exhibit improvements in CO_2 intensity, especially the service-sector categories (DVC, FBC, IC, LSC) improved considerably. Except for two components, namely the Construction Component (FC) and the Mining and Quarrying Component (CC), the structure effect leads to increasing CO_2 emissions embodied in the supply chain of high-skilled services. Again the service categories FBC, IC and LSC are most pronounced while also the Electricity Component exhibits a structural effect towards more emissions. The reason for the sharp rise of emissions embodied in the inputs from transport lies in the relatively small improvement in intensity of less than 20%. In all sectors, the demand effect was the main driver of increasing carbon emissions. It differs slightly across sectors because the different subsectors have heterogeneous input requirements and grow with different pace.

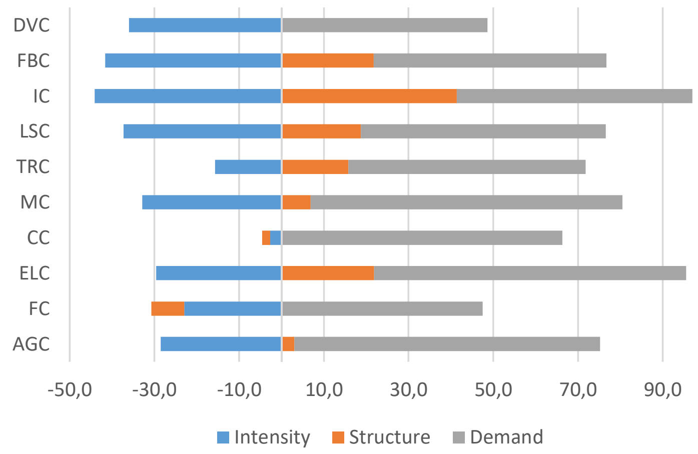

Figure 4.9: SDA results for the changes in components between 1995-2009

With respect to the question whether there is a greening of supply chains of the high-skilled service sectors, the negative effect of the economic structure is the most important result and suggests that the high-skilled sectors do not move towards a cleaner supply chain. High-skilled services tend to rely more on electricity and transport and therefore increase its footprint relative to its output.

4.5 Conclusion

This paper contains a global subsystem analysis of high-skilled service sectors. The service sectors were classified according to their composition of educated workers , and I find that the resulting subsystem contributes remarkably to global CO_2 emissions. Most emissions embodied

[22]Note that I refer to a structure effect to the effect of changes in the Leontief matrix, and not to changing patterns in final demand.

in those services stem from the use of electricity. Manufacturing and transport are also important input channels with respect to emissions. Those patterns increase with time while the Direct Volume Component is decreasing. This observation has an interesting insight: While high-skilled sectors are not emitting more directly, they are more and more dependent on carbon-intensive inputs. The high dependency on electricity is distinctive for all countries; however, there is some divergence with respect to the share of electricity, manufacturing and direct emissions. Among the high-skilled sectors, public administration and defence are most important in terms of CO_2 emissions. On this sectoral level of the analysis, electricity was the most important component for all sectors as well. A structural decomposition analysis revealed that the economic structure and an increasing final demand for HS services drives the growing demand of carbon-intensive inputs, which is only partly offset by the improvements of CO_2 intensity in each sector. The analysis on a regional level of the EU showed that most emissions in the supply chain of high-skilled services occurred within the EU but globalization increasingly drives emissions in other regions as well, especially in Asia.

For decoupling economic activity from CO_2 emissions, the production of intangible goods becomes more and more important. Efficiency gains will hardly be able to offset the higher demand of a growing world population. Therefore the economy also needs a structural demand shift towards intangible products like IT services or medical services. However, the results in this paper indicate that it is unlikely that the structural evolution in developed countries towards those skill-intensive sectors leads to absolute decoupling. Even though, the carbon intensity of high-skilled services is still among the lowest, the dependency on carbon emissions in other sectors is increasing.

This has some important implications: First, an increasing share of specialized human capital used in production of services will most likely not lead to a decrease of the carbon emissions of an economy. Growth in these sectors might go along with increasing CO_2 emissions in other sectors. Second, policies which affect carbon intensive industries in production will also have a strong effect on services which seem to be relative independent from carbon emissions. Therefore, strict environmental policies and economic growth could be conflicting goals, because even those sectors, which produce relatively clean are affected via its supply chains. Third, in order to induce the emergence of low carbon sectors, efforts have to be made to reach absolute decoupling of the high-skilled services from electricity, transport and manufacturing products. For example, travel efforts in academic jobs are quite common and could partly be replaced by video conferences. Fourth, if the measures above are not sufficient to decouple those services from emissions, a zero growth policy is necessary in order to reach the 2 degree global warming goal.

Future research should also focus on trade relations as a cause of CO_2 emissions in the supply chain. For example, it is likely that increasing trade integration leads to a more carbon-intensive supply chain which can be tackled by policies giving incentives for more localized supply chains. On the other hand, a country level analysis which goes more into sectoral details than the analysis provided above, can reveal causes of heterogeneity and therefore provide scope for new policy measures by adopting strategies of the most efficient countries. A deeper sectoral analysis can reveal the reasons of strong carbon intensity, especially in the sector "Public Admin and Defence".

4.6 Appendix

Sector	Sector Name	Subsystem	Name
AtB	Agriculture, Hunting, Forestry and Fishing	AtB	Agriculture
C	Mining and Quarrying	C	Mining
15t16	Food, Beverages and Tobacco	M	Manufacturing
17t18	Textiles and Textile Products	M	
19	Leather, Leather and Footwear	M	
20	Wood and Products of Wood and Cork	M	
21t22	Pulp, Paper, Paper , Printing and Publishing	M	
23	Coke, Refined Petroleum and Nuclear Fuel	M	
24	Chemicals and Chemical Products	M	
25	Rubber and Plastics	M	
26	Other Non-Metallic Mineral	M	
27t28	Basic Metals and Fabricated Metal	M	
29	Machinery, Nec	M	
30t33	Electrical and Optical Equipment	M	
34t35	Transport Equipment	M	
36t37	Manufacturing, Nec; Recycling	M	
E	Electricity, Gas and Water Supply	EL	Electricity
F	Construction	F	Construction
50	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	LS	Low Skilled Services
51	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	LS	
52	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	LS	
H	Hotels and Restaurants	LS	
64	Post and Telecommunications	LS	
O	Other Community, Social and Personal Services	LS	
P	Private Households with Employed Persons	LS	
60	Inland Transport	TR	Transport
61	Water Transport	TR	
62	Air Transport	TR	
63	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	TR	
J	Financial Intermediation	HS	High Skilled Services
70	Real Estate Activities	HS	
71t74	Renting of M&Eq and Other Business Activities	HS	
L	Public Admin and Defence; Compulsory Social Security	HS	
M	Education	HS	
N	Health and Social Work	HS	

Table 4.3: Subsystem Overview

Country	Country Abbr.	Region	MC	LSC	TRC	CC	ELC	FC	AGC	DVC	FBC	IC
Australia	AUS	RoW	9.195	1.579	7.418	1.250	30.518	173	251	6.024	223	1.126
Austria	AUT	EU	4.053	305	1.222	571	4.780	271	87	843	64	172
Belgium	BEL	EU	5.044	598	2.173	654	7.364	149	169	1.988	107	530
Bulgaria	BGR	EU	1.401	31	209	144	2.916	307	47	214	21	36
Brasilia	BRA	RoW	16.099	2.942	10.992	2.298	8.245	380	914	13.939	346	1.134
Canada	CAN	RoW	14.855	8.203	7.137	4.966	27.362	676	552	36.223	782	6.668
China	CHN	Asia	137.972	9.127	29.438	18.713	369.822	1.018	7.538	42.784	1.479	3.088
Cyprus	CYP	EU	397	13	101	58	870	60	5	92	7	19
Czech Rep.	CZE	EU	2.968	278	702	633	7.529	250	122	1.465	73	236
Germany	DEU	EU	22.083	3.104	9.059	3.505	48.645	875	973	20.439	622	4.272
Denmark	DNK	EU	2.968	347	2.231	359	4.304	251	180	932	73	236
Spain	ESP	EU	14.507	1.129	5.200	1.610	22.314	390	411	1.833	212	616
Estonia	EST	EU	320	13	105	34	1.689	22	10	83	6	16
Finland	FIN	EU	2.963	254	1.685	511	9.274	179	185	1.313	72	238
France	FRA	EU	17.969	2.669	7.380	2.133	14.790	452	647	13.116	448	2.116
UK	GBR	EU	31.347	4.772	15.320	4.403	43.121	1.274	892	14.874	773	4.487
Greece	GRC	EU	3.014	147	1.253	1.171	11.392	25	94	894	62	234
Hungary	HUN	EU	1.923	162	682	328	3.224	12	58	2.751	38	189
Indonesia	IDN	Asia	6.849	608	1.761	1.569	8.626	240	825	2.969	62	148
India	IND	Asia	12.571	598	1.326	1.404	20.919	272	329	3.243	49	126
Ireland	IRL	EU	2.366	248	1.057	260	3.775	89	64	1.143	83	365
Italiy	ITA	EU	14.236	1.995	5.120	1.856	22.465	238	361	7.064	354	1.467
Japan	JPN	Asia	60.862	9.698	17.280	9.382	93.011	2.210	1.403	44.992	1.339	4.587
Korea	KOR	Asia	17.929	1.916	5.725	2.713	41.294	332	569	13.895	360	1.734
Lithuenia	LTU	EU	611	35	186	90	1.032	5	12	165	9	35
Luxembourg	LUX	EU	445	79	223	60	759	24	16	172	20	175
Latvia	LVA	EU	458	54	228	58	596	35	17	293	10	32
Mexico	MEX	RoW	6.709	1.041	1.473	858	14.787	76	81	15.067	159	1.073
Malta	MLT	EU	89	6	74	13	282	1	2	26	2	8
Netherlands	NLD	EU	7.778	2.424	2.748	1.159	12.443	517	414	5.559	292	1.378
Poland	POL	EU	7.593	637	2.103	1.271	43.876	150	296	6.628	172	594
Portugal	PRT	EU	2.473	254	842	293	3.367	124	97	3.029	42	317
Romenia	ROU	EU	4.328	195	919	405	7.664	144	41	1.336	54	132
Russia	RUS	RoW	34.538	4.990	9.919	6.524	156.307	330	1.153	16.666	356	2.250
Slovakia	SVK	EU	1.056	117	285	215	1.547	55	28	579	21	103
Slovenia	SVN	EU	578	52	190	66	863	9	16	0	8	13
Sweden	SWE	EU	4.673	463	2.497	511	5.129	444	296	1.489	153	474
Turkey	TUR	RoW	12.915	555	3.533	1.248	15.543	354	263	5.001	77	211
Taiwan	TWN	Asia	5.775	417	1.297	1.496	11.788	46	51	1.894	60	203
United States	USA	USA	238.915	38.046	105.271	39.619	531.006	4.557	7.382	384.960	9.085	60.119

Table 4.4: Subsystem Analysis Result for all WIOD Countries.

Year	CO2	AGC	FC	MC	ELC	FBC	IC	LSC	CC	TRC	DVC
1995	18.946.572	0,13	0,10	3,55	6,82	0,10	0,51	0,60	0,48	1,39	5,08
1996	19.372.166	0,13	0,10	3,57	6,98	0,11	0,52	0,61	0,50	1,50	5,10
1997	19.600.336	0,13	0,09	3,59	7,18	0,11	0,53	0,62	0,53	1,56	5,04
1998	19.787.284	0,13	0,09	3,68	7,21	0,11	0,56	0,63	0,54	1,47	5,10
1999	19.927.794	0,12	0,09	3,60	7,31	0,11	0,57	0,62	0,53	1,53	5,20
2000	20.421.332	0,12	0,09	3,70	7,89	0,11	0,54	0,58	0,51	1,59	4,35
2001	20.472.886	0,12	0,10	3,62	8,19	0,11	0,56	0,60	0,52	1,53	4,42
2002	20.889.910	0,12	0,10	3,61	7,83	0,11	0,56	0,59	0,53	1,53	4,57
2003	21.755.486	0,12	0,10	3,51	7,73	0,10	0,56	0,58	0,54	1,50	4,40
2004	22.864.530	0,13	0,08	3,44	7,68	0,10	0,54	0,57	0,54	1,55	4,16
2005	23.576.938	0,13	0,08	3,41	7,78	0,09	0,50	0,53	0,54	1,58	3,83
2006	24.355.960	0,13	0,08	3,38	7,69	0,09	0,48	0,51	0,52	1,55	3,62
2007	25.261.658	0,12	0,07	3,36	7,58	0,08	0,46	0,49	0,52	1,59	3,50
2008	25.598.080	0,12	0,07	3,36	7,45	0,09	0,45	0,50	0,53	1,58	3,53
2009	24.870.226	0,12	0,08	3,36	7,69	0,09	0,48	0,54	0,57	1,61	3,69

Table 4.5: % of Each Component in Total Global CO_2 Emissions excluding Emissions from Private Household Consumption.

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Curriculum Vitae

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Professional Experience

Institution	*Description*	*Date*
University of Vienna	University Assistant at the Institute of Industry, Energy and Environment	Februar 2013 -January 2017
Institute for Industrial Research (IWI)	Research Assistant	March 2017 - now

Education

Institution	*Degree*	*Year*
University of Applied Science Regensburg	Prediploma Mathematics (FH)	2006
University of Regensburg	Prediploma Mathematics (Uni) Minor in Economics	2008
University of Regensburg	Diploma Mathematics Minor in Philosophy	2012
TU Vienna	Doctoral Program	Since 2013

Title of Diploma Thesis: About a Nonlinear Heat Equation driven by Poisson White Noise.

Teaching

Institution	*Subject*	*Date*
University of Vienna	Law and Economics	Summer Term 2014
University of Vienna	Management under Legal Constraints	Summer Term 2015 and 2016

Publications

Working Paper:

Croner, Daniel and Frankovic, Ivan. A Structural Decomposition Analysis of Global and National Energy Intensity Trends, TU Vienna Working Paper, 08/2016: http://www.econ.tuwien.ac.at/wps/econ_wp_2016_08.pdf (Accepted at The Energy Journal).

Croner, Daniel. Directed Technical Change with Human Capital and Natural Resources (February 15, 2017). Available at SSRN: https://ssrn.com/abstract=2917105 (Re-Submitted to Mathematical Social Science).

Work in Progress

Croner, Daniel. Decoupling or Upstream Dispersion. A CO2 Subsystem of Global High-Skilled Service Sectors.

Croner, Daniel and Koller, Wolfgang and Mahlberg, Bernhard. Economic Drivers of CO_2 - Emissions in small open economies: A hierarchical structural decomposition analysis.

Conference/Workshop Presentations

Croner, Daniel. Directed Technical Change and Human Capital. Oral presentation at the "Young Scholar Workshop for Environmental and Resource Economics" from the German Economic Association in Leipzig, February, 2016.

Croner, Daniel. A Structural Decomposition Analysis of global and national energy intensity trends. Poster presentation at the PhD Meeting of the Royal Economic Society. London, UK, January 2017.

Croner, Daniel. A Structural Decomposition Analysis of global and national energy intensity trends. Public Lecture TU Wien, Austria, November 2016.

Croner, Daniel. . Decoupling or Upstream Dispersion. A CO2 Subsystem of Global High-Skilled Service Sectors. Consumption Based Greenhouse Gas Accounting: From Assessments to Policy. Organized by the Innovate Project Team. Vienna. October 2017.

Attended Summer School

Barcelona Graduate School of Economics. Modelling Non-stationary and Non-linear Time Series. June 27th to July 1st 2016.

EAERE European Summer School in Resource and Environmental Economics. From 2th – 8th July 2017, Venice.

Memberships in Professional Associations

International Association for Energy Economics (IAEE)
Royal Economic Society (RES)
European Association of Environmental and Resource Economists (EAERE)