Computable General Equilibrium Modelling in the Context of Trade and Environmental Policy

Dissertation

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Chapter 1

Introduction

Many of today's societal challenges originate from market failures. One of the most prominent examples is climate change (Stern, 2007). Anthropogenic climate change results from greenhouse gasses (GHG) that are emitted as an unanticipated side product of modern economic activity. In this sense, the emission of GHG is a text book example of a negative externality. If for example a firm burns fossil fuels in its production processes, it will rarely be directly affected by the occurring GHG emissions. At the same time, it will contribute to the accumulation of GHG in the atmosphere and thus climate change. In such a setting, despite the negative effects triggered by its actions, an individual firm will have no incentives to reduce its emissions and eventually global GHG emissions will exceed the socially optimal level.

But not just the cause of climate change can be related to market failures. Combatting climate change is difficult precisely because a set of market failures avert a simple limitation of GHG emissions. As in Hardin's (1968) famous theory termed the 'tragedy of the commons', the lack of enforceable ownership rights for a sustainable climate results in an unfavourable incentive structure for global climate action. The issue originates from the problem that public goods, here an atmosphere with sustainable GHG concentrations, are characterised by the fact that they are non-excludable and non-rival, meaning that they cannot be safeguarded from their use and the use of the good by one agent does not preclude the use of the good by another agent. This implies that providing a public good benefits not only the agent supplying it, but also others. The provision of public goods thus generates a positive externality. As a consequence, on a voluntary basis, a public good is supplied at too low levels compared to its Pareto-optimal provision. In the context of climate changes, this problematic implies that individual agents have no or only insufficient incentives to reduce GHG emissions. Therewith it impedes inter alia a global agreement for joint emission mitigation efforts and results in a patchwork of uncoordinated unilateral policy approaches.

According to economic theory, the presence of market-failures – and only that – justifies a regulative intervention seeking to correct for the distortions induced by them. As this is the case in the context of anthropogenic climate change, this raises the question what policies should be used to control GHG emissions and how these should be designed such that they can support an invisible hand in installing sustainable GHG concentrations. This thesis addresses this question and is dedicated to the problem of finding cost-efficient and effective policies that overcome the challenges associated with human induced climate change. On that account, its first part is devoted to the development of potent instruments for quantitative impact analysis of environmental policy (Chapters 2 to 4). Building on these tools, the second part applies the methodological advancements and studies the economic implications of different environmental policies (Chapters 5 to 8).

Development and advancement of tools to evaluate climate policy

When faced with market failures, policy-makers can choose from a variety of instruments to restore the social optimum. The portfolio at their disposal includes in particular law and order policies, R&D subsidies, market-based mechanisms and adaptation policies. From an economic perspective, and in particular in times of turbulent economic outlook and scarce financial resources, effectiveness, cost-efficiency and distributional issues are thereby crucial for any form of future regulation. Accordingly, the decision of policy-makers with respect to which instrument should to be applied and how it is designed should always be based on a comprehensive cost-benefit analysis.

Ultimately, this results in the need for capable and above all reliable tools to assess regulations ex ante in order to give policy-makers an indication of the effects that can be expected from introducing a policy. In modern applied economic research, computable general equilibrium (CGE) models have become one of the key instruments to evaluate implications of alternative policy measures (Böhringer et al., 2003; Devarajan and Robinson, 2002; Sue Wing, 2004). They are frequently used by a variety of national as well as international organizations for economic policy analysis at the sector- as well as the economy-wide level and have become a standard tool for the quantitative analysis of policy effects in many domains. Examples of their application can be found in many fields ranging from labour economics (e.g. Conrad et al., 2008), climate policy (e.g. Böhringer et al., 2009; Löschel and Otto, 2009), sustainability impact assessment (e.g. Böhringer and Löschel, 2006), and fiscal reform as well as development planning (e.g. Gunning and Keyzer, 1995; Perry et al., 2001).

But despite its benefits, the standard CGE approach implies some important issues and from time to time its actual usefulness is questioned by researchers. The criticism often relates to two aspects. First, CGE models are complex representations of the economy and require a huge amount of information in order to be able to replicate economic activity. As a consequence, CGE models in general, and in particular such models that explore not just economic aspects but also for instance the environmental dimension of policies, have to incorporate data from various, initially unrelated sources. With respect to its economic structure, the CGE model PACE for example (c.f. Böhringer et al., 2009), builds on data provided by the Global Trade Analysis Project (GTAP), but with regard to data for energy demand it turns to data from the US Energy Information Administration (EIA). Insufficient data is also the main reason why CGE models are calibrated or apply parameter values from the literature instead of having a proper and consistent econometric foundation. When required information is missing altogether, as is often the case for behavioural parameters such as substitution elasticities for instance, modellers are forced to build on their intuition and have to include assumed parameter values in their models (Dawkins et al., 2001). Although these data issues have been acknowledged for a while, they seem to persist and especially from an econometric perspective they are a major shortcoming (McKitrick, 1998). The issue is however not only of academic nature. Misspecifications of models inevitably lead to distorted findings and limit the validity of model based analyses of policy measures.

The second aspect relates to one of the key advantages of CGE models. Compared to partial analyses, the main benefit of CGE models is their capability of capturing complex economic interdependencies, for instance between different sectors or regions. But although most CGE models feature a broad set of sectors, not all sectors are sufficiently elaborated to be able to generate reliable insights and researchers tend to focus on specific sectors where one would expect the principal effects, for example the energy sector (Bergman, 2005). This may limit the models' capability of accounting for important side effects outside prime sectors. The same holds true for trade. While most models allow for interregional trade, they often only poorly replicate international trade flows. In most cases they just capture sectoral imports and exports of a region but not the specific origin or destination of trade. But in particular in times of globalised supply chains and the possibility to relocate production as a response to regulations, not truly accounting for trade patterns and/or the particularities of important trade related sectors such as transportation services may mean missing important insights.

In its first of two main objectives, this thesis addresses the aforementioned shortcomings of CGE models and seeks to advance the CGE approach in order to provide policy-makers with potent tools for policy evaluation. In this context, the main contributions include the development of a new CGE model which makes use of the new comprehensive and coherent World Input-Output Dataset (WIOD) and which features a detailed representation of bilateral and bisectoral trade flows (Chapter 2). Moreover, to increase the validity and robustness of CGE models, it features an investigation of input substitutability to provide modellers with adequate estimates for key elasticities (Chapter 3) as well as a discussion and amelioration of the standard parameter specification of CGE models (Chapter 4).

Evaluation of climate policy

The second main objective of this thesis regards the choice and design of instruments aiming at correcting market failures to eventually limit climate change. Every policy instrument at the disposal of policy makers comes with its own advantages and shortcomings. While it goes without saying that there also exist other criteria that should be taken into consideration before setting up a policy, this (economic) thesis focuses on whether an instrument is effective and cost-efficient in achieving a proclaimed objective. In terms of applications, this thesis includes a quantitative economic impact analysis of so called rebound effects, which are triggered by energy efficiency improvements and reduce their net benefit regarding energy savings. Furthermore, it features an evaluation of the effects of unilateral emission regulation in the sense of regionally limited carbon pricing mechanisms.

Rebound effects

By far most GHG emissions arise in the production of energy (OECD, 2013). This suggests that policies decreasing energy demand and thus related GHG emissions can be an important element to curb global GHG emissions. On that note, energy efficiency improvements are generally seen as an ideal way to become more sustainable. As a matter of fact, for example, the European Union (EU) Energy Efficiency Directive (EU, 2012*a*) establishes a common framework of measures to increase energy efficiency in order to reduce primary energy consumption across Europe by 20 percent by 2020.

But, if consumers react to an energy efficiency improvement by directly or indirectly increasing their demand for energy, the actual energy savings may turn out to be substantially smaller than originally expected. This so called 'rebound' effect may thus limit the effectiveness of measures seeking to reduce emissions through energy efficiency improvements. While the existence of rebound is generally acknowledged throughout the economic literature, the relevance of the issue is still contested (c.f. Frondel and Vance, 2013; Gillingham et al., 2013) and estimates of rebound effects vary significantly depending on the type of efficiency improvement (c.f. Sorrell, 2007; Sorrell et al., 2009; Turner, 2013). So far, most of the research on rebound has focused on direct rebound or price effects, thereby neglecting the potential of other channels such as income effects (indirect rebound) or spillover effects to other – originally not affected – parts of the economy. What is more, the few studies that investigate economy-wide rebound focus on energy efficiency improvements in sectoral production. The wider implications of efficiency changes at households remain largely unconsidered.

This thesis adds value to the state of knowledge regarding rebound in two key aspects. For one thing, it investigates the rebound effect of an energy efficiency improvement in the provision of private transport services by households (Chapter 5). Thereby the analysis takes into account that in contrast to firms, households may be influenced by habits and may only slowly adapt their consumption behaviour to an efficiency improvement. In addition to this, the thesis extends the standard national perspective of rebound and studies rebound in a multiregional setup (Chapter 6). Specifically, it examines whether via trade in energy and non-energy commodities, rebound from an efficiency improvement in sectoral production in one region spills over in other regions where originally no efficiency change has taken place.

Unilateral climate policy

GHG are global pollutants and thus local mitigation efforts are not effective in fighting climate change if they do not lead to a GHG reduction on a global scale. At the same time, mitigation costs vary globally and cost-efficiency requires that GHG emissions are reduced where they are the least costly, irrespective of where this is the case. Hence, efficacy and cost-efficiency call for a global effort involving all GHG sources and abatement possibilities to combat climate change. But as mentioned before, among other reasons due to the fact that 'clean air' – here in the sense of an atmosphere with sustainable GHG concentrations – is a public good and as a consequence is generally supplied at too low levels, the global community has up to date failed to agree on a joint mechanism limiting GHG emissions. Nevertheless, there are some parties which are prepared and committed to take action, even if others are reluctant to do so. If required, they even pursue their policies on a unilateral or regional basis. Present examples are the parties engaged in fulfilling and extending the Kyoto Protocol or the EU with its 2020 climate and energy package (c.f. EC, 2010). Moreover, also in the future, regional initiatives currently seem to be more likely to come to live than a global agreement.

Within the course of the last decades, a large literature devoted to the evaluation of unilateral action has developed. Yet there remain unanswered questions and the continuing emergence of new regionally limited policies calls for more research in this field. Still within its second main objective, this thesis features an analysis of a regional maritime emission trading scheme (ETS) as one of the possible options to reduce emissions of international shipping in the EU context (Chapter 7). Thereby the analysis centers on a discussion of how to define the scope of a regionally limited emission regulation, that is what share of the regulated shipping routes should be included in the scheme.

Lastly, this thesis addresses the question how international supply chains are affected by environmental policy. While for example carbon leakage and the shift of whole production activities from regulated to unregulated regions have been intensively studied (e.g. Felder and Rutherford, 1993; Copeland and Taylor, 1994; Böhringer et al., 2012), the implications on vertical specialisation of industries remain unexplored. To close this gap in the literature, this thesis includes an investigation of how firms restructure their production processes in the presence of a carbon pricing mechanism and carbon import taxes (Chapter 8). Particular attention is thereby given to the relocation of production steps and a change in the regional origin of intermediate inputs.

Chapter 2

The Basic WIOD CGE Model: A computable general equilibrium model based on the World Input-Output Database

Abstract

This chapter presents the Basic WIOD CGE model. The model represents the first implementation of the World Input-Output Database (WIOD) into the computable general equilibrium (CGE) framework and is tailored to provide a maximum fit with WIOD data. The model is specifically designed such that it can serve as the basis for research in fields like environmental, climate and trade policy. It incorporates key features of WIOD such as bilateral and bisectoral trade flows, satellite accounts for energy consumption, greenhouse gas as well as other emissions to air on a sectoral level. As all WIOD data is available in the form of a consistent time series ranging from 1995 to 2009, the model can be calibrated to any year within this time period. The model relies on substitution elasticities which are consistently estimated from the same dataset the model itself is calibrated to. Moreover, the data preparation facilities and model are designed deliberately as flexible as possible in order to allow researchers to use them as a basis for various applications. This enables researchers to secure the numerous advantages of the WIOD dataset when using CGE models for future research.

This chapter is based on the following paper:

Koesler, Simon and Frank Pothen (2013), The Basic WIOD CGE Model: A Computable General Equilibrium Model Based on the World Input-Output Database, ZEW Documentation No. 13-04, Mannheim, Germany.

2.1 Introduction

Computable general equilibrium (CGE) models have proven to be an important instrument to study alternative policy measures (Devarajan and Robinson, 2002; Böhringer et al., 2003; Sue Wing, 2004). At large, numerical models allow for a thorough analysis of economic problems where analytical solutions are either not available or do not provide adequate information due to their simplifying approach. Quantitative simulations facilitate the analysis of intricate economic interactions and the assessment of consequences of structural policy changes. The main advantage of the general equilibrium approach lies thereby in its micro-consistent representation of price-dependent market interactions. The simultaneous explanation of the origin and spending of the agents' income makes it possible to address both economy-wide efficiency as well as distributional impacts of policy interference.

A large share of CGE models is calibrated on data prepared within the Global Trade Analysis Project (GTAP).[1] Today, the World Input-Output Database (WIOD), developed in a project of the same name, can serve as an alternative basis to parameterize CGE models.[2] The objective underlying WIOD is to construct and apply a dataset capable of accounting for the dynamic socio-economic and environmental interrelatedness of countries and industries (c.f. Timmer et al., 2012; Dietzenbacher et al., 2013). The core of the WIOD database is a set of harmonized supply and use tables (SUT) alongside data on international trade in commodities and services. These two sets of data are integrated into sets of intercountry input-output (IO) tables. Taken together with extensive satellite accounts containing environmental and socio-economic indicators, these industry-level data provide the necessary input to several types of models that can be used to evaluate policies aiming for a suitable balance between growth, environmental degradation and inequality across the world. In this spirit, one of the main tasks of WIOD is to develop models using the new database for applied economic research, inter alia a computable general equilibrium model capable of implementing the WIOD data. In this chapter we present a basic model implementing some of those features in a straightforward CGE framework.

Making the WIOD data available for the use in policy analysis by means of CGE models allows capturing a range of unique features of the WIOD dataset and brings several ameliorations to the CGE approach:

- Mutually consistent and harmonized SUT and IO tables:
  WIOD tables are harmonized in terms of product- and industry- classifications and in their definitions (such as price concepts). WIOD allows using a single source of harmonized data and avoids combining a large variety of data sources.

- Inter-country Input-output tables:
  WIOD provides bilateral and bisectoral trade flows for all industries and nations

[1]Global Trade Analysis Project, http://www.gtap.agecon.purdue.edu

[2]World Input-Output Database, http://www.wiod.org

covered by the data. It captures international trade in more detail than other datasets and makes it possible to thoroughly investigate changes in trade patterns in a general equilibrium setting.

- Time-series:
  The WIOD database provides consistent time-series of annual IO tables. Time series of variables are required to study and account for developments over time, such as the calibration of time-varying parameters in CGE models.

- Prices and quantities:
  The WIOD-database provides tables at current and constant prices. Constant price tables allow for a distinction between price and quantity developments, which opens up new avenues of research such as transmission of inflationary trends through imports.

- Satellite accounts:
  The WIOD-database provides satellite accounts including data on employment and wages by skills, various types of investment in tangible and intangible assets and environmental indicators in consistent sectoral classification. This allows to implement sub-modules which make it possible to study for example environmental aspects of economic activity in great detail.

- Services:
  By developing a services trade database and by providing maximum detail in service industries, WIOD captures a wide range of sectors that are not taken into account in other databases. An application of WIOD therefore extends the possible range of applications for economic models.

The chapter is structured as follows. Section 2.2 describes the individual data sources the Basic WIOD CGE model builds on and presents how the WIOD data is prepared to make it available for the usage in the CGE framework. Subsequently, Section 2.3 provides a full description of the Basic WIOD CGE model. A shortened presentation of the Basic WIOD CGE Model is also given in Section A.1 of the Appendix.

2.2 Preparing the World Input-Output Database for the model

2.2.1 Data sources

CGE models primarily require data describing the flows of income and expenditures in an economy at a certain point in time and elasticities of substitution governing the sensitivity of consumption and production towards (price) shocks. Depending on the desired field of application, the standard CGE data can then be supplemented with information regarding other aspects of economic activity. For example with satellite accounts giving detailed information on labour compensation or environmental issues.

The Basic WIOD CGE model itself draws only on data generated within the framework of the WIOD project (e.g. Timmer et al., 2012; Dietzenbacher et al., 2013). Specifically it uses data describing the overall structure of the economy, energy uses data, data linking economic activity to emissions and substitution elasticities. Figure 2.1 gives an overview of the data used in the Basic WIOD CGE model and how it is prepared prior to the implementation into the model.

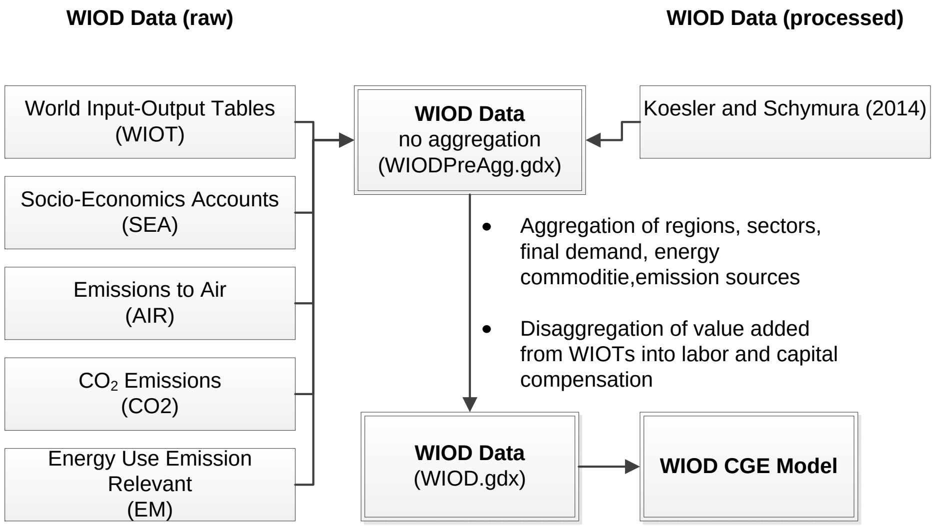


Figure 2.1: Data structure of Basic WIOD CGE model

2.2.1.1 Economic and trade data

The basis of any CGE model is the economic structure of an economy in a predefined benchmark year given by an Input-Output (IO) table. An IO table includes information on the production and consumption of every industry and agent specified in the economy and illustrates the relationships between producers and consumers in monetary terms.

To replicate the core economic structure and the trade activities of the economies under investigation, the Basic WIOD CGE model builds on WIOD's World Input-Output Tables (WIOT Analytics). The WIOT Analytics table is a joined set of regional IO covering the whole world. This dataset is available for the years from 1995 to 2009, features data from 40 developed and developing countries as well as a rest of the world region (ROW) and is disaggregated to 35 industries.

For every region, industry and agent covered by WIOD, the current WIOT Analytics features information regarding its intermediate use, final consumption as well as related taxes (net of subsidies), international transport margins, and value added. Furthermore, they contain information on direct purchases on the domestic territory by non-residents, and direct purchases abroad by residents.[3] Figure 2.2 illustrates the basic structure of the WIOT Analytics.

Unfortunately, WIOT Analytics contain no separate information regarding the compensation for labour and capital services and feature only information on value added. In order to overcome this shortcoming we supplement the WIOT data with information from the WIOD Socio-Economics Accounts (SEA). On a country specific basis, each of these files contains detailed information regarding labour and capital inputs of all industries. From the SEAs we retrieve data on the labour $LAB\_YL_{(r,i,t)}$ and capital $CAP\_YL_{(r,i,t)}$ compensation for each WIOD industry. Subsequently $LAB\_YL_{(r,i,t)}$ and $CAP\_YL_{(r,i,t)}$ are used to disaggregate the value added data from the WIOTs $VA_{(r,i,t)}$ into labour and capital compensation.[4]

[3]For more detailed information regarding WIOTs the interested reader is kindly referred to Timmer et al. (2012).

[4]For some regions WIOD Output and Labour Files contain no information regarding $LAB\_YL_{(r,i,t)}$ and $CAP\_YL_{(r,i,t)}$. Consequently we cannot compute the labour share needed to divide $VA_{(r,i,t)}$. In this case we assume a labour share of $\frac{70}{100}$.

		Region A Intermediate Use Industry	Region B Intermediate Use Industry	Region A Finale Use	Region B Finale Use	Total Output
Region A	Industry	Intermediate use of domestic production	Intermediate use of production from country A in country B	Final use of domestic prodction	Final use of production from country A in country B	Total output of country A
Region B	Industry	Intermediate use of production from country B in country A	Intermediate use of domestic production	Final use of production from country B in country A	Final use of domestic prodction	Total output of country B
Total intermediate consumption						
taxes less subsidies on products						
Cif/ fob adjustments on exports						
Direct purchases abroad by residents						
Purchases on the domestic territory by non-residents						
Value added at basic prices						
International Transport Margins						
Output at basic prices		Total intermediate output of region A	Total intermediate output of region B	Total final use output of region A	Total final use output of region B	

Figure 2.2: Schematic outline of a WIOT Analytic (for the case of two regions)

2.2.1.2 Environmental satellite accounts

Aside from replicating the basic economic structures contained in the World Input-Output Tables, the basic WIOD CGE model incorporates information from many of the environmental satellite accounts available in the WIOD database. The Basic WIOD CGE model implements information on energy use (broken down into a number of energy carriers), CO_2 emissions, and other emissions to air.[5] If required, further data available in the WIOD, for example on land use, material use or water use, can be implemented similarly, but is currently not included in the basic WIOD CGE model.

All satellite accounts consist of time series ranging from 1995 to 2009 and are provided in a sectoral aggregation consistent to WIOT's sectoral structure. They also include data on the final demand of private households.[6] Figure 2.3 gives a schematic representation of the WIOD satellite accounts.

Region	
Time	
	Air Emissions (AIR)
	Sources of CO_2 Emissions (CO2)
	Energy Use, Gross (EU)
	Energy Use, Emission Relevant (EM)
	Land Use (LAN)
	Material Use (MAT)
	Water Use (WAT)
WIOD Sectors	*Data*
Final Demand	*Data*
Totals	*Data*

Figure 2.3: Schematic representation of WIOD Emissions to Air (AIR), CO_2 Emissions (CO2), Energy Use, Gross (EU) and Energy Use, Emission Relevant (EM) tables, Land Use (LAN), Material Use (MAT) and Water Use (WAT)

We retrieve non-CO_2 air emission data for all WIOD sectors and final demand from the WIOD Emissions to Air tables (AIR). Carbon dioxide emissions are taken from the CO_2 Emissions tables (CO2). The data allows us to differentiate between energy-related and process related CO_2 emissions, which is of importance for climate policy analyses (Bednar-Friedl et al. 2012). Furthermore, to replicate the energy system in the WIOD CGE model, we draw on information from the WIOD Emission Relevant Energy Use tables (EM).

[5] With regard to non CO_2 emissions, WIOD includes N_2O, CH_4, NO_X, SO_X, NH_3, NMVOC, CO and it is planned to enlarge its scope of air emissions to SF_6, PFC, HFC, CFC, HCFC, HALON, CH_3Br, CH_3CCl_3.

[6] For more information regarding the WIOD environmental satellite accounts the interested reader is kindly referred to Timmer et al. (2012).

2.2.1.3 Substitution elasticities

Elasticities are key parameters determining the comparative static behavior of economic models and thereby strongly influence the results of counterfactual policy analysis (Dawkins et al., 2001). Consequently, the choice of adequate elasticities is a crucial element in the development of all models. But despite their importance, the availability of consistent elasticities for CGE model appears to be unsatisfying. In particular only few estimates of elasticities of substitution suited for CGE modeling are available, e.g. Okagawa and Ban (2008), van der Werf (2008) and Kemfert (1998). This problem has also been tackled within the framework of the WIOD project. Exploiting the time series nature of the data, Koesler and Schymura (2015) estimate substitution elasticities for all sectors included in WIOD.[7] Their results are incorporated into the Basic WIOD CGE model. Thus the model uses substitution elasticities which are consistent to the data it is calibrated to.

2.2.2 Transfer XLSX to GDX

Originally all WIOD data is available as Microsoft Excel spread sheets. The WIOT Analytics are organised in 15 different files, each covering one year of the WIOD reporting period from 1995 to 2009. WIOD SEA, WIOD EM, WIOD CO2 and WIOD AIR are provided on a region specific basis, each including several worksheets covering one specific year. Other satellite accounts exhibit the same format.

As the Basic WIOD CGE model is implemented in the mathematical optimization program GAMS, the WIOD data needs to be transferred into the GAMS compatible data format GDX in order to make it available for the further data handling and modelling. In the process, all data points in the Excel spread sheets are transferred to the core data GDX file WIOD_PreAgg.gdx using the GAMS Data Exchange facilities. For example all variables associated with the intermediate use of products are integrated into the GDX parameter $Intermed_{r,i,rr,ii,t}$ with the dimensions r (region of origin), i (industry of origin), rr (importing region), i (importing industry) and t (year) and stored in the GDX data files.[8] A comprehensive overview of the notation used in the core GDX file is given in the Appendix. It is important to note that at this stage all data are transferred to the GDX file. Further aggregation and merging of the data is done at a later stage.

2.2.3 Aggregation of the data

Originally, the WIOD data covers 40 regions plus ROW, 35 industries, 26 energy carriers and five forms of final demand. A complete list of regions, sectors and final demand types is given in the Appendix. Depending on the specific research question, it is important to balance the level of detail needed with the benefits of a small, highly aggregated database

[7]For more information regarding their estimation procedure and the results, the interested reader is referred to Koesler and Schymura (2015).

[8]Here and throughout the text, r alias rr or s stands for a region and i alias ii or j for a sector.

offering easier handling and interpretation in the light of economic theory. Choosing an adequate aggregation level is therefore an important step when preparing data for the use in numerical models.

To facilitate future policy analyses and research using the WIOD data and to ease the implementation of the desired aggregation level, we developed a simple but effective aggregation routine based on GAMS. It can be applied using the visual interface of the Java program WIODAgg developed by ZEW. This program enables researchers to easily implement any desired aggregation scheme to the WIOD data and produces the data file WIOD.gdx containing all aggregated values required by the Basic WIOD CGE model. The aggregation routine allows researchers to aggregate industries, regions, energy carriers, and final demand according to their proper needs. The elements of the core data file are summed up according to aggregation matrices specified by the researcher. As an example, Figure 2.4 gives a simplified illustration of the process when aggregating parameter $TotIntermed\_PreAgg_{(origR,origSec,t)}$ into two industries and two regions. $origR$ and $origSec$ denote the region and sector in the original WIOD data, prior to aggregation.

$$TotIntermed_{(t)} = flagAggSec^{-1} * TotIntermed\_PreAgg_{(t)} * flagAggR$$

with:

$$TotIntermed_{(t)} = \begin{pmatrix} TotIntermed_{(r,i,t)} & \cdots \\ \vdots & \ddots \end{pmatrix} \qquad i \times r$$

$$TotIntermed\_PreAgg_{(t)} = \begin{pmatrix} TotIntermed\_PreAgg_{(OrigR,OrigSec,t)} & \cdots \\ \vdots & \ddots \end{pmatrix} \qquad OrigSec \times OrigR$$

$$flagAggR = \begin{pmatrix} Agg_{(OrigR,r)} & \cdots \\ \vdots & \ddots \end{pmatrix} \text{ with } Agg_{(OrigR,r)} \in \{0,1\} \qquad OrigR \times r$$

$$flagAggSec = \begin{pmatrix} Agg_{(OrigSec,i)} & \cdots \\ \vdots & \ddots \end{pmatrix} \text{ with } Agg_{(OrigSec,i)} \in \{0,1\} \qquad OrigSec \times i$$

Figure 2.4: Illustration of general aggregation procedure

Where substitution elasticities are concerned, we deviate from this procedure. In this case we weigh the respective substitution elasticities according to the value share of total output of an industry within the associated industry aggregate ($s_{(OrigR,OrigSec,r,i,t)}$) and sum up the corresponding elasticities using these shares. As a result of this procedure, although the substitution elasticities estimated by Koesler and Schymura (2015) feature no temporal or regional specification, the computed aggregate substitution elasticities may vary over time and space. This is due to the fact that the value shares of total output vary over time and space and this characteristic is conveyed to the aggregated substitution elasticities through the aggregation process. Figure 2.5 illustrates the aggregation procedure for substitution elasticities.

An important shortcoming of the WIOD dataset concerns the modelling of energy related sectors. Though the WIOD energy use data differentiates 26 energy carriers, current WIOT data does not allow for a detailed replication of the energy sector and

$$es\_kl\_KS_{(t)} = flagAggSec^{-1} * es\_kl\_KS\_PreAgg_{(t)} * flagAggR * Sec$$

with:

$$es\_kl\_KS_{(t)} = \begin{pmatrix} es\_kl\_KS_{(r,i,t)} & \cdots \\ \vdots & \ddots \end{pmatrix} \qquad i \times r$$

$$es\_kl\_KS\_PreAgg_{(t)} = \begin{pmatrix} es\_kl\_KS\_PreAgg_{(r,i,t)} * s_{(origR,origSec,r,i,t)} & \cdots \\ \vdots & \ddots \end{pmatrix} \qquad OrigSec \times OrigR$$

$$flagAggR = \begin{pmatrix} Agg_{(OrigR,r)} & \cdots \\ \vdots & \ddots \end{pmatrix} \text{ with } Agg_{(OrigR,r)} \in \{0,1\} \qquad OrigR \times r$$

$$flagAggSec = \begin{pmatrix} Agg_{(OrigSec,i)} & \cdots \\ \vdots & \ddots \end{pmatrix} \text{ with } Agg_{(OrigSec,i)} \in \{0,1\} \qquad OrigSec \times i$$

Figure 2.5: Illustration of the aggregation procedure for substitution elasticities

thus the 26 energy carriers can only enter the model in a highly aggregated form. This results from the ambiguous specification of the industries in the original WIOT's. With respect to the energy systems this concerns in particular the industries Mining and Quarrying (C), Coke, Refined Petroleum and Nuclear Fuel (23), and Electricity, Gas and Water Supply (E). Subsuming the supply of coke, refined petroleum and nuclear fuel into one industry, for example, prohibits explicitly distinguishing between demand and supply for coke, refined petroleum products and nuclear fuel. To be able to replicate the individual energy usage of the industries in detail and to allow for the substitution of different energy carriers, information on the production and consumption flows within the energy system is imperative. We would like to stress that the Basic WIOD CGE model itself is capable of handling a wide range of energy commodities and as soon as the energy related industries are disaggregate. A proper replication of the energy sector is easily possible. But until then, the model distinguishes only between conventional (fossil fuels apart from gas) and alternative energy carriers (non fossil fuels and gas).

2.3 The model

The model is a basic, static, multi-region, multi-sector CGE model replicating the production and distribution of commodities in the global economy. In line with the WIOD database and depending on the chosen aggregation scheme, it differentiates up to 40 regions plus ROW, 35 sectors and five forms of final demand. Figure 2.6 provides a diagrammatic overview of the basic economic structure of the model. The corresponding notation is given in the Appendix.

The model has been designed in such a way that it can easily be calibrated to any base year within the period from 1995 to 2009 according to the requirements of researchers. This is possible thanks to the panel character of the WIOD dataset and may help overcoming some of critique CGE models frequently face related to their calibration to one specific base year.

Following Rutherford (2005) and Böhringer et al. (2003), the equilibrium is charac-

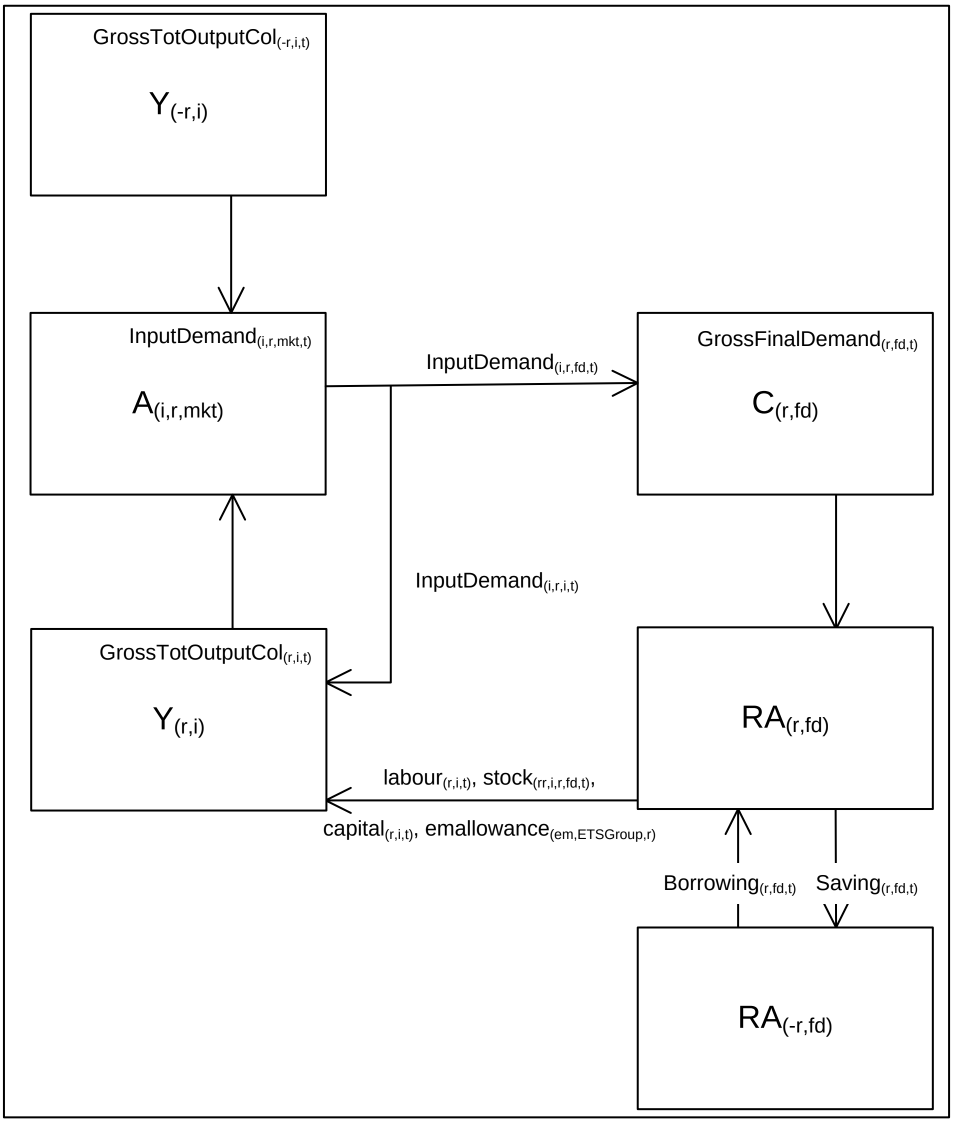


Figure 2.6: Basic structure of WIOD CGE Model

terised through three types of equilibrium conditions, namely market clearance conditions for all commodities and factors (supply = demand), income balances (net income = net expenditure) and zero profit conditions (cost of inputs = value of output). The variables defining the equilibrium are activity levels for the constant-returns-to-scale production, commodity and factor prices, and the price of final consumption. In the basic model, we assume perfect competition on all markets and constant returns to scale.

Numerically, the model is formulated as a mixed complementarity problem (MCP) in the mathematical optimization program GAMS, a program that is frequently used to develop and run CGE models. It is written in GAMS using the MPSGE syntax (c.f. Rosenthal, 2010; Rutherford, 1999). The model is solved using the PATH algorithm (c.f. Dirkse and Ferris, 1993).

2.3.1 Commodity production

The model distinguishes between two groups of commodities within the set i, energy commodities (set eg) and non-energy commodities (set neg). The production of all commodities $Y_{(r,i)}$ is captured by production functions characterizing technology through substitution possibilities between various energy, non-energy inputs and old stock of $Y_{(r,i)}$. Introducing stocks of $Y_{(r,i)}$ is necessary because of negative changes in inventories, represented by negative consumption, in the WIOT Analytics. They reflect the reduction of stocks and are interpreted as a perfect substitute to new $Y_{(r,i)}$ ($es\_stock_{(r,i)} = \text{inf}$).

Nested CES functions with five levels are employed to specify the substitution possibilities between labour, capital, energy inputs, non-energy intermediate inputs and existing stocks of $Y_{(r,i)}$. As described in Section 2.2.1.3, the corresponding substitution elasticities are taken from Koesler and Schymura (2015). To account for air emissions during commodity production (process and energy related emissions), the production structure is supplemented with Leontief nests capturing emissions during the production process.[9] While the following highlights crucial blocks of the commodity production structure, Figure 2.7 presents the production structure of the commodity production in detail. The corresponding zero-profit condition is illustrated in Equation 2.1. Throughout the text, π denotes profits and CES stands for a constant elasticity of substitution function. The arguments of the CES function is given in parentheses and the corresponding elasticity of substitution in the upper index.

$$\begin{aligned}\pi^{Y}_{(r,i)} \leq & CES_{(r,i)}^{\sigma^{es\_stock}_{(r,i,t)}} \Big[pstock_{(r,i,rr,FC\_HH)}, CES^{0}_{(r,i)} \Big[CES^{0}_{(r,i)}(pem_{(em,ETSGroup)}), \\ & CES_{(r,i)}^{\sigma^{klem}_{(r,i,t)}} \big[CES_{(r,i)}^{\sigma^{ms}_{(r,i,t)}}(pa_{(neg,r,i)}), CES_{(r,i)}^{\sigma^{kle}_{(r,i,t)}} \big[CES_{(r,i)}^{\sigma^{e}_{(r,i,t)}}(pe\_em_{(eg,r,i)}), \\ & CES_{(r,i)}^{\sigma^{kl}_{(r,i,t)}}(pl_{(r)}, pk_{(r)}) \big] \big] \Big] \Big].\end{aligned} \tag{2.1}$$

[9] For more details regarding the modelling of air emission the interested reader is referred to Section 2.3.4 of this chapter.

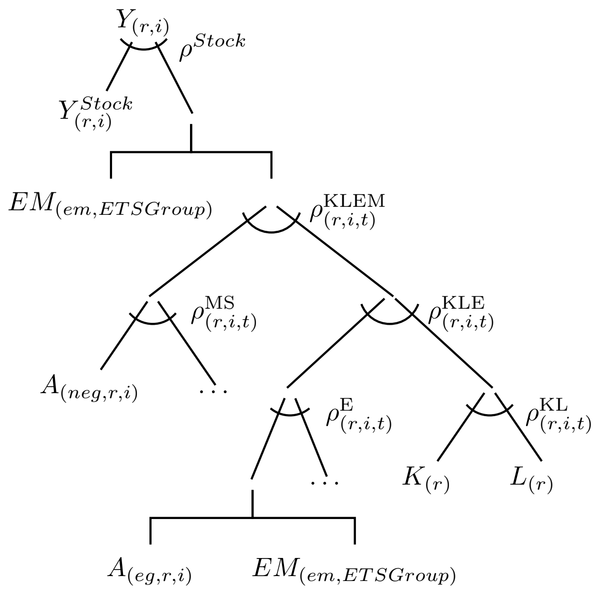


Figure 2.7: Structure of commodity production

At the top level of the production structure, a CES function describes the substitution possibilities between newly produced $Y_{(r,i)}$ and stocks of $Y_{(r,i)}$. Process emissions join the production in the second level. An aggregate of non-energy intermediate inputs enter in the third level. The fourth level describes the substitution possibilities between value added and energy. Finally, in separate nests in the fifth level of the CES production functions, labour and capital are combined to generate value added and energy is composed from a set of energy commodities. Total output $Y_{(r,i)}$ is taxed and transport margins are applied.[10]

2.3.2 Trade structure

The model features up to 40 regions plus one aggregate for 'Rest of the World' (ROW) to close the model. ROW is modelled as any other region in the model, the only exception being that no CO_2 or other air emissions are taken into account because no environmental information for ROW is available in the WIOD dataset.

According to the general equilibrium approach, in a static setting the trade between an individual region with all other regions should be balanced in the benchmark. Hence no trade deficits or surpluses should exist in the economy. But in practice this is rarely the case. Accordingly, when implementing the WIOD data, regions consume either more or less than their income would allow for. Therefore, budget surpluses and deficits occur regularly. To deal with these imbalances, international capital flows which equate the surpluses and deficits on a global level have to be modelled. Following Rutherford (2005), we denominate the account deficits or surpluses with the consumption price of

[10] For more information on taxes and transport margins, the interested reader is referred to Section 2.3.5 of this chapter.

the numeraire region and adjust the endowments of the representative agents in order to match households' expenditures with their income.

Within the countries, the choice among imports and domestically produced commodities is based on Armington's idea of regional product differentiation (Armington, 1969). Domestic and foreign commodities are distinguished by origin and they are imperfect substitutes. Consequently, before the commodities can enter production as intermediates, an Armington composite $A_{(i,r,mkt)}$ is produced from domestic production and an import aggregate on the basis of a CES function. The import aggregate is a CES composite of all imports of a commodity composed in the second level of the Armington production function. WIOD does not feature any information on the substitutability of domestic and foreign commodities, as a consequence the corresponding Armington elasticities are set in the original version of the Basic WIOD CGE model to a fictive value ($es\_a_{(r,mkt,t)} = es\_mm_{(r,mkt,t)} = 5$). However, if deemed appropriate, Armington elasticities can easily be adjusted to appropriate levels.[11]

Each Armington composite is produced individually for the importing sectors or types of final demand in each region. Thereby, bisectoral and bilateral trade flows can be modelled specifically. This one of the main differences of model to other CGE models and allows the WIOD CGE model to depict international trade in much greater detail than standard CGE models. Figure 2.8 displays the structures underlying the Armington aggregation. Equation 2.2 presents the corresponding zero-profit condition.

$$\pi^{A}_{(i,r,mkt)} \leq CES^{\sigma^{es\_a}_{(r,mkt,t)}}_{(i,r,mkt)} \left[py_{(r,i)}, CES^{\sigma^{es\_mm}_{(r,mkt,t)}}_{(i,r,mkt)} (py_{(rr,i)}) \right] \text{ with } rr \neq r. \tag{2.2}$$

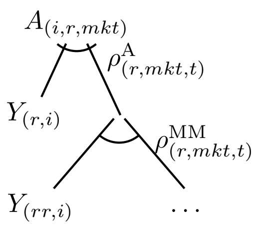


Figure 2.8: Structure of Armington aggregation

2.3.3 Final demand

For each region, the model incorporates the behaviour of representative agents $RA_{(r,fd)}$ who in sum represent total final demand. In its standard version, the Basic WIOD CGE model includes at least a representative household FC_HH and a government agent GOV. If desired, the model can encompass all five forms of final demand supported by WIOD data or can subsume all final demand types in only one agent per region. In the standard version, FC_HH is endowed with the primary factors labour and capital, stocks

[11] Armington elasticities are for example supplied within the GTAP 7 dataset (c.f. Badri and Walmsley, 2008).

of commodities (see subsection 2.3.1) and potentially emission allowances. Labour and capital are mobile across sectors within regions but cannot be traded between different regions. Commodity stocks are mobile across regions. In its basic version, the model abstracts from interregional factor mobility and investment. Government GOV receives income from taxes and possibly from selling emission allowances. As the budget of final demand agents need not be balanced in the benchmark, savings and borrowing adjust the budget appropriately and are incorporated as a fix additional endowment.

The behaviour of the representative agents can be described as choosing the bundle of consumption goods maximizing their individual utility taking into account their budget constraint. As described in Equations 2.3 and 2.4, their budget constraint is determined from factor income, tax revenues, revenues from the auctioning of emission allowances as well as by interregional and intertemporal saving or borrowing of the agent:

$$\begin{aligned} B_{(r,FC\_HH)} =& pk_{(r)} \sum_{i} \left(K_{(r,i)}\right) + pl_{(r)} \sum_{i} \left(L_{(r,i)}\right) + \sum_{rr} \sum_{i} \left(Stock_{(rr,i,r,FC\_HH)}\right) \\ &+ \alpha^{EMA}_{(r,FC\_HH)} EMA_{(em,ETSGroup)} \\ &- Saving_{(r,FC\_HH)} + Borrowing_{(r,FC\_HH)}, \end{aligned} \tag{2.3}$$

respectively

$$\begin{aligned} B_{(r,GOV)} =& Tax(r) + \alpha^{EMA}_{(r,GOV)} EMA_{(em,ETSGroup)} \\ &- Saving_{(r,GOV)} + Borrowing_{(r,GOV)}. \end{aligned} \tag{2.4}$$

where $EMA_{(em,ETSGroup)}$ denotes the value of emission allowances available in $ETSGroup$ and $\alpha^{EMA}_{(r,fd)}$ the share of $EMA_{(em,ETSGroup)}$ sold in region r by GOV or FC_HH. This approach allows for emissions trading systems spanning over more than one region.

Final demand of the representative agent is modelled as a constant elasticity of substitution (CES) composite combining energy with a non-energy Armington bundle. Energy is composed from a set of energy commodities on the basis of another CES function. Substitution patterns within the non-energy Armington bundle are also reflected via CES functions. As WIOD once more does not supply the corresponding elasticities, in the original Basic WIOD CGE model all three nests are reflected by Leontief functions ($es\_c_{(fd,r,t)} = es\_ca_{(fd,r,t)} = es\_ce_{(fd,r,t)} = 0$). But again, if deemed appropriate, the elasticites can easily be updated accordingly. Furthermore, to account for air emissions during consumption, Leontief nests capturing emissions from final demand are introduced.[12] Eventually total final demand $C_{(r,fd)}$ is taxed and transport margins are applied.[13] The structure underlying final demand is displayed in Figure 2.9. The corresponding zero-profit is presented in Equation 2.5.

[12]For more details regarding the modelling of air emission the interested reader is referred to Section 2.3.4 of this chapter.

[13]For more information on taxes and transport margins, the interested reader is referred to Section 2.3.5 of this chapter.

$$
\begin{aligned}
\pi^C_{(r,fd)} \leq & CES^0_{(r,fd)} \Bigg[CES^0_{(r,fd)} \Bigg[CES^{\sigma^{es\_ca}_{(r,fd,t)}}_{(r,fd)} (pa_{(neg,r,fd)}), \\
& CES^{\sigma^{es\_ce}_{(r,fd,t)}}_{(r,fd)} (pe\_em_{(eg,r,fd)}) \Bigg], CES^0_{(r,fd)} (pem_{(em,ETSGroup)}) \Bigg]
\end{aligned} \tag{2.5}
$$

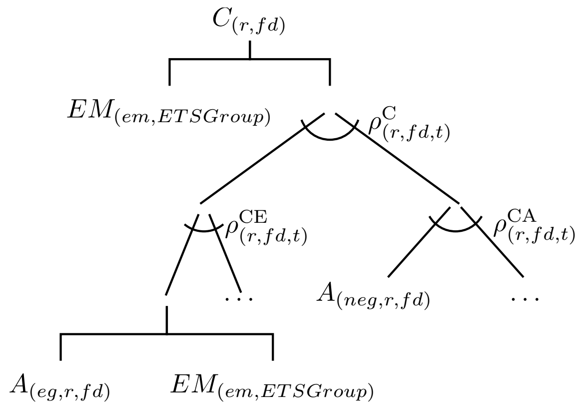


Figure 2.9: Structure of final demand

2.3.4 Carbon dioxide and other emissions

Besides the standard economic activity, the model makes provisions for the accounting of CO_2 and other air emissions caused by economic activity. According to Xepapadeas (2005) and Koesler (2010) there are three basic approaches of how pollution can be incorporated into an economic model. Firstly, emissions can be linked to the level of private consumption. In such a setting emissions can be seen as a by-product of consumption and final demand is directly responsible for determining how much pollution is generated in the economy. Secondly, emissions can be related to the production process, such that pollution is a necessary by-product of production. In this context, the production sectors are directly responsible of how much emissions are generated, although they have only an indirect influence on emissions by choosing their level of output. Both approaches would imply determining the prevailing amount of emissions in a model by combining consumption respectively output with a fixed factor outside the actual optimisation problems of the agents. But, while this would enable the model to account for emissions, it would do so in a rather passive manner and emissions would have no direct effect on the agents' behaviour.

As a third possibility, emissions may arise because they are needed as an input in the production process for the goods traded in the economy. Here, the producing sectors decide directly how much pollution will prevail in the economy by choosing which inputs they use and what amount of output they will produce. Following the recent CGE literature, we model emissions as the fictive necessary input $pem_{(em,ETSGroup)}$ into the production of commodities and the consumption good. While the fictive input is

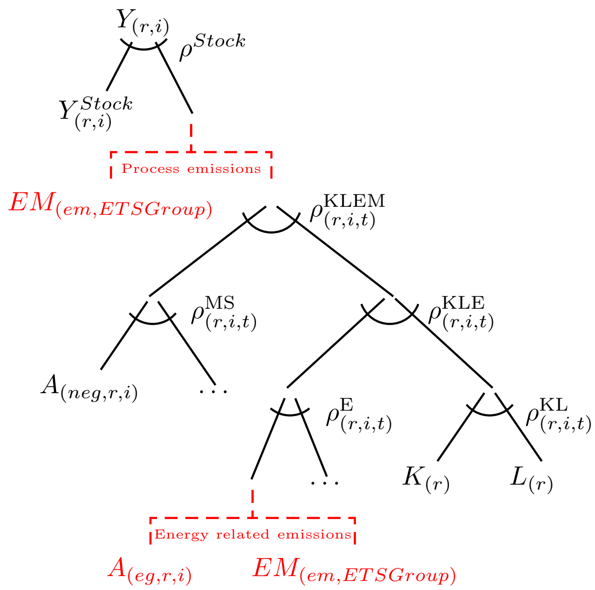


Figure 2.10: Air emissions from commodity production

supplied by the representative agent $GOV_{(r)}$, it is paired with the input causing the emission in a Leontief nest in the respective production function. Setting the endowment of $pem_{(em,ETSGroup)}$ sufficiently large implies the supply of the fictive input to outnumber demand as long as no regulation is assumed for. Hence, if emissions are not taxed, the production costs induced by the usage of the fictive input are zero. Furthermore, $pem_{(em,ETSGroup)}$ is mobile between all sectors assigned to a group within the set ETSGroup.

As far as CO_2 emissions are concerned, the model distinguishes between energy related CO_2 emissions (arising due to the burning of fossil fuels) and process emissions (e.g. caused during the production of cement). With respect to other air emissions (N_2O, CH_4, NO_X, SO_X, NH_3, NMVOC, CO), we also take into account that in principle these emissions can emerge as a result of the general production process (process emissions) as well as from energy-related processes. But at present the WIOD data does not allow for a distinction between energy related air emissions and air emissions related to general production because it includes only one general air emission data file for emissions regardless of their origin. To overcome this problem, WIOD air emissions data should be assigned to their respective point of origin, similar to the WIOD CO2 Emission files which attribute CO_2 emissions to their source.

This discussion is of particular interest, as the modeller has to decide with which input he associates the different pollutant, in our case emissions. Let us take CO_2 as an example. The majority of CO_2 arises from the burning fossil fuels and should be linked to the energy input. But a certain share of CO_2 emissions is generated as process emissions, for example in cement or steel production. Hence CO_2 emissions should be assigned to different parts in the production structure. Bednar-Friedl et al. (2012) show that differentiating between energy-related and process emissions is of importance for

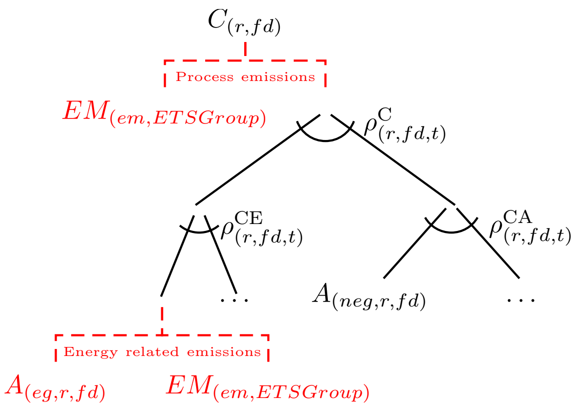


Figure 2.11: Air emissions from final demand

climate policy.

The case is more complicated for other air pollutants for whom emissions cannot be calculated as straightforwardly as for CO_2. Emissions of NO_x, for example, also occur when burning fossil fuels. Their amount can be reduced by modifying the burning process or by end-of-pipe measures. This is not possible for CO_2.

Modelling pollutants other than carbon dioxide is beyond the scope of the basic WIOD CGE model and needs further information. We only distinguish between energy and process emissions of CO_2 and treat all other air pollutants as process emissions arising with from the general production process. However, the Basic WIOD CGE model has been modelled in such a way that modellers can easily implement a split in energy and process emissions for all air emission types if desired and the corresponding data is available.

From a modelling perspective, when emissions are related to energy consumption, they enter the production process parallel to the input energy. That is to say, the respective emissions build with energy an energy-emission composite on the basis of fix input shares which is then employed in the standard production process. Input shares $EmissionPerUnit_{(em,co2energy,r,mkt,t)}$ vary depending on the type of accompanied energy good and are determined according to

$$EmissionPerUnit_{(em,co2energy,r,mkt,t)} = \frac{Emission_{(em,co2energy,r,mkt,t)}}{InputDemand_{(eg,r,mkt,t)}}. \tag{2.6}$$

The modelling of process emissions is carried out along the same lines, with the exception that process emissions appear only in the production in the top nest of the production function. Figure 2.10 highlights the relevant nests in the structure of the commodity production. Figure 2.11 does the same for the production of the consumption good.

2.3.5 Taxes and international transport Margins

Besides consumption and production flows as well as air emissions, the model also replicates the existing tax structure as well as international transport margins in a specific benchmark year. But in the current version of the WIOT Analytics taxes and international trade margins are supplied only in the form of separate rows below the WIOD Input-output table. Taxes have not been divided by product or final demand and international trade margins are not allocated to the region/industry responsible for the delivery of these services.[14] As a result, no realistic tax, tariff and transport structure can be incorporated into the model because taxes and transport margins can only be assigned globally to the sector paying them. Given this problem of the presently available WIOD data, we model all taxes and transport margins as an ad valorem tax on the production of commodities and consumption goods. Note that the WIOD data also does not feature tariffs or input and factor taxes. Nevertheless, in order to allow for a simple extension of the basic model, we include input taxes $ti_{(r,i,t)}$ and factor taxes $tf_{(r,i,t)}$ in the commodity production structure, although in the benchmark these are set to be zero. In the basic WIOD CGE model all tax income generated in region r is assigned to the government $GOV_{(r)}$.

2.3.6 Climate policy

In order to allow for a first application of the Basic WIOD CGE model, we have implemented basic climate policies and allow each air emission to be regulated by means of an emission trading scheme. As described in Section 2.3.4, emissions are modelled as an input $pem_{(em,ETSGroup)}$ into the production of commodities and the consumption good. This additional input can be interpreted as an emission allowance. By assigning sectors and consumption to a group whose members all use the same type of input, respectively allowance, one can implement a trading group encompassing a set of sectors and final demands subject to a common emission trading scheme. We assume that emission allowances $EMA_{(em,ETSGroup)}$ are auctioned by $GOV_{(r)}$ or $FC\_HH_{(r)}$.

Originally, the price for allowances is zero as long as the supply of allowances by $GOV_{(r)}$ is equal or bigger than demand. When capping their supply, the price of emission allowance becomes positive. In this case allowances become an ordinary (costly) input into production. In this spirit we have incorporated into the model the parameter $EmissionRdcTarget_{(em,ETSGroup,t)}$. It expresses the reduction targets for a certain group of sectors defined within the set $ETSGroup$, relative to the benchmark emissions.

This effectively implements an emission trading scheme in the model. By choosing different emission reduction targets and assigning sectors to different trading groups one can effectively simulate different emission trading regimes.

[14]For more information the interested reader is referred to Timmer et al. (2012).

2.3.7 Market clearance conditions

Finally, in equilibrium, a set of market clearance conditions must hold. The market clearance condition for domestic production is given by:

$$\begin{aligned} Y_{(r,i)} \geq & \sum_{ii} \left(\frac{\partial \pi^Y_{(r,ii)}}{\partial py_{(r,i)}} Y_{(r,ii)} \right) + \sum_{fd} \left(\frac{\partial \pi^C_{(r,fd)}}{\partial py_{(r,i)}} C_{(r,fd)} \right) \\ & + \sum_{rr;r \neq rr} \left(\frac{\partial \pi^M_{(rr,i)}}{\partial py_{(r,i)}} M_{(rr,i)} \right) - \sum_{rr} \left(Stock_{(r,i,rr,FC\_HH)} \right), \end{aligned} \tag{2.7}$$

where $Y_{(r,i)}$ is the value of domestic production, $C_{(r,i)}$ the value of domestic final demand, $M_{(r,i)}$ the value of imports by foreign regions, and $Stock_{(r,i,rr,FC\_HH)}$ the value of commodities stocked by households. The clearance of international commodity markets demand:

$$M_{(r,i)} \geq \sum_{rr;rr \neq r} \left(\frac{\partial \pi^M_{(rr,i)}}{\partial pm_{(r,i)}} Y_{(rr,i)} \right). \tag{2.8}$$

Factor markets clear if:

$$K_{(r,i)} \geq \sum_{ii} \left(\frac{\partial \pi^Y_{(r,ii)}}{\partial pk_{(r)}} Y_{(r,ii)} \right), \tag{2.9}$$

and

$$L_{(r,i)} \geq \sum_{ii} \left(\frac{\partial \pi^Y_{(r,ii)}}{\partial pl_{(r)}} Y_{(r,ii)} \right). \tag{2.10}$$

The market for emission allowances is cleared if:

$$\begin{aligned} EMA_{(em,ETSGroup)} \geq & \sum_{r} \sum_{i} \left(\frac{\partial \pi^Y_{(r,i)}}{\partial pem_{(em,ETSGroup)}} Y_{(r,i)} \right) \\ & + \sum_{r} \sum_{fd} \left(\frac{\partial \pi^C_{(r,fd)}}{\partial pem_{(em,ETSGroup)}} C_{(r,fd)} \right), \end{aligned} \tag{2.11}$$

To ensure that markets for the consumer goods clear the following must hold:

$$B_{(r,fd)} \geq C_{(r,fd)}. \tag{2.12}$$

2.4 Summary

This report presents the Basic WIOD CGE model. The model represents the first implementation of the novel World Input-Output Database (WIOD) into the computable general equilibrium (CGE) framework and is tailored to provide a maximum fit with the available WIOD data. The model is set up as a basic, static, multi-region, multi-sector CGE model which replicates the production and distribution of commodities in the global economy. The data preparation facilities and model are designed deliberately as flexible as possible in order to allow researchers to use them as a basis for various applications.

The Baisc WIOD CGE model incorporates key features of WIOD including: bilateral and bisectoral trade flows, satellite accounts for different types of energy consumption and greenhouse gas as well as other emissions to air on a sectoral level. Thereby all required data stems from one consistent database. As all WIOD data is available in the form of a consistent time series ranging from 1995 to 2009, the model can be calibrated to any year within this time period. For substitution elasticities, the Basic WIOD CGE model relies on parameters which are consistently estimated from the same dataset the model itself is calibrated to.

Given the comprehensive coverage of bilateral and bisectoral trade flows, the detailed information on energy use and its potential to account for various types of environmental aspects of economic activity, the Basic WIOD CGE model seems particularly potent in serving as as the basis for research in fields of energy and environmental policy or trade policy. Overall, the Basic WIOD CGE model enables researchers to secure the numerous advantages of the WIOD dataset when using CGE models for future research.

Note

To allow interested researchers to use the WIOD data within the mathematical optimization program GAMS, this presentation of the Basic WIOD CGE model is accompanied by a GDX file including all the WIOD data required within the context of the WIOD CGE model (Version: 14.4.2013). Moreover, we supply an aggregation routine which enables researchers to tailor the WIOD data depending on their needs. The corresponding ZIP file is available at www.zew.de/WIODAgg2013.

Chapter 3

Substitution elasticities in a CES framework: Empirical estimates using non-linear least squares

Abstract

Elasticities are key parameters for any economic analysis. Using the World Input-Output Database (WIOD), we estimate substitution elasticities for a three level nested CES KLEM production structure using up to date non-linear least squares estimation procedures. This allows us for the first time to use one coherent dataset for the estimation process. Furthermore, it gives us the opportunity to derive elasticities from the same data which researchers can use to calibrate their models. On the basis of our estimations, we demonstrate that the practice of using Cobb-Douglas or Leontief production functions in economic models must be rejected for the majority of sectors. We provide a comprehensive set of estimated substitution elasticities covering a wide range of sectors. Our results suggest that no substantial change in input substitutability takes place during the time period we consider. Moreover, there is no substantial variation in substitution elasticities across regions.

This chapter is based on the following paper:

Koesler, Simon and Michael Schymura (2015), Substitution Elasticities in a CES Framework - Empirical Estimates Using Non-Linear Least Squares, *Economic Systems Research* 27(1), 101-121.

3.1 Introduction

Elasticities are key parameters for any economic analysis. Ultimately, this results in the need for informed and reliable estimates of elasticities. In this paper we provide a comprehensive set of estimated elasticities covering a wide range of sectors. We focus on substitution elasticities as they are in most cases required by Computable General Equilibrium (CGE) models. However, in principle there exist a multitude of potential applications where our estimates could be used. Our main objective is twofold. First, we want to contribute to the existing literature by employing a coherent dataset with a balanced panel structure including a comprehensive sectoral and regional coverage, namely the new World Input-Output Database (WIOD) (Timmer et al., 2012; Dietzenbacher et al., 2013). Second, we apply an up to date estimation procedure in the form of non-linear least squares estimation.

For any policy-oriented numerical model, such as for example CGE models, elasticities are key parameters since they are crucial for determining comparative static behaviour and thereby strongly influence the results of any counterfactual policy analysis undertaken with the help of these models (Dawkins et al., 2001). A good illustration is provided by Jacoby et al. (2006), who perform a sensitivity analysis of structural parameters of their MIT-EPPA model. They conclude that assumptions with respect to technical progress and in particular elasticities of substitution between energy and value added are the main drivers of model results. Other crucial behavioural parameters are Armington elasticities of trade. Hertel et al. (2007) illustrate the problem by demonstrating that the choice of Armington elasticities can invert the predicted implications of free trade agreements. However, in this paper, we focus on substitution elasticities and leave the investigation of Armington elasticities to future research.

But despite the central role of elasticities within the framework of applied quantitative simulations, only few studies address the issue in depth and although this situation has been acknowledged for a long time (Mansur and Whalley, 1984; Dawkins et al., 2001), there still appears to be room for improvements. According to Okagawa and Ban (2008), this holds particularly true for the constant elasticity of substitution (CES) framework commonly employed in CGE modelling and substitution elasticities. In this context, few estimates of the required elasticities exist. Kemfert (1998) studies production structures and substitution elasticities within the German industry. Her findings suggest that substitution elasticities are positive but smaller than one. Balistreri et al. (2003) focus on the input substitutability between capital and labour and estimate the respective substitution elasticity for 28 US sectors. For the majority of sectors their results support the use of the Cobb-Douglas specification in the nest including capital and labour. Van der Werf (2008) supplies parameters for a set of two-level nested CES functions with capital, labour and energy inputs. His results do also imply that substitution elasticities are commonly smaller than one. Okagawa and Ban (2008) estimate CES production functions using panel data from the EU KLEMS dataset. They find that substitution elasticities for non-energy sectors are commonly set too high in existing models evaluating climate policy.

Due to the limited data availability, modellers frequently feel impelled to use elasticities from various unrelated sources. Thereby they expose themselves to criticism with respect to the use of potentially inconsistent parameter estimates. Another issue regarding the problematic use of elasticity estimates in models relates to the inappropriate use of elasticities and the conceptual mismatch between estimation results and the policy experiment explored in the modelling framework. McKitrick (1998) for example deplores the use of elasticities estimated for commodity classifications which are in disaccord with those represented in the model or for regions the model does not cover. In turn, Browning et al. (1999) highlight the difficulties possibly arising due to the mismatch of definitions, for instance the disregard of the differences between short-term and long-term substitution elasticities. In some extreme cases, when estimates are not available altogether, modellers even resort to the use of rather arbitrary values. In this regard Dawkins et al. (2001) most fittingly term the frequent use of elasticities of unity the 'idiot's law of elasticities' or the use of rather arbitrary values as 'coffee table elasticities'. Both the use of inappropriate estimates or 'coffee table elasticities' has resulted in skepticism regarding, for example, CGE modelling, especially from an econometric perspective (McKitrick, 1998).[1]

In this paper we seek to contribute to the solution to this problem and aim at supplying elasticities for modellers. To this end, we estimate substitution elasticities building on CES production functions as they are often employed in CGE models. More specifically, we estimate elasticities of substitution for the well-established three level nested KLEM production structure using non-linear least squares estimation procedures. In the process we take advantage of the new WIOD data Timmer et al. (2012); Dietzenbacher et al. (2013). The originality of our approach is that we combine a new dataset with recently developed estimation techniques for non-linear estimations of CES functions presented by Henningsen and Henningsen (2012). Furthermore, the new WIOD database allows us for the first time to use one coherent dataset for the estimation process and gives us the opportunity to derive elasticities from the same data, which researchers can use to calibrate their simulations.

The remainder of this paper is organised as follows. After presenting in Section 3.2 the production structures for which the elasticities of substitution are estimated, we describe the data and outline the estimation procedure in Section 3.3. The estimation results are presented and discussed in Section 3.4. Finally, we summarise and conclude in Section 3.5.

[1] If no generally accepted elasticities are employed, the validity of models should be tested ex-post on the basis of a validation approach (e.g. Kehoe et al., 1995). We thank an anonymous referee for suggesting such an approach.

3.2 Specification of production structures

A multitude of different elasticities define the substitutability between inputs. In the following section we introduce the underlying economic structure, for which we estimate elasticities. Constant Elasticity of Substitution (CES) functions have become very popular among modellers not only in general equilibrium models but also in other economic applications with a micro-consistent basis. There are three main reasons for this. First, in contrast to less restricted functions such as translog functions, CES functions feature convenient mathematical characteristics (regularity) allowing for easier analytical treatment (Böhringer et al., 2003). Second, they are sufficiently flexible to characterise a range of different economic behaviour (Böhringer et al., 2003; Sancho, 2009). Third, CES functions can be expressed in such a way that they can be easily be calibrated to benchmark values (Rutherford, 2002; Klump and Saam, 2008; Sancho, 2009).

The question to what extent factors of production are substitutable in a production process has long been an important focus of economic research. It originates in the fundamental work of Solow (1956). Solow considered three cases of production functions. He called the first 'Harrod-Domar' (Solow, 1956, p. 73) function with an elasticity of substitution equal to zero, the 'Cobb-Douglas' case (Solow, 1956, p. 76) with an elasticity of one and a third, not explicitly named possibility with a flexible elasticity (Solow, 1956, p. 77). Solow elaborated the idea of CES production functions for the first time, and, five years later, together with his co-authors (Arrow et al., 1961) he conceptualised the general form of the two-factor constant-elasticity-of-substitution (CES) production function (see e.g. Klump and De la Grandville (2000)). This CES production function can be seen as a generalisation of the two older concepts of the Harrod-Domar-Leontief production function, which is based on the assumption that there is no substitutability between factors, and the Cobb-Douglas production function, which assumes unitary factor substitution elasticity. Since the introduction of the CES production function in 1956, a multitude of extensive studies on the elasticities of substitution between production inputs have been published. One of the latest studies in this regard is the work of Léon-Ledesma et al. (2010), who investigate if a simultaneous identification of the capital-labour substitution elasticity and the direction of technical change is feasible.

For the n-input case the basic CES function takes the form:

$$y^{\text{CES n-input}} = \gamma \left(\sum_{i=1}^{n} \alpha_i x_i^{-\rho} \right)^{\frac{1}{-\rho}}, \tag{3.1}$$

where y is output, x_i is input i, α_i is the distribution parameter related to input i, γ represents a productivity parameter and ρ is the substitution parameter. Thereby the following conditions must hold: $0 \leq \alpha_i \leq 1$, $\sum_{i=1}^{n} \alpha_i = 1$, $\gamma \geq 0$ and $\rho \geq -1$. The elasticity of substitution σ is given by $\sigma = \frac{1}{1+\rho}$ and thus $\sigma \geq 0$ must also hold.

But in such a basic CES framework the production structure is limited to feature equal substitution elasticities between all inputs. To overcome this Sato (1967) extended the CES functional form and suggests the use of nested CES functions. The general idea behind Sato's approach is to construct a separate CES function for each group of inputs that share the same substitution elasticity and to combine different CES functions in different levels or nests of the overall CES function. This allows easy implementation even for complicated production structures and is one of the main advantages of the CES functional form. In this estimation exercise, we focus on estimating elasticity of substitutions for a three-level CES production representing the production structure with the final output Y and including the inputs capital (K), labour (L), energy (E) and intermediate inputs (M).[2] In addition, during our analysis we concentrate on a $((KL)\,E)\,M$ nesting structure. The $(KL)\,E$ structure has been confirmed as a good approximation of the production behaviour in several studies (e.g. Kemfert, 1998; van der Werf, 2008) and the extended version $((KL)\,E)\,M$ has become a very popular CES form in CGE models (e.g. Alexeeva-Talebi et al., 2012). Nevertheless, we are aware that a $((KL)\,E)\,M$, respectively KLEM, structure is not the only way incorporate capital, labour, energy and intermediate inputs in a CES production function (e.g. Lecca et al., 2011). But with regard to this paper, we leave the analysis of other specifications to future research. Following Sato (1967) and Henningsen and Henningsen (2011) with regard to the Hicks-neutral technological change, a three-level CES nesting structure with capital and labour in the lowest nest, where energy joins the capital-labour composite in the middle nest and intermediates enter in the top nest, has the functional form:

$$\begin{aligned} Y_t =& \gamma e^{t\lambda} \left(\alpha_{KLEM}(M_t)^{-\rho_{KLEM}} + (1-\alpha_{KLEM}) \left(\left(\alpha_{KLE}(E_t)^{-\rho_{KLE}} + \right.\right.\right. \\ & \left.\left.\left. (1-\alpha_{KLE})\,(VA_t)^{-\rho_{KLE}} \right)^{\frac{1}{-\rho_{KLE}}} \right)^{-\rho_{KLEM}} \right)^{\frac{1}{-\rho_{KLEM}}} \end{aligned} \tag{3.2}$$

with

$$VA_t = \left(\alpha_{KL}(K_t)^{-\rho_{KL}} + (1-\alpha_{KL})\,(L_t)^{-\rho_{KL}}\right)^{\frac{1}{-\rho_{KL}}}. \tag{3.3}$$

In both equations t is a time variable and λ is the rate of technological change with $\lambda \geq 0$. Moreover, Y is again final output, K is capital, L is labour, VA is value-added as a compound of capital and labour, E energy and M intermediate inputs. From Equations 3.2 and 3.3 one can already see, thanks to the characteristics of the CES functional form, a three-level CES function can be segmented into one two-level structure and one one-level structure which can be analysed separately if desired.

[2] Note, that we are not dependent of input prices due to the duality relationship of production functions and cost functions (c.f. Varian, 2010).

3.3 Data and estimation procedure

3.3.1 Data

For our analysis we make use of the World Input-Output Database (WIOD) (Timmer et al., 2012; Dietzenbacher et al., 2013).[3] Employing the WIOD dataset in our estimation process involves three main benefits. First, we can estimate substitution elasticities using one coherent dataset and do not have to merge potentially incompatible data. Second, the comprehensive sectoral coverage of WIOD allows us to estimate substitution elasticities for a broad set of sectors. Finally, for the first time, we can derive elasticities from the same data which other researchers can use to calibrate their simulations.

The WIOD database has been constructed on the basis of national accounts data and harmonisation procedures were applied in order to ensure international comparability. The dataset covers 40 countries (27 EU countries and 13 other major regions), which together account for approximately 85 % of world's GDP in 2006. The WIOD data is disaggregated in 35 industries and provides detailed information on primary (agriculture and raw materials), secondary (manufacturing) as well as tertiary (services) sectors. In addition, it offers annual data which range from 1995 to 2009, in some cases to 2011. Beside its broad regional coverage, detailed sectoral disaggregation and time series character, the dataset has another important feature: it covers various aspects of economic activity and involves accounts for energy and environmental issues, socioeconomic factors, and bilateral trade data. For more information in the WIOD dataset, the interested reader is kindly referred to Timmer et al. (2012) and Dietzenbacher et al. (2013).

In our analysis, we use the WIOD Socio-Economic Accounts (SEA files) and the WIOD Energy Use tables (EU files). Taken together, they form a balanced panel covering 40 regions and 34 sectors plus an economy-wide sector aggregate over a period of 15 years (1995 to 2009) and include detailed information on production in- and outputs.[4] More specifically WIOD supplies us with data regarding the number of total hours worked by persons engaged for the independent variable labour L, physical capital stock for the independent variable K , gross value added at basic prices for the independent variable value added VA, intermediate inputs at purchasers' prices for the independent variable materials M, gross energy use for the independent variable energy E and finally gross output at basic prices for the dependent variable output Y. Even though WIOD provides the necessary data up to the year 2009, in order to avoid drawing conclusions from a period of economic turmoil we drop the years 2008 and 2009 from our analysis and focus on the period from 1995 to 2007. For the estimation, all monetary values have been transformed to 1995-US Dollars using the exchange rates provided in WIOD and are reported at 1995 prices. Energy is measured in Terajoule. Labour is given in million

[3]The WIOD database is available at http://www.wiod.org. We use data from March 2012 in this paper.

[4]While originally the WIOD dataset features information for 35 sectors, entries for the sector private households with employed persons remain empty in the SEA and EU files. Consequently we undertake the analysis only for the 34 remaining sectors plus the economy-wide sector total.

Table 3.1: List of variables used in the estimation process

Variable	Short	Definition	File	Unit
Output	Y	Gross output at basic prices	SEA	million 1995 USD
Capital	K	Fixed capital stock	SEA	million 1995 USD
Labour	L	Total hours worked by persons engaged	SEA	million hours
Value Added	VA	Gross value added at basic prices	SEA	million 1995 USD
Energy	E	Gross energy use	EU	Terajouls
Materials	M	Intermediate inputs at purchasers' prices	SEA	million 1995 USD

Table 3.2: Descriptive statistics

Variable	Short	Mean	Std. Dev.	Min.	Max.
Output	Y	89776.3	653518.5	0.00	2.57e+07
Capital	K	141423.7	1056758.0	0.04	3.02e+07
Labour	L	2270.3	16497.5	0.00	468780.9
Value Added	VA	45086.2	349024.7	0.00	1.40e+07
Energy	E	660332.3	4649308.0	0.01	1.33e+08
Materials	M	43330.9	278077.5	0.00	8992552

hours worked. Table 3.1 provides an overview of the variables used in the estimation process and Table 3.2 presents the descriptive statistics. Overall, all variables are more or less of comparable magnitude and we expect not to have problems with floating-point numbers in our estimation process. A complete list of regions and sectors covered by this analysis is given in the Appendix.

3.3.2 Estimation procedure

The elasticity estimates available in the literature have been produced using different estimation approaches. In this paper we rely on non-linear least squares estimation procedures. Nested CES functions feature additive components and are non-linear in parameters; hence, parameters can initially not be estimated using standard non-linear estimation techniques. For this reason and due to the so far rather tedious implementation of non-linear estimation procedures (Henningsen and Henningsen, 2012), most researchers estimating elasticities of substitution within a CES framework work with CES functions that have been linearised in some form or the other. Thereby, the so-called Kmenta approximation (Kmenta, 1967) has been very popular. However, the original CES function cannot be linarised analytically and using approximation methods to linearise the CES function can have drawbacks. Kmenta (1967) himself notes that if in the production function under investigation the input ratio as well as the elasticity of substitution are either very high or very low, his approximation method may not perform well. Maddala and Kadane (1967) and Thursby and Lovell (1978) confirm this problem and show that the standard Kmenta procedure may not lead to reliable estimates of parameters in a CES framework.

To avoid issues related to Kmenta approximations or linear estimation approaches in general without having to use cumbersome non-linear estimation procedures, researchers also make use of the cost function approach (e.g. van der Werf, 2008; Okagawa and Ban, 2008). Thereby one can take advantage of the optimal cost function associated with a specific production function and derive a linear system of equations from the corresponding optimal input demand. This can subsequently be used to estimate the function coefficients in question. But this approach requires comprehensive price data, which in most cases is rather difficult to come by, especially when undertaking sector specific analysis.

In contrast to the majority of other studies investigating the substitutability of inputs within a CES production structure, we estimate substitution elasticities directly from the CES production function and build on non-linear least-squares estimation procedures as outlined by Henningsen and Henningsen (2012). As suggested by Henningsen and Henningsen, we make use of starting values compiled by means of a preceding grid search for the substitution parameter ρ.[5] For the grid search, we employ the Levenberg-Marquardt algorithm (LM) (Marquardt, 1963). For the estimations we rely on PORT routines (Gay, 1990) which take longer but in contrast to LM allow us to run unrestricted as well as restricted estimations.

For the actual estimation process we use the programming environment R with the package micEconCES developed by Henningsen and Henningsen (2011). Besides allowing for a convenient implementation of our estimation approach, the work of Henningsen and Henningsen enables us to overcome the main issues when estimating the non-linear CES functions outlined by Henningsen and Henningsen (2012). The micEconCES package in its current version only allows estimation of parameters for a two-level nested CES production function. To overcome this minor limitation, we benefit from the separability implied by the CES framework and split the originally three-level nested KLEM CES function into two individual CES functions. Accordingly we estimate the substitution elasticities for the non-nested CES function

$$VA_t = \gamma_{KL} e^{t\lambda_{KL}} \left(\alpha_{KL} (K_t)^{-\rho_{KL}} + (1 - \alpha_{KL}) (L_t)^{-\rho_{KL}} \right)^{\frac{1}{-\rho_{KL}}}, \tag{3.4}$$

with the substitution elasticity $\sigma_{KL} = \frac{1}{1+\rho_{KL}}$ and do the same for the two-level CES

[5]For more information on how adequate starting values are derived applying a preceding grid search, the interested reader is kindly referred to Henningsen and Henningsen (2011). To check for sensitivity with regard to starting values, we run the estimation twice, once with standard starting values given by Henningsen and Henningsen (2011) and once with the starting values indicated by a grid search. This admittedly limited sensitivity analysis suggests that the results do not depend on the choice of the to starting values - although it does influence the rate of convergence, which is higher in the case of starting values from a preceding grid search. Thus we proceed as suggested by Henningsen and Henningsen (2012).

function

$$Y_t = \gamma_{KLEM} e^{t\lambda_{KLEM}} \left(\alpha_{KLEM}(M_t)^{-\rho_{KLEM}} + (1-\alpha_{KLEM}) \left(\left(\alpha_{KLE}(E_t)^{-\rho_{KLE}} + (1-\alpha_{KLE})\left(VA_t\right)^{-\rho_{KLE}}\right)^{\frac{1}{-\rho_{KLE}}}\right)^{-\rho_{KLEM}}\right)^{\frac{1}{-\rho_{KLEM}}}, \tag{3.5}$$

with the substitution elasticities $\sigma_{KLE} = \frac{1}{1+\rho_{KLE}}$ and $\sigma_{KLEM} = \frac{1}{1+\rho_{KLEM}}$. Taken together, Equation (3.4) and Equation (3.5) represent the overall CES function in question, whereas, as already indicated by Equation (3.2), Equation (3.4) is the bottom nest and Equation (3.5) corresponds to the middle and upper nests of the production function under investigation. We choose to split the original CES function into these two functions instead of applying other possible segmentations, because, although we have data for K, L, VA, E, M and Y, we do not have information on the value-added-energy composite. Hence we can not analyse a single level CES function combining materials and the value-added-energy composite.

We however deviate from Henningsen and Henningsen (2011) at one point and calculate the estimated variation of the residuals ($\widehat{VAR}$) by:

$$\widehat{VAR} = \frac{1}{N-k} \sum_{i=1}^{N} u_i^2, \tag{3.6}$$

where N is the number of observations, k is the number of estimated coefficients and u_i is the residual of the i-th observation. That is, in contrast to Henningsen and Henningsen (2011), we correct for the degrees of freedom.

The substitution elasticities are estimated individually for each of the 34 sectors and one sector aggregate representing the total of all industries available in the WIOD dataset. Thereby, we first pool all sectoral data across all regions. At a later stage we evaluate whether input substitutability varies across regions. As indicated by Equation (3.4) and (3.5), initially we assume that elasticities are constant over time. Hence, in our setting technological progress can only take place through changes in overall productivity. This assumption is relaxed at a later stage.

3.4 Estimation results

3.4.1 Basic results of estimations

Having described the data and the estimation procedure, we now turn to the empirical implementation and present our results. In the unrestricted estimation, for several sectors the estimated substitution elasticities on the three different nests are negative ($\sigma_{KL} < 0$, $\sigma_{KLE} < 0$ or $\sigma KLEM < 0$) and thus violate the basic assumptions of the standard CES framework which requires positive elasticities ($\sigma \geq 0$ respectively $\rho \geq -1$). These violations indicate the need to incorporate the three parameter constraints implied by the CES framework into our estimations, i.e. a positive productivity parameter

($\gamma > 0$), distributional parameters between zero and one ($0 \geq \alpha \geq 1$) and positive substitution elasticities ($\sigma \geq 0$). Table 3.3 summarises the results for the substitution elasticities σ when applying the restricted estimation to the time period 1995 to 2007 with pooled data including all regions.

We do not achieve convergence for the bottom nest of sector 23 (coke, refined petroleum and nuclear fuel) for any acceptable convergence criteria and do not report a value for the parameter controlling the substitutability between capital and labour (ρ_{KL}). Moreover, some of the estimates for substitution elasticities (σ) feature high standard errors, these estimates are reported in parentheses. For six out of the 105 estimated elasticities, the condition that $\sigma \geq 0$ is binding, which results in a reported estimated elasticity of Inf. This could be an indication that, for a small set of sectors, the assumption of CES production structures provides a poor fit to the actual prevailing production structure. However, for the large majority of sectors and nests our estimation results seem to be reliable with regard to fit to the data and standard errors, and as the use of of CES functions has proven to be very popular in particular in CGE models, we proceed with our estimation process and continue including the constraints on productivity, distribution parameters and substitution elasticities given by the CES framework.

With few exceptions, most estimated substitution elasticities are smaller than one. Sectors featuring a comparatively high substitutability between capital and labour include 61 (water transport), 64 (post and telecommunication) and AtB (agriculture, hunting, forestry and fishing). Sectors 52 (retail trade and repair of household goods) and H (hotels and restaurants) find it rather difficult to use this substitution possibility. Value-added and energy can be substituted relatively easily in sectors 27t28 (basic and fabricated metal), 30t33 (electrical and optical equipment) and 61 (water transport). The opposite seems to be true, for example, for sectors J (financial intermediation) and M (education). A relatively high substitution elasticity between the value-added-energy composite and intermediate inputs can be reported for M (education), 62 (air transport) and AtB (agriculture, hunting, forestry and fishing). A low substitutability in this nest is observed in the sectors 27t28 (basic and fabricated metal), C (mining and quarrying) and 60 (inland transport). When comparing the substitutability of inputs across different nests, our results suggest that, while capital and labour tend to be more difficult to substitute with each other than value-added and energy, the value-added-energy composite can be substituted with intermediate inputs relatively easily.

3.4.2 Cobb-Douglas or Leontief production structure

Given our estimates, we continue and investigate whether the common simplification of using Cobb-Douglas or Leontief functions in economic models can be rejected by our estimation results. On that account, we make use of a Lagrange-multiplier test and benefit from the high number of observations which allows us to assume that our data has a normal distribution. For all three nests the assumption of a Cobb-Douglas function

Table 3.3: Estimation results for σ (restricted PORT routine with starting values, 1995-2007, all regions)

Sector	NACE Code	N	σ_{KL}-Est.	Std. Error	σ_{KLE}-Est.	Std. Error	σ_{KLEM}-Est.	Std. Error
Agriculture, hunting, forestry and fishing	AtB	520	1.07	0.08	0.40	0.10	0.98	0.08
Mining and quarrying	C	521	0.79	0.08	(0.42)	> 10	0.22	0.04
Food, beverages and tobacco	15t16	522	0.22	0.06	0.19	0.21	0.63	0.11
Textiles and textile	17t18	523	0.10	0.05	0.28	0.07	0.59	0.04
Leather, leather and footwear	19	524	Inf	NA	0.19	0.04	0.56	0.03
Wood and products of wood and cork	20	525	0.12	0.07	0.21	0.06	0.71	0.08
Pulp, paper. paper. printing and publishing	21t22	526	0.12	0.04	0.25	0.10	0.66	0.08
Coke, refined petroleum and nuclear fuel	23	527	NA		Inf	NA	0.42	0.05
Chemicals and chemical	24	528	0.24	0.03	0.72	0.11	0.94	0.23
Rubber and plastics	25	529	0.12	0.03	0.18	0.02	0.68	0.06
Other non-metallic mineral	26	530	0.20	0.04	0.25	0.16	0.81	0.07
Basic metals and fabricated metal	27t28	531	0.18	0.04	1.01	0.14	0.11	0.01
Machinery, nec	29	532	0.48	0.03	0.20	0.05	0.55	0.06
Electrical and optical equipment	30t33	533	0.10	0.10	1.06	0.10	(0.64)	> 10
Transport equipment	34t35	534	0.18	0.03	0.16	0.10	0.38	0.04
Manufacturing nec; recycling	36t37	535	0.23	0.03	0.18	0.06	0.53	0.04
Electricity, gas and water supply	E	536	Inf	NA	0.46	0.05	0.68	0.06
Construction	F	537	0.17	0.03	0.15	0.30	0.61	0.08
Sale. maintenance and repair of vehicles; sale of fuel	50	538	Inf	NA	0.15	0.22	0.60	0.05
Wholesale trade and commission trade	51	539	0.10	0.03	0.24	0.15	0.44	0.02
Retail trade; repair of household goods	52	540	0.06	0.03	0.24	0.09	0.78	0.05
Hotels and restaurants	H	541	0.08	0.02	0.22	0.11	0.63	0.06
Inland transport	60	542	0.14	0.02	0.42	0.61	0.22	0.02
Water transport	61	543	3.36	1.38	1.27	0.14	0.45	0.06
Air transport	62	544	0.24	0.06	0.37	0.08	1.03	0.09
Supporting and auxiliary transport activities	63	545	0.26	0.03	0.39	0.04	0.58	0.01
Post and telecommunications	64	546	2.39	1.58	0.15	0.38	0.68	0.23
Financial intermediation	J	547	0.18	0.04	0.09	0.12	0.52	0.10
Real estate activities	70	548	0.31	0.03	0.68	0.05	(0.84)	> 10
Renting of m&eq and other business activities	71t74	549	0.25	0.02	0.18	0.04	0.63	0.09
Public admin and defence; compulsory social security	L	550	0.18	0.04	0.50	0.05	Inf	NA
Education	M	551	Inf	NA	0.13	0.08	1.01	0.08
Health and social work	N	552	0.58	0.04	0.16	0.07	0.80	0.05
Other community. social and personal services	O	553	0.17	0.08	0.21	1.07	0.67	0.11
Total industries	TOT	554	0.13	0.02	0.38	0.06	1.15	0.25

($\sigma_{KL} = 1$, $\sigma_{KLE} = 1$ or $\sigma_{KLEM} = 1$) can be dismissed with acceptable validity levels (p-value > 0.1) for almost all sectors. Hence we can confirm the findings by van der Werf (2008). A similar picture emerges for the assumption of a Leontief functional form ($\sigma_{KL} = 0$, $\sigma_{KLE} = 0$ or $\sigma_{KLEM} = 0$). To be exact, in the bottom nest the Leontief and the Cobb-Douglas framework must be rejected for the all sectors. While in the middle nest the assumption of a Leontief-like production structure can not be discarded for sector C (mining and quarrying), a Cobb-Douglas production function can not be excluded in sectors C (mining and quarrying) and 27t28 (basic metals and fabricated metal). A Leontief framework in the top nest can be rejected for all sectors except sectors 30t33 (electrical and optical equipment) and 70 (real estate activities). The same hold true for a Cobb-Douglas production structure. Overall, this strongly suggests that a simplified approach to the choice of substitution elasticities including only Cobb-Douglas or Leontief production functions is not appropriate and will eventually lead to misleading results of any counterfactual analysis. This clearly emphasises the need for appropriately estimated behavioural parameters.

3.4.3 Comparison with previous studies

With our estimates we contribute to the existing literature on substitution elasticities. We compare the result of our estimations to the findings of Okagawa and Ban (2008), van der Werf (2008) and Kemfert (1998). We focus on these three papers as they are very popular among CGE modellers. At the same time we are aware of the critique that has been stated in relation to these studies (e.g. Henningsen and Henningsen (2011)). Table 3.4 summarises the comparison. However, it must be noted that for several reasons a direct comparison of the results is difficult. First, none of the studies exploits the same data. But, as Okagawa and Ban (2008), van der Werf (2008) as well as Kemfert (1998) use rather similar data and variables, these issues do not immediately suggest themselves as the main reasons for the deviations. Second, all researchers undertake estimations for a different set of sectors. Hence their findings can only be compared on the basis of a specific (possibly arbitrary) sectoral mapping. Third, Okagawa and Ban (2008) as well as Kemfert (1998) do not supply information on the standard error of their results. Fourth, the studies employ different estimation techniques. In effect, while Okagawa and Ban (2008) and van der Werf (2008) estimate substitution elasticities using linear estimation processes and apply a cost function approach, the elasticities derived in this paper stem from a non-linear estimation process using the original functional form of a CES production function. Only Kemfert (1998) applies also a non-linear estimation to the problem. As a consequence, we can not truly test whether our results differ from the findings of other frequently cited studies. Nevertheless, keeping this in mind and being aware of the standard errors of our own estimation, we observe that overall our estimates for the substitution elasticities σ_{KL}, σ_{KLE} and σ_{KLEM} are neither consistently higher nor smaller than the ones supplied by Okagawa and Ban. With few exceptions, compared to the elasticities derived by van der Werf (2008) or Kemfert (1998), our estimates tend to be smaller.

3.4.4 Changes in substitution elasticities over time

The time series character of our data allows us to engage in an additional analysis and makes it possible to investigate whether substitution elasticities change over time. In the economic literature, technological progress within the CES framework is mainly understood as a change in input productivity, and researchers focus primarily on determining the rate of technological change in the form of a general (neutral) or factor augmenting (non-neutral) productivity increase. But in principle the CES framework leaves room for technological change affecting not only productivity but also the substitutability between different production inputs. The textile industry at the end of the 18th century provides an excellent example of this form of technological change. As looms became more and more advanced, human labour could be replaced more easily in the production process ('Spinning Jenny Effect'). Eventually this had a huge effect on business and society in that period (Allen, 2009). A modified CES function that takes into account changes of the substitution parameter over time and incorporates Hicks-neutral technological change takes the form:

$$y^{\text{CES neutral time-dependent}} = \gamma e^{t\lambda} \left(\sum_i \alpha_i (x_i)^{-\rho_t} \right)^{\frac{1}{-\rho_t}} . \qquad (3.7)$$

Unfortunately, our non-linear estimation structure does not allow direct estimates of time fixed effects. Instead, we embark on a simple approach and test whether we can observe a change in input substitutability over time by reestimating Equations (3.4) and (3.5) and comparing the estimated elasticities for two different time periods (1995 to 1997 and 2005 to 2007). Table 3.5 summarises the results. Note that for some sectors convergence or CES constraint issues arise when using a constraint time period, the respective sectors are marked with an NA value. Again, blanks indicate that the null hypothesis can not be rejected at an acceptable level (p-value > 0.1). In the bottom, middle nest and top nest, the hypothesis that the substitution elasticities do not change over time can be rejected at an acceptable level (p-value < 0.1) for about two thirds of the sectors under investigation. When evaluating a less stringent comparison between the two periods, the picture becomes even clearer, and we can reject an economically substantial change in input substitutability for all but a handful of sectors.[6] To allow for a more detailed analysis investigating of whether there have been any structural changes of the substitution elasticities over time, we split the results in five groups depending on the evaluated sector, namely Basic Materials, Energy, Manufacturing, Services and Transport, the underlying mapping is outlined in Table B.2 in the Appendix. But

[6] To make the issue tangible, we assume that an economically substantial change would imply substitution elasticities changing by more than one. That is $|\sigma_{95-97} - \sigma_{05-07}| > 1$. In the special illustrative case that $\sigma_{95-97} = 0$ and $\sigma_{05-07} = 1$, this would imply a production structure changing from Leontief to Cobb Douglas.

Table 3.4: Comparison of results, OB: Okagawa and Ban (2008), W: van der Werf (2008), K: Kemfert (1998)

				σ_{KL}-Est				σ_{KLE}-Est				σ_{KLEM}-Est	
Sector	O	W	K	Own	O	W	K	Own	O	W	K	Own	O
Agriculture, hunting, forestry and fishing	AGR			1.07	0.02			0.40	0.52			0.98	0.39
Mining and quarrying	MIN		Stone and earth	0.79	0.14		0.21	0.42	0.55		0.56	0.22	0.73
Food, beverages and tobacco	FOO	Food and tob.	Food	0.22	0.38	0.46	0.66	0.19	0.40	0.40	0.78	0.63	0.33
Textiles and textile	TEX	Textiles etc.		0.10	0.16	0.27		0.28	0.64	0.29		0.59	0.72
Leather, leather and footwear				(Inf)				0.19				0.56	
Wood and products of wood and cork	WOO			0.12	0.09			0.21	0.46			0.71	0.70
Pulp, paper, printing and publishing	PPP	Paper etc.	Paper	0.12	0.38	0.41	0.35	0.25	0.21	0.45	0.73	0.66	0.19
Coke, refined petroleum and nuclear fuel				NA				(Inf)				0.42	
Chemicals and chemical	CHM		Chemical industry	0.24	0.33		0.37	0.72	-0.07		0.97	0.94	0.85
Rubber and plastics				0.12				0.18				0.68	
Other non-metallic mineral	NMM	Non-metallic minerals		0.20	0.36	0.45		0.25	0.41	0.25		0.81	0.31
Basic metals and fabricated metal	BME	Basis metals	Iron	0.18	0.22	0.62	0.50	1.01	0.64	0.65	0.4	0.11	1.17
Machinery, nec	MAC			0.48	0.30			0.20	0.29			0.55	0.13
Electrical and optical equipment	EEQ			0.10	0.16			1.06	0.52			0.64	0.88
Transport equipment	TEQ	Transport eq.	Vehicle	0.18	0.14	0.46	0.10	0.16	0.52	0.17	0.35	0.38	0.55
Manufacturing nec; recycling	MAN			0.23	0.05			0.18	0.53			0.53	0.41
Electricity, gas and water supply	EGW			(Inf)	0.46			0.46	0.26			0.68	-0.04
Construction	CON	Construction		0.17	0.07	0.22		0.15	0.53	0.29		0.61	1.26
Sale, maintenance and repair													
of vehicles; sale of fuel				(Inf)				0.15				0.60	
Wholesale trade and commission trade				0.10				0.24				0.44	
Retail trade; repair of household goods				0.06				0.24				0.78	
Hotels and restaurants				0.08				0.22				0.63	
Inland transport	TRN			0.14	0.31			0.42	0.28			0.22	0.35
Water transport	TRN			3.36	0.31			1.27	0.28			0.45	0.35
Air transport	TRN			0.24	0.31			0.37	0.28			1.03	0.35
Supporting and auxiliary transport activities	TRN			0.26	0.31			0.39	0.28			0.58	0.35
Post and telecommunications	TEL			2.39	0.37			0.15	0.52			0.68	0.65
Financial intermediation	FBS			0.18	0.26			0.09	0.32			0.52	0.49
Real estate activities				0.31				0.68				0.84	
Renting of m&eq and other business activities				0.25				0.18				0.63	
Public admin and defence; compulsory social security				0.18				0.50				(Inf)	
Education				(Inf)				0.13				1.01	
Health and social work				0.58				0.16				0.80	
Other community, social and personal services	PSE			0.17	0.32			0.21	0.78			0.67	0.90
Total industries				0.13				0.38				1.15	

even when investigating only specific sectors groups, we do not observe any substantial changes over time. Moreover, for all sector groups, the hypothesis that there has been an increase in elasticities has to be rejected equally often as the hypothesis that elasticities have decreased. Hence, our results suggest that there has been no structural change in elasticities over time. One possible explanation for this could for instance be a 'putty-clay' structure of the physical capital stock which adjusts only slowly and hence elasticities are not affected in the short run (Fuss, 1997). This implies also that changing substitution elasticities are not a problem for our estimations, which originally consider the complete time period between 1995 to 2007. But nevertheless, the issue is potentially important. As a consequence, in future research this particular dimension of technological progress needs to be taken into account and should be investigated with more rigour. Ultimately this will require studying longer time periods as those under investigation so far in studies on the substitutability of inputs and also a formalisation of the issue within the CES framework.

3.4.5 Differences of substitution elasticities between regions

Having investigated the variability of input substitutability over time, we next evaluate whether there are differences of elasticities between regions. Again, as our estimation process does not allow to directly estimate regional fixed effects, we apply a similar approach as before and compare estimates for different regions with each other to test for regional variation. Here we only present the results of a comparison between the estimates for the EU27 and the BRIC countries (Brazil, Russia, India and China). A similar picture emerges when contrasting the results for regions with a high productivity to those featuring a relatively low productivity.[7] Table 3.6 compares the results for the EU27 with those for BRIC. Again, we do not achieve convergence for the bottom nest of sector 23 (coke, refined petroleum and nuclear fuel) and in particular in the bottom nest several estimates are driven by the constraints of the CES framework. These estimates are marked with NAs. Once more, blank elements in the table indicate that the null hypothesis can not be rejected at an acceptable level (p-value > 0.1). For all three nests, there is no substantial difference in input substitutability between regions for the large majority of sectors. Only for the groups associated with service and manufacturing activities in the BRIC countries, we can not reject a higher input substitutability between the capital-labour-energy composite and materials compared to estimates for the EU for a fair number of sectors. For the other two nests and sector groups, one can not conclude that elasticities are higher or lower in the EU compared to the BRIC countries, and vice versa. Hence, there appears to be no regional variation in elasticities of substitution.

[7] For this analysis, we rank the regions under investigation according to their score in the index GDP per person employed (constant 1990 PPP USD) from the World Bank.

Table 3.5: Comparison of the substitution elasticities for the periods 1995-1997 and 2005-2007

NACE Code	H0 for σ_{KL}-Est.: $\sigma_{95-97} \leq \sigma_{05-07}$	$\sigma_{95-97} \geq \sigma_{05-07}$	$\lvert\sigma_{95-97} - \sigma_{05-07}\rvert > 1$	H0 for σ_{KLE}-Est.: $\sigma_{95-97} \leq \sigma_{05-07}$	$\sigma_{95-97} \geq \sigma_{05-07}$	$\lvert\sigma_{95-97} - \sigma_{05-07}\rvert > 1$	H0 for σ_{KLEM}-Est.: $\sigma_{95-97} \leq \sigma_{05-07}$	$\sigma_{95-97} \geq \sigma_{05-07}$	$\lvert\sigma_{95-97} - \sigma_{05-07}\rvert > 1$
AtB	< 0.01		< 0.01		< 0.01	< 0.01		< 0.1	< 0.01
C		< 0.01	< 0.01				< 0.01		< 0.01
15t16			< 0.01			< 0.01			< 0.01
17t18			< 0.01	< 0.01		< 0.01		< 0.01	< 0.01
19	NA	NA	NA	NA	NA	NA	NA	NA	NA
20			< 0.01			< 0.01		< 0.01	< 0.01
21t22	< 0.05		< 0.01			< 0.01	< 0.01		< 0.01
23	NA	NA	NA	NA	NA	NA	< 0.01		< 0.01
24	< 0.1		< 0.01		< 0.01	< 0.01		< 0.01	< 0.01
25			< 0.01			< 0.01		< 0.01	< 0.01
26		< 0.01	< 0.01	< 0.01		< 0.01			< 0.01
27t28		< 0.05	< 0.01		< 0.01	< 0.01	< 0.01		< 0.01
29		< 0.01	< 0.01		< 0.01	< 0.01	< 0.01		< 0.01
30t33			< 0.01	< 0.05		< 0.05			
34t35			< 0.01			< 0.01			< 0.01
36t37	< 0.01		< 0.01	< 0.01		< 0.01		< 0.01	< 0.01
E	NA	NA	NA	< 0.01		< 0.01			< 0.01
F		< 0.01	< 0.01			< 0.01	< 0.05		< 0.01
50	NA	NA	NA			< 0.01	< 0.05		< 0.01
51			< 0.01			< 0.01	< 0.01		< 0.01
52		< 0.01	< 0.01	< 0.01		< 0.01	< 0.05		< 0.01
H	< 0.01		< 0.01	< 0.01		< 0.01		< 0.01	< 0.01
60		< 0.01	< 0.01			< 0.01	< 0.01		< 0.01
61				< 0.01		< 0.01		< 0.01	< 0.01
62	< 0.01		< 0.01	< 0.01		< 0.01		< 0.01	< 0.01
63	< 0.01		< 0.01		< 0.01	< 0.01	< 0.01		< 0.01
64									< 0.01
J	< 0.01		< 0.01			< 0.01		< 0.01	< 0.01
70		< 0.01	< 0.01	< 0.01		< 0.01			
71t74	< 0.05		< 0.01	< 0.01		< 0.01	< 0.01		< 0.01
L	< 0.01		< 0.01		< 0.05	< 0.01	< 0.01		< 0.01
M	NA	NA	NA		< 0.01	< 0.01	< 0.01		< 0.01
N	< 0.01		< 0.01			< 0.01		< 0.05	< 0.01
O			< 0.01			< 0.1		< 0.05	< 0.01
TOT	< 0.01		< 0.01		< 0.01	< 0.01		< 0.01	< 0.01

Table 3.6: Comparison of the substitution elasticities for the regions EU and BRIC

NACE Code	H0 for σ_{KL}-Est.: $\sigma_{EU} \leq \sigma_{BRIC}$	$\sigma_{EU} \geq \sigma_{BRIC}$	$\lvert\sigma_{EU} - \sigma_{BRIC}\rvert > 1$	H0 for σ_{KLE}-Est.: $\sigma_{EU} \leq \sigma_{BRIC}$	$\sigma_{EU} \geq \sigma_{BRIC}$	$\lvert\sigma_{EU} - \sigma_{BRIC}\rvert > 1$	H0 for σ_{KLEM}-Est.: $\sigma_{EU} \leq \sigma_{BRIC}$	$\sigma_{EU} \geq \sigma_{BRIC}$	$\lvert\sigma_{EU} - \sigma_{BRIC}\rvert > 1$
AtB	< 0.01		< 0.01		< 0.01	< 0.01		< 0.01	< 0.01
C	< 0.01		< 0.01			< 0.01		< 0.01	< 0.01
15t16	< 0.01		< 0.01			< 0.05			< 0.01
17t18			< 0.01		< 0.05	< 0.01		< 0.01	< 0.01
19	< 0.01		< 0.01			< 0.01	< 0.01		< 0.01
20		< 0.01	< 0.01		< 0.05	< 0.01	< 0.01		< 0.01
21t22	NA	NA	NA		< 0.01	< 0.01		< 0.01	< 0.01
23	NA	NA	NA					< 0.01	< 0.01
24	NA	NA	NA		< 0.01	< 0.01		< 0.01	< 0.01
25	NA	NA	NA			< 0.01	< 0.01		< 0.01
26						< 0.01		< 0.05	< 0.01
27t28		< 0.01	< 0.01					< 0.01	< 0.01
29		< 0.01	< 0.01						< 0.01
30t33	NA	NA	NA					< 0.01	< 0.01
34t35	NA	NA	NA			< 0.01		< 0.01	< 0.01
36t37		< 0.01	< 0.01			< 0.01		< 0.01	< 0.01
E	NA	NA	NA			< 0.05			< 0.01
F		< 0.01	< 0.01		< 0.05	< 0.01			< 0.01
50		< 0.01	< 0.01		< 0.01	< 0.01	< 0.01		< 0.01
51	NA	NA	NA			< 0.01		< 0.01	< 0.01
52	< 0.01		< 0.01	< 0.01		< 0.01		< 0.01	< 0.01
H	NA	NA	NA		< 0.1	< 0.01		< 0.01	< 0.01
60	< 0.01		< 0.01						< 0.01
61	NA	NA	NA	NA	NA	NA			< 0.05
62	< 0.01		< 0.01	NA	NA	NA			
63	< 0.01		< 0.01		< 0.01	< 0.01		< 0.01	< 0.01
64	NA	NA	NA			< 0.01		< 0.01	< 0.01
J	< 0.01		< 0.01	< 0.1		< 0.01		< 0.01	< 0.01
70		< 0.01	< 0.01		< 0.01	< 0.01			
71t74		< 0.01	< 0.01			< 0.01	< 0.05		< 0.01
L	NA	NA	NA		< 0.01	< 0.01		< 0.01	< 0.01
M	< 0.01		< 0.01		< 0.01	< 0.01			< 0.01
N		< 0.01	< 0.01	< 0.05		< 0.01	< 0.01		< 0.01
O	NA	NA	NA		< 0.01	< 0.01	< 0.01		< 0.01
TOT	< 0.01		< 0.01			< 0.05			< 0.01

3.5 Summary and conclusion

Elasticities, in particular substitution elasticities, are vital parameters for any micro-consistent economic model and crucially influence the results of any economic analysis. But so far only few estimates of elasticities exist which rely on a consistent database. With this paper we aim at overcoming this problem. Building on a coherent data set based on WIOD data, we systematically investigate input substitutability in a CES production framework for a KLEM production structure using non-linear estimation procedures.

On the basis of our estimations, we confirm the findings by van der Werf (2008) and demonstrate that the common practice of using Cobb-Douglas or Leontief production functions in economic models must be rejected for the majority of sectors. This calls for a more elaborate approach with regard to substitution elasticities. In particular in response to this result, we provide a comprehensive set of estimated substitution elasticities covering a wide range of sectors. Our results suggest that no economically substantial change in input substitutability takes place during the time period we consider. Hence, for most sectors we do not observe technological change through this channel, although technological progress in the form of changing substitution elasticities may potentially be an issue when studying longer time periods. Moreover, there is no substantial regional variation in substitution elasticities. By providing an exhaustive set of substitution elasticities and with our analysis of input substitutability over time and between regions, we hope to make a valuable contribution to making economic analyses more reliable and to support researchers as well as policy makers in their efforts to find solutions for today's challenges.

With regard to how the research presented here could be developed in the future, we believe that applying the approach used in this paper to production setups other than KLEM or for example Armington elasticities can unlock further insights on behaviourial parameters. Moreover, a validation exercise studying different assumptions on the substitutability of production inputs could be used to evaluate our estimates in a modelling framework.

Chapter 4

Specifying parameters in CGE models using Optimal Fingerprint Detection Methods

Abstract

The specification of parameters is a crucial task in the development of economic models. The objective of this paper is to improve the standard parameter specification of computable general equilibrium (CGE) models. On that account, we illustrate how Optimal Fingerprint Detection Methods can be used to identify appropriate values for various parameters. This method originates from climate science and combines a simple model validation exercise with a structured sensitivity analysis. The new approach has various benefits: 1) It uses a structured optimisation procedure and does not revert to ad-hoc model improvements. 2) It allows to account for uncertainty in parameter estimates by using information on the distribution of parameter estimates from the literature. 3) It can be applied for the specification of a range of parameters required in CGE models, for example for the definition of elasticities or productivity growth rates.

This chapter is based on the following papers:

Koesler, Simon (2014), Specifying Parameters in Computable General Equilibrium Models using Optimal Fingerprint Detection Methods, ZEW Discussion Paper No. 14-092, Mannheim, Germany.

Koesler, Simon (2015), Specifying Parameters in Computable General Equilibrium Models using Optimal Fingerprint Detection Methods, MIT Joint Program Report Series No. 276, Cambridge, USA.

4.1 Introduction

The development of computable general equilibrium (CGE) models requires many assumptions regarding their theoretical setup (e.g. the underlying factor market specification) as well as the definition of required parameters (e.g. the specification of substitution elasticities). While without doubt both elements of model design are important and require utmost accuracy to avoid false model results, in this paper we discuss the amelioration of the process of parameter specification and present an alternative approach that can be used to parameterise CGE models.

For the specification of parameters, modellers normally make use of calibration technics (c.f. Dawkins et al., 2001) or build on estimates from the literature. These approaches entail some important limitations. Standard benchmark calibration for instance does not account for fluctuations over time and is thus prone to errors when special events or situations in the benchmark year are not specifically taken into account. Picture for example building on a biased economic structure because of an inflated tourism and construction sector in a year where the Olympic Games take place. Applying estimates from the literature is also not as straightforward as it may seem at first glance. If for instance parameters are not specifically estimated for the implementation in models or at least studied on the basis of the same underlying theoretical structure, conceptual and definitional mismatches may lead to the misspecification of parameter values (Browning et al., 1999). McKitrick (1998) illustrates the issue for the case of substitution elasticities. What is more, simply using values from the literature neglects that in most cases the information originates from estimation procedures and must thus associated with some degree of uncertainty. While for instance most of the substitution elasticities estimated by Koesler and Schymura (2015) feature small standard deviations, some estimates imply an important amount of variability of which modellers should be aware of. All too often, modellers are also confronted with a situation in which no estimates or data is available for the definition of required parameters. In this case, they have to build on their experience and intuition and have only few options to truly evaluate their model specification. This leads directly to the critique of McKitrick (1998) that CGE models lack empirical foundations.

These difficulties motivate the main objective of this paper which is to improve the parameter specification of CGE models. In the following we illustrate how Optimal Fingerprint Detection Methods - an approach originally used in climate science (e.g. IPCC, 2007; Forest et al., 2000, 2001) – can inspire the identification of appropriate parameter values for CGE models. This method builds on a generalised multivariate regression analysis and combines a simple model validation exercise with a structured sensitivity analysis. Compared to other procedures, the new approach has various benefits: 1) It uses a structured optimisation procedure and does not revert to ad-hoc model improvements. 2) It allows to account for uncertainty in parameter estimates by using information on the distribution of parameter estimates from the literature. 3) It can be applied for the specification of various parameters required in CGE models, for example for the definition of elasticities or productivity growth rates.

The paper is structured as follows. First, we briefly provide a background on Optimal Fingerprint Detection Methods, henceforth referred to as OFDM. Second, we demonstrate how OFDM can be applied in the context of CGE modelling and explore its capabilities in a CGE framework using a stylised small scale CGE model. Subsequently we apply the new approach to the still simple but full-fledged Basic WIOD CGE Model developed by Koesler and Pothen (2013) and derive a set of substitution elasticities for the specification of production in the model. Finally, we summarise and conclude in the last section.

4.2 Optimal Fingerprint Detection Methods (OFDM)

OFDM originate from climate science (e.g. Hasselmann, 1997; Allen and Tett, 1999). Above all, they are used to detect climate change and to identify climate change drivers (c.f. IPCC, 2007). On that account, a multivariate regression analysis is set up which generally has the following form:

$$\mathbf{Y} = \mathbf{X}\mathbf{a} + \mathbf{e}, \tag{4.1}$$

where the vector $\mathbf{Y}$ includes data from observations (i.e. the climate record), $\mathbf{X}$ is a vector of (expected) response patterns which determine the climate system in the model, $\mathbf{a}$ is a vector of scaling factors which are used to adjust the response patterns so that the simulation outcomes correspond the observational data and $\mathbf{e}$ is a vector with error terms that is to be minimised. The underlying logic is thereby that if the estimated response patterns in vector $\mathbf{X}$ is capable of replicating real world observations under normal circumstances, that is in a situation with no climate change, then if the elements in the vector $\mathbf{a}$ do not equal one when trying to replicate the current climate, there is some disturbance of the climate system. Deviations can then potentially be attributed to climate change.

OFDM have however also been applied to specify parameters in models simulating the climate. To that end, Forest et al. (2000, 2001) use a multivariate regression analysis as described in Equation 4.1, but with the difference that in their work the vector $\mathbf{X}$ includes simulation results instead of expected response patterns. This regression setup relates the climate record one to one to the climate model output (e.g. observed temperature to simulated temperature) and allows for a structured validation of model results with observed data. Also in this context, the underlying logic of the OFDM approach is straightforward. As long as not all elements in the scaling vector $\mathbf{a}$ are equal to one, the model is not perfectly capable of replicating the observed data and thus needs to be refined. To judge the overall performance of the model when contrasting its output to observed data, Forest et al. (2000, 2001) use a goodness-of-fit criterion r^2 which builds on the difference between actual observations and model results without scaling. That is $\tilde{\mathbf{u}} = \mathbf{Y} - \mathbf{X}$ with $\mathbf{a}$ being a unity vector ($a_i = 1 \forall i$). The error $\tilde{\mathbf{u}}$ captures element that are not taken into account by the model (e.g. internal climate variability) as well as deviations that occur because of a non-perfect model specification. While the first type of variability is intrinsic in any modeling approach - after all models are always a simplification of the real world - it is the later that the method eventually seeks to minimise. The criterion r^2 itself is defined as:

$$r^2 = \tilde{\mathbf{u}}^T \mathbf{COV}^{-1} \tilde{\mathbf{u}}, \tag{4.2}$$

where **COV** is the error covariance matrix, which - as we illustrate in the next section - can be estimated using model control runs. The aim of the modeler must then be to minimise r^2, respectively the deviations resulting from any model misspecification. This can be done by means of a sensitivity analysis implementing different parameter specifications and reevaluating each model setup using the goodness-of-fit criteria. The most apt parameter specification will then be the one which provides the lowest r^2.

4.3 Illustrative application of OFDM to CGE framework

4.3.1 Process

As indicated in the previous section, OFDM consists basically of a validation exercise combined with a sensitivity analysis. The process of using OFDM to find adequate parameter specifications for a CGE model involves three main steps.

To begin with, modellers have to chose a set of parameters for which they require guidance regarding their specification and must create a portfolio of different specifications that should be tested. While in principle any parameter value can be evaluated using ODFM, the choice of possible values can be guided in particular by available estimates from the literature. In this case, it is recommendable to build the portfolio of different parameter values not just using the actual estimates, but in addition any available information of the distribution of the parameter value (i.e. information on standard deviations and other higher moments). This allows to implement a more informed sensitivity analysis similar to the structured sensitivity analyses described by Harrison and Vinod (1992) or Hermeling et al. (2013) later in the process. This brings the additional benefit of being able to account for the uncertainty attached to parameter estimates when setting up the model.

The next step implements a validation exercise and investigates whether the CGE model with a specific parameter setup from the portfolio developed in the previous step is capable of replicating an observed record. Thereby a validation procedure as described by Kehoe et al. (1995) and Kehoe (2005) is applied which contrasts historical developments to model predictions. Although instead of using correlation and deviation coefficients to judge the fit of the model output, here we use the goodness-of-fit criteria presented in Equation 4.2. The procedure requires information on key economic indicators at two points in time and knowledge of changes in variables exogenous to the model that have taken place in the meantime.[1] The model is then calibrated to the earlier point in time and equipped with the parameter setup that is to be tested. Subsequently, to generate a set of predicted changes, the model is shocked with all observed changes in exogenous variables. Finally the simulation result is compared to the observations from the second point in time on the basis of the OFDM criteria from Equation 4.2. The resulting value of r^2 provides a first indication of the quality of the parameter setup under investigation.

The third and final step can be referred to as the sensitivity analysis part of the OFDM. Basically, it involves repeating the previous step for all parameter specifications that are to be tested and to compare the respective r^2 values. The parameters combination featuring the lowest r^2 and thus providing the best fit to the observed data without having to scale the model output, can then be considered the most adequate parameter specification.

4.3.2 Stylised CGE model

Before applying the OFDM method to a full scale CGE model, we demonstrate the process and capabilities of OFDM in a CGE setting by making use of a small stylised CGE model. The model is deliberately simple and features only one region, one final demand agent and two production sectors. The model covers the time period t to $t+n$ with $n \geq 1$. Agents are assumed behave myopic and do not link different periods through saving or investment. In accordance to this, in the following, we drop the time subscript when describing agents behaviour.

The final demand agent supplies capital K and labour L and consumes two different commodities A and B. Its consumption function is characterised by a constant elasticity of substitution (CES) function of the form:

$$C = \left(\alpha_C A^{\rho_C} + (1-\alpha_C)\, B^{\rho_C}\right)^{\frac{1}{\rho_C}}, \tag{4.3}$$

where ρ_C is the substitution parameter of final consumption which relates to the elasticity of substitution for final consumption through $\rho_C = \frac{\sigma_C - 1}{\sigma_C}$ and α_C the input share of final consumption goods. The factor endowments grow at the constant rate γ every period.

In addition, there are two sectors A and B that produce commodities A and B on the basis of two CES production functions:

$$\begin{aligned} A = \Bigg(& \alpha_{KLM}^{A} \left(\alpha_{KL}^{A} K^{\rho_{KL}} + \left(1-\alpha_{KL}^{A}\right) L^{\rho_{KL}}\right)^{\frac{\rho_{KLM}}{\rho_{KL}}} \\ & + \left(1-\alpha_{KLM}^{A}\right) \left(\alpha_{M}^{A} A^{\rho_M} + \left(1-\alpha_{M}^{A}\right) B^{\rho_M}\right)^{\frac{\rho_{KLM}}{\rho_M}} \Bigg)^{\frac{1}{\rho_{KLM}}}, \end{aligned} \tag{4.4}$$

[1] While in general it is fairly easy to have access to data describing two points in time, it is difficult to account for all changes that have taken place in between. We are aware of this problem, which we believe is intrinsic in any validation exercises, and discuss this issue in more detail in Section 4.3.5.

Table 4.1: Structure of generic model economy in period t and t+1

Period t	Sector A	Sector B	Period t+1	Sector A	Sector B
Input A	30.00	10.00	Input A	30.48	10.16
Input B	10.00	30.00	Input B	10.37	31.11
Capital	25.00	75.00	Capital	26.25	78.75
Labor	75.00	25.00	Labor	75.00	25.00
Output	140.00	140.00	Output	142.10	145.02
Final Demand	100.00	100.00	Final Demand	101.46	103.54

and

$$B = \Bigg(\alpha^B_{KLM} \left(\alpha^B_{KL} K^{\rho_{KL}} + \left(1 - \alpha^B_{KL}\right) L^{\rho_{KL}} \right)^{\frac{\rho_{KLM}}{\rho_{KL}}} + \left(1 - \alpha^B_{KLM}\right) \left(\alpha^B_{M} A^{\rho_M} + \left(1 - \alpha^B_{M}\right) B^{\rho_M} \right)^{\frac{\rho_{KLM}}{\rho_M}} \Bigg)^{\frac{1}{\rho_{KLM}}}, \tag{4.5}$$

where again ρ are the substitution parameters and α the input share parameters for the different production nests.

For the sake of being able to assess the potential of OFDM, we assume that the 'true' setup of the model involves all substitution elasticities being equal to one ($\sigma_C = \sigma_{KL} = \sigma_M = \sigma_{KLM} = 1$), the capital growth rate γ_K is 5%, and there is no change in the endowments of labour ($\gamma_L = 0$). However, to make the case for the need of an approach to find an adequate parameter specification, we also assume that the true values of the elasticities and the endowment growth rates are initially unknown. The objective of the OFDM is then to identify the 'true' parameter values. The input share parameters α are calibrated to the overall structure of the economy which is given in Table 4.1 for the periods t and $t + 1$. The data for $t + 1$ has been generated by running the model featuring the aforementioned 'true' parameter specification for one period.

Besides illustrating how OFDM can be applied to the CGE framework, the stylised CGE model allows to explore its potential in a general equilibrium setting and how it is best applied in this context. On that note, we seek to answer three main questions: 1) Is OFDM successful in identifying an apt parameter specification and for what parameters can it be applied? 2) What output variables should be included in the computation if the goodness-of-fit criterion? 3) What type of shocks can be used in the validation process necessary for OFDM?

4.3.3 Computation of covariance matrix

As becomes clear from Equation 4.2, OFDM requires knowledge of the interrelationship between model output variables or more formally the covariance matrix **COV**. Ideally **COV** would emerge from actual observations, but given the artificial nature of the stylised model used in this section this is obviously no option. As a matter of fact, deriving **COV** is also a problem that climate scientist face when applying OFDM. The size of their models does not allow inferring **COV** from the relatively short available climate record as there are are not enough degrees of freedom available and the record might be affected by external forcings which would lead to a bias (IPCC, 2007). The first issue is also a problem when applying OFDM in the context of CGE modelling, as also here there rarely exist appropriate time series data that could be used. The problem can however be overcome by using 'pseudo-observations' generated by control runs of the model (Allen and Tett, 1999). The underlying idea is thereby to use the model itself and a series of simulations to generate a data set that mimics the missing actual observations.

We apply this approach and generate a series of pseudo observations in the form of an artificial time series by solving the stylised CGE model described above with the 'true' parameter setting for the period $t = 0$ to $t = 150$.[2] Note, although we make use of a change in factor endowments by applying the growth rate γ for different points in time, the pseudo observations could in principle also be generated by using a change in any other exogenous variable as a shock. Subsequently, to break the direct relationship between the reported variables and to overcome the deterministic nature of the data generated by the model, we multiply all reported variables with a parameter which follows a normal distribution of the form $\mathcal{N}(1, 0.01)$. Finally, **COV** can be estimated by:

$$\widehat{\mathbf{COV}} = \frac{1}{n}\mathbf{Y}_{PO}\mathbf{Y}_{PO}^{T}, \tag{4.6}$$

where n is the number of observation vectors (here 151) and $\mathbf{Y}_{PO}$ a matrix including all observation vectors derived from the generated pseudo observations. The choice of variables that is included in the observation vectors depends on the variable that will be used in the actual OFDM process. Exploring which these should be in order to have optimal results of the OFDM is one of the objectives of the next section. For the illustrative example of this section, we eventually use all input variables, sectoral output and total final demand.

4.3.4 Potential and best practice of OFDM in CGE context

4.3.4.1 Type of parameters that can be specified using OFDM

In CGE models there exists multitude of different parameters that need to be specified. This includes in particular elasticities, input shares and growth rates. For the objective of this paper we focus on substitution elasticities and the growth rates of productivity or endowments. However, in principle, the approach could also be applied to other required parameters.

To explore if applying the OFDM to the stylised model reveals the 'true' underlying substitution elasticities and growth rates we first generate a portfolio of different param-

[2] We demonstrate later in the paper that the pseudo observations could also be generated using a model with other parameter settings.

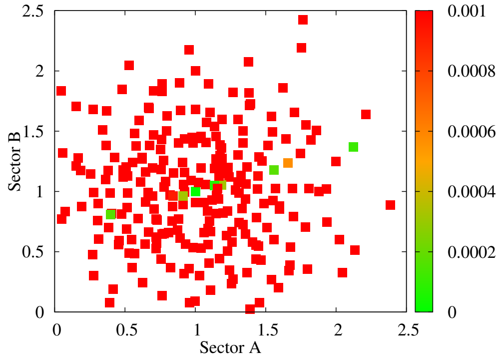
eter setups. For this we choose for each elasticity of substitution ($\sigma_C, \sigma_{KL}, \sigma_M, \sigma_{KLM}$) 250 different values on the basis of a normal distribution of the form $\mathcal{N}(1, 0.5)$. If this process provides negative values for any of the elasticities, we repeat the draw and eventually implement a truncated normal distribution. Analogous to this but assuming a distribution of the form $\mathcal{N}(0.05, 0.05)$, we also determine 250 different values for the growth rates of capital γ_K and labour γ_L. Here negative values are not discarded. Besides using these stochastic process to generate parameter values, we also include the 'true' parameter values presented above in the portfolio. Subsequently the model is run several times and for each simulation one or two different parameter setting from the parameter portfolio is applied. Parameters values that are not iterated remain at their 'true' values. For each run the model output is then contrasted to the 'observations' in time $t + 1$ presented in Table 4.1 and we compute the goodness-of-fit criterion r^2 of the OFDM. Thereby and for the time being, we focus on the model predictions for factor input, intermediate input, sectoral output and overall final demand. If the OFDM approach works, then r^2 should be minimal - or even zero - for all model runs that apply a parameter setup close to the 'true' parameter values of the stylised model.

Figure 4.1 presents the r^2 values for different model runs. Each dot represents a different parameter specification. The axes depict the parameter values and the color of the dots indicate the value of r^2. Green dots translate into low levels of r^2 and red dots to high levels of r^2. As becomes clear from all graphs and also when exploring the underlying numerical values, there is only one parameter specification with a minimal r^2. Moreover, the parameter specification with the minimal r^2 - in this illustrative the situation where $r^2 = 0$ - corresponds to the 'true' parameter values of the stylised model. Therefore we can conclude that the OFDM is capable of identifying the (here by definition) most apt parameter setup for all substitution elasticities and growth rates. Another important insight from all graphs in Figure 4.1 is that as the tested parameter values approach their 'true' value, deviations of model results and observed data become smaller and r^2 decreases.[3] This suggests that even in a situation where the number of parameter setups that can be tested is limited (e.g. because of long solving times) OFDM is useful, because even then it can give guidance in what direction parameters should be adjusted.

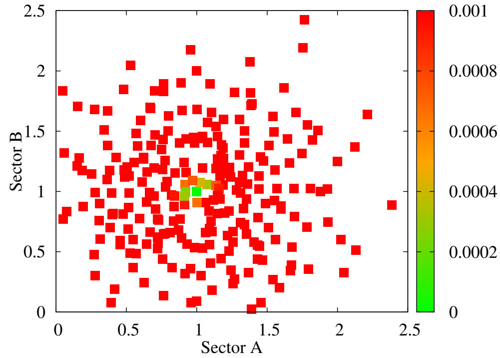
The combination of parameters that are iterated in the model runs is of no importance for the accuracy of the OFDM procedure. As becomes clear from Graphs 4.1d and 4.1e, OFDM is in both cases capable of identifying the 'true' parameter value of the growth rate of capital. This holds regardless of whether the capital growth rate is tested jointly with a substitution elasticity or the labour growth rate.

While all other graphs in Figure 4.1 have been generated using the 'true' parameter specification described in the previous section, Graph 4.1f emerges from model setup

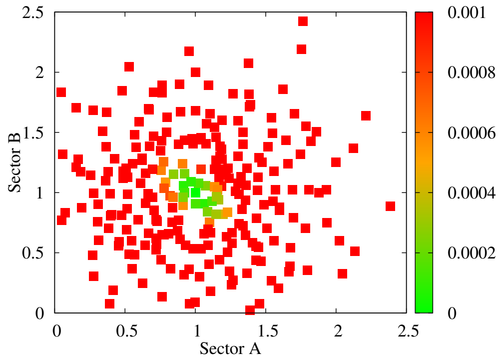
[3] At first sight, this may not be the case in Graph 4.1d. Note however that this is due to the fact that as closer the growth rate of capital is to zero, the less important is the level of the substitution elasticity σ_C and thus potentially any value of σ_C provides the same result.



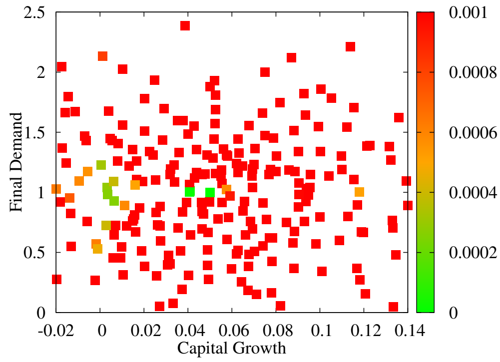
(a) σ_{KL}



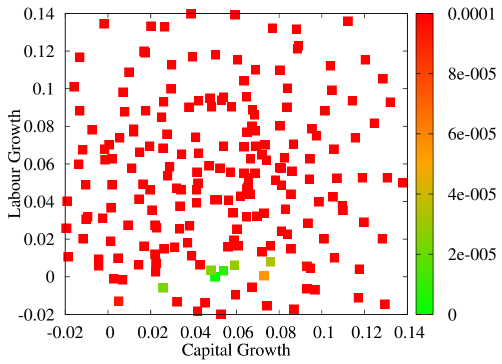
(b) σ_M



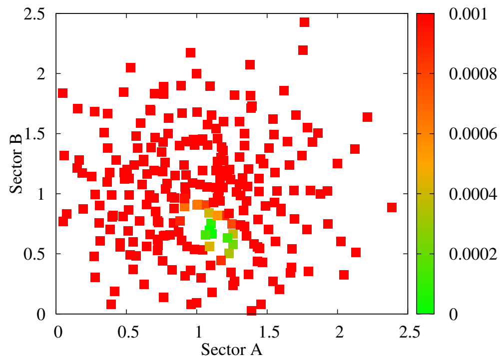
(c) σ_{KLM}



(d) γ_K and σ_C



(e) γ_L and γ_K



(f) σ_{KLM} where 'true' values are $\sigma^B_{KLM} = 0.75$ and $\sigma^A_{KLM} = 1.25$

Figure 4.1: Goodness-of-fit criteria of OFDM for different parameters [axes give parameter values, color gives value of r^2]

where the 'true' parameter values for the substitutability between intermediates and value added (the capital-labour-composite) is no longer $\sigma^A_{KLM} = \sigma^A_{KLM} = 1$ but is set to be $\sigma^A_{KLM} = 1.25$ and $\sigma^B_{KLM} = 0.75$. Since we use the same covariance matrix as before, this also implies that here **COV** has been derived from pseudo-observations which have been generated using an 'incorrectly' specified model. What is more, in this particular OFDM process, all substitution elasticities that are not tested have been set so that they deliberately not match their 'true' value, that is for this analysis we specify the model such that ($\sigma_C = \sigma_M = \sigma_{KLM} = 0.9$). As OFDM is also in this case capable of giving an identifying of the true parameter values, this allows to reveal three important capabilities of OFDM. First, the approach is not limited to a situation where where all elasticities are equal to one. Second, OFDM also works in a setting where not just the tested parameters are unknown and potentially not correctly specified. Third, the method is not affected by the (mis)specification of parameter values in the model that is used to generate the pseudo-observations required for the estimation of the **COV**. However, it must be noted that in this case the precision of the process is reduced. The lowest r^2 is achieved for $\sigma^A_{KLM} = 1.11$ and $\sigma^B_{KLM} = 0.67$, so the 'true' values are slightly missed.

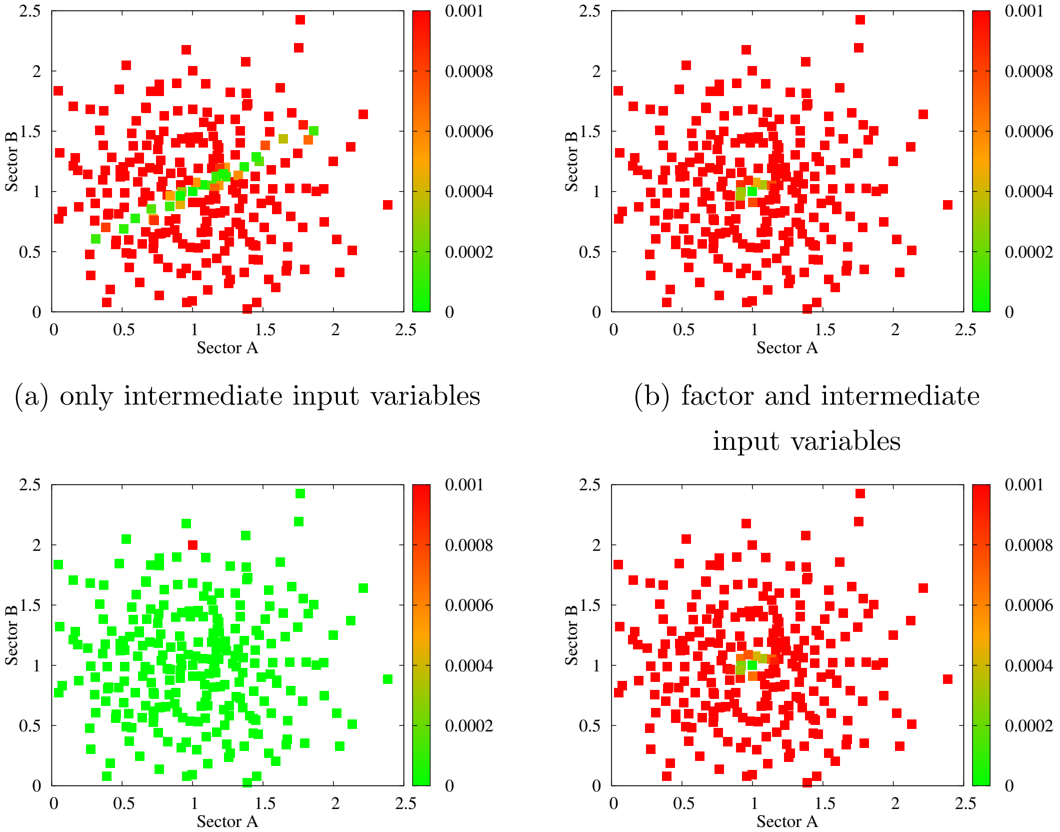
4.3.4.2 Choice of output variables included in goodness-of-fit criteria

The computation of the goodness-of-fit measure r^2 and therefore also the covariance matrix $\widehat{\mathbf{COV}}$ requires choosing a set of relevant output variables. CGE models generally provide a wide range of simulation results, including for example information on prices, output levels, trade activities, factor use, employment, environmental indicators, etc.. In addition, potentially all data is available on a sectoral and/or regional level therewith increasing the number of output variables. This raises the question, which of the output variables are crucial and should be used in the OFDM process. While at first sight it seems tempting to include all available variables, it soon becomes clear that even for small models this involves processing a large amount of data. Especially for the computation of the covariance matrix including a large number of output variables is problematic as it requires to increase the amount of observations accordingly in order to ensure that enough degrees of freedom are available. The issue is aggravated by the use of pseudo-observations when deriving the covariance matrix. In a general equilibrium context, many of the output variables feature linear relationships, thus feature a high correlation, and therefore make it impossible to compute the inverse of the covariance matrix required by Equation 4.2. For this reason for example total factor input and total final demand cannot be used simultaneously in the computation of r^2.

But if more is not better, what is the least amount of variables that should be considered? Figure 4.2 provides the results of an analysis of σ_M, whereas once more the OFDM procedure has been applied to the stylised model with the original 'true' values of $\sigma_C = \sigma_{KL} = \sigma_M = \sigma_{KLM} = 1$, $\gamma_K = 0.05$ and $\gamma_L = 0$, but with the difference that here various output variables are used to compute $\widehat{\mathbf{COV}}$ and r^2. For Graph 4.2a only intermediate inputs into the production of good A and B are considered. Although $\sigma_M = 1$ is part of the parameter sets that can be deemed to provide a good fit, the 'true' value can not be identified as the only apt specification. But if in addition to the intermediate inputs also factor inputs to the two sectors are considered, as it is in Graph 4.2b, the 'true' value of σ_M is revealed unambiguously. Then again, using only output variables in the OFDM process that are not directly related to the tested parameter, such as for example sectoral output and total final demand in Graph 4.2c, makes it impossible to find an adequate parameter specification. However, as becomes the clear from Graph 4.2d, adding these variables to the analysis using all input variables does not affect the good result of the OFDM process. This allows us to reason that in order to ensure that OFDM works well, at least the directly affected variables should be included in the process and more variables do not harm the process - as long as the number of variables is still tractable and variables are not a linear combination of each other. In accordance to this and if not stated otherwise, we use for the OFDM applications in this paper all input variables, sectoral output and total final demand to compute r^2 and $\widehat{\mathbf{COV}}$.

4.3.4.3 Type of shocks that can be used for ODFM

For a real world application, the validation step in the OFDM procedure will eventually require keeping track of various types of changes and using these in the replication attempt. This implies that OFDM must be able to identify the 'true' underlying parameter values independent of the type of shock that is applied. To explore this issue, we run yet another series of OFDM procedures and seek to identify the 'true' value of σ_{KLM} for sector A and B, but this time use three different types of shocks. Figure 4.3 presents the corresponding results. The first shock used for Graph 4.3a is an increase in the available endowments, which is the type of shock that we have used so far in our deliberations. Note that this type of shock corresponds to a change in factor productivity. For the second Graph 4.3b we apply a tax on output of sector A and for the third Graph 4.3c we consider a tax on capital inputs in sector A. Thereby it can be expected that the effect of taxes will be similar to that of tariffs, although due to the limited scope of our single region model we cannot undertake a true analysis of this here. As can be seen from all graphs, OFDM always succeeds in identifying the 'true' value of σ_{KLM}. Thus we can conclude that OFDM appears to work with a variety of different shocks. It must be noted however, that the shock that is applied must have a certain magnitude to allow OFDM to work reliably. In our stylised example for instance, the results become blurry if a tax of 5% or less is applied.



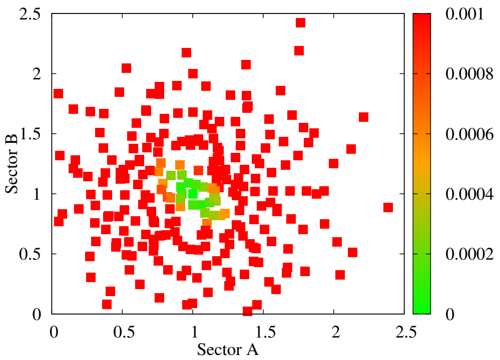
(a) only intermediate input variables

(b) factor and intermediate input variables

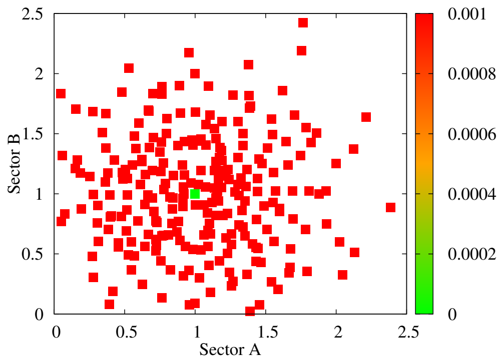
(c) sectoral output and final demand variables

(d) factor and intermediate input, sectoral output and final demand variables

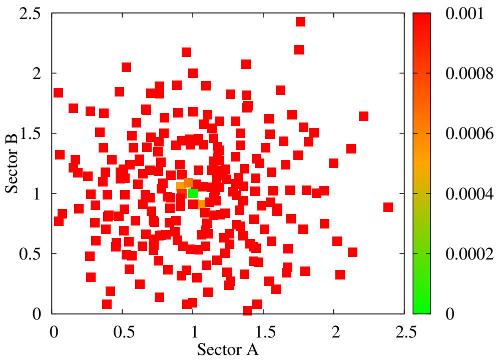
Figure 4.2: Goodness-of-fit criteria of OFDM for σ_M using different output variables for the computation of r^2 and $\widehat{\mathbf{COV}}$ [axes give parameter values, color gives value of r^2]



(a) increase of capital stock



(b) output tax in sector A



(c) tax on capital input in sector A

Figure 4.3: Goodness-of-fit criteria of OFDM for σ_{KLM} using different shocks in the process [axes give parameter values, color gives value of r^2]

4.3.5 Discussion

Limits of validation

OFDM builds on a series of validation exercises. Therefore its results strongly dependent on the availability of data for two different points in time and information on the exogenous shocks that moved the economy from one state to the other. In particular the latter is generally hard to come by, because at any moment in time there exists a multitude of different shocks that influence the economy and it is clearly impossible to account for all of them. This however implies that any validation exercise will always miss a potentially important element of change and will as a consequence attribute the adjustment of the system to a different (but accounted) channel. Ultimately this will also affect the capabilities of the OFDM method. Research can however confine the problem by limiting the number of relevant changes that are not accounted for. For this purpose using comprehensive datasets such as the World Input-Output Database (WIOD, Timmer et al. (2012); Dietzenbacher et al. (2013)) offer an opportunity to modellers. WIOD offers a rich and consistent representation of most important economies and their trade linkages in the form a time series. This allows to infer many changes that have taken place over time, for example with respect to changes in endowments, taxes and tariffs, trade structure, interregional and intertemporal saving and borrowing, and to take them into account when validating models.

Multiple adequate parameter setups

In a general equilibrium model, the value of some parameters may influence the level or importance of other parameters. To be able to judge the flexibility of production for example, it is necessary to consider all substitution elasticities related to the process. If the substitutability between intermediate and value added is very low, then the elasticity of substitution between capital and labour may become less important when assessing a shock in factor supply and could in an extreme case take any value without affecting the model outcome. Potentially this may lead to a situation where there exists more than one 'true' parameter setup. For the OFDM process, this would imply that there is not just one minimal r^2, but many locally minimal r^2. Although such as situation has never occurred when using OFDM in our small stylised model framework, it is in principle a possible outcome of OFDM. In this case either parameter setup seems equally valid, as from a modelling perspective they all minimise the deviation of model output to observations. To be able to judge whether there are multiple adequate parameter setups, modellers should always consider in their parameter portfolio a sufficiently large range of values and ideally include all possible parameter values in the OFDM process. Taking a broader perspective with regard to possible parameter values also helps to prevent identifying a locally minimal r^2 as the optimal value by mistake.

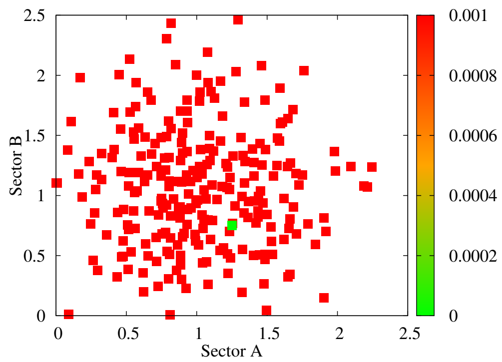


Figure 4.4: Goodness-of-fit criteria of OFDM for σ_{KLM} which includes all other elasticities in the analysis [axes give parameter values, color gives value of r^2]

Inaccuracy of OFDM if parameters are misspecified

As illustrated when discussing Graph 4.1f, OFDM appears become imprecise if some of the model parameters are misspecified when seeking an adequate specification for another set of parameters. Unfortunately, due to the lack of information on adequate parameter values criticised in the outset of this paper, in any real world application this will most likely be an issue for most applications of OFDM. The problem can however be overcome by including all parameters of which modellers are unsure of in the OFDM procedure. While this may require to enlarge the portfolio of parameter setups that is to be tested and thus will be more demanding from a computational perspective, it increases the degree of freedom and therefore the likelihood of applying the 'true' parameter setup in one of the model runs. This in turn will allow to find a model setup with truly minimal deviations and thus most adequate parameter values. Figure 4.4 demonstrates the functioning of this comprehensive approach. Here, the setup is similar to the OFDM process used to generate Graph 4.1f, but instead of applying the false parameter specifications, we include all elasticities in the process. Eventually and in contrast to the earlier attempted, the 'true' values of $\sigma^A_{KLM} = 1.25$, $\sigma^B_{KLM} = 0.75$ and although not pictured $\sigma_C = \sigma_{KL} = \sigma_M = 1$ are identified without any inaccuracy.

Optimisation vs. sensitivity analysis

Instead of using a structured sensitivity analysis with different parameter setups to identify the most apt parameter setup, researchers could also apply an optimisation process which minimises the goodness-of-fit criterion r^2 to derive a suitable parameter specification. Such an idea would follow an approach presented by Liu et al. (2004) in a paper seeking to find a set of optimum Armington elasticities. Compared to a self-contained optimisation, a sensitivity analysis has two main advantages. First, it does not require to solve a complex system of equations and can be expected to be much less computationally demanding. Second, it allows for an easy and straightforward implementation of additional information on potentially good parameter values that has been supplied for example by estimates from the literature. However, using the goodness-of-fit criteria from OFDM in an optimisation approach and contrasting the results to a standard OFDM procedure is an interesting question for future research.

4.4 Application of OFDM to Basic WIOD CGE Model

After having presented and illustrated OFDM on the basis of a small stylised CGE model, in this section we apply the method to a full scale CGE model. On that account, we seek to identify adequate substitution elasticities for the specification of production ($\sigma_{KL}, \sigma_{KLE}$ and σ_{KLEM}) for the Basic WIOD CGE Model. This model is a static, multi-region, multi-sector CGE model that has been developed by Koesler and Pothen (2013). With regard to the basic economic structure, the model builds on the comprehensive World Input-Output Database (WIOD, Timmer et al., 2012; Dietzenbacher et al., 2013) which will be an advantage for the validation part of OFDM.[4] Details on the Basic WIOD CGE Model are provided in Chapter 2 and in Appendix A.1.

Most importantly for our analysis, the model distinguishes between three groups of commodities: energy commodities $Y_{(eg,r)}$, industry commodities $Y_{(ind,r)}$ and services $Y_{(ser,r)}$. The production of these goods is characterised by production functions with constant elasticities of substitution (CES) and constant returns to scale. Nested functions with three levels are employed to specify the substitution possibilities between capital K, labour L, energy inputs $A_{(eg,r)}$ and non-energy $A_{(neg,r)}$ inputs (including intermediates form industry and services). We apply a KLEM production structure, thus capital and labour enter the production function on the lowest level, on the second level value added is combined with energy and finally on the top level of the CES function the energy-value-added composite is combined with a non-energy material aggregate. An overview of the production structure is given in Figure 4.5.

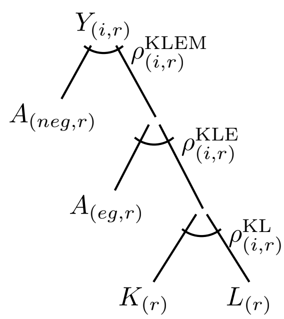


Figure 4.5: Structure of KLEM production function in Basic WIOD CGE Model

For our purpose, the WIOD data is aggregated into two regions (Europe (EUR) and 'Rest of the World' (ROW)), three sectors (energy goods (EG), industry (IND) and services (SER)) and two final demand agents (households (FC_HH) and government

[4]The WIOD database is available at http://www.wiod.org. We use data downloaded on the 17th of April 2013.

(GOV)). Additional information on the aggregation is given in the Appendix of this paper. With regard to the specification of parameters, the model is calibrated to the year 2003. We choose 2003 to avoid possible distortions from the economic crisis in later years. The required Armington elasticities are taken from GTAP7 (Badri and Walmsley, 2008; Hertel et al., 2007, 2008) and are mapped to the sectors we consider prior to the implementation into the model. Consumption and the intermediate mix in production are characterised by a Leontief function. In its initial setup and if not stated otherwise, we use estimates from Koesler and Schymura (2015), henceforth abbreviated as KS, to specify the flexibility of production with regard to different inputs. The respective substitution elasticities are given in Table 4.3. But eventually OFDM is applied to determine an adequate specification of the substitution elasticities $\sigma_{KL}, \sigma_{KLE}$ and σ_{KLEM}.

For the descriptive purpose of this paper, we undertake three different OFDM processes. The first is limited to an investigation of the elasticity of substitution between capital and labour in the energy sector (σ_{KL}^{EG}). The second explores substitutability on a more general basis and considers different values for $\sigma_{KL}, \sigma_{KLE}$ and σ_{KLEM} for all sectors on the basis of a OFDM process without starting values. The third repeats the second process but this time takes estimates from KS as starting values.

For the reasons presented before, it is also not possible to use the time series data provided in WIOD to derive the required covariance matrix. Therefore, we generate a set of 250 pseudo observations by shocking the model with a series of different changes in total factor productivity, respectively a uniform increase in the endowment of labour and capital of households to be able to estimate the covariance matrix. Furthermore, following the insights from the previous section, we use output variables for total final demand, sectoral output as well as total factor and intermediate input in production to compute $\widehat{\mathbf{COV}}$.

For the validation step in all three OFDM processes, we seek to replicate with the model the economy of the year 2004. An that account, we first compute all changes from 2003 to 2004 that we can observe in the WIOD dataset and subsequently apply the changes to the model in the form of a series of simultaneous shocks. This involves changes in household labour and capital endowments, intertemporal and interregional saving or borrowing, the prevailing tax structure, and international transport margins. As discussed before, our approach will clearly miss some changes that have occurred during this period. But given the comprehensive coverage of WIOD we hope to limit the number of omitted variables to a minimum.

4.4.1 Factor substitutability in the energy sector

In the first of three applications of OFDM, we seek to determine σ_{KL} for the sector producing the energy good (EG) in both regions EUR and ROW. On that account, we generate a portfolio of 250 different specifications of $\sigma_{KL}^{EG,EUR}$ and $\sigma_{KL}^{EG,ROW}$ that are to be tested. Thereby we arbitrary draw parameter values from a distribution of the

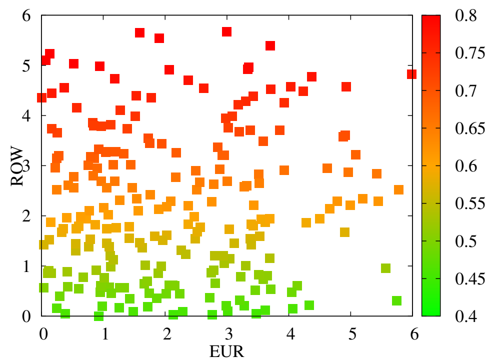


Figure 4.6: Standardised goodness-of-fit criteria of OFDM for σ_{KL} of the energy sector (EG) in Europe (EUR) and 'Rest of the world' (ROW) [axes give parameter values, color gives value of $r^2_{Standard}$]

form $\mathcal{N}(1, 1)$, whereas we repeat the draw if values smaller than zero or bigger than ten occur.[5]

The results of applying the parameter setups in the validation of is presented in Figure 4.6. To ease the presentation, we standardised the goodness-of-fit measure using:

$$r^2_{Standard} = \frac{|r^2|}{|r^2_{MAX}|}, \tag{4.7}$$

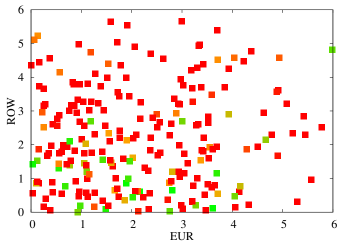
such that $0 \leq r^2_{Standard} \leq 1$. Thus parameter specifications featuring a $r^2_{Standard}$ of zero achieve a perfect fit and a $r^2_{Standard}$ value of one indicates that the parameter setup in question is the worst of all tested specifications. Although no clear locus with adequate parameter values can be identified in Figure 4.6, the OFDM clearly suggest that low values for $\sigma_{KL}^{EG,ROW}$ are better than high values. The parameter values featuring the smallest $r^2_{Standard}$ are $\sigma_{KL}^{EG,EUR} = 2.76$ and $\sigma_{KL}^{EG,ROW} = 0.03$. But given the big range of $\sigma_{KL}^{EG,EUR}$ with relatively similar low $r^2_{Standard}$ values, the factual best result for $\sigma_{KL}^{EG,EUR}$ should not be overrated.

4.4.2 General input substitutability in production

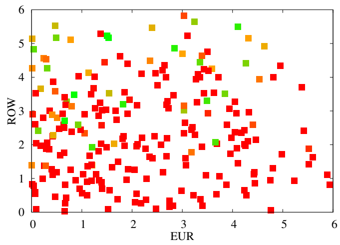
For the next application we broaden the scope of the OFDM process and consider different values for σ_{KL} as well as σ_{KLE} and σ_{KLEM} for all sectors. We once more generate a portfolio of 250 parameter setup using the aforementioned distribution and constraints. Thereby all 18 parameters are iterated simultaneously.

Figure 4.7 presents the result of this OFDM application for the Basic WIOD CGE Model. From the different graphs it becomes clear that for all sectors and elasticities, some parameter specification are better suited than others to replicate the 2004 situation. But in this bigger application, the graphs are not as informative in our previous

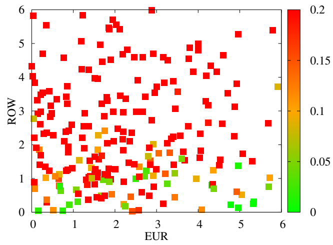
[5]The CES functional form used in the model requires all elasticities to be weakly positive and as in the context of CGE models a substitution elasticity of ten already implies a very high substitutability, we do not consider values bigger than ten.



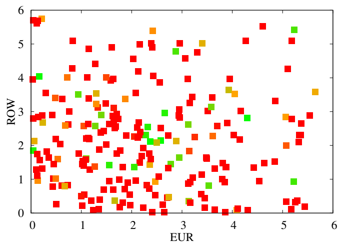
(a) σ_{KL} for EG



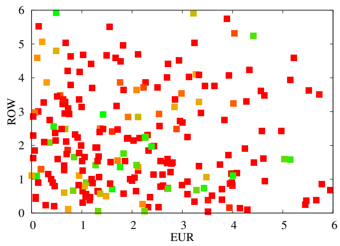
$(b)\sigma_{KL}$ for IND



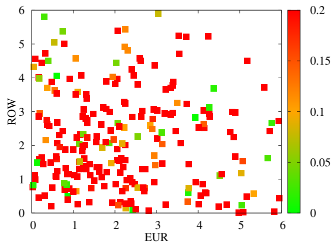
(c) σ_{KL} for SER



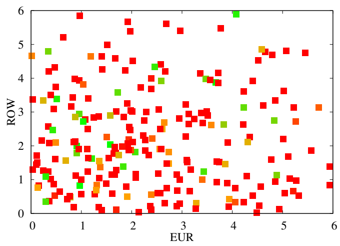
(d) σ_{KLE} for EG



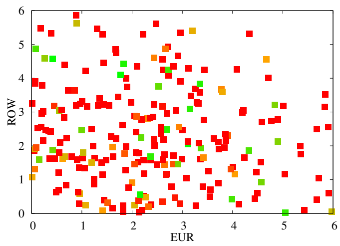
$(e)\sigma_{KLE}$ for IND



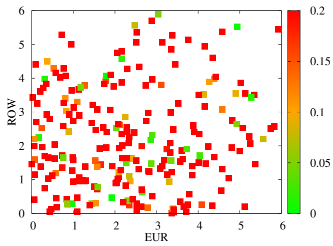
(f) σ_{KLE} for SER



(g) σ_{KLEM} for EG



$(h)\sigma_{KLEM}$ for IND



(i) σ_{KLEM} for SER

Figure 4.7: Standardised goodness-of-fit criteria of OFDM for $\sigma_{KL}, \sigma_{KLE}$ and σ_{KLEM} when applied to Basic WIOD CGE Model [axes give parameter values, color gives value of r^2]

Table 4.2: Results of OFDM for $\sigma_{KL}, \sigma_{KLE}$ and σ_{KLEM} when applied to Basic WIOD CGE Model

	ROW			EUR		
	EG	IND	SER	EG	IND	SER
σ_{KL}	0.12	6.82	0.31	3.62	4.54	5.33
σ_{KLE}	4.25	5.92	4.06	8.37	0.49	0.60
σ_{KLEM}	0.83	4.10	4.07	0.97	1.77	1.79

applications and in most cases we cannot identify a parameter area around which the fit is better than elsewhere. Only for σ_{KL} in Graphs 4.7a-c we can identify patterns. It suggest that for in EG and SER lower values seem to fit better for σ_{KL}, while in IND higher values seem more appropriate. The reason for the graphical ambiguity is that because all 18 values for $\sigma_{KL}, \sigma_{KLE}$ and σ_{KLEM} are iterated simultaneously, even parameter settings that seem similar in one of the graphs potentially feature very different values for the other 16 parameter values. The graphical interpretation of the results is therefore limited. Still, from looking at the numerical values of $r^2_{Standard}$ we can derive the parameter setup which provides the best model fit. The respective values for $\sigma_{KL}, \sigma_{KLE}$ and σ_{KLEM} are given in Table 4.2. Note also that compared to the previous analysis the overall goodness-of-fit tends to be better which results in lower $r^2_{Standard}$ values. The reason for this is straightforward, including more parameters in the OFDM process increases the degrees of freedom and therewith the possibilities to adjust the model so that it can eventually generate a good fit.

4.4.3 General input substitutability in production with starting values

For the third application of OFDM, we build a portfolio of 250 different parameter specifications for $\sigma_{KL}, \sigma_{KLE}$ and σ_{KLEM} on the basis of the estimates and standard deviations provided by KS. That is we use their estimates as initial values and iterate the parameters around these starting points assuming a normal distribution with the standard deviation presented also in their study.[6] Again we apply the constraints for parameter values smaller than zero and higher than ten and, as before, repeat the draw in such a case. As this paper uses of a different aggregation than KS, we aggregate their estimates and standard deviations on the basis of the following equations:

$$\sigma_{Aggregate} = \sum_i (\alpha_i \sigma_i), \tag{4.8}$$

[6]KS do not provide a substitution elasticity between capital and labour for the Coke Refined Petroleum and Nuclear Fuel (CPN) sector, here we assume that this elasticity is equal to the corresponding elasticity for the chemical and chemical products sector (0.24). For estimates that equal $+Inf$ we take an elasticity value of 10. Furthermore, for elasticities were no standard deviation is provided or were it is bigger than 10 we assume that it is equal to 2.5.

and

$$VAR\left(\sigma_{Aggregate}\right) = \sum_{i} \left(\alpha_i^2 VAR\left(\sigma_i\right)\right), \tag{4.9}$$

where α_i is the relative sector size in the aggregate and the later assumes that the elasticities between sectors are not correlated. Note that although KS reject variations across regions and over time for the substitution elasticities they estimate, here changes in the sector share may lead to elasticities that vary across regions and over time. The estimates we eventually use as starting values and the related standard deviations are given in Table 4.3 and correspond to the aggregated 2004 values for Europe. Note also that here we iterate $\sigma_{KL}, \sigma_{KLE}$ and σ_{KLEM} again simultaneously for the generation of the different parameter setups.

As described before, the graphical interpretation of the results of the OFDM process applied here is only of limited value. Therefore we move directly to the presentation of the parameter setup featuring the best model fit. The corresponding values are given in Table 4.3 together with the starting values and standard deviations from KS. Compared to KS in particular the values for EG and SER in ROW seem to be higher. The other parameters are rather stable with only few minor adjustments. But it must be noted that of course the standard deviation attached to the original estimate critically influence the potential for updating the parameter values. This is also the reason why the OFDM process with starting values results in an overall less good fit relative to a OFDM process without starting values. Again this is due to the fact that if the tested parameter values are not restrained because of low standard deviations, the likelihood that a fitting parameter setup is included in the investigated portfolio is higher and thus the overall model fit is potentially better.

Ultimately, the availability of a set of suitable elasticity values from the literature raises the question why a OFDM process should be applied in the first place. There are two reasons for this. For one thing, to be able to use parameter values from the literature these should ideally have been estimated specifically for the use in the underlying model or at least build on the same theoretical structure. Otherwise this can result in a misspecification of the model (Browning et al., 1999). Unfortunately, although this is the case for the estimates from KS which have been estimate using the same dataset and functional form as the Basic WIOD CGE Model, this favourable situation is unlikely to apply for most models and parameters. What is more, estimates must always be associated with some degree of uncertainty. Directly applying estimates in a model neglects that they are basically also a - admittedly well informed and elaborated - 'best guess'. Modellers should be aware of these issues and if possible take measures that account for the limitations of estimates form the literature. Applying OFDM allows this.

Table 4.3: Results of OFDM for $\sigma_{KL}, \sigma_{KLE}$ and σ_{KLEM} when applied to Basic WIOD CGE Model using estimated starting values from KS, standard deviations are given in parentheses

	ROW			EUR		
	EG	IND	SER	EG	IND	SER
σ_{KL}	3.59	0.38	1.24	5.13	0.35	1.21
σ_{KLE}	3.83	0.44	0.25	3.37	0.39	0.26
σ_{KLEM}	0.52	0.61	1.60	0.52	0.71	1.37
σ_{KL}^{KS}	3.44 (0.61)	0.35 (0.02)	0.82 (0.09)	5.75 (0.93)	0.34 (0.02)	1.17 (0.12)
σ_{KLE}^{KS}	2.85 (1.34)	0.43 (0.03)	0.29 (0.04)	3.30 (0.59)	0.40 (0.02)	0.27 (0.03)
σ_{KLEM}^{KS}	0.41 (0.01)	0.59 (0.19)	1.95 (0.55)	0.53 (0.01)	0.58 (0.14)	1.47 (0.27)

4.5 Summary and conclusion

This paper is devoted to the enhancement of CGE modelling and presents OFDM as an alternative method to the specification of parameter values in CGE models. We first provide some background information on OFDM and outline how it has been used in climate science to detect distortions in the climate system and to specify climate models. Next we illustrate how the process of OFDM can be applied within a CGE framework and apply it to a stylised CGE model with the aim of demonstrating OFDM and exploring its potential in a CGE context. We show that OFDM is capable of identifying the 'true' parameter values for substitution elasticities as well as growth rates of endowments respectively factor productivity. Furthermore, our results suggest that the process can be applied using a range of different types of shocks such as changes in endowments or taxes. Finally we apply the OFDM approach to a full scale CGE model and derive a set of substitution elasticities for the Basic WIOD CGE Model.

Overall, using OFDM to specify parameters in CGE models allows to secure three main benefits: 1) OFDM employs a structured optimisation procedure and does not require modellers to update the model specification on the basis of their intuition as is the case for most other validation exercises or sensitivity analyses. 2) It enables modellers to account the uncertainty that is associated with parameter estimates from the literature. 3) OFDM is versatile and can be used to identify adequate parameter specifications for a range of different parameters such as elasticities or growth rates.

There remain some limitations however. In its process, OFDM involves model validation and because of the difficulty to account for all changes that take place over a certain period of time, the results might be somewhat distorted. The issue might however be alleviated by using datasets such as WIOD which provide comprehensive and consistent information on changes throughout economies. In addition, OFDM requires information on the relationship between model output in the form of a covariance matrix, this information might also prove hard to provide, in particular when many of the model output variables are to be used in the OFDM process. Furthermore, the choice of which parameter values are to be included in OFDM process and the question within which range these should be tested confronts modellers with a tradeoff. On the one hand, exploring a wide range of parameters and values increases the likelihood of achieving better results in the validation exercise and potentially provides values which are highly suitable according to the goodness-of-fit criteria of OFDM. Using additional information on parameter values from estimates found in the literature on the other hand, decreases the parameter space and may result in a less good model model fit. This implies that the process provides parameter values that are less adequate according to the OFDM criteria, but allows to include information from previous studies in the analysis.

With regard to future research, one obvious next step would be to apply the OFDM approach to a full scale CGE model and to use the resulting parameter specification in a CGE analysis. This would help overcome some of the critique CGE models are frequently confronted with and eventually will make CGE simulations more reliable.

Chapter 5

Catching the rebound: Economy-wide implications of an efficiency shock in the provision of transport services by households

Abstract

We investigate the rebound effect of a 10% energy efficiency improvement in the provision of private transport services by German households. In the process, we take into account that household behaviour may be influenced by habits, build on a detailed representation of the provision of private transport services, and disentangle the direct and indirect rebound effect. Our analysis shows that rebound has the potential to significantly reduce the expected energy savings of an energy efficiency improvement at households. In particular if households have a flexible demand structure, rebound can erode large parts of efficiency increases. Household habits have an initial detrimental effect on rebound. They limit the ability of households to adapt to changes in the prevailing price and income system and therewith temporally block parts of the channels that lead to rebound. In the long run, however, if habits are formed on the basis of historic consumption, habits do not affect rebound. In isolation, the direct and indirect rebound effect of the efficiency shock are positive, but direct rebound is much stronger.

This chapter is based on the following paper:

Koesler, Simon (2013), Catching the Rebound: Economy-wide Implications of an Efficiency Shock in the Provision of Transport Services by Households, ZEW Discussion Paper No. 13-082, Mannheim, Germany.

5.1 Introduction

Efficiency improvements - in particular in the field of energy - are generally seen as one of the major steps towards sustainability. But if consumers and/or firms react to the change in efficiency by adopting their behaviour and choices, the actual benefits of an efficiency improvement can in reality be much lower as originally expected. In the context of energy efficiency improvements, this phenomenon is commonly termed as 'rebound'. It refers to a situation where consumers and firms take advantage of the efficiency improvement and eventually increase their demand for energy (c.f. van den Bergh, 2011).

That rebound may be an issue has been noted as early as the 19th century, when Jevons (1866) described that the augmented efficiency of coal-fired steam engines will increase the use of coal. He reasoned that the increased productivity makes the technology more competitive. As a result, the use of steam engines becomes more popular and therewith the demand for its main input - coal - increases. Since then, a vast stream of literature has emerged discussing this problem. A portfolio of papers on the rebound can, for example, be found in the special issue edited by Schipper (2000). Other articles providing an excellent overview include inter alia Sorrell (2007), Sorrell et al. (2009), van den Bergh (2011) and Turner (2013). But putting a number to the rebound effect is not straightforward and depends crucially, on the context one investigates. As a consequence, a wide range of different rebound estimates exist and presenting a selection would most likely draw a biased picture. Nevertheless, most studies indicate that rebound is not a negligible side effect (e.g. Sorrell, 2007; Sorrell et al., 2009; Frondel et al., 2012). Some researchers, however, do argue that the rebound effect is overplayed (e.g. Gillingham et al., 2013) and only marginally affects the benefits of efficiency improvements, although such critique is quickly rejected by others (e.g. Frondel and Vance, 2013). Some of the controversy around the rebound effect may steam from unclear terminology and a lack of solid analytical foundation in different studies (Turner, 2013). Thus, the economic evaluation of the rebound effect should be accompanied by a clear definition of what is under investigation and build on a sound formal foundation. What is more, much research on the rebound phenomenon has focused on direct rebound or price effects impacting the user whose efficiency has increased, thereby neglecting the potential of other channels such as income effects (impacting direct and indirect or respending rebound) or spillover effects to other – originally not affected – parts of the economy.

The literature on the economy-wide implications of an efficiency shock has so far focused on efficiency improvements on the production side. To our limited knowledge, studies on the economy-wide effects of an efficiency improvement on the household level remain the exception. The paper by Lecca et al. (2014) is such an exception. They provide inter alia a clear approach of how to measure rebound both at the economy-wide level as well as on the household level. With this paper, we extend the discussion of economy-wide rebound effects and continue the analysis of the implications of an efficiency improvement at households. Specifically, we investigate the economy-wide effects of augmented energy efficiency in the provision of private transport services by German households. Note, in line with the existing rebound literature we focus on changes in the relative price system and concentrate on effects after the efficiency improvement has taken place. Hence our study is no full policy analysis and does in particular consider the costs of the efficiency improvement as sunk costs.

To have a clear understanding of the underlying effects, we first formally illustrate through which channels rebound emerges on the basis of a simple stylised example. Subsequently, we evaluate the effects of a 10% energy efficiency improvement in the provision of private transport services by German households by means of a more comprehensive computable general equilibrium (CGE) analysis. Thereby, we take into account that, unlike firms, the behaviour of households may be governed by consumer habits. Consumption persistence is an important aspect in this regard, because it will at first limit the potential of households to react to an efficiency shock and potentially the implications of the efficiency change will only take place later in time. In this paper, we explicitly focus on an efficiency improvement on the demand side of households and do not consider the possibility that the efficiency improvement itself may trigger additional labour or capital supply by households. Therewith we rule out supply side effects which would lead to general productivity-led growth (c.f. Turner, 2013). Moreover, we take up the critique by Turner (2013) and provide a simple but thorough analytical framework on the basis of which we can illustrate different effects that overall result in rebound.

Our results indicate that rebound is not an overplayed phenomenon. If anything, it seems that in the context of energy efficiency improvements in households, rebound is an important issue. In our setup rebound amounts to up to 56%, that is more than half of the expected energy savings are lost due to rebound. Because they temporally block parts of the channels that lead to rebound, household habits have an initial detrimental effect on rebound. When comparing price and income effects on the basis of a ceteris paribus analysis, we can conclude that in isolation direct rebound is considerably larger that indirect rebound. With regard to implications, our results suggest that policy makers should be fully aware of the true potential of energy efficiency improvements as these may may turn out to be significantly less effective than expected. In addition, the time lag between the efficiency improvement and the change in behaviour is important and should be taken into account when studying rebound. Otherwise, the rebound effect may be underestimated.

The remainder of this paper is structured as follows. We first give a formal illustration of how rebound can arise in the context of an energy efficiency improvement at households and present different rebound channels on the basis of a small stylised example. Next, we apply the mechanism of the small theoretical model in a more general setting and evaluate the different drivers of the rebound effect on the basis of a CGE model. Finally, we summarise our results and conclude.

5.2 Rebound in the context of households

Most of the literature on the economy-wide rebound effect focusses on efficiency improvements in production sectors. In this paper, we turn our attention to the rebound effect and its channels in the context of households. But before we specifically investigate the implications of a 10% efficiency shock in the provision of private transport services by German households, we present the different effects that ought to be expected on the basis of a simple illustrative example. Later, we generalise the setup and turn to a more comprehensive setting, which nevertheless incorporates the main mechanisms of the example presented in the following.

The example features one representative household, a set of n services used for final consumption, and m intermediate commodities used by the households to produce the utility-generating services they eventually consume. The distinction between services and commodities is based on the idea that households do rarely actually consume commodities, such as cars and gasoline or light bulbs and electricity, but combine these to form a service they enjoy such as mobility/transport services or light. The potentially rebound-triggering efficiency increase eventually takes place on the level of the provision of the services and makes a specific intermediate input more productive. All agents take prices as given.

5.2.1 Household problem

Household utility is given by a Cobb-Douglas utility function encompassing n different services. The same mechanisms and conclusion emerge when applying a more general Constant Elasticity of Substitution (CES) utility function. But for the sake of clarity, we limit ourself in this stylised example to a Cobb-Douglas utility function and generalise at a later stage. In our analysis, we include a particularity of the household context, namely habits. We model habits in the spirit of Pollak (1970) and von Weizsäcker (1971) and include a habit formation process in the household problem by extending the standard Cobb-Douglas utility function with a term that can be interpreted as some form of necessary consumption. Necessary consumption results from the consumption level in absolute terms in the previous period and thus relates the current consumption decision to the past.[1] Accordingly, household utility at time t is given by:

$$U_t(x_{i;t}; x_{i;t-1}) = \prod_{i=1}^{n} (x_{i;t} - \theta_i x_{i;t-1})^{\alpha_i}, \text{ with } \sum_{i=1}^{n} \alpha_i = 1. \tag{5.1}$$

[1] Here we assume that habits rest on consumption in absolute terms. That is if for example a household has been on holiday for two weeks in the last year, he will also be inclined to go for two weeks on holiday in this year. But in principle habits could also rely on consumption levels in value terms. In this case the household would accept also only one week of vacation if prices have doubled. Whether habits build on absolute or value terms depend not only on the type of household, but most likely also on the type of good in question. Basic goods such as food are likely to be valued in absolute terms and luxury goods such as sports cars rather in value terms. As our product portfolio cannot be separated in a meaningful way into basic and luxury goods, we directly follow Pollak (1970) and other seminal papers considering habits (e.g. Abel, 1990) and assume that habits rest on consumption in absolute terms.

$x_{i,t}$ gives the amount of service i that is consumed by the household in period t and α_i is the corresponding expenditure share. The strength of the persistence of past consumption or, in other words, the strength of the habit formation process is given by θ_i's. Note that for simplicity we limit the habit formation process to one period. But it is straightforward that extending the range of habits has the same effect as increasing all θ_is. Households have to obey a budget constraint of the form $M = \sum_{i=1}^{n} (px_i x_{i;t})$. We assume that households have a fix income M which is not influenced by the efficiency change. As described by Turner (2013), this ensures that the efficiency shock will not trigger a productivity-led growth process and allows us to focus on demand side effects. If households take past consumption as given, demand for service x_i in period t by households is given by:

$$x_{i;t} = \frac{M - \sum_{j=1}^{n} (px_j \theta_j x_{j;t-1})}{px_i \sum_{j=1}^{n} \left(\frac{\alpha_j}{\alpha_i}\right)} + \theta_i x_{i;t-1}. \tag{5.2}$$

5.2.2 Provision of services

The provision of the service x_i by households is characterised by a CES function with input-specific efficiency:

$$x_i(z_j) = \left(\sum_{j=1}^{m} \left(\beta_{j;i} \left(\gamma_{j;i} z_j \right)^{\rho_i} \right) \right)^{\frac{1}{\rho_i}}, \tag{5.3}$$

z_j are commodities required to produce the service x_i, $\gamma_{j;i}$ the corresponding level of input efficiency which is initially assumed to equal one, $\beta_{j;i}$ the respective input share and $\rho_i \leq 1$ a parameter defining the substitutability between intermediate inputs which is related to the respective elasticity of substitution through $\rho_i = \frac{\sigma_i - 1}{\sigma_i}$. Note that for the generation of x_i we have omitted the time indices as production always refers to the current period t. Note also that in order to be able to focus on the rebound effect, we assume that commodities required to generate the services come from a sufficiently large market and are supplied to households at a demand-independent price of pz_j. Demand for a commodity j for the generation of service x_i is given by:

$$z_{j;i}(x_i) = \left(\frac{\gamma_{j;i}^{\rho_i} \beta_{j;i}}{pz_j} \right)^{\frac{1}{1-\rho_i}} \left(\sum_{j=1}^{m} \left(\left(\gamma_{j;i}^{\rho_i} \beta_{j;i} \right)^{\frac{1}{1-\rho_i}} (pz_j)^{\frac{\rho_i}{\rho_i - 1}} \right) \right)^{-\frac{1}{\rho_i}} .x_i. \tag{5.4}$$

Combining Equation 5.2 with Equation 5.4 provides the amount of commodity input

$z_{j;t}$ that is required to fulfill the demand of the household for $x_{i;t}$ at time t:

$$fz_{j;i;t} = \underbrace{\left(\frac{\gamma_{j;i}^{\rho_i}\beta_{j;i}}{pz_j}\right)^{\frac{1}{1-\rho_i}} \left(\sum_{j=1}^{m}\left(\left(\gamma_{j;i}^{\rho_i}\beta_{j;i}\right)^{\frac{1}{1-\rho_i}} (pz_j)^{\frac{\rho_i}{\rho_i-1}}\right)\right)^{-\frac{1}{\rho_i}}}_{\text{A}}$$
$$\left[\underbrace{\left(\frac{M-\sum_{l=1}^{n}(px_l\theta_l x_{l;t-1})}{px_i\sum_{l=1}^{n}\left(\frac{\alpha_l}{\alpha_i}\right)}\right)}_{\text{B}} + \underbrace{\theta_i x_{i;t-1}}_{\text{C}}\right]. \tag{5.5}$$

$fz_{j;i;t}$ can be decomposed in three main elements: the intermediate intensity of a service A, the household demand for a service in the current period B and the household demand for a service resulting from the habit formation process C.

5.2.3 Rebound effect

The rebound effect is generally understood as an increase in the use of an intermediate input of a product or service triggered by an amelioration of the input-specific efficiency of the intermediate in question. While in principle rebound is a universal concept and can be applied to any input of a production process, it is mainly studied in the context of energy and environmental policy as it makes the net effect of any increase in energy efficiency ambiguous and may undermine such policies (cf. Sorrell and Dimitropoulos, 2008; van den Bergh, 2011). For the sake of generality, we take a broader perspective on the rebound in this section and will only later turn our attention to energy as an input into the production of private transport services. In our small stylised example, the rebound effect boils down to a change in the amount of intermediate commodities z_{j^*} employed in the provision of services as a consequence of a change in the efficiency γ_{j^*}.

The rebound effect is frequently divided into three separate effects (e.g. Sorrell and Dimitropoulos, 2008), the direct rebound, the indirect rebound or income effect and the economy-wide rebound effect. Although we acknowledge that such a categorisation of the rebound effect may be limited (Turner, 2013), for the illustrative purpose of this section, we adhere to the approach of dividing the rebound effect into the direct, indirect and economy-wide effects.

5.2.3.1 Direct Rebound

The direct rebound effect emerges from the fact that efficiency improvements in the provision of a product or service will lead to a decrease in the effective price of that product or service. Ceteris paribus, this will lead to an increase in the demand for that product or service and thus a higher demand for the intermediates necessary to meet the additional demand. Following others (e.g. Berkhout et al., 2000; Sorrell and Dimitropoulos, 2008), we define the direct rebound effect as the efficiency elasticity of demand for service $\eta^{\text{Service}}_{i^*;t}$ and build on the fact that the efficiency elasticity of demand for the services is equal to the efficiency elasticity of demand for the input commodity $\eta^{\text{Commodity}}_{i^*;t}$ plus one $\left(\eta^{\text{Service}}_{i^*;t} = \eta^{\text{Commodity}}_{j^*;i^*;t} + 1\right)$. The direct rebound $R^{\text{Direct}}_{j^*;i^*;t}$ with regard to the service i^* resulting from an efficiency increase in use of the intermediate commodity j^* at time t can thus be computed as:

$$R^{\text{Direct}}_{j^*;i^*;t} = \eta^{\text{Service}}_{i^*;t} = \eta^{\text{Commodity}}_{j^*;i^*;t} + 1 = \frac{\partial fz_{j^*;i^*;t}}{\partial \gamma_{j^*;i^*}} \frac{\gamma_{j^*;i^*}}{fz_{j^*;i^*;t}} + 1. \tag{5.6}$$

The direct rebound originates from each of the three main components of the demand for commodities: the intermediate intensity A and the household demands for the service B and C. It can be decomposed to:

$$\begin{aligned} R^{\text{Direct}}_{j^*;i^*;t} = & \underbrace{\frac{\partial A}{\partial \gamma_{j^*;i^*;t}} \left(\frac{\gamma_{j^*;i^*;t} B}{AB + AC} + \frac{\gamma_{j^*;i^*;t} C}{AB + AC} \right)}_{\text{input change due to change of input intensity}} \\ & + \underbrace{\frac{\partial B}{\partial \gamma_{j^*;i^*;t}} \frac{\gamma_{j^*;i^*;t}}{B + C}}_{\text{input change due to change in current demand}} \\ & + \underbrace{\frac{\partial C}{\partial \gamma_{j^*;i^*;t}} \frac{\gamma_{j^*;i^*;t}}{B + C}}_{\text{input change due to change in demand due to habit}} \end{aligned} \tag{5.7}$$

The first term is the input change due to change of input intensity, the second is the input change related to a change of current consumption decision and the third term is the input change attributable to the habit formation process.

In contrast to many other studies, we take into account that household demand can feature rigidities and thus the rebound effect can also be expected to depend on how fast household demand changes. In our context, which includes a habit formation process over two periods, the rebound effect is thus time specific and can be expected to vary between the period of the actual efficiency shock and the subsequent periods. The overall direct rebound effect must be evaluated by taking into account the changes of $fz_{j^*;i^*;t}$ over the period of the efficiency change s and all subsequent periods $s+1, s+2, \ldots$. But as we limit ourselves to the direct rebound and for the time being abstract from income and general equilibrium effects, we can focus on the period of the efficiency shock and the period directly afterwards. Accordingly, in the following we will first determine the rebound at period s and then at $s+1$.

5.2.3.1.1 Rebound in t=s:

Since demand arising from habits is based on the previous period and thus will not instantly react to a efficiency increase in period s, or more formally $\frac{\partial C}{\partial \gamma_{j;s}} = 0$, the rebound in s is only driven by the change in input intensity and change in current demand. Thus:

$$R^{\text{Direct}}_{j^*;i^*;s} = \frac{\partial A}{\partial \gamma_{j^*;i^*;s}} \left(\frac{\gamma_{j^*;i^*;s} B}{AB + AC} + \frac{\gamma_{j^*;i^*;s} C}{AB + AC} \right) + \frac{\partial B}{\partial \gamma_{j^*;i^*;s}} \frac{\gamma_{j^*;i^*;s}}{B + C}. \tag{5.8}$$

The change in input intensity is governed by the same mechanism as for input-augmenting / input-biased technical change, which is illustrated in Acemoglu (2002). If $\sigma_{i^*} < 1$, producers of the service find it difficult to substitute in favour of the input experiencing a higher efficiency and the corresponding input intensity falls after the efficiency shock. If, however, input substitutability is rather high and $\sigma_{i^*} > 1$, producers will take advantage of the efficiency increase by using more of the respective input in relative terms and the input intensity rises. Since $\left(\frac{\gamma_{j^*;i^*;t}B}{AB+AC} + \frac{\gamma_{j^*;i^*;t}C}{AB+AC}\right) \geq 0$ holds for all plausible parameter specifications, this implies that the rebound from an input change associated with a change of input intensity is negative if $\sigma_{i^*} < 1$, zero if $\sigma_{i^*} = 0$ (this implies a Cobb-Douglas production function in which input intensities are constant) and positive if $\sigma_{i^*} > 1$.

With regard to changes in current demand, following the logic that $\frac{\partial px_{i^*}}{\partial \gamma_{j^*;i^*;s}} \leq 0$ must hold as otherwise the efficiency improvement would be discarded, $\frac{\partial B}{\partial \gamma_{j^*;i^*;s}} \geq 0$ and current demand will increase. In combination with the fact that for all possible parameter values $\frac{\gamma_{j^*;i^*;t}}{B+C} \geq 0$, there is a positive rebound arising from a change in current demand.

But due to the ambiguity with regard to the effect arising from the input intensity, the total direct rebound effect in period s remains unclear and depends on the parameterisation of the model, in particular with regard to the definition of σ_{i^*}.

5.2.3.1.2 Rebound in t=s+1:

Putting any general equilibrium effects aside, in the period following the efficiency shock $s+1$, there are no further adjustments attributable to the change in efficiency with regard to input intensity and current demand or formally $\frac{\partial A}{\partial \gamma_{j^*;i^*;s+1}} = 0$ and $\frac{\partial B}{\partial \gamma_{j^*;i^*;s+1}} = 0$. Consequently, the direct rebound in period $s + 1$ reduces to:

$$R^{\text{Direct}}_{j^*;i^*;s+1} = \frac{\partial C}{\partial \gamma_{j^*;i^*;s+1}} \frac{\gamma_{j^*;i^*;s+1}}{B + C}. \tag{5.9}$$

Following the same logic as for the rebound effect arising from additional current demand. The rebound from a change in demand due to the habit of consuming more is positive since $\frac{\gamma_{j^*;i^*;t}}{B+C} \geq 0$ and $\frac{\partial C}{\partial \gamma_{j^*;i^*;s+1}} \geq 0$.

5.2.3.1.3 Overall direct rebound:

Table 5.1 gives an overview of the different direct rebound channels in this simple illustrative example. As expected, if due to habits, households do not instantaneously adjust their consumption decision in face of a efficiency shock, the direct rebound effect is time dependent. In the period of the efficiency change, only two of the three possible direct rebound channels are active and the effect is reduced compared to a situation without a habit formation process. In the subsequent period, the remaining direct rebound channel is open and can add to the overall effect. Although the other channels are now closed. From a long-run perspective, all direct rebound channels are active and the overall effect is the same as in a situation without demand-side rigidity because of habits. However, given the uncertainty of the direction of the effect from the change in the input intensity,

Table 5.1: Overview of direct rebound effects

Period	Rebound Channel	Effect on Input and Rebound
t=s	Input intensity	negative if $\sigma_{i^*} < 1$;
		neutral if $\sigma_{i^*} = 1$;
		positive if $\sigma_{i^*} > 1$
	Current demand	positive
	Demand from habits	neutral
t=s+1	Input intensity	neutral
	Current demand	neutral
	Demand from habits	positive
overall	Input intensity	negative if $\sigma_{i^*} < 1$;
		neutral if $\sigma_{i^*} = 1$;
		positive if $\sigma_{i^*} > 1$
	Current demand	positive
	Demand from habits	positive

the overall rebound effect remains ambiguous at first. Only in the case of $\sigma_{i^*} > 1$, we can be sure that in total there is a positive direct rebound from an efficiency improvement.

5.2.3.2 Indirect Rebound

The indirect rebound effect or income effect as it is also termed occasionally, builds on the logic that a decrease in the effective price of a product or service resulting from the more efficient provision of the product or service, will also relax the budget constraint of consumers. That is, if not all of the cost savings are used up by the direct rebound. This enables consumers to demand more of other products or services and may again lead to an increase in intermediate demand which can be interpreted as rebound (e.g. Sorrell and Dimitropoulos, 2008). Thereby the amount of intermediates embodied in the additional consumption of other products or services is crucial. For a ceteris paribus analysis, it is thereby irrelevant what initially triggered the relaxation of the budget constraint and the demand shock associated to the indirect rebound is thus equivalent to a general income increase experienced by the consumer. Accordingly, we define the indirect rebound effect of an efficiency change in the provision of service i^* related to the intermediate input j^* as the change in the embodied intermediate j^* resulting from a change of the consumption of other services following a general change in the budget M in relation to the expected change in intermediate consumption of j^* due to the efficiency gain:

$$R_{j^*;i^*;t}^{Indirect} = \frac{\sum_{i=1;i\neq i^*}^{m} \left(\frac{\partial x_{i;t}}{\partial M} \frac{M}{x_{i;t}} \Delta M f z_{j^*;i;t} \right)}{(\Delta \gamma_{j^*;i^*}) z_{j^*;i^*;t}}. \tag{5.10}$$

The nominator is based on Equation 5.5, which ultimately represents the intermediate j inputs embodied in service i. Note that in our model $\frac{\partial x_{i;t}}{\partial M}\frac{M}{x_{i;t}} = 1$ as we build on a CES framework for the utility function. The denominator features the amount of intermediates j^* that one would expect to be saved in the consequence of the productivity increase on the basis of technical deliberations.

The interpretation of Equation 5.10 is straightforward. All components of $R^{Indirect}_{j^*;i^*;t}$ are positive, thus the budget increase leads to an increase in the use of intermediates and opens an additional channel for the rebound effect. Similar to the direct rebound effect and resulting from the consideration of household habits, the indirect effect is time dependent. As $\frac{\partial fz_{j;i;t}}{\partial \theta_i} \geq 0$, habits have an initial depressing effect on the indirect rebound effect, but in the long run consumption persistence has no effect on the indirect rebound.

5.2.3.3 Economy-wide rebound

As presented above, a change in the efficiency leads to an adjustment of prices and available income. But so far, we have limited ourself to a ceteris paribus analysis of the efficiency change. In a more general setting, where prices and quantities are free to adjust, the change in prices and demand initiated by the efficiency shock will lead to a series of secondary adjustments of prices and quantities beyond the specific area of efficiency change throughout the economy. An example for such a processes would be an increase in the demand of energy of firms if the efficiency improvement in the provision of private services reduces the demand for energy of households and therewith has a lowering effect on general energy prices. Such adjustments are commonly termed as the economy-wide rebound effect as they may also result in an increase in the demand of intermediates and may counter the benefits of the efficiency change.

Since the consecutive adjustment of all prices and quantities can no longer be illustrated in a meaningful manner, an evaluation of the economy-wide rebound effect is beyond the scope of our stylised example. For such an analysis, a general equilibrium framework is well suited. For this reason, we now turn to a general equilibrium analysis of the rebound. At this point, we also become more specific with regard to our evaluation of the rebound effect and study the economy-wide implications of an increase in the efficiency of energy in the provision of transport services by households in the presence of consumer habits on the basis of a computable general equilibrium (CGE) analysis.

5.3 CGE analysis

5.3.1 Model

After having given a comprehensive formal overview of the rebound effect in the context of households, we now explore the rebound effect in a more general setting. On that account, we include the main elements of the stylised example of the previous section in a general equilibrium model. This relates mainly to the utility function with habits and the idea that households are responsible for the provision of certain services such as transportation. Although in order to have a good representation of household behaviour, we implement a somewhat more elaborated nesting structure for household utility and the provision of transport services. Though the mechanisms nevertheless remain the same. We build on a basic version of the WIOD CGE model (Koesler and Pothen, 2013), which is a static (in the sense that there is no investment decision and a fix factor supply), multi-region, multi-sector CGE model. Details on the general setup of the basic CGE model are presented in Chapter 2 and Annex A.1. In the following we present the changes we made to the basic model for the analysis in this paper.

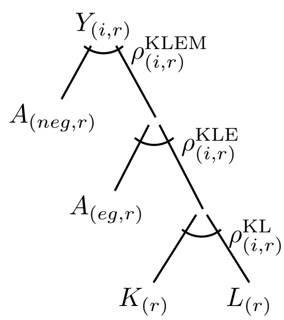


Figure 5.1: Structure of KLEM production function

As we are interested in the effects of a change in the efficiency of the generation of transport services at the households, we extend original structure of household demand in the basic WIOD CGE model with regard to three aspects. First, we extend the basic utility function to feature a distinction between transport services and non-transport consumption. Accordingly, the utility of the representative agent is given by:

$$U_{(r)} = \left(\alpha^{\text{Utrns}}_{(r)} \left(TRNs^{\text{total}}_{(r)} \right)^{\rho^{\text{Utrnsme}}} + \alpha^{\text{Ume}}_{(r)} \left(ME_{(r)} \right)^{\rho^{\text{Utrnsme}}} \right)^{\frac{1}{\rho^{\text{Utrnsme}}}}, \tag{5.11}$$

where

$$ME_{(r)} = \left(\alpha^{\text{Um}}_{(r)} \left(M^{\text{total}}_{(r)} \right)^{\rho^{\text{Ume}}} + \alpha^{\text{Ue}}_{(r)} \left(E^{\text{total}}_{(r)} \right)^{\rho^{\text{Ume}}} \right)^{\frac{1}{\rho^{\text{Ume}}}}, \tag{5.12}$$

and

$$\begin{aligned} TRNs^{\text{total}}_{(r)} &= TRNs_{(t;r)} - \theta^{\text{Utrns}} TRNs_{(t-1;r)}, \\ M^{\text{total}}_{(r)} &= M_{(t;r)} - \theta^{\text{Um}} M_{(t-1;r)}, \\ E^{\text{total}}_{(r)} &= E_{(t;r)} - \theta^{\text{Ue}} E_{(t-1;r)}. \end{aligned} \tag{5.13}$$

Thus, utility is a CES aggregate where non-transport material $M_{(t;r)}$ and energy $E_{(t;r)}$ are combined on the bottom level and transport services $TRNs_{(t;r)}$ enters at the top level. Note, whenever no ambiguity arises with respect to the underlying time period, we omit the t index when we relate variables to the present period t. Following the notation of the theoretical model presented before, α's are input shares and θ's determine the degree of habit persistence. Substitutability between different types of consumption is given by the different ρ's which relate to the respective substitution elasticity through $\sigma = \frac{1}{1+\rho}$. Figure 5.2 illustrates the utility function used in the general equilibrium analysis.

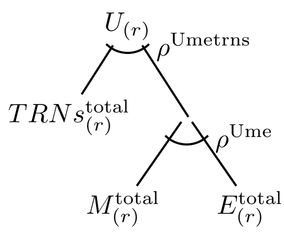


Figure 5.2: Structure of the utility function of households

Secondly, we include in the standard utility function a habit formation process similar to the one described in Section 5.2.1. If household have habits, they adjust only a share of their consumption bundle to the current situation and the other share is determined by their habits. Households must always consume at least $\theta^{\text{Ue}}E_{(t-1;r)}$ of energy, $\theta^{\text{Utrns}}TRNs_{(t-1;r)}$ of transport services, and $\theta^{\text{Um}}M_{(t-1;r)}$ of non-transport material consumed in the previous period. Household habits are formed on the basis of the consumption bundle of the previous period and thus a change in a consumption decision will be quickly incorporated in household habits. The direct interdependence between current consumption and habits results in an adaptation process where current consumption and habits are adjusted period for period until a situation is reached where current consumption equals household habits. As was the case in the previous section, we therefore distinguish between a situation where the adaptation process has just started and habits have not been updated yet (here referred to as short-term) and a situation where the process is completed (here long-term) when illustrating the implications of consumption persistence.

Thirdly, we include a submodule describing the generation of transport services at the representative household $TRNs_{(t;r)}$. We apply a similar formulation as in the MIT EPPA CGE model Paltsev et al. (2004) or Abrell (2010) and assume that households provide $TRNs_{(t;r)}$ on the basis of a two-level nested CES production function of the form:

$$TRNs_{(r)} = \Big(\alpha^{\text{TRNpro}}_{(r)} \left(TRNpro_{(r)}\right)^{\rho^{\text{TRNpropriv}}} + \alpha^{\text{TRNpriv}}_{(r)} \left(TRNpriv_{(r)}\right)^{\rho^{\text{TRNpropriv}}}\Big)^{\frac{1}{\rho^{\text{TRNpropriv}}}}, \tag{5.14}$$

where

$$TRNpriv_{(r)} = \left(\alpha^{\text{TRNe}}_{(r)} \left(\gamma^{\text{TRNe}}_{(r)} E_{(r)}\right)^{\rho^{\text{TRNma}}} + \alpha^{\text{TRNma}}_{(r)} \left(TRNma_{(r)}\right)^{\rho^{\text{TRNetrnma}}}\right)^{\frac{1}{\rho^{\text{TRNetrnma}}}}. \tag{5.15}$$

On the bottom level, energy $E_{(r)}$ used for private transport activities is paired with transport material $TRNma_{(r)}$ to form private transport services $TRNpriv_{(r)}$. On the top level, private transport services are combined with transportation services supplied by professionals, such as airlines or coach companies $TRNpro_{(r)}$. Again, α's are input shares and the degree of substitutability is given by the different ρ's. The level of energy efficiency is described by $\gamma^{\text{TRNe}}_{(r)}$, whereas in the benchmark $\gamma^{\text{TRNe}}_{(r)}$ is normalised to one. The overall structure of the production of transport services is given in Figure 5.3. Although again the nesting structure is slightly more complex, it nevertheless builds on the same concept as the illustrative example from the previous section.

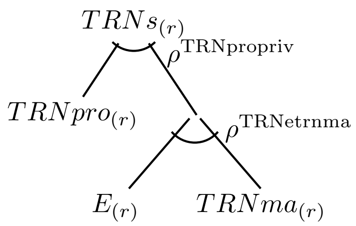


Figure 5.3: Structure of the provision of transport services

Furthermore, households are endowed with a fixed amount of capital and labour. Thus, as in our stylised example, factor supply and therewith the main income source of households is independent of the efficiency shock and enables us to focus on demand side effects. Capital and labour is mobile across sectors within regions but not across regions.

5.3.2 Calibration, aggregation, key parameters and scenario definition

With regard to the general economic structure and energy use, the model is calibrated to 2009 WIOD data (Timmer et al., 2012; Dietzenbacher et al., 2013). Substitution elasticities for production are taken from Koesler and Schymura (2015). We assume for the Armington elasticities of substitution between imports of different regions σ^{MvsM} and between the import aggregate and domestic products σ^{LvsM} that $\sigma^{\text{MvsM}} = \sigma^{\text{LvsM}} = 5$.[2]

Originally, the WIOD dataset covers 40 regions and 35 sectors. But to be able to provide more pertinent, results we aggregate the extensive WIOD data to two regions and 19 sectors. Although our model includes the two regions Germany (GER) and Rest of the World (ROW), for our analysis, we focus on the effects within Germany and abstract from interregional effects. The setup of the sectoral aggregation has been chosen in particular such that it allows to explicitly model the provision of transport services to the households and to allow drawing conclusions regarding energy demand. This includes in particular the sectors providing professional transportation (ATRN, ITRN, WTRN), energy (ENER), and transport material (STRN, TREQ). A detailed overview of the regions and sectors is given in Tables C.1 and C.2 in the Appendix.

[2]To check for sensitivity with regard to Armington elasticities, we also match Armington elasticites from GTAP7 (Badri and Walmsley, 2008) to our dataset and evaluate the rebound. Albeit this requires a somewhat arbitrary match of WIOD sectors to GTAP7 sectors, there are no significant changes and our results seem to be robust to this regard.

Besides having to know the share of household energy consumption relative to the economy-wide energy consumption for our analysis, we also require information on how much energy households use for private transport services. But while WIOD supplies detailed information on what type of energy households consume, it does not include information on the underlying purpose of household energy consumption. By making use of the facts that in Germany (bio-) diesel and (bio-) gasoline brought by households is used exclusively for transportation and that so far alternative propulsion technologies such as electric or gas powered cars are not wide-spread (cf. Kraftfahrt-Bundesamt, 2011, 2012), we can derive the necessary information on the basis of the data reported in the energy use tables of WIOD. By these means, we conclude that household energy consumption accounts for 39.3% of total energy demand in Germany and households use 38.2% of this energy for the provision of private transport services which in turn corresponds to 15.0% of total German energy use.

With respect to our research question, there are a set of crucial parameters. These relate mainly to the degree of demand persistence respectively the strength of the habit, the substitution possibilities between transport services and non transport related consumption and the possibility to substitute energy with transport material in the generation of private transportation services. To account for sensitivity of the model results with regard to these key parameters, we run the simulations for a set of different scenarios. There are two main differences between scenarios. First, we distinguish between model runs with three different levels of demand persistence ($\theta_{\text{NP}} = 0$, $\theta_{\text{MP}} = 0.5$ and $\theta_{\text{HP}} = 0.9$) to account for variation in degree by which households demand is driven by habits. Note that although in reality θ is likely to vary for different households and goods, for this analysis, we focus on a case where household habits are homogenous for all services and consumer goods, i.e. $\theta^{\text{Utrns}} = \theta^{\text{Um}} = \theta^{\text{Ue}}$.[3] Secondly, to give an indication of the range of the implications of the efficiency shock in question, we run a set of simulations with a ridged demand structure and an inflexible provision of private transport services. In this setting, we assume that households do not substitute between other consumer goods and transport services as well as between professional and private transportation ($\sigma_{\text{MIN}}^{\text{Umetrns}} = 0$, $\sigma_{\text{MIN}}^{\text{TRNpropriv}} = 0$ and $\sigma_{\text{MIN}}^{\text{TRNetrnma}} = 0$) and that energy and transport material cannot be substituted when providing private transport services ($\sigma_{\text{MIN}}^{\text{TRNema}} = 0$). These scenarios are supposed to provide us with rather conservative estimations of the effects. We also run a set of simulations with a more flexible demand structure. There, we assume that households adjust there consumption in such a way that the expenditure shares with regard to transportation services and other consumption and between private and professional transport services are constant ($\sigma_{\text{FLEX}}^{\text{Umetrns}} = 1$ and $\sigma_{\text{FLEX}}^{\text{TRNpropriv}} = 1$). Moreover, we assume that the generation of private transport services by households is characterised by a CES function featuring an elasticity of sub-

[3]It is to be expected that the level of demand persistence again depends not only of the type of household, but also on whether the habit relates to basic or luxury goods, whereas the former will feature higher levels of persistence. Moreover, the durability of a good will play an important role in this context. Although, due to the static nature of our analysis, we abstract from this aspect in our study.

stitution of $\sigma_{\text{FLEX}}^{\text{TRNetrnma}} = 0.42$. This value corresponds to the substitution elasticity between value added and energy for the sector providing inland transportation given in Koesler and Schymura (2015). An overview of the scenarios is given in Table C.3 in the Appendix of this paper.

5.3.3 Simulation results

In the following, we present the simulation results regarding the economy-wide implications of a costless and permanent energy efficiency shock of 10% in the generation of private transport services by households in Germany. The efficiency improvement is applied by updating $\gamma_{\text{scen}(GER)}^{\text{TRNe}}$ such that $\gamma_{\text{scen}(GER)}^{\text{TRNe}} = 1.1$. We begin with a situation where household demand features no persistence (NP-MIN and NP-FLEX). Later, we investigate how habits affect the results (MP-MIN, MP-FLEX, HP-MIN and HP-FLEX). Finally, in order to be able to pin down the magnitude of different rebound effects, we decompose the overall rebound observed in scenario NP-FLEX into the direct and indirect rebound effect.

5.3.3.1 Implications without habits

A brief overview of the effects of the efficiency improvement in a setting without habits is given in Table 5.2. Naturally, the effects of the efficiency shock originate from the generation of transport services by households. As energy becomes more effective, input cost are reduced and the costs for one unit of transport services falls by 1.5% in the NP scenarios. Consequently, the demand of households for transport services and thus also its production increases by about 1.5% in the NP-FLEX scenario where household demand is flexible with regard to expenses for different consumption goods, but only increases slightly by +0.1% in the less flexible NP-MIN scenario. As the demand for professional transport (air, inland and water) remains at its original level, any increase in transport demand can be attributed to an increased demand in private transportation services. Resulting from the increased provision of transport services, the demand for transport material ($TREQ$ and $STRN$) and effective energy used for private transport should increase.[4] In fact, in scenario NP-FLEX, demand for transport material ($TREQ$ and $STRN$) increases slightly by 1.1% while the demand for energy increases by 5.3% in efficiency terms or decreases by 4.3% in natural units. Most of the change regarding energy inputs in the provision of private transport services can thereby be related to the the first and second term on the right hand side of Equation 5.7 from the stylised example presented in the previews section, meaning to changes in input intensity and current demand. Moreover, since the transport material intensity of transport services falls, at least a share of the energy increase must thereby be attributed to a change in

[4]Note, in the context of changes in efficiency it is necessary to distinguish between 'natural' and 'efficiency' units. For example, assuming all other things remain unchanged, a 10% efficiency increase of an input will result in a 10% decrease of the input usage measured in 'natural' units, but input usage in 'efficiency' units will remain constant.

input intensity. In deed, the divergent development of transport material and energy inputs in scenario NP-FLEX, where $0 \leq \sigma^{\mathrm{TRNetrnma}} \leq 1$, can fully be attributed to the fact that households substitute transport material with comparatively cheap energy. Of course, as transport material and energy cannot be substituted and the demand for transport remains unchanged, there is no such rebound channel in in scenario NP-MIN and no change in intensities takes place.

Total household consumption increases only marginally by about 0.15% in NP-FLEX and about 0.14% in NP-MIN. As argued before, parts of this increase can be attributed to the fact that a reduction in prices for private transport services generates additional household demand. The other part can be related to the effect which was described in the stylised example by Equation 5.10. As households need to spend less on energy input, they can consume more. This includes energy as well as other goods and services. All this should in general have a positive effect on all sectoral outputs. In NP-FLEX and to a lesser extent in NP-MIN the sectors related to transport do indeed benefit from the additional demand for private transport services and expand their production by up to 0.61%. However, the overall output of non-transport sectors does slightly decrease. The reason for this are general equilibrium effects and crowding-out. The additional demand by households and transport related sectors puts positive pressure on prices and increases input costs of all sectors. Sectors that cannot secure much extra demand must therefore limit their production. With a reduction of 0.69% in the NP-FLEX scenario and 1.42% in the NP-MIN case, the sector reducing its output most is the energy supplying sector ENER. Here the crowding-out is complemented by a drop in demand because of the energy efficiency improvement.

In terms of demand for energy (all measured in 'natural' units), we observe an economy-wide decrease of energy use in Germany of 0.8% in scenario NP-FLEX and of 1.6% in NP-MIN. German household demand for energy reduces by 1.7% (NP-FLEX) and 3.4% (NP-MIN) respectively. Energy used for transportation decreases by 4.4% (NP-FLEX) and 9.0% (NP-MIN). Since the possibilities to substitute towards energy are limited in the NP-MIN scenario, this once more illustrates that energy savings are eroded by an important share by substitution effects. The changes in energy use leads us to the main point of interest, the rebound effect. Building on the work of Lecca et al. (2014), we measure rebound on the basis of the relationship between changes in the use of energy measured in 'natural' units and the relative size of the efficiency increase:

$$R_s = \left(1 + \frac{\Delta E_s}{\left(\frac{E_u}{E_s}\right) \Delta\gamma} \right) 100\%, \tag{5.16}$$

This rebound measure includes direct, indirect as well as economy-wide effects. In a general equilibrium setting which simultaneously incorporates different supply- and demand side processes, rebound can be evaluated for different scopes or perspectives. In Equation (5.16) s is the scope and u the activity where the efficiency change takes place. Accordingly, E_s respectively E_u is energy use, ΔE_s is the change in energy use within the scope s (all three are measured in 'natural' units) and $\Delta\gamma$ is the change in efficiency taking place in activity u. In this analysis, we consider three scopes and compute the rebound for the provision of transport services R_{TRNS}, household consumption R_C and the economy as a whole R_E. If households are flexible with regard to their preferred consumption bundle (NP-FLEX), 56.2% of the energy efficiency improvement in the provision of transport services is lost because of rebound. Because of the absence of substitution effects when households are less flexible, the loss is much lower and amounts only to 10.4% in the NP-MIN scenario. The rebound on the level of total household consumption is 56.2% in the NP-FLEX scenario and again reduces to 12.6% in the NP-MIN scenario. The increase of the rebound effect when changing from a transport service perspective to a more comprehensive household perspective can be explained by the additional energy consumption by households thanks to lower costs for the provision of transport services when these services become more energy efficient. Broadening the scope of the rebound to an economy-wide perspective, results in a rebound of 48.5% (NP-FLEX) and −4.5% (NP-MIN) respectively. When taking a more comprehensive perspective, the energy savings from the energy efficiency improvement are reinforced by the reduction of sectoral output in particular in energy intensive sectors such as ENER, ATRN, ONME and META. As a consequence rebound is reduced. This is in line with the findings of Lecca et al. (2014) who postulate that the rebound effect on the economy level should be smaller than the rebound on the household level if total energy consumption decreases. As a matter of fact, in scenario NP-MIN, the total German energy demand decreases so strong that we can report a negative rebound effect. Thus, in this special case, the usually counterproductive rebound channels eventually generate an additional benefit.

5.3.3.2 Implications in the presence of habits

As previously illustrated formally, consumer habits can have an initial negative effect on rebound triggered from an energy efficiency improvement. Table 5.2 also provides an overview of key effects of a 10% energy efficiency increase in the provision of private transportation in the presence of consumer habits. If households feature a rigid demand structure with regard to substitution between different goods (MP-MIN, HP-MIN), there is no difference between a situation with or without habits. The reason for this is straightforward. If households do not change the nature of their demand, there is no need to update the consumption bundle they are already used to, and thus there is no effect of habits.

If households are ready to substitute but are bound by habits (MP-FLEX, HP-FLEX), household energy demand for the provision of transportation services initially declines by 5.0% (MP-FLEX) and 5.6% (HP-FLEX), respectively. Total household energy demand reduces by 1.9% (MP-FLEX) and 2.1% (HP-FLEX), while economy-wide energy use decreases by only 0.9% (MP-FLEX) and 1.0% (HP-FLEX). Again, all changes are measured in 'natural' units. Compared to a situation without habits (NP-FLEX) there is thus a stronger decline of energy use at each level. The effect is stronger the higher the persistency level θ. As the provision of transport services itself is not constraint by habits, and thus input substitution can still take place, the increased decline can be attributed to the comparatively limited change in demand for transport services. In the presence of habits, households refrain from taking advantage of the cost decrease the efficiency improvement implies and demand for transport services does only rise by 0.8% (MP-FLEX) and 0.3% (HP-FLEX) compared to an increase of 1.5% in a situation where habits are no issue (NP-FLEX). This also implies that the general equilibrium effects through which other sectors where affected by the efficiency shock are now also weakened. Output in the transport material sectors for example is now only expanded by up to 0.2% in comparison to 0.6% in the NP-FLEX scenario. An exception is the energy sector ENER, which reduces its output more strongly by 0.8% (MP-FLEX) respectively 0.9% (HP-FLEX). This is mainly because additional demand for transport services is constrained by habits.

In terms of rebound, this results in the predicted initial reduction of the rebound effect for scenario MP-FLEX and HP-FLEX compared to NP-FLEX. Rebound at the transport service level amounts to 49.7% (MP-FLEX) respectively 44.5% (HP-FLEX), at the household level to 50.8% (MP-FLEX) and 41.0% (HP-FLEX) and 34.9% (MP-FLEX) respectively 46.5% (HP-FLEX) at the economy-wide level. Again the differences of between the rebound for different scopes can be explained by additional household energy demand and negative effects on the output of non-transport sectors. But the effect of habits on the rebound is limited to the short run. In the long run, when households have had the chance to truly update their consumption bundle to the new situation, energy demand and correspondingly the rebound effect would have returned to those values emerging from a situation without consumption persistence (NP-FLEX). The effect of habit is only permanent if household consumption is fully determined by habits. Obviously, in such a situation households would never react to the efficiency improvement with a change of their consumption bundle.

5.3.3.3 Decomposing the rebound

In order to shed more light on the strength of different rebound channels, we disentangle the rebound observed in scenario NP-FLEX into the direct and indirect rebound effect. Thereby, we build on the respective definitions elaborated in the section presenting the stylised model of the previous section which are formalised in Equations 5.6 and 5.10. In the process, we use numerical approximations of the required partial derivatives and for parameterisation turn to the same data we use in the CGE model. It must be noted however, that this approach relies on a ceteris paribus analysis and only holds at the margin. As a consequence, the direct and indirect rebound are isolated effects and are not additive in forming an overall demand side effect. Thus $R^{\text{Total}} \equiv R^{\text{Direct}} + R^{\text{Indirect}} + R^{\text{Equilibrium}}$ does not apply in this setup.

In a situation without consumer habits and where household demand is flexible with

Table 5.2: Overview of results of CGE analysis

	NP-FLEX	NP-MIN	MP-FLEX		MP-MIN		HP-FLEX		HP-MIN	
			short-run	long-run	short-run	long-run	short-run	long-run	short-run	long-run
Change total transport services	1.5%	0.1%	0.8%	1.5%	0.1%	0.1%	0.3%	1.5%	0.1%	0.1%
Change transport energy use	-4.4%	-9.0%	-5.0%	-4.4%	-9.0%	-9.0%	-5.6%	-4.4%	-9.0%	-9.0%
Change household energy use	-1.7%	-3.4%	-1.9%	-1.7%	-3.4%	-3.4%	-2.1%	-1.7%	-3.4%	-3.4%
Change total energy use	-0.8%	-1.6%	-0.9%	-0.8%	-1.6%	-1.6%	-1.0%	-0.8%	-1.6%	-1.6%
Rebound transport	56.2%	10.4%	49.7%	56.2%	10.4%	10.4%	44.5%	56.2%	10.4%	10.4%
Rebound household	56.2%	12.6%	50.8%	56.2%	12.6%	12.7%	46.5%	56.3%	12.6%	12.8%
Rebound total economy	48.5%	-4.5%	41.0%	48.5%	-4.5%	-4.5%	34.9%	48.7%	-4.5%	-4.3%

regard to expenses for different consumption goods (NP-FLEX), the direct rebound of a 10% increase of energy efficiency in the provision of private transport in Germany amounts to 64.7%. This implies that in isolation, the direct rebound effect would erode a large part of the energy efficiency shock. At first, such a high estimate for the direct rebound seems to be at odds with other estimates that can be found in the literature, which, according to a comprehensive review by Sorrell et al. (2009), range from 10% to 30%. But considering that, in particular in Germany and in the context of transportation, the direct rebound appears to be higher and amounts to something around 60% (Frondel et al., 2008, 2012), our estimate nevertheless seems plausible.

Based on our definition as outlined in 5.10, the indirect rebound resulting from a 10% efficiency increase of transport energy in Germany is 19.9% in the NP-FLEX scenario. So while the indirect rebound does reduce the expected savings of an energy efficiency measure, in isolation, this channel is weaker than the price effect leading to direct rebound. To our humble knowledge, there exist only few estimates of the indirect rebound and often the underlying definition varies. The lack of estimates makes it difficult to contrast our finding with the literature. The only study we found that matches roughly our definition is Sorrell (2007), who reports an indirect rebound of 11%. This estimate is clearly smaller than ours, but still it seems to be within range.

5.4 Summary and conclusion

In this paper, we turn our attention to the rebound effect of an efficiency improvement at households and investigate the implications of an efficiency change in the provision of private services by households. In the process, we take into account that household behaviour may be influenced by habits and build on a detailed representation of the provision of private transport services. To have a clear understanding of the underlying effects, we first formally illustrate through which channels the rebound effect emerges on the basis of a simple stylised example. Subsequently, we evaluate the effects of a 10% energy efficiency improvement in the provision of private transport services by German households by means of a more comprehensive CGE analysis.

Our analysis shows that rebound has the potential to significantly reduce the expected energy savings of an energy efficiency improvement at households. Particularly if households have a flexible demand structure, rebound can erode large parts of efficiency increases and in our setting rebound amounts to up to 56%. As is to be expected, household habits have an initial detrimental effect on rebound. They limit the ability of households to adapt to changes in the prevailing price and income system and therewith temporally block parts of the channels that lead to rebound. In the long run however, if habits are formed on the basis of historic consumption and household behaviour is not totally driven by habits, they do not affect rebound. In isolation and on the basis of a ceteris paribus analysis, the direct rebound effect of the 10% efficiency improvement can amount up to 64.7% and the indirect rebound to 19.9%.

On the basis of our study, we cannot concur with the statement of Gillingham et al. (2013) that the rebound is overplayed. On the contrary, in the context of energy efficiency improvements in households, rebound is crucial. Although, in our study, we concentrate on an ad-hoc efficiency improvement, this is also an important finding for policy makers. Efficiency improvements are often believed to be vital to achieve sustainability and policy makers are frequently tempted to prescribe energy efficiency improvements by regulatory law (e.g. EU, 2009). But when discussing such measures, policy makers should be fully aware of the associated rebound potential. This is not to say that compulsory efficiency improvements cannot be beneficial, but the rebound effect puts the effectiveness of such measures to a real test. The results of our study point also to another aspect of the rebound that policy makers should take into account. In the presence of consumer habits, rebound can take some time until its full extent manifests itself. Consequently, an evaluation of energy efficiency measures should always allow for sufficient amount of time so that households can adopt their behaviour to the new situation. The longer habits take to be formed, the longer the time span should be that passes before the rebound effect can be assessed properly. Otherwise, the rebound effect will be underestimated.

Chapter 6

Beyond national economy-wide rebound effects: A CGE analysis incorporating international spillover effects

Abstract

In this chapter we proposes that the national focus of energy 'rebound' studies should be extended to an international context. The potential for energy efficiency improvements in one nation to impact energy use in others means that national targets and actions cannot be considered independently. We develop a general equilibrium analysis of increased efficiency in productive energy use, identifying a range of channels through which spillover effects may be transmitted as a result of trade in goods and services. The results show that energy efficiency in one nation does impact energy use in others. However, the sectoral and spatial distribution of positive and negative effects depends on the nature of the efficiency improvement and factor supply conditions. In particular, changes in relative competitiveness and energy supply conditions act to dampen economy-wide rebound as the boundaries of the economy are expanded.

This chapter is based on the following paper:

Koesler, Simon, Kim Swales and Karen Turner (2014), Beyond National Economy-wide Rebound Effects. An Applied General Equilibrium Analysis Incorporating International Spillover Effects, ZEW Discussion Paper No. 14-025, Mannheim, Germany.

6.1 Introduction

Existing research on the phenomenon of economy-wide rebound effects from increased energy efficiency have identified the importance of trade effects determining the nature and magnitude of economy-wide rebound effects in national economies where efficiency improvements have occurred (e.g. Hanley et al., 2009; van den Bergh, 2011). However, the issue of potential spillover effects on energy demand (and supply) from energy efficiency improvements in one region/nation on others have generally been neglected (Madlener and Alcott, 2009; Sorrell, 2009; van den Bergh, 2011; Turner, 2013). This paper considers how the concept and consideration of economy-wide or 'macro-level' rebound may be extended to consider the impacts of increased energy efficiency in one country on energy use in others. While basic theoretical contributions on the issue of 'global rebound' have been made (e.g. Wei, 2010) and some applied studies have been conducted (e.g. Barker et al., 2009), there exist no applied macro-level rebound studies to date that attempt to fully consider and identify the types of channels through which energy efficiency increases in one region/nation may impact energy demand and supply conditions in others. This is an important knowledge gap, particularly given the global nature of energy-related climate change and the context of supra-national policy targets such as the EU 20-20-20 framework. The potential for energy efficiency policy actions taken in one country to impact energy use (and related emissions) in others implies that target setting and implementation decisions in different member states may not be regarded as independent.

Rebound occurs when improvements in energy efficiency stimulate the direct and derived demand for energy in production and/or final consumption. It is triggered by the fact that an increase in the efficiency in the use of energy acts to reduce the implicit price of energy by increasing the effective energy services gained from each physical unit of energy used (e.g. Jevons, 1866; Sorrell and Dimitropoulos, 2008; Turner, 2013). Moreover, economic impacts in general and rebound pressure in particular will spread to the wider economy through a series of price and income effects. So called 'economy-wide rebound' studies have generally been conducted in the context of improved efficiency in industrial energy use within individual national or regional economies, and most commonly using multi-sector computable general equilibrium, CGE, models (reviewed in Sorrell (2007), with more recent studies including Anson and Turner (2009) and Turner and Hanley (2010)).

The aim of this paper is to add to this literature by extending the spatial focus of the economy-wide rebound effect. In Section 6.2 we consider the type of channels through which an efficiency improvement in productive energy use (i.e. within industries/production sectors rather than the household final consumption sector)[1] in one region/nation may spillover to impact energy demand and supply conditions in direct

[1]Lecca et al. (2014) show that the economy-wide impacts of increased efficiency in household energy use through the Competitiveness Channel in particular (but not solely) are likely to be very different from those in the case of productive energy use considered here.

and indirect trade partners. We also derive the analytical specification through which economy-wide rebound may be quantified for different levels of production activity and final consumption in different spatial settings. In Section 6.3, we provide an overview of an international CGE framework, based on the type of specification commonly used to consider issues of pollution leakage resulting from implementation of environmental policies (e.g. Babiker, 2005; Böhringer and Löschel, 2006; Löschel and Otto, 2009; Elliot et al., 2010). In Section 6.4, we explain how efficiency improvements in productive energy use are simulated in this framework before presenting results of illustrative case studies for first a general energy efficiency improvement in German production (Section 6.5), then a shock targeted specifically in German manufacturing (Section 6.6), and how these shocks transmit to the wider EU and global economies. Conclusions and recommendations for future research are drawn in Section 6.7. Note, in line with the existing rebound literature we focus on changes in the relative price system and concentrate on effects after the efficiency improvement has taken place. Hence our study is no full policy analysis and does in particular consider the costs of the efficiency improvement as sunk costs.

6.2 Extending the boundaries of the economy-wide rebound effect

6.2.1 Potential nature of international trade spillover effects affecting rebound at a supra-national level

Individual regions and nations are linked by goods and factor markets. Consequently, the impacts of economic disturbances and policy interventions in one region/nation may spillover to affect activity in others. The focus of this paper is to consider how analyses of economy-wide rebound effects from increased efficiency in industrial energy use in a given nation may be impacted if the boundaries of 'the economy' are extended. We take a first step in doing so by focussing attention on potential spillover effects resulting from trade in goods and services. Three broad channels are identified:

6.2.1.1 General demand channels

When technical efficiency increases in productive energy use this equates to a positive supply-side shock in the nation where the improvement takes place. The most basic impact will be a general expansion in activity on both the production and final consumption sides of the domestic economy. Where producers and final consumers use a combination of domestic and imported goods and services, positive income and multiplier effects will stimulate both foreign and domestic production, allowing the benefits of the expansion to spread to the wider global economy. This would underlie concerns that rebound in energy use will grow as the boundaries under consideration expand.

However, the source of this expansion is reduced costs of production and therefore output prices in the domestic sector(s) where the efficiency improvement occurs, and in any downstream sectors (foreign or domestic) that (directly or indirectly) use the outputs of the targeted sector as intermediate inputs to production. Thus, the nature of the demand expansion will not simply depend on the nature of domestic and international supply chain linkages but also on changes in relative prices. Moreover, where there are any constraints in factor supply conditions in different regions, there will be opposing upward pressure on prices, which will in turn put downward pressure on economy-wide rebound. On the other hand, where factor returns increase this equates to additional income effects from increased domestic and/or foreign household consumption demands. Thus, a mix of positive and negative pressures on rebound in global energy use will come into play.

6.2.1.2 Competitiveness channel

Another important channel for international spillover effects emerges from the discussion above. First, an increase in the input efficiency of a particular sector results in a comparative advantage of this sector relative to its counterparts in other regions, with the benefits spreading to other domestic sectors that use the targeted sector's outputs as intermediate inputs. Thus, there is pressure for production, particularly in the targeted activity, to increase in the region where the productivity improvements take place. While this is part of the process that causes rebound in local energy demand, any consequent contraction in external production will reduce foreign energy demand and economy-wide rebound viewed from a multiregional perspective. Interestingly, this competitiveness channel could be argued to build on the same mechanism as that in the context of carbon leakage, where production is shifted abroad as a result of higher production costs resulting from environmental policies, but acting in the opposite direction by shifting production to the region where the policy action occurs (see Böhringer et al. (2012)).

6.2.1.3 Energy market channel

Earlier work reported in Turner 2009b; 2013 highlights another 'negative rebound' channel that will also apply in the context of international spillover effects from increased efficiency in productive energy use (but would also apply in the case of increased energy efficiency in final consumption activity – see Lecca et al. (2014)). This is the impact of changing demands on energy supply sectors. Initially, any increase in energy efficiency leads to a decrease in energy demand. Three basic types of effects may result.

First, any reduction in energy demand will ultimately reduce the overall amount of produced energy. Because energy supplying sectors, particularly those that are reliant on non-renewable energy sources and technologies, are generally relative energy intensive, this by itself will curb energy use (both directly and upstream). This is what Turner (2009b) describes as negative rebound pressure from negative multiplier effects (where, for example, increased efficiency in the use of electricity generated from non-renewable sources depresses coal and gas production). However, this will not be limited to domestic energy supply in the nation where the efficiency improvement takes place. Given the high level of integration in international energy markets negative multiplier effects are likely to spillover to external energy supply chain. Whether this has the potential to decrease local or foreign rebound depends thereby crucially of the location of the main energy supply of sector and wider economy where the efficiency improvement takes place. If a large share of the affected energy use is imported, the reduction of energy demand will have a depressing effect on foreign rather than domestic rebound.

Second, the initial decrease in energy demand as efficiency improves will generate downward pressure on domestic and – if energy markets are sufficiently integrated – also external energy prices. Where energy prices are depressed, this will trigger additional energy demand and put upward pressure on rebound in the respective regions. Again, note that this mechanism is very similar to the energy market channel provoking carbon leakage in highly integrated energy markets (see Böhringer et al., 2012), though, again, the shock triggering the drop in local energy demand is different.

Third, Turner (2009a) identifies another potential impact on energy supply conditions where prices and/or revenues enjoyed by energy suppliers are negatively affected by a net reduction in energy demand following from an efficiency improvement. This is that where factor returns fall, particularly returns to capital in what tend to be relatively capital-intensive production processes, this will affect the availability of capital to and the incentive to invest in energy supply capacity. If energy supply conditions tighten, and in order to restore equilibrium in capital markets, market prices for energy will have to rise, which will act to offset positive demand pressure driving rebound.

Overall, the nature and importance of impacts on energy supply, demand and rebound through these different channels in different regions will vary depending on the structure of the existing trade linkages in different energy and non-energy goods and services between regions that have and have not directly benefited from increased energy efficiency. In Section 6.3 we outline an international computable general equilibrium (CGE) modelling framework that is then used (Sections 6.4 to 6.6) to simulate a range of illustrative scenarios that allow us to consider the different channels identified above in an applied setting. First, in order to focus on the specific issue of rebound that is stimulating current academic and policy debate regarding the effectiveness of energy efficiency policies, we consider how the basic specification of economy-wide rebound should be adjusted to consider spillover effects as the boundaries of the economy are expanded from a national to a global level.

6.2.2 Quantifying rebound in a multi-regional setting

Here we build on the economy-wide rebound specifications derived in Lecca et al. (2014) to consider the general equilibrium rebound effects of a proportionate improvement in the efficiency with which energy is used in a single production sector. Own-sector rebound in the targeted sector i, R_i, (incorporating general equilibrium feedback effects on sector

i energy use in addition to direct and indirect rebound effects and reported in percentage terms) is measured as:

$$R_i = \left(1 + \frac{\dot{E}_i}{\gamma}\right) \times 100, \tag{6.1}$$

where $\dot{E}_i$ is the change in energy use in sector i after all agents have adjusted their behaviour in consequence of the technical energy efficiency improvement $\gamma > 0$, both given in percentage terms. To reiterate, this is not direct rebound; rather it is the rebound calculated incorporating the change in energy use in sector i with all general equilibrium effects of the efficiency improvement taken into account.

The first step in considering the own-country economy-wide rebound effect is to consider the impact of the proportionate energy efficiency improvement in the target sector i on total energy use in the aggregate production side of the economy (all $i = 1, \ldots, N$ sectors), E_p. The own-country total production rebound formulation, R_p (in percentage terms), is given as:

$$R_p = \left(1 + \frac{\dot{E}_p}{\alpha\gamma}\right) \times 100, \tag{6.2}$$

where α is the initial (base/reference year) share of sector i energy use in total energy use in production (across all $i = 1, \ldots, N$ sectors) in the domestic economy (which we label d below). The term $\frac{\dot{E}_p}{\alpha\gamma}$ can be expressed as:

$$\frac{\dot{E}_p}{\alpha\gamma} = \frac{\delta E_p}{\alpha E_i} = \frac{\delta E_i + \delta E_p^{-i}}{\gamma E_i} = \frac{\dot{E}_i}{\gamma} + \frac{\delta E_p^{-i}}{\gamma E_i}, \tag{6.3}$$

where δ represents absolute change and the $-i$ superscript indicates all production excluding sector i. Substituting Equation (6.3) into Equation (6.2) and using Equation (6.1) gives:

$$R_p = R_i + \left(\frac{\delta E_p^{-1}}{\gamma E_i}\right) \times 100. \tag{6.4}$$

This shows that the total (own-country) rebound in productive energy use will be greater than the own-sector rebound if there is a net increase in aggregate energy use across all other production sectors. On the other hand, if there is a net decrease in total energy use across all other domestic production sectors, then total rebound in production will be lower than own-sector rebound.

Using a similar procedure (which is outlined in the Appendix to this chapter), we can show that the full economy-wide rebound effect in the domestic economy, R_d, can be expressed as:

$$R_d = R_p + \left(\frac{\delta E_c}{\gamma E_i}\right) \times 100, \tag{6.5}$$

where the c subscript indicates 'consumption' (households).This shows that the total economy-wide rebound in the home country, d, will be larger (smaller) than rebound in the aggregate production sector if there is a net increase (decrease) in energy use in household final consumption.

Here we are also interested in international spillover effects of the energy efficiency improvement on energy use in other countries. Therefore, we define a global rebound rebound effect, R_g, relating to the total impact on energy use in all countries resulting from increased efficiency in the use of energy in sector i within the home economy, d. Again, using a similar procedure, as given in detail in the Appendix to this chapter, this can be expressed as:

$$R_g = R_d + \left(\frac{\delta E_g^{-d}}{\gamma E_i} \right) \times 100, \tag{6.6}$$

where represents global energy use outwith the domestic economy receiving the efficiency shock. Again this shows that the total economy-wide global rebound will be greater than the own-country rebound if there is a net increase in external aggregate energy use following the efficiency improvement within country d. If there is a net decrease then total global rebound will be lower than own-country rebound. Note that it is possible to identify more than one region within the external global economy and disaggregate the changes in global non-domestic energy use accordingly. We do this below in our case study of increased efficiency in German industrial energy use by separately identifying the change in energy use in the rest of the EU-27 and the rest of the world.

6.3 The global CGE modelling framework

To evaluate the economy-wide rebound effect and provide a first analysis of the international spillover effects that come along with an energy efficiency increase, we make use of a static, multi-region, multi-sector CGE model which has been developed along the lines of the Basic WIOD CGE (Koesler and Pothen, 2013). The details on the general setup of the model are presented in Chapter 2 and in Appendix A.1. To be able to asses the role of factor markets on rebound, the basic model is extended to include a (admittedly stylised) flexible labour and capital supply. The respective changes are presented in the following.

Each region is represented by one aggregated representative agent who embraces all households and governmental final demand in a region. The representative agent maximizes his utility by purchasing bundles of consumption goods subject to a budget constraint. The budget is determined by factor and tax income along with (intertemporal and interregional) borrowing or saving. In the initial scenarios modelled we assume that agents supply a fix amount of capital and labour. Then, to allow for a stylised analysis of factor constraints, we relax this assumption and implement a simple flexible factor supply within each region. Then labour is supplied on the basis of a simplified consumption-leisure decision where we account for an stylised unemployment rate of $unemp_{(r)} = 5\%$ which in combination with the benchmark regional labour supply $L0_{(r)}$

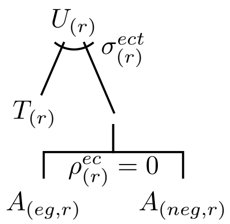


Figure 6.1: Structure of utility function

gives the maximum amount of available labour in an economy $Lmax_{(r)} = \frac{L0_{(r)}}{1-unemp_{(r)}}$ and assume that the elasticity of substitution between consumption and leisure is $ect_{(r)} = 2.0$. Moreover, the extended model implements capital supply functions featuring a stylised price elasticity of $eks_{(r)} = 0.5$. In all cases, capital and labour is mobile across sectors within regions but not across regions. As in this paper we focus on spillovers from trade in commodities, we abstract from interregional factor mobility and investment. Consumption of representative agents $C_{(r)}$ is given as a Leontief composite of energy $A_{eg,r}$ and a non-energy Armington bundle $A_{neg,r}$.[2] Utility $U_{(r)}$ is characterised by a CES function bundling consumption and whenever applicable leisure $T_{(r)}$. The structure of the utility functions is given in Figure 6.1.

For our analysis, the model has been set to feature 28 regions (all EU27 member states, and Rest of the World (ROW)) and to include eight sectors, two of which are energy supply sectors, (Electricity and Gas (E) and Coke Refined Petroleum and Nuclear Fuel (CPN)), along with six others, (Services (SER), Transport (TRN), Construction (CON), Manufacturing (MAN), Food, Beverages and Tobacco (FOB), and Primary Goods (PRI)). However, in the interest of clarity, we aggregate the results of all EU member states apart of Germany to a new region 'Rest of EU' (REU) and limit ourselves to the regions GER, REU and ROW when reporting the results of the simulations. A detailed overview of the regions and sectors covered in our analysis is given the Appendix (Tables D.2 and D.1).

Regarding the basic economic structure, the model builds on data from the World Input-Output Database (WIOD) (Timmer et al., 2012; Dietzenbacher et al., 2013) and is calibrated to the year 2009.[3] The required Armington elasticities are taken from GTAP7 (Badri and Walmsley, 2008; Hertel et al., 2007, 2008) and are mapped to the sectors we consider prior to the implementation into the model. For substitution elasticities

[2]We are aware that modelling consumption on the basis of a Leontief function is not the only possible option and implies that representative agents cannot substitute between different commodities. Although this approach has recently been endorsed by Herrendorf et al. (2013), we nevertheless present the implications for household energy consumption and the rebound effect for different assumptions regarding the substitutability of consumption goods in Tables A.4 and A. 5 in the Appendix and discuss them in Section 6.5 below. However, we maintain the Leontief specification as a conservative assumption in the main simulation results.

[3]The WIOD database is available at http://www.wiod.org. We use data downloaded on the 17th of April 2013.

determining the flexibility of production with regard to inputs, we turn to estimates from Koesler and Schymura (2015).[4]

6.4 Scenario design for CGE analysis

6.4.1 Simulation strategy

We follow the standard approach adopted in CGE studies of economy-wide rebound by examining the effects of a positive exogenous energy efficiency shock first in all production sectors then limit it to a single production sector.[5] This involves applying a single shock in the form a step increase in energy-augmenting technological progress to one or more sectors of a case study economy within a global modelling framework, and contrasting the resulting new equilibrium to the benchmark situation (without efficiency changes). This approach thus implements a ceteris paribus analysis and allows us to attribute all changes to the efficiency shock.

The energy efficiency shock is applied to the second nest of the production function of sectors which has the form:

$$CES^{\text{KLEM}}_{\text{KLE}_{(i,r)}} = \left(\eta^{\text{KLE}}_{\text{KL}} \left(CES^{\text{KLE}}_{\text{KL}_{(i,r)}} \right)^{\rho^{\text{KLE}}_{(i,r)}} + \gamma^{Energy}_{(i,r)} \eta^{\text{KLE}}_{E_{(i,r)}} \left(\min_{eg} \left(\frac{A_{(eg,r)}}{\eta^{\text{E}}_{(eg,r)}} \right)^{\rho^{\text{KLE}}_{(i,r)}} \right) \right)^{\frac{1}{\rho^{\text{KLE}}_{(i,r)}}}, \tag{6.7}$$

where, η are input shares, ρ are substitution parameters and γ^{Energy} indicates the level of energy efficiency which is normalised to be one in the benchmark.

In this paper we consider four scenarios. All involve an illustrative exogenous permanent increase in the (technical) energy efficiency of 10%.[6] The first scenario is characterised by an improvement in energy efficiency at all eight German production sectors $\left(\gamma^{Energy}_{(i,GER)} = 1.1\right)$ in Equation 6.7. In this initial simulation national supplies of capital and labour are fixed to the benchmark level but mobile across sectors. Applying a general efficiency shock to the German economy has significant potential to affect trade

[4]Note, Koesler and Schymura (2015) do not provide substitution elasticities between capital and labour for the Electricity and Gas sector (E). We assume that this elasticity is equal to the corresponding elasticity in the manufacturing sector (0.234). They also do not provide an adequate substitution elasticity between value-added and energy for the Coke Refined Petroleum and Nuclear Fuel (CPN) sector, here we assume that this elasticity is equal to the corresponding elasticity for the chemical and chemical products sector (0.717).

[5]In future work we aim to consider more sophisticated ways of simulating efficiency improvements (e.g. as proposed by Fisher-Vanden and Ho (2010), in modelling a link with R&D activity). Here we confine our attention to a simple exogenous step change, and compare to an unchanging baseline given by the base year dataset, in order to isolate the rebound pressures and spillover channels being studied.

[6]On average the energy efficiency of the German industry has increased by about 1.6% per annum (BMWi, 2013). In the process of our analysis, we also considered efficiency improvements of 5%, 20% and 30%. But as the magnitude of the shock only affects the scale of the different effects and does not change the underlying basic effects, we focus in here on reporting our findings for a medium term (ca. 5 years), mapping to an energy efficiency improvement of 10%.

between regions. This scenario is therefore well-suited to study the international spillover channels identified in Section 6.2.1. Because a flexible supply of factors can for itself affect rebound and trade impacts (c.f. Hanley et al., 2009; Turner and Hanley, 2010), we begin by assuming fixed capital and labour supply. Then in the second simulation we examine the impact of even a partial relaxation of the factor supply constraint in two simple ways. First, we partially relax the labour supply using the simple treatment explained in Section 6.3, where existing households respond to changing returns on labour by substituting between labour and leisure. Second, as also noted in Section 6.3, we permit excess capacity in capital supply that is released in response to increases in the return to (price of) capital. The results of these first two simulations (Scenarios 1 and 2) are discussed in Section 6.5.

However, in practice efficiency improvements are likely to be targeted at specific rather than all sectors. Moreover, in considering a universal efficiency improvement, important sectoral and inter-sectoral effects, such as changes in relative competitiveness, may be masked. Therefore, in the third and fourth simulations we repeat the process above with the same model assumptions as the first and second simulations (respectively) but limit the implementation of the 10% energy efficiency improvement to the German manufacturing (MAN) sector $\left(\gamma^{Energy}_{(MAN,GER)} = 1.1\right)$. The results of the latter two simulations (Scenarios 3 and 4) are discussed in Section 6.6.

6.4.2 The case study of Germany (within the EU and global economies)

Efficiency improvements and the way they diffuse throughout the economy depend crucially on the structure of the economies and in our context in particular their trade structure is of key importance. An overview of some stylised facts about the German economy and the German manufacturing sector are given in in the Appendix (Table D.3). The respective figures relate to our aggregation scheme also illustrated in in the Appendix (Tables D.2 and D.1).

In terms of the sector-specific focus on the simulations reported in Section 6.6, note that, with a share of 26.73% of total production, MAN is one of Germany's main sectors. It accounts for 28.58% of energy use in German production and 16.57% of Germany's total energy consumption (see Table 1 below). Own-sector purchases dominate the intermediate input demand of MAN, with the second most important being SER inputs. However, all inputs may be sourced domestically or imported and non-domestic inputs in German MAN are mainly sourced from the MAN and SER sectors in REU and ROW. In terms of exports, the main customers of German MAN products are the intermediate demand agents MAN and SER in REU and ROW.

In terms of reporting the various general equilibrium rebound effects explained in Section 6.2.2, the energy use shares reported in Table 6.1 below inform the corresponding parameters in the denominator of the rebound equations.

Table 6.1: Energy shares for German rebound calculations - Source: Authors' calculations based on WIOD

	German Manufacturing	German Production	German Economy
Share of Energy Use in German Production (α)	28.58%	100%	NA
Share of Energy Use in German Economy (β)	16.57%	57.99%	100%
Share of Energy Use in EU (ψ)	3.09%	10.81%	18.65%
Share of Energy Use Worldwide (χ)	0.84%	2.95%	5.09%

Table 6.2: Change in key macroeconomic indicators - Scenario 1: 10% increase in energy efficiency in all German sectors fixed national labour and capital supply

	Germany	REU	ROW
GDP (Expenditure Approach)	0.5159%	-0.0050%	-0.0024%
Exports	-0.0873%	-0.0168%	-0.0021%
Imports	-0.1503%	-0.0108%	-0.0001%
Household consumption	0.4948%	0.0005%	-0.0003%
CPI	0.2079%	0.0048%	0.0000%
Price of capital	0.5998%	-0.0069%	-0.0009%
Price of labour	0.7173%	0.0094%	0.0001%
Price of energy (aggregate)	-12698%	-0.0082%	-0.0006%
Household energy use	0.4948%	0.0005%	-0.0003%
Industrial energy use	-5.3403%	-0.0600%	-0.0036%
Total domestic energy use	-2.8892%	-0.0386%	-0.0028%

6.5 Impacts of a 10% increase in energy-augmenting technological progress targeted at all German production sectors (Scenarios 1 and 2)

6.5.1 Macro-level results (Scenario 1 - fixed regional labour and capital supply)

In the first of our four scenarios, we study the effects of simulating a 10% energy efficiency improvement in all German sectors $\left(\gamma_{(i,GER)}^{Energy} = 1.1\right)$. We begin with a situation where total labour and capital supply is assumed fixed within all regions/nations but mobile across sectors. Table 6.2 provides an overview of the main macro-level effects of the efficiency improvement.

The comprehensive efficiency improvement can be interpreted as a general productivity increase in the German economy, putting downward pressure on output prices and

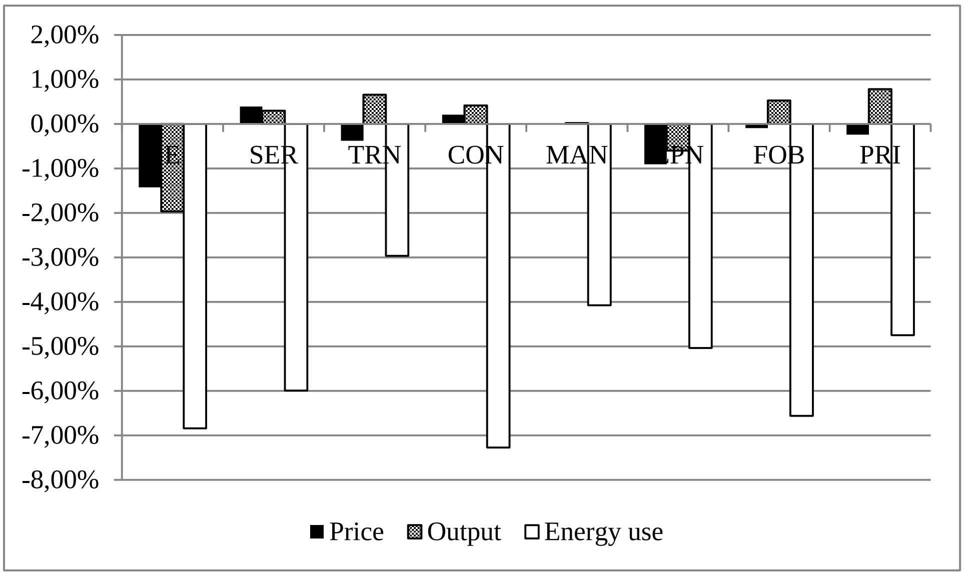


Figure 6.2: Changes in sectoral prices, output and energy use in Germany - Scenario 1

upward pressure on export demand. However, two factors introduce opposing pressures in this scenario. First, constrained factor supply at the national level dampens growth and, as Table 6.2 shows, increases the price of capital (+0.60%) and labour (+0.72%). This is sufficient to cause a net increase in price in the SER and CON sectors (which are less energy-intensive). Second, the energy efficiency improvement causes a net reduction in demand for energy, and the price of energy falls (-1.23%) along with output in the two domestic energy supply sectors (E and CPN – see Figure 6.2).

As the German non-energy supply sectors generally become more competitive and expand their production (this is most limited in the case of MAN, which is not particularly energy-intensive and thus does not benefit as much in terms of reduced costs of production as efficiency improves), there is a net increase in German GDP of 0.52%. However, this is largely as a result of increased domestic demand: despite an increase in the consumer price index, the higher return on capital and labour facilitates an increase in household consumption (+0.49%). While exports rise in the non-energy supply sectors, reduced export demand for the output of the German energy supply sectors causes a net reduction in German exports of -0.09% (though this is offset by a reduction in total import demand of 0.15% as German production generally becomes more competitive so that Germany's trade surplus increases by 0.89%). However, this reduction in export demand to the German energy supply sectors is not due to a negative competitiveness effect (the price of output falls in German E and CPN – Figure 6.2). Rather, this is due to contraction in the global energy supply chain resulting from reduced energy demand in all German production sectors (see discussion of REU and ROW results below). Moreover, taken with the net reduction in total energy use across all production sectors (given the general increase in productive energy efficiency), this is sufficient to elicit the

Table 6.3: General equilibrium rebound effects - Scenario 1: 10% increase in energy efficiency in all German sectors fixed national labour and capital supply

	Own-country production R_p	Own-country total R_d	EU R_g	World R_g
Rebound [%]	46.60	50.18	47.28	46.58
Change [percentage points]		3.58	-2.90	-0.70

first key result concerning economy-wide rebound as the borders of the economy are expanded. Table 6.3 shows that the proportionate rebound effect contracts as we move from German to REU to ROW, which are calculated twice, first for REU, then for ROW (with REU treated as domestic, i.e. within the REU economy).

6.5.2 Energy use (Scenario 1 - fixed regional labour and capital supply)

Let us consider the impacts on energy use in more detail. Table 6.2 shows that the reduction in productive energy use as a direct result of increased in energy efficiency across all sectors causes a drop in the overall price of energy in Germany (this all spills over to negatively impact output prices in the REU and ROW energy supply sectors – see below). This decrease in the market price of physical energy exacerbates the (direct) positive rebound pressure (from the reduced cost of energy services extracted per physical unit on energy). At the economy-wide level, positive rebound on the production-side of the German economy is triggered by two distinct effects. First, as energy becomes cheaper, firms opt for additional energy inputs and substitute energy for relatively more expensive inputs in particular capital and labour. Second, the general expansion of production and final demand increases the demand for all types of inputs, including energy (the General Demand Channels identified in Section 6.2.1). However, the strength and impact of these effects varies across sectors based on production technology and the strength of the positive competitiveness effect. The most marked different is observed in the domestic energy supply sectors, E and CPN, where the negative output effect dominates. As a result, the positive rebound pressure in German productive energy use is partly offset by the reduction in energy use in the contracted energy supply sectors (the Energy Market Channel). The net impact is a reduction in total energy use in German production of -5.34%, which generates the general equilibrium 'own-country production' rebound effect of 46.6% in Table 3 (calculated from Equation (6.2), where $\alpha = 1$ given that the efficiency improvement affects all German sectors, and our results show that element $\frac{\delta E_{op}}{\gamma E_i}$ in the decomposition through Equations (6.4) and (6.4) is negative).

However, while productive energy use falls, Table 6.2 shows that energy use in the German household sector increases in line with the general expansion of consumption (note that this is proportionate due to the Leontief assumption between consumption of energy and non-energy in the utility function – energy use may be expected to rise more if substitution were possible given the reduced price of energy).[7] Thus, total economy-wide general equilibrium rebound effect rises as household energy uses rises where element $\frac{\delta E_c}{\gamma E_i}$ is positive). This increase is from 46.6% (own-country production) to 50.2% (full own-country economy-wide rebound) in the central case reported in the second column of Table 3. This equates to a decrease in total German energy use of just -2.89%. The net impact on the aggregate price of energy in German as a result of reduced total demand is the drop of -1.27% reported above.

6.5.3 International spillover effects (Scenario 1 - fixed regional labour and capital supply)

The economy-wide efficiency shock also has spillover effects in REU and ROW (with results reported at aggregate level in Figures 6.3 and 6.4, but with EU members states modelled separately in generating the results). The key result in terms of the general equilibrium calculation of economy-wide rebound is the negative impact through the Energy Market Channel and has already been mentioned in the context of the impact on energy use in domestic German production. This reflects what Turner (2009b) refers to as negative multiplier effects in energy supply, and which, triggered by the general increase in German productive energy efficiency, equates to an intermediate demand contraction in both domestic and external energy supply chain activity. Accordingly, Figures 6.3 and 6.4 show contractions in output and energy use (despite a small decrease in price) in the REU and ROW energy supply sectors (E and CPN). This exacerbates the negative rebound pressure accompanying the contraction in German energy supply and exports and the economy-wide rebound reported in Table 3 falls from 50.18% to 47.28% in moving from a German to a European level, and reduces further to 46.58% when taking a global perspective of the economy. However, the drop in rebound as we expand the boundaries of the economy from German to EU to world levels is also partly explained by a wider contraction in production activity in the latter two regions resulting from reduced competitiveness relative to the more efficient German sectors, with crowding out worsened by upward pressure on prices due to fixed factor supply. Thus, the Competitiveness Channel also plays an important role here.

In terms of the wider impacts in REU and ROW, Table 6.2 shows that there is a slight contraction in GDP in both regions, and that this is greater in REU where

[7] Indeed the summary results of the sensitivity analysis reported in Table D.4 in the Appendix show that the economy-wide rebound effect grows at all levels as we increase substitutability from zero (in the central Leontief case) up to one (Cobb-Douglas specification). Moreover, the change in moving from the own-country production to total own-country rebound becomes larger (more positive), while the contraction in economy-wide rebound as we expand the boundaries of the economy from Germany to EU and then to the world economy becomes smaller (less negative). Table D.5 in the Appendix shows that the increase in rebound effects with increased substitutability is much smaller when the magnitude of the efficiency improvement is reduced (limited to the German manufacturing) in the results reported in Section 6.6 below. We proceed in our discussion of results based on the somewhat conservative Leontief assumption but note that the specification of the household energy use decision is worthy of future investigation.

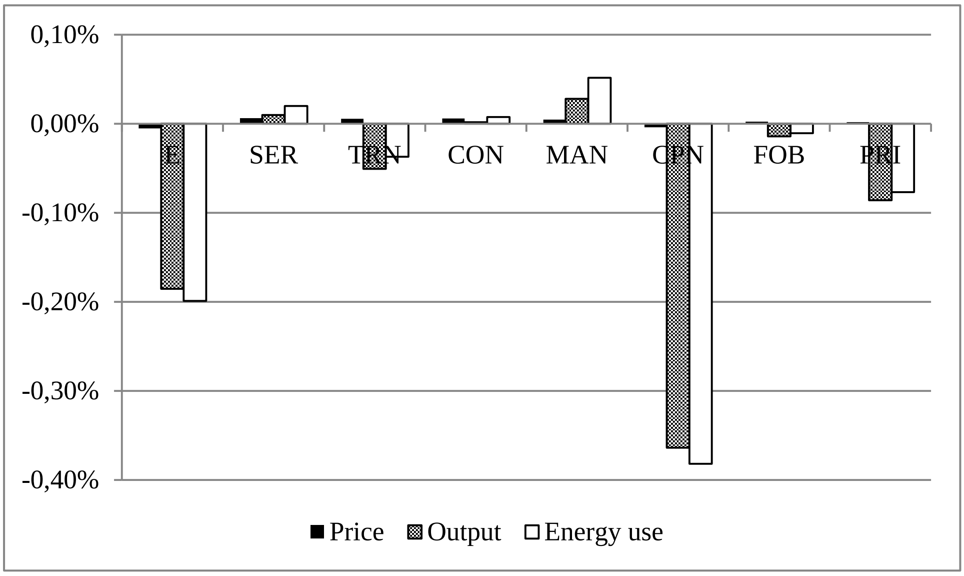


Figure 6.3: Changes in sectoral prices, output and energy use in the rest of Europe - Scenario 1

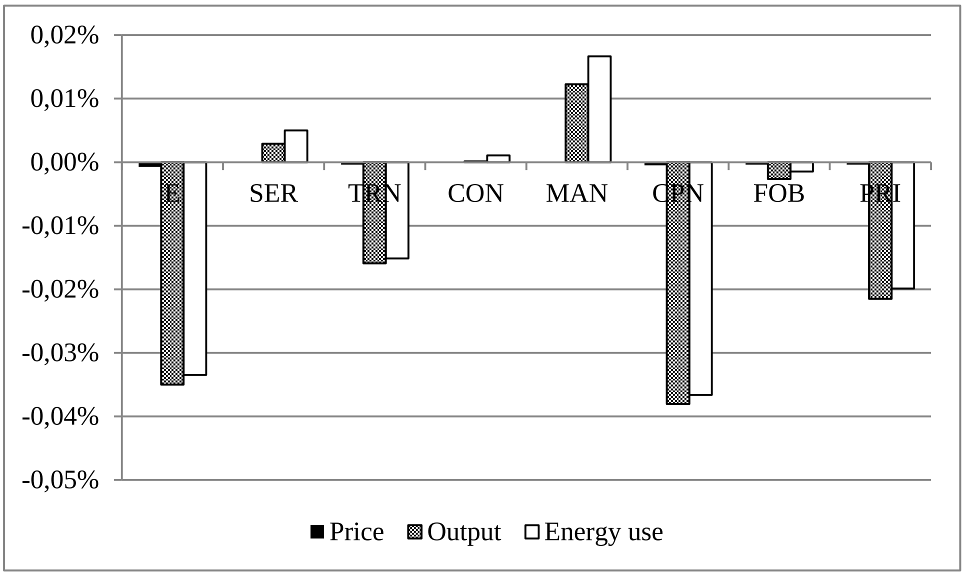


Figure 6.4: Changes in sectoral prices, output and energy use in the rest of the World - Scenario 1

trade linkages with Germany are stronger. What happens at the sectoral level in REU and ROW depends on the relative importance of positive demand effects as the German economy expands (both production activity and household final consumption) and negative competitiveness effects where German prices fall. Moreover, this is set in the context of fixed labour and capital supplies within each country/region. Table 6.2 shows that the supply constraint causes a rise in the price of labour due to the demand effect (which is sufficient to facilitate an expansion in household consumption in REU) but the price/return on capital falls due to the negative relative competitiveness effect combined with reduced energy supply activity. While some REU and ROW sectors do receive a net boost, particularly MAN (due to the weakness of the positive competitiveness effect in the German sector, multiplier effects from the overall expansion of German production and the strength of the income effect as German household consumption rises). Overall, however, Table 2 shows that there is a net crowding out of REU and ROW GDP as a result of the general boost to German producers' energy efficiency in the presence of the supply constraint on labour and capital. This is accompanied by a more than proportionate decrease in productive energy use in both regions due to the negative multiplier effect in the relatively energy-intensive energy supply sectors (though this effect is much more significant in REU, where energy supply linkages with Germany are stronger) are a key element underlying the contracting economy-wide rebound results in Table 6.3.

6.5.4 Partial relaxation of labour and capital supply constraints (Scenario 2)

In Scenario 2 the simulation above is repeated but with some stylised relaxation of factor supply constraints. While we do not model investment and migration processes as in other economy-wide rebound studies such as Hanley et al. (2009), as explained in Section 6.3 we do allow the total labour and capital supplies in each nation/region to adjust according to the currently prevailing capital and labour prices (i.e. assuming some excess capacity in capital and labour that may now be accessed).

The key differences in results from making this one change are apparent in Table 6.4. First, there is a markedly larger increase in German GDP as a result of the general energy efficiency improvement in German production (+0.76% relative to +0.52% in Scenario 1 as reported in Table 6.2 above). There is also a lesser degree of crowding out of activity as reflected by GDP in REU and ROW (though the magnitudes remain small). Thus, positive pressure increases and negative pressures from increased factor supply prices decrease within the General Demand Channels. With only partial relaxation of supply constraints, Table 4 shows that the prices of labour and capital still rise in Germany (but to a lesser extent than under Scenario 1). However, in REU and ROW there are smaller decreases in the price of capital and larger increases in the price of labour. This is due to the fact that, with a stronger German expansion, there is a greater indirect demand shock in REU and ROW, but this still takes place in the presence of some constraints on factor supply. While we do not report the equivalents of Figures 6.2

Table 6.4: Change in key macroeconomic indicators - Scenario 2: 10% increase in energy efficiency in all German sectors flexible national labour and capital supply

	Germany	REU	ROW
GDP (Expenditure Approach)	0.7605%	-0.0022%	-0.0021%
Exports	0.1361%	-0.0145%	-0.0024%
Imports	0.0755%	-0.0071%	0.0000%
Household consumption	0.7427%	0.0046%	0.0003%
CPI	0.1717%	0.0037%	0.0000%
Price of capital	0.5266%	-0.0007%	-0.0002%
Price of labour	0.6835%	0.0096%	0.0005%
Price of energy (aggregate)	-1.3110%	-0.0064%	-0.0004%
Household energy use	0.7427%	0.0049%	0.0003%
Industrial energy use	-5.1201%	-0.0574%	-0.0039%
Total domestic energy use	-2.6574%	-0.0353%	-0.0028%

Table 6.5: General equilibrium rebound effects - Scenario 2: 10% increase in energy efficiency in all German sectors flexible national labour and capital supply

	Own-country production R_p	Own-country total R_d	EU R_g	World R_g
Rebound [%]	47.55	51.81	48.92	48.20
Change [percentage points]		4.26	-2.89	-0.72

to 6.4 for Scenario 2 here, we can report that the pattern of sectoral level changes in prices, output and energy use are similar; however, positive competitiveness effects from falling German output prices is larger and this now leads to the net increase in German exports (+0.14%). The Competitiveness Channel still favours Germany but positive income effects mean that the demand boost to REU and ROW is reflected in an increase in total imports (+.0.08%). Thus, in contrast to Scenario 1, the (larger) boost to Germany's trade surplus (+1.08% relative to +0.89%) reflects an expansion rather than a contraction in international trade activity.

However, while trade increases overall, the key result is still present in that production in and trade between the energy supply sectors (E and CPN) in all regions is reduced as a result of the energy efficiency improvement in German (but to a slightly lesser extent than in Scenario 1). Thus, negative pressure from the Energy Market Channel is still important, just to a lesser degree. At the sectoral level, the pattern of energy use changes are similar but, again, slightly smaller (and the increase in household energy use is larger at +0.74% relative to +0.49% in Scenario 1) so that general equilibrium rebound grows at all levels in Table 6.5. Moreover, the upward pressure on energy use is exacerbated by a slightly larger drop in the aggregate price of energy.

Table 6.6: Change in key macroeconomic indicators - Scenario 3: 10% increase in energy efficiency in German manufacturing fixed national labour and capital supply

	Germany	REU	ROW
GDP (Expenditure Approach)	0.1332%	-0.0006%	0.0002%
Exports	0.0254%	-0.0079%	-0.0041%
Imports	0.0322%	-0.0070%	-0.0047%
Household consumption	0.1453%	0.0003%	-0.0004%
CPI	0.2309%	0.0034%	0.0000%
Price of capital	0.3255%	0.0088%	-0.0007%
Price of labour	0.3696%	0.0077%	0.0000%
Price of energy (aggregate)	0.2440%	0.0078%	0.0001%
Household energy use	0.1453%	0.0004%	-0.0004%
Industrial energy use	-1.4965%	-0.0067%	-0.0031%
Total domestic energy use	-0.8069%	-0.0041%	-0.0024%

6.6 Impacts of a 10% increase in energy-augmenting technological progress targeted at a single German production sector, Manufacturing (Scenarios 3 and 4)

6.6.1 Economic impacts

In this section we consider the impacts of a more focussed energy efficiency improvement, targeted at just one sector of the German economy, MAN. Given the more limited nature of the positive supply-side shock in the German economy, we would expect to observe a smaller expansion in GDP. Tables 6.6 and 6.7 (Scenarios 3 and 4 respectively) reflect this, with a +0.13% increase in German GDP where labour and capital supplies are fixed at the national level (Table 6.6, Scenario 3) growing to +0.22% where a slight relaxation of constraints is possible with supply responding to changing returns (Table 6.7, Scenario 4).

With any extent of supply constraint, there is upward pressure on capital and labour prices. This is shown in Tables 6.6 and 6.7 (declining but still present in the latter). This means that the competitiveness of all sectors not directly benefiting from the efficiency enhancement is likely to be negatively affected as they compete for the factors required to facilitate the expansion of the targeted sector (in the case of downstream producers this acts against the positive effects from lower priced intermediate inputs from MAN). This is apparent in Table 6.8, where the price of output rises in all German sectors except MAN (which itself only enjoys a small reduction in price due to the relatively low energy intensity noted in the discussion of results in Section 6.5). In general, this causes a reduction in output in all but the targeted MAN and the SER and CON sectors within Germany. Exports rise in MAN and CON, but the latter, along with SER, is also boosted as a result of increased intermediate demand from the targeted MAN sector.

Table 6.7: Change in key macroeconomic indicators - Scenario 4: 10% increase in energy efficiency in German manufacturing flexible national labour and capital supply

	Germany	REU	ROW
GDP (Expenditure Approach)	0.2243%	0.0005%	0.0002%
Exports	0.1082%	-0.0070%	-0.0042%
Imports	0.1155%	-0.0055%	-0.0046%
Household consumption	0.2372%	0.0018%	-0.0002%
CPI	0.2140%	0.0029%	0.0000%
Price of capital	0.2593%	0.0076%	-0.0003%
Price of labour	0.3716%	0.0093%	0.0001%
Price of energy (aggregate)	0.2173%	0.0073%	0.0002%
Household energy use	0.2372%	0.0023%	-0.0002%
Industrial energy use	-1.4079%	-0.0053%	-0.0033%
Total domestic energy use	-0.7169%	-0.0026%	-0.0025%

SER in particular benefits as the main intermediate supplier to MAN. However, note that the energy intensity of both SER and CON rises as they substitute in favour of energy in response to the larger rise in factor input prices. The German E and CPN sectors, which suffer as result of the contraction in energy demand in MAN activity as efficiency increases are further impacted by the rise in domestic capital and labour costs. On the other hand, the smaller increase in REU and ROW factor costs, means that the REU electricity and gas (E) sector at least is able to realise a net benefit as a result of the General Demand Channels (offsetting negative effects through the Energy Market Channel).

Similarly, while the REU and ROW MAN sectors are crowded out as a result of the increased competitiveness of the German sector, other external sectors enjoy net boosts (to varying degrees) as a result of both the indirect demand shock of the boost to German activity and through substitution away from German production in favour of now relatively cheaper imports. Table 6.8 illustrates that there is upward pressure on REU and ROW prices due to the (smaller) increase in factor prices in these regions also, but the relative price shift favours the external regions. However, given that the German efficiency improvement is targeted in the MAN sector, the corresponding external sectors suffer in the opposite manner (and to a greater extent given the positive boost to German MAN rather than the purely supply constrained negative effect in the other German sectors).

In terms of the balance of trade activity, under Scenario 3 (factor supply fixed at national level) total German exports receive a net boost of +0.25%, but this is entirely due to the increase in MAN and CON exports given the contraction in all other sectors. On the other hand, imports are driven by both income and substitution effects and rise by more (+0.32%) so that there is a net negative effect on Germany's trade surplus.

All in all, under Scenario 4 (with some relaxation of factor supply), a similar pattern

Table 6.8: Changes in sectoral price, output and energy use - Scenario 3: 10% increase in energy efficiency in German manufacturing fix national labour and capital supply and Scenario 4: 10% increase in energy efficiency in German manufacturing flexible national labour and capital supply

		Scenario 3			Scenario 4	
	Price	Output	Energy use	Price	Output	Energy use
GER						
E	0.2732%	-0.9322%	-0.9261%	0.2406%	-0.8321%	-0.8261%
SER	0.3186%	0.0675%	0.0612%	0.2966%	0.1559%	0.1523%
TRN	0.2820%	-0.2761%	-0.1814%	0.2675%	-0.1969%	-0.1036%
CON	0.2368%	0.1145%	0.0690%	0.2236%	0.2042%	0.1592%
MAN	-0.0833%	0.4328%	-43559%	-0.0945%	0.5145%	-42723%
CPN	0.1741%	-0.7427%	-0.7105%	0.1616%	-0.6582%	-0.6266%
FOB	0.2479%	-0.5512%	-0.5910%	0.2374%	-0.4675%	-0.5060%
PRI	0.2628%	-0.6743%	-0.6907%	0.2582%	-0.5965%	-0.6123%
REU						
E	0.0065%	0.0073%	0.0053%	0.0058%	0.0067%	0.0050%
SER	0.0044%	0.0059%	0.0044%	0.0043%	0.0073%	0.0059%
TRN	0.0059%	0.0292%	0.0296%	0.0057%	0.0300%	0.0310%
CON	0.0026%	0.0032%	0.0018%	0.0025%	0.0050%	0.0036%
MAN	-0.0003%	-0.0719%	-0.0780%	-0.0010%	-0.0723%	-0.0780%
CPN	0.0057%	-0.0172%	-0.0247%	0.0054%	-0.0121%	-0.0185%
FOB	0.0059%	0.0872%	0.0842%	0.0055%	0.0895%	0.0863%
PRI	0.0062%	0.0403%	0.0395%	0.0059%	0.0462%	0.0461%
ROW						
E	0.0000%	-0.0008%	-0.0010%	0.0001%	-0.0012%	-0.0015%
SER	0.0002%	0.0014%	0.0019%	0.0003%	0.0016%	0.0021%
TRN	0.0005%	0.0087%	0.0085%	0.0005%	0.0088%	0.0087%
CON	0.0000%	0.0002%	0.0001%	0.0000%	0.0004%	0.0002%
MAN	-0.0004%	-0.0183%	-0.0194%	-0.0005%	-0.0191%	-0.0202%
CPN	0.0001%	0.0003%	-0.0002%	0.0002%	0.0004%	0.0000%
FOB	0.0005%	0.0113%	0.0115%	0.0005%	0.0116%	0.0117%
PRI	0.0001%	0.0027%	0.0025%	0.0002%	0.0033%	0.0031%

Table 6.9: General equilibrium rebound effects - Scenario 3: 10% increase in energy efficiency in German manufacturing fix national labour and capital supply and Scenario 4: 10% increase in energy efficiency in German manufacturing flexible national labour and capital supply

	Own-sector R_i	Own-country production R_p	Own-country total R_d	EU R_g	World R_g
Scenario 3					
Rebound [%]	56.44	47.63	51.31	50.22	48.11
Change [percentage points]		-8.81	3.68	-1.09	-2.11
Scenario 4					
Rebound [%]	57.28	50.73	56.74	56.05	53.88
Change [percentage points]		-6.55	6.01	-0.69	-2.17

of results emerges as observed under Scenario 3. However, with a more flexible factor supply, the growth effect is stronger and for example GDP increases by 0.22% in Scenario 4, almost twice the 0.13% rise in Scenario 3. Nonetheless, the stronger overall expansion of German production means that, despite the additional factor supply, only the price of capital decreases. Labour is in Scenario 4 even scarcer than in Scenario 3, indicating that eventually capital will be the limiting factor here.

6.6.2 Energy use and rebound

In terms of energy use, the expected energy saving (with no rebound) will be smaller in Scenarios 3 and 4 relative to Scenarios 1 and 2 as a result of the more limited energy efficiency improvement. This is why the α parameter is introduced to the calculation of equation (2) and an additional 'own-sector' general equilibrium rebound effect is introduced in Table 6.9. Remember that this is not limited to the direct rebound effect; rather it reflects the total change in MAN energy use taking into account the full expansionary process and how this acts to further boost the sector's activity level. This is now less energy intensive: Figure 6 shows that output rises but with a reduction in energy use that is less than half the proportionate size the 10% efficiency, reflecting the 54.4% own-sector rebound for Scenario 3, growing to 57.3% in Scenario 4 where the factor supply constraint is partially relaxed.

The changes in total energy use in each region in Tables 6.6 and 6.7 follow a similar pattern to that observed for Scenarios 1 and 2 (Tables 6.2 and 6.4), though these map to slightly larger proportionate rebound effects in Table 6.9. Note that this is despite increased prices in the domestic and foreign energy sectors (Table 6.8), which translates to an increase in the aggregate energy price in Tables 6.6 and 6.7. In Scenarios 1 and 2 the aggregate price of energy was reduced in all regions. When the efficiency improvement is limited to German MAN falling energy market prices is lost as a source of upward pressure on rebound but replaced by the greater proportionate increase in activity levels that is possible even in the presence of factor supply constraints and crowding out of German sectors where efficiency doesn't improve.

In terms of the qualitative pattern of increases and decreases in moving from own-country production to total rebound, and then to EU and global levels, while the results in Table 6.9 (Scenarios 3 and 4) follow the same pattern as what is observed in Tables 6.3 and 6.5 (Scenarios 1 and 2), the underlying composition of effects is different. First, given that the energy efficiency improvement in Scenarios 3 and 4 is not targeted at all German production sectors, a new result is introduced in the first column of Table 6.9. The reduction in the magnitude of the economy-wide rebound effect in moving from the own-sector (MAN) effect to own-country production results in Table 6.9 is explained by the reduction in activity in most other German production sectors. Part of this is due to crowding out of other non-energy supply sectors (which haven't received the efficiency boost). However, negative multiplier effects in energy supply triggered by the reduction in MAN demand for energy as its efficiency improves also make an important contribution, just as they did in Scenarios 1 and 2 (where crowding out also occurred, but all sectors benefited from the efficiency improvement).

Second, as in Scenarios 1 and 2, rebound increases when the change (increase) in household energy use is incorporated to move to the total German (own-country) economy-wide rebound. Note that this element increases by proportionately more in Scenarios 3 and 4 relative to Scenarios 1 and 2 respectively. This is because, while the absolute magnitude of the increase in household consumption and energy use is greater in Scenarios 1 and 2, in relative terms (given the smaller shock) households receive a bigger income boost with proportionately larger increases in capital and labour returns in Scenarios 3 and 4.

Finally, as we expand the geographical focus first from German to EU level, there is a smaller contraction in the size of the rebound effect relative to Scenarios 1 and 2. This is explained by the greater boost to REU production under Scenarios 3 and 4, where only the targeted German MAN benefits from positive competitiveness effects. Here the negative multiplier effects in energy supply triggered by the energy efficiency improvement are only sufficient to bring about a decrease in the REU CPN (coke, refined petroleum and nuclear fuel) sector. The sector E (electricity and gas sector), on the other hand, receives a net boost as a result of the expansion in German MAN, household and other REU activity. As we further expand the geographical focus from EU to world economy level the impact on the energy supply sectors is negligible. Given the boost to all non-MAN, non-energy supply sectors in REU and ROW, the contraction in economy-wide rebound as we expand spatial focus is almost entirely attributable to the crowding out of the external MAN sectors.

6.7 Conclusions and directions for future research

This paper extends the analyses of 'economy-wide' rebound from the national focus of previous studies and investigates whether international spillover effects from trade in goods and services have the potential to change the overall (global) rebound of local energy efficiency improvements. On that account, we propose a measure of economy-wide rebound that is appropriate for use if the boundaries of 'the economy' in question are expanded beyond the borders of the national economy where an efficiency improvement takes place (in one or all sectors). Whether rebound rises or falls as the boundaries are extended depends on whether there is a net increase or decrease in energy use in the area of activity being introduced. While demand-side factors may be expected to cause incremental increases in the size of the proportionate rebound measure as the boundaries are expanded (i.e. considering spatial boundaries in the same additive way as implicitly proposed in the wider literature by, for example, Sorrell (2009)), our findings concur with those of Turner (2009b) and Lecca et al. (2014) in demonstrating that there are downward pressures on economy-wide rebound once price and supply considerations are introduced to the analysis. In the course of our analysis, we share Turner's (2009) focus on increased efficiency in productive energy use through consideration of how positive and negative rebound pressures interact when international spillover effects are taken into account in considering economy-wide rebound at a supra-national level. However, Lecca et al. (2014) demonstrate that similar negative pressures impact the economy-wide response to increased efficiency in household energy use (though the nature of positive rebound pressures is somewhat different).

We identify and study three broad channels through which international spillover of local efficiency improvements regarding sectoral energy use can occur. First, we consider General Demand Channels and how these are restricted by constraints on factor supply. Positive demand effects affecting energy use in non-energy production and household consumption are present in all of the simulation results. However, the strength of these depends particularly on the strength of effects through the second channel identified. This is referred to as the Competitiveness Channel and the nature and magnitude of impacts depends on changes in the price of output in domestic sectors (which may or may not be the target of efficiency improvements) relative to those in corresponding external sectors. The strength of competitiveness effects again depend generally on factor supply conditions but their nature – who benefits (directly or indirectly) – depends very much on the case under study. Here we found that a general efficiency improvement across all German production sectors means that (despite opposing pressure from increased factor prices) any positive demand boost to external production will be offset from a relative reduction in foreign competitiveness. On, the other hand, where only one German production sector (manufacturing) benefited from an efficiency improvement, both demand and competitiveness effects/channels were enjoyed by non-competing sectors in the wider EU and global economies. Nonetheless, in one of the two cases simulated here, with only the German manufacturing sector experiencing an efficiency improvement, the positive competitiveness effect in the targeted German sector was strong enough (even given its relatively low energy efficiency) to be the main determinant of the observed contraction in economy-wide rebound in moving first from German to EU-wide then the global level.

Within the third spillover channel identified, the Energy Market Channel, contractions in both domestic and external energy supply chain resulting from the initial demand reduction as efficiency improves dominate and were shown to have the strongest negating impact on rebound (at all spatial levels) the larger the efficiency improvement. That is, where the efficiency improvement is applied to all German sectors and there is the strongest initial contraction in demand. When we limit the efficiency improvement to German manufacturing, which has a relatively low energy-intensity to begin with, positive demand effects in energy supply from boosted activity in household consumption in all regions, and in REU and ROW production sectors, lessens the negating impact of the Energy Market Channel on rebound at all levels.

In terms of how the research presented here should be developed in the future, supply side issues would seem to be the main priority. First, given the importance of what is assumed about factor supply in the simulations reported here, a key area for developing this strand of research will be to introduce more sophisticated treatment of labour and capital markets. For example, permitting factor mobility between regions would permit consideration of additional potential spillover channels. Moreover, introducing treatment of dynamic adjustment of factor supply would allow us to consider the evolution of economy-wide rebound over time. Second, given the importance of energy supply responses in the results reported here, a priority must be to develop a more sophisticated treatment of energy supply. This should include (but not be limited to) consideration of issues such as just how capacity decision are made (which adds emphasis to the need for consideration of dynamic adjustment), the impact of increasing exploitation of renewable energy sources and technologies, and how energy prices are determined in local and international markets. Finally, application of the type of framework developed here (and further developed through the aforementioned future research priorities) wold be invaluable in considering the domestic and international spillover effects of domestic policies to increase efficiency in household energy use, and the implications in terms of interdependence of energy efficiency policy implementation (for example, under EU 20-20-20) in one nation on energy use in others.

Chapter 7

Sailing into a dilemma: An economic and legal analysis of an EU trading scheme for maritime emissions

Abstract

On the basis of a joint economic and legal analysis, we evaluate the effects of a regional (European) emission trading scheme aiming at reducing emissions of international shipping. The focus lies on the question which share of emissions from maritime transport activities to and from the EU can and should be included in such a system. Our findings suggest that the attempt to implement an EU maritime ETS runs into a dilemma. It is not possible to design a system that achieves emission reductions in a cost-efficient manner and is compatible with international law.

This chapter is based on the following paper:

Hermeling, Claudia, Jan Henrik Klement, Simon Koesler, Jonathan Köhler and Dorothee Klement (2014), Sailing Into a Dilemma - An Economic and Legal Analysis of an EU Trading Scheme for Maritime Emissions, ZEW Discussion Paper No. 14-021, Mannheim, Germany.

7.1 Introduction

7.1.1 Background

Transport is a key contributor to global greenhouse gas (GHG) emissions (ITF, 2010). Despite the need for a comprehensive approach to fight global warming, so far, the global community has failed to agree on global mechanisms to reduce GHG emissions resulting from transport. At date, emissions from air and water transport are generally excluded from the United Nations Framework Convention on Climate Change (UNFCC). According to Article 2(2) of the Kyoto Protocol to the UNFCC, states shall pursue the limitation or reduction of emissions of GHG from aviation and marine bunker fuels, working through the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO). The duty of the contracting states to co-operate within IMO and ICAO refers to the potentially most effective way forward for international climate politics. However, a prohibition of unilateral measures such as the implementation of a regional regulation by the EU cannot be derived from the Kyoto Protocol.

Given this situation, the EU has decided to consider unilateral action. In fact, since 2012, air transport emissions are regulated in the EU by means of an inclusion of aviation activities in the existing European emission trading scheme (EUETS) (EU (2009): EU Directive 2009/29/EC). In addition, the EU has made clear that it is willing to regulate maritime emission as well if IMO does not develop a mechanism targeting shipping emissions in the near future (EU (2002): EU Decision 1600/2002/EC). Indeed, in summer 2013 the European Commission submitted a Proposal for a Regulation on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport and (EU (2013): EU Proposal 2013/0224 (COD), hereinafter referred to as MRV-Proposal). According to the Commission "a robust system for monitoring, reporting and verification (MRV) of greenhouse gas emissions from maritime transport is a prerequisite for any market-based measure or efficiency standard, whether applied at EU level or globally" ((European Commission Proposal 2013/0224, p. 3).Thus, the provided regulation could be extended in the future and evolve into a mechanism aiming at reducing maritime emissions (cf. Engel, 2013). In 2014, the European Parliament has approved the proposal with amendments after first reading. The proceedings have not yet been concluded.

With respect to aviation in 2013 the EU has backed away from applying its scheme for aviation fully to flights to and from the EU to third party countries (EU (2012*b*): EU Memo MEMO/12/854; EU (2012*c*): EU Proposal 2012/328 (COD)) reacting to the difficult economic situation, the criticisms made by foreign states as the United States of America, China, India and Russia as well as the progress made at ICAO regarding a global mechanism. Instead, the EU now proposes amending the EUETS so that only the part of a flight that takes place in European airspace is covered by the EUETS (EU (2013): EU Proposal 2013/0344 (COD)). It is hence conceivable that the EU may choose a corresponding approach also for maritime emissions and may consider regulating only emissions generated by ships in EU waters in the future.

In this paper we evaluate the effects of a potential regional emission trading scheme (ETS) aiming at reducing emissions of international shipping. Thereby we focus specifically on a possible future scheme for maritime emissions by the EU and evaluate the implications of regulating different parts of voyages to and from EU ports. Building on a joint economic and legal analysis, we show that a comprehensive regional EU-scheme that regulates not only shipping emissions in the territorial waters of EU Member States but also in the Exclusive Economic Zones (EEZ) and on the High Sea could, in fact, contribute to a reduction of emissions and bring about an environmental benefit in an efficient manner. However, a trading scheme with such a wide field of application would presumably not comply with international law.

The remainder of this paper is organised as follows. First, we provide a brief overview of the literature discussing market-based mechanisms to reduce emissions from international shipping. Then we outline and briefly review the general setup of a possible European maritime emission trading scheme (EUMETS) seeking to reduce maritime emissions. The described ETS will serve as a basis for the subsequent analysis. Next and on the basis of different possible definitions of the scope, we study the environmental effectiveness, the economic rational and the legal feasibility of the scheme and discuss associated issues in detail. Subsequently, we contrast our findings from the different dimensions and elaborate the implications of our findings regarding the design of a regional scheme for maritime emissions. Finally, we conclude with a brief summary of our findings and relate them to the current developments at the EU and IMO level.

7.1.2 Current state of research

While there exists a rather broad literature with regard to regulating emissions from aviation using a regional emission trading scheme (e.g. Klement, 2007; Pache, 2008; Anger and Köhler, 2010; Athen, 2012), reducing maritime emissions by means of a market-based mechanism (MBM) has so far not attracted so much attention. However, there is a small set of economic and legal reports dealing with some form of European action to regulate shipping GHG emissions.

On the field of economic research, Miola et al. (2011) provide an overview of the instruments that are being discussed at IMO. Above all, they reason that due to its diversity and complexity, the maritime industry does not allow for a simple and clear-cut GHG reduction policy. As a result policy makers will have to dare to balance binding long-term targets with a high degree of flexibility with regard to the implementation of the measure.

In a technical support paper commissioned by the EU Commission, a consortium around CE Delft discusses various policy options to reduce CO_2 emissions from maritime transport (Faber et al., 2009). Overall, they conclude that an ETS or a tax for maritime emissions should be the instrument of choice when targeting a reduction of CO_2 emissions of maritime transport. Reports realised at the MEDDE (2012) and by Franc and Sutto (2014) investigate on the basis of a modelling exercise a cap-and-trade scheme in the maritime sector focusing on the effects of shipping lines and ports. Their findings suggest that an ETS restricted to Europe will lead to distortions and thus argue in favour of a global scheme. In this context, they point in particular to the risk of an undesired modal shift for inter-european transport services.

Koesler et al. (2012) in turn take the perspective of ship operators and evaluate the effects of an ETS for maritime emissions on the organisation and operations of shipping companies. According to their analysis which builds on a series of interviews among ship operators, it is unlikely that a maritime ETS will add significant overhead costs to shipping operations because most of the required monitoring and reporting processes and similar trading activities are already in place due to business reasons or other regulations.

The literature features also some analysis of legal aspects. König and Morgenstern (2009) focus on whether a regional EU trading scheme for maritime transport would comply with international law and give a negative answer, while Lassen (2010) reaches the opposite conclusion. Kremlis (2010) deals with different design options for the implementation of a trading scheme from a legal perspective. Ringbom (2011) addresses various international law questions linked to a potential future EU emission trading scheme for shipping. According to him, international law does "not necessarily" prevent the establishment of a trading scheme that covers emissions that have occurred beyond the territorial waters of the member states or even in other states' maritime zones but places "a number of important limitations on its design". Engel (2013) gives a short legal analysis of the EU Commission's MRV-proposal mentioned above. He concludes that the Commission has not yet decided whether to use market based instruments to combat maritime greenhouse gas emissions. However, he believes that the inclusion of an EUMETS into the existing European trading scheme would be a "likely scenario".

A detailed interdisciplinary research on environmental, economic and legal aspects of the integration of Marine Transport into the European Emissions Trading System is carried out by Bräuerle et al. (2010) in a study on behalf of the German Federal Environment Agency. This work tackles a similar research question as our paper. It also investigates a possible integration of maritime transport into the EUETS and studies the issue taking a legal and an economic perspective. However, the authors build their analysis on a different concept with regard to which emissions are covered in the scheme and explore considering a ship's historic emissions over a certain period as a baseline, regulating the emissions of a ship during its last voyage and an approach regulating not the ship's emissions but rather the maritime transport emissions related to the carried cargo. With regard to a potential environmental benefit, they argue that regulating historic emissions is more effective than the other two options. The legal analysis takes the position that in principle the implementation of an EUMETS does not infringe international law even if it covers emissions arising from vessels outside the territorial seas of EU Member States. Thus, the authors conclude that regulating maritime emissions by including shipping transport into the EUETS is environmentally effective, possible from a legal point of view and it will not entail significant negative effects. This holds true in particular if the reach of the scheme is extended beyond only European shipping activities. But this approach seems to be prone to some legal challenges such as the definition of adequate penalties in case of noncompliance, the discrimination of specific types of ships or the implementation of the scheme without affecting the „Construction, Design, Equipment and Manning Standards“ of UNCLOS. Nevertheless, they conclude that regulating maritime emissions by including shipping transport into the EUETS is environmentally effective, possible from a legal point of view and it will not entail significant negative effects. This holds true in particular if the reach of the scheme is extended beyond only European shipping activities.

7.1.3 Outline of a EU maritime emission trading scheme

There are many possible options of how a future European maritime emission trading scheme could be designed. We focus in our analysis on the implications of different definitions of the scope of the scheme, that is we explore the effects of regulating different parts of shipping routes from and to EU ports. For the time being, we take all other elements of the system as given.[1] In Table 7.1 we outline the basic elements of the scheme which we use as a framework for our analysis if not explicitly stated otherwise. Thereby we build on the IMO proposal for a global emission trading scheme by Norway (IMO (2010): IMO Submission MEPC 60/4/22) and the EU regulation for emissions from aviation (EU (2009): EU Directive 2009/29/EC; EU (2013): EU Proposal 2013/0344 (COD)).

7.1.4 Methodology of environmental and economic impact assessment

We assess and quantify the changes in emissions and economic implications of a regional maritime ETS building on a general equilibrium analysis using a task-specific extended version of the Basic WIOD CGE model (Koesler and Pothen, 2013). The WIOD model is particularly suited for this analysis, as it is capable of reproducing international trade flows on the basis of trade in intermediates. To be able to address the research question of this paper, we developed a transport module which is integrated into the basic model. Thereby the model is enlarged by three main elements: an explicit modelling of international transport services, a modified trading structure accounting for trade specific transport costs, and special provisions required by a regional market based mechanism targeting transport emissions. The respective changes are presented in the following. Other parts of the basic WIOD CGE model remain unchanged.[2]

[1] Discussions of other design elements can be found inter alia in Faber et al. (2009) and Koesler et al. (2012).

[2] For more information on the Basic WIOD CGE model, the reader is kindly referred the short overview of the Basic WIOD CGE model in the Appendix and to the report of Koesler and Pothen (2013).

Table 7.1: Principle design elements of the maritime emission trading scheme under investigation

Element	Design Option
Regulated entity:	All ships with more than 400GT traveling to or from EU ports irrespective the flag they are sailing under
Geographical scope:	Depends on scenario:
	WR: emission on the whole route are regulated
	EEZp: only emissions within the EU Economic Zone and EU territorial waters are regulated
	ETW: only emissions within EU territorial waters are regulated
Links with other ETS systems:	No, allowances cannot be traded with other ETS schemes
Allocation of emission rights:	Full auctioning by EU
Use of revenues:	Possible revenues are included in national budgets
Reference value for emissions:	Bunker fuel consumption during the voyage to or from the EU
Reduction target:	0%, 5%, 10%, 20%, 30% with respect to 2009 emission levels

The original WIOD data includes for each region three sectors associated to transport services, namely air, inland and water transport. But in reality transport service providers can be active globally and their activity need not be in relation to their home region. As a consequence, input-output data does not allow inferring where the activity of a regional transport sector has actually taken place. For example, although one knows that there has been some form of activity in the US water transport sector, it is impossible to say whether this is generated by a US ship travelling from Japan to the US or from Australia to China.

But a regional maritime market based mechanism targets emissions and thus activity arising at certain point of the globe and does not differentiate between the origins of the transport service provider. In contrast to a more standard application of a cap-and-trade approach, for example the EUETS for stationary installations, such a scheme has to cater for the fact that only a certain part of the emissions of the international transport pool is subject to the regulation. Imagine for example an ETS regulating only the total amount of emissions resulting from shipping freight to the EU and leaving out emissions for instance arising from transporting freight from Australia to China. Given the importance of specific transport flows for our research question, instead of using the potentially misleading regional input-output data of the WIOD model all regional transport sectors are aggregated and our model eventually includes only three – now international – transport sectors that supply transport services for each trade flow worldwide. The relevant trade-flow-specific transport costs are calculated on the basis of ad-valorem costs implied by transporting commodities from one region to another region. Thereby, the global transport sectors source their inputs (e.g. energy) and sell their output (i.e. transport services) on world markets as all other sectors in the economy.

Similar to the production of standard commodities in the basic WIOD CGE model, all transport services associated with a particular trade flow are produced on the basis of a four-level constant elasticity of substitution (CES) function as outlined in Figure 7.1. The sum of value-added $VA_{(r)}$ from all regions is joined with a Leontief aggregate of energy $A_{(eg,r)}$ and related emissions $EM_{(em)}$ in the third nest. The value-added-energy composite is then combined with an aggregate of non-energy commodities $A_{(neg,r)}$ at the second level of the production function. Potential process emissions of transport arise at the last production stage.

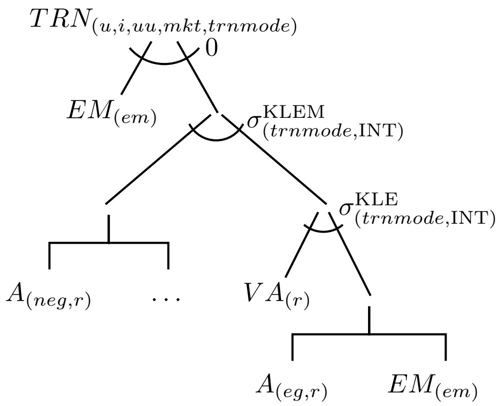


Figure 7.1: Production structure of trade-specific transport flows

In all sectors, emissions are modelled as a necessary input in production which is required if energy or process emission related intermediates are used. The amount of emission required to produce one unit of output is given by the emission intensity of production provided for all sectors in WIOD. The necessary input is supplied by the government agent and in particular in our context can be understood as an emission allowance. Initially the supply of allowances is unlimited and emissions are therefore costless. Only when emissions are capped, the supply is restricted according to the reduction target and as for any other input, market forces determine a price of the allowances, respectively the emissions. If emissions are costly, there are basically three options of how sectors can react. First, sectors can reduce their activity and therefore their need for inputs including emissions to reduce costs. Second, they can adjust their input mix in such a way that fewer emissions are required. They can for example choose to employ more capital, labour or non-energy intermediates instead of energy. All substitution possibilities of the transport sectors are outlined in Figure 7.1. Third, provided that demand for their output is sufficiently inelastic, they can increase their prices to compensate for the additional costs. In this study, we only consider CO_2 emissions.

Moreover, as a consequence of interpreting transport as a complement to trade flows, the Armington (1969) aggregation of the basic model is updated so that it additionally includes transport costs. As illustrated in Figure 7.2, the Armington composite is now produced on the basis of a four-level CES production function. As before, the Armington composite is domestic production in combination with an import aggregate and the import aggregate is a composite of all imports of a commodity composed in the second level of the Armington production function. On the now additional third level, imports of a commodity are combined with necessary transports cost from all transport modes arising from moving the commodity from its origin to the importing region. The fourth level combines the transport costs from the different transport modes (air, inland, water). Note that transport costs are trade flow specific.

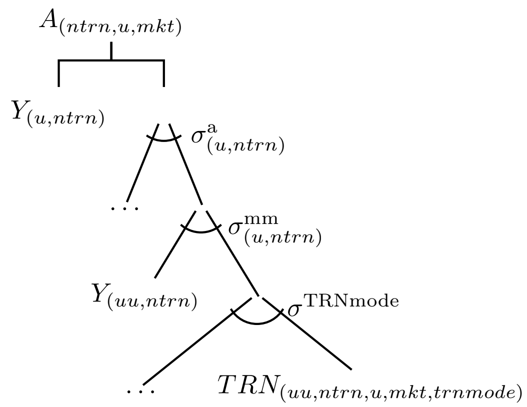


Figure 7.2: Armington structure of trade-specific transport flows

The model is calibrated to the year 2009 using an extended WIOD input-output table including the transport costs implied by each individual trade flow. The analysis is done for the year 2015. To cast the economic structure of 2009 into the future, we employ estimations for annual average real GDP growth rates from the OECD (2012). The basis for computing trade-flow-specific transport costs is information on ad-valorem costs implied by transporting commodities from one region to another region. Ad valorem transport costs for maritime transport were calculated on the basis of the Maritime Transport Costs (MTC) database provided by OECD (2012). Costs for air and road/inland transport were approximated on the basis of average cost proportions between maritime, air and inland transportation given in Group (2009).[3] For substitution elasticities we turn to estimates from Koesler and Schymura (2015). Armington elasticities are taken from GTAP7 (Badri and Walmsley, 2008). We assume that air, water and inland transport are perfect substitutes for transportation between regions. Inland transport between regions with no land link is however not possible.

For our analysis of a regional maritime ETS installed by the EU, we consider five regions with different distances to the EU namely “Europe” (EU), “North America” (NAM), “Middle Distance” (MID), “Far East” (FEA) and “Rest of the World” (ROW).

[3]In order to ensure that the WIOD dataset remains balanced, we are obliged to adjust some of the data provided by the MTC database. In the process we scale the ad-valorem transport costs of all inputs to one sector / final demand agent by the same parameter such that the overall input transport costs of the sector / final demand agent match the corresponding transport input in the WIOD dataset. Note that this process does not distort the original input cost structure of the sector, as it does not affect relative input costs.

An overview of the regions is given in Table E.1 in the Annex of this paper. With regard to the sectoral aggregation, we distinguish between three different sectors on the basis of their ad-valorem transportation costs: HIGH, LOW and NTR, three transport modes: AIR, INLAND, WATER and one energy carrier ENERGY which also features high ad-valorem transport costs. NTR covers sectors with no cross-regional international transport needs like construction. Table E.2 in the Annex gives an overview of the sectors. To analyse the effects of different geographical scopes of a regional maritime emission trading scheme installed by the EU, we use information on shipping routes and lengths given in USNGA (2001) to calculate the share of emissions which are released within the limits of European territorial waters (ETW) and the European economic zone plus European territorial waters (EEZp) for different routes. Thereby we assume that for all routes at least 50 nautical miles are travelled within ETW. An overview of the respective shares is given in Table E.4 in the Annex. The model is run for a set of scenarios covering different scopes (Whole Route, only EEZp and only ETW) and emission reduction targets with regard to 2009 emission levels (0% to -30%). An overview of the scenarios studied in this paper is given in Table E.3 in the Annex. All results are compared to a business as usual situation (BAU), that is a situation where maritime emissions are not regulated.

7.2 Effectiveness with regard to emission reductions

The overall aim of the ETS is to reduce emissions. Given the effectiveness of the cap-and-trade approach, the introduction of the system clearly reduces emissions within the scope of the scheme and could upfront be considered to be environmentally successful. But in the context of a regional scheme with only limited coverage, the more intriguing question are if the scheme is successful in reducing global emissions and if the definition of the scope of the system, in the sense of the share of emissions considered from a regulated entity, affect its environmental effectiveness.

Figure 7.3 presents our simulation results with regard to changes in global transport CO_2 emissions in the year 2015. They suggest that a regional ETS regulating all maritime emissions on voyages to and from the EU on global emissions is effective in reducing emissions. Compared to a business as usual situation (BAU), global transport emissions drop in 2015 by 0.8% when a 5% reduction target is applied and by 2.8% in case of a 30% target. Details on results from other reduction targets are given in Table 7.3 There are no noteworthy effects on emissions of other non-transport sectors. This was to be expected as transport generally composes only a very small share of input costs. Global emissions from water transport reduce between 5.2% and 19% compared to BAU. The emission change for inland transport is positive but in no case more than 1.2%. Emissions from air transport do not change much as a result of regulating shipping emissions and even in the case of a very stringent reduction target (-30%), air transport emissions increase only by a maximum of 0.2%. So while there is some carbon leakage to other transport modes in consequence of the EU scheme capping a part of shipping emissions, the overall emission reduction is positive. There are three main reasons for such a limited shift of transport emissions. First, of all transport modes, water transport is the cheapest option for transporting most commodities and apparently even the introduction of a regional emission regulation does not impede this comparative advantage. Second, leakage to inland transport is limited to the cases where there is a land link between regions. Third, until recently and still in our simulations, European air transport is also included in the EUETS and thus a corresponding shift would also incur additional emission costs.

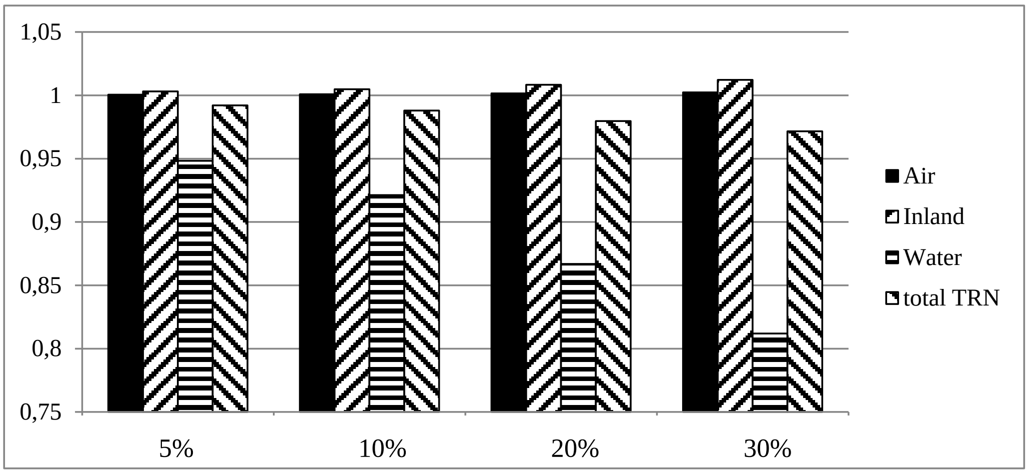


Figure 7.3: Global transport CO_2 emissions in 2015 relative to BAU as a result of a regional ETS regulating all maritime emissions arising on voyages to and from the EU for different emission reduction targets [Index value of one indicates 2015 BAU level]

When determining the scope of the scheme, policy makers are often primarily concerned about the potential environmental benefit, that is how many emissions can be reduced by the scheme implied by their choice. But from an aggregated perspective, for a given stringency (equal reduction targets), the scope of the scheme has no direct effect on the amount of avoided emissions. This becomes clear when recalling two things. First, although the total amount of regulated emission may vary for different scopes, for a specific requested absolute emission reduction, the cap implied by a certain reduction target will be scaled accordingly. Thus if the regulation covers a bigger amount of emissions but the same absolute emission reductions are demanded, the corresponding reduction target can be set less strict and the overall cap will be bigger. Second, for ships, almost all CO_2 abatement technologies involve high fix costs or are non-variable in their use.[4] This implies that in total, abatement options are applied homogenously

[4]Consider for example the installation of alternative propulsion systems such as Sky Sails or the application of special hull coatings to reduce water resistance. Since there is a strictly positive and convex relationship between emissions and speed, except for extreme cases, also slow steaming makes most sense when applied homogenously along the whole route.

during the complete voyage of a ship and are not applied only when a ship enters regulated waters. As a consequence emission intensities can be assumed to be constant along the whole route.

So eventually it is the stringency of the system that determines how many emissions are reduced and the costs of the regulation. The mere scaling of the regulated emissions, that is what share of emissions is included, has no effect to this regard. This also becomes clear when recalling that the total amount of emission of a regulated industry TE is:

$$TE = \sum_j \left(\left(\alpha_j \frac{e_j}{s_j} s_j - a_j \right) + (1 - \alpha_j) \frac{e_j}{s_j} s_j \right), \tag{7.1}$$

where a_j is the total amount of emission that are reduced by entity j as a result of the regulation, e_j is emissions irrespective of any regulation, s_j is the distance travelled and α_j the share of e_j that is regulated. Thereby the term in the first parenthesis of the sum includes regulated emissions and the entities reaction in form of abated emission. The second term includes the unregulated emissions of the entity. Both feature the constant emission intensity $\frac{e_j}{s_j}$. Summing over all a_j makes it clear that the total amount of emissions is independent of α_j and thus the total amount of emissions is not directly influenced by the choice of the scope. Accordingly, from an environmental point of view, when designing a regional maritime ETS, policymakers can choose whatever scope they prefer and do not have to fear consequences with regard to the effectiveness of the scheme.

7.3 Economic perspective

Thanks to their effectiveness in establishing financial incentives for emission abatement in the form of an emission price and the cost-efficiency that comes along with it, market based mechanisms are generally acknowledged by economists to be a superior approach to deal with the externalities of CO_2 emissions (e.g. Stavins, 2003). Thereby the potential advantages of such mechanisms depend crucially on what they cover and initially hold only within the system. Cost-efficiency in the EUETS for example is only granted among entities regulated by the EUETS (e.g. other EU power plants) and not relative to entities outside the EUETS (e.g. domestic heating in EU or US power plant). But while usually this problem relates to the question which entities are incorporated, in a regional system covering mobile entities such as ships, cost-efficiency may not always be granted even among regulated entities and may not be achieved for certain designs of the scope of the system. The stringency of a scheme is generally seen as the parameter determining the costs of the regulation. The mere scaling of the emissions should have no effect. This however neglects that the neutrality of the scope holds only if the scaling of the emissions is homogenous across entities. In the context of regulating transport emissions this may however not be the case. Transport services with European involvement feature a highly varying share of regulated emissions with respect to different definitions of the scope.

Table 7.2: Example illustrating the economic issues associated with the definition of the scope of a maritime ETS

	Distance Travelled	Emission Intensity	Share of Emissions in Coastal Waters
Ship 1	100 nm	1 t per 1 nm	100%
Ship 2	100 nm	1 t per 1 nm	50%

Case 1 Whole Route	Emission Reduction	Acquired Allowances	Allowance required for one additional Ton of Emissions	Share of Allowances Costs
Ship 1	10t	90	1	50.0%
Ship 2	10t	90	1	50.0%
Total	20t	180 (=cap)		
Case 2 Costal Waters	Emission Reduction	Acquired Allowances	Allowance required for one additional Ton of Emissions	Share of Allowances Costs
Ship 1	10t	90	1	66.7%
Ship 2	5t + 5t	45	0.5	33.3%
total	20t	135 (=cap)		

In such a case, emission costs of entities are not distributed solely on the basis of their share of emissions.

Table 7.2 illustrates the issue on the basis of a simple example. There are two ships which both travel the same distance of 100 nautical miles (nm) and feature the same emission intensity of one tonne (t) per nautical mile and same convex abatement costs. The only difference between the two ships is that the first cruises solely through coastal waters while the second is 50% on the high sea and only 50% in coastal waters. Both ships are subject to an ETS with a 10% reduction target, but depending on the scope may not see the same amount of emissions regulated. In the first case, emissions along the whole route are regulated. Thus in the face of the 10% reduction target both ships implement emission reductions to reduce their emission by 10t and buy 90 allowances. If one of the ships would choose to emit one ton more, it would be required to buy one additional emission allowance. In the second case only emissions in coastal waters are regulated. To comply with the regulation, the first ship again abates 10t of emissions and buys 90 allowances. The second ship in turn finds only 50% of its route / emissions subject to the regulation, but must also reduce its emission intensity by 10% and buys 45 allowances to comply. Because of the reasons stated before, the emission intensity is however constant along the whole route, so Ship 2 also saves 10t $(5t + 5t)$ of emission in total. In this situation Ship 1 again requires one allowance to emit an additional ton of emission on its route. But at the same time, Ship 2 now needs only half an allowance for the same purpose. Thus in the second case, the marginal costs for one additional ton of emissions are not equal and cost-efficiency – the main benefit of a market based mechanism – is not achieved. What is more, for the same environmental benefit, Ship 1 has to carry a higher share of the burden associated with the reduction target. This implies that a scheme regulating only a share of total emission along a route comes along with distortions which may have a disproportional negative effect to routes featuring a relatively high share of regulated emissions.

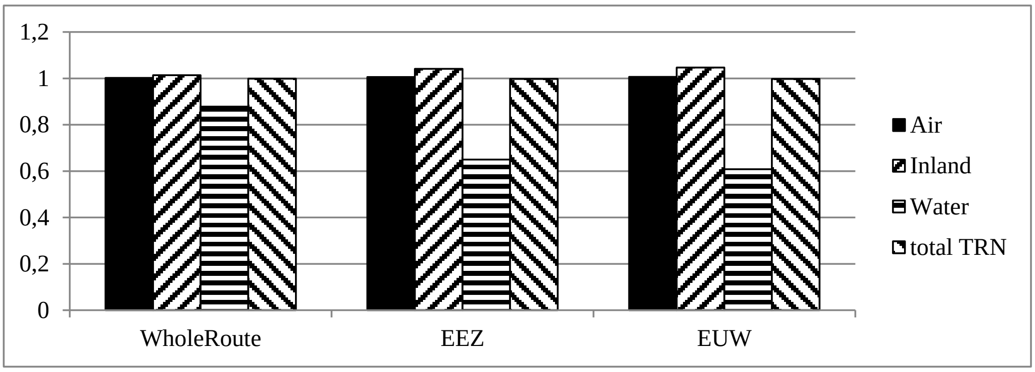


Figure 7.4: Transport activities in 2015 from or to Europe relative to BAU for different definitions of the scope in the case of a maritime ETS with a 20% reduction target [Index value of one indicates 2015 BAU level]

This issue is also apparent in our simulation results. Figure 7.4 illustrates the development of all transport activities in 2015 either originating from or traveling to Europe for different definitions of the scope in the case of a 20% reduction target. Clearly, limiting the scope of the scheme to a share of emissions arising along the routes of ships has a negative effect on shipping activities and leads to a modest increase in modal shift, in particular to inland transport. There are three main reasons why shipping is not replaced by other transport modes to a larger extent. First, of all transport modes, water transport is the cheapest option and even with the ETS in place it remains so for most applications. Second, a shift to inland transport is limited to the cases where there is a land link between regions and the infrastructure between the regions is sufficiently good. Third, if European air transport is also regulated, activity there cannot increase without additional emission costs. The effect of the distortions is even clearer when studying the effect on specific routes which are illustrated for the year 2015 in Figure 7.5 for a 20% reduction target. In a setting covering all emissions of a voyage, all routes are affected in a similar manner (-15.5% to -19.5% relative to BAU). Differences relate to the possibilities to substitute to other transport modes. Transport between NAM and Europe for example cannot be shifted to inland transport because there is no land link and thus water transport is affected less. But the picture is different for other definitions of the scope. For the reasons outlined above, short routes with a relative high share of regulated emissions are affected more than longer routes in such a case. As they must carry a comparatively high burden, in particular voyages linking MID and Europe suffer from a limited scope (-63.5%).

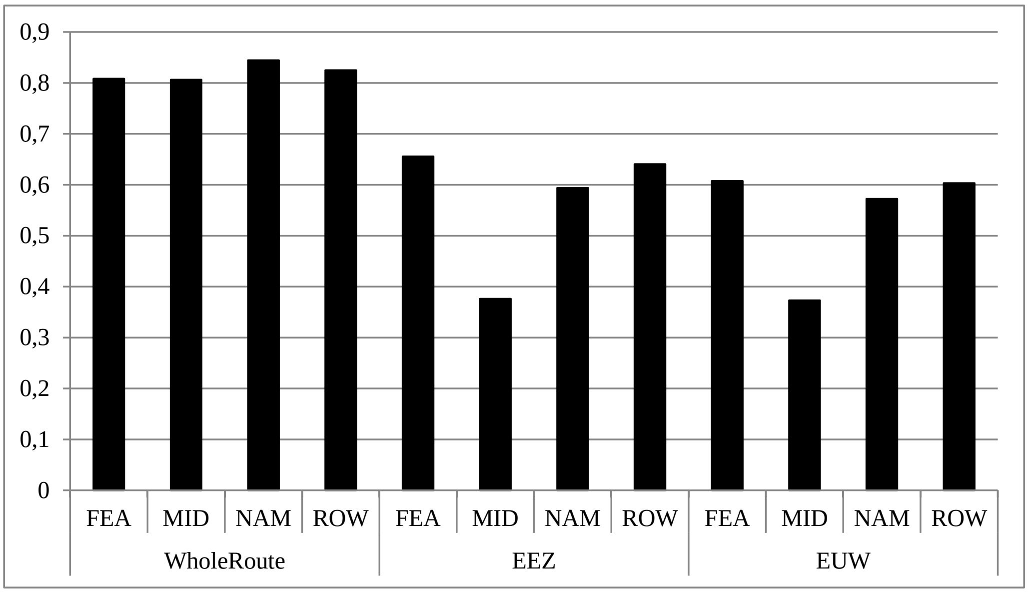


Figure 7.5: Water transport activities in 2015 on different routes from or to Europe relative to BAU for different definitions of the scope in the case of a maritime ETS with a 20% reduction target [Index value of one indicates 2015 BAU level]

Hence, limiting the scope of a maritime ETS provokes distortions and puts a higher burden on routes featuring a high share of regulated emissions. Moreover it impedes cost-efficiency. As a consequence, from an economic point of view, policy makers should choose a comprehensive definition of the scope and include all emissions arising on the whole route that is travelled by a ship.

7.4 Legal feasibility

7.4.1 Assumptions, applicable law and legal methodology

From a legal point of view, a maritime ETS is based on the obligation to surrender allowances ("permission to emit one ton of carbon dioxide during a specified period", cf. EU (2003): EU Directive 2003/87/EC) equal to the total emissions of shipping activities calculated on the basis of a ship's fuel consumption in a past period. Under the regime of a maritime ETS the total annual amount of allowances for navigation is capped in order to achieve a reduction in GHG emissions. Allowances may, however, be sold and purchased. Non-compliance with the obligation to surrender allowances would lead to penalties and the loss of the right to carry out shipping activities within the EU.

Within a comprehensive EUMETS model, the obligation to surrender allowances would not only apply to vessels sailing under a flag of a Member State, but also to vessels from anywhere else. Moreover, it would include all emissions stemming from sea voyages arriving at or departing from a port situated in the territory of an EU-Member State regardless of their point of departure and their destination and would include all parts of a sea voyage and not only to the parts that lie within EU-Member States Exclusive Economic Zones (EEZ) or their territorial seas. However, with respect to the right to innocent passage (Article 17 UNCLOS) vessels just passing through the territorial sea of an EU-Member State would not fall within the scope of the application of a comprehensive EUMETS.

Such a legal design raises a number of questions concerning the compatibility of an EUMETS with international law. We have focussed our legal analysis on the following legal provisions:

- UNCLOS, as the "constitution for the oceans" (Tan, 2006, 192) with many of its provisions merely expressing and clarifying customary international maritime law as developed over time (ECJ, Case C-286/90 – Poulsen and Diva Navigation [1992], ECR I-6019, para. 10; Ringbom (2011), p. 613 (629); Graf Vitzthum (2006), chap. 4 para. 106).
- In the absence of explicit provision in UNCLOS by directly applying rules of customary international law. In any case, the special provisions of UNCLOS have to be seen and interpreted in the light of these underlying more general rules.
- The International Convention for the Prevention of Pollution From Ships, 1973 as modified by the Protocol of 1978 (MARPOL), which has been drafted and is exercised by IMO.
- Bilateral treaties in form of so called mixed agreements concluded between both the EU and its Member States on the one hand and a third country on the other, in particular the Agreement on maritime transport between the European Community and its Member States and the government of the People's Republic of China which came into force on 1st March 2008.
- Bilateral treaties that have been concluded by Member States of the European Union with third countries, e.g. the Friendship, Commerce and Navigation Treaty (Freundschafts-, Handels- und Schiffahrtsvertrag) between the Federal Republic of Germany and the United States of America, which was signed 29 October 1954 and entered into force 14 July 1956.
- World Trade Law, namely the General Agreement on Tariffs and Trade (GATT) and the General Agreement on Trade in Services (GATS).

The analysis is based on the principles of interpretation as recognised in jurisprudence. It has not covered legal limitations arising from European Union Law itself. Needless to say a Directive establishing a scheme for the trade of emission allowances would have to comply with the various legal provisions as set forth in the Treaty on European Union (TEU), the Treaty on the Functioning of the European Union (TFEU) and the Charter of Fundamental Rights of the European Union (ChFREU).

7.4.2 Infringements of international law

The analysis of the legal provisions mentioned above cannot be presented here in detail. For this reason, we will draw attention to the most significant outcome of our considerations. We will show that the EU and its Member States do not have law-making competence (prescriptive jurisdiction) for the regulation of GHG emissions resulting from vessels sailing under Non-EU flags outside the territorial seas due to the EU lacking jurisdiction to regulate these kinds of activities.

7.4.2.1 Division of jurisdiction

The core prerequisite of the legality of a legislative act is that the legislator has "Prescriptive Jurisdiction" on this subject. The division of powers to set binding rules for international shipping activities is basically governed by UNCLOS as interpreted in the light of and amended by customary law. Within this legal framework jurisdiction is distributed between three key players, namely the port state, the coastal state and the flag state (Molenaar (1998), p. 91–95). Furthermore, jurisdiction depends on where the regulated activity takes place. In this respect the law distinguishes the territorial sea (Article 2 UNCLOS), the EEZ (Article 55 UNCLOS) and the high seas (Article 86 UNCLOS). For the purpose of this paper the differentiation between the EEZ and the high seas is not of importance since in general the UNCLOS-provisions for the high seas "apply to the exclusive economic zone in so far as they are not incompatible with this Part" (Article 58 (2) UNCLOS). Consequently, with respect to the international jurisdiction emissions in the EEZ are to be considered emissions on the high seas. In the following, the jurisdiction of the EU to implement an EUMETS is considered for three different models of regulation. To be discussed first is an EUMETS designed to cover solely emissions produced on the territorial seas of the EU-Member States (4.2.2). The second and third models of an EUMETS impose the obligation to surrender allowances for emissions irrespective of where the emissions were produced. Insofar one has to distinguish between an EUMETS encompassing EU-vessels only (4.2.3) and a comprehensive scheme applicable irrespective of the flag the ship is sailing under (4.2.4).

7.4.2.2 Jurisdiction for emissions on the territorial seas of EU-Member States

In general, each sovereign state exercises prescriptive jurisdiction over its own territory (territorial principle). With regard to the law of the seas this principle of customary international law is confirmed by Article 2 UNCLOS. The territorial sea forms the maritime part of the territory of a State and covers a zone not exceeding 12 nautical miles from the baseline (Article 3 UNCLOS) plus the maritime internal waters (Article 8 UNCLOS).

The territorial principle is in some respects limited by UNCLOS and other rules of international law (explicitly Article 2 (3) UNCLOS), namely by the right to innocent passage through the territorial sea (Article 17 UNCLOS) and by the obligation not to hamper the free entry into a State's port or internal waters (Article 211 (3) UNCLOS). Though Coastal States may implement regulations for the prevention, reduction and control of marine pollution from foreign vessels passing through their territorial water (Article 211 (4) UNCLOS), these regulations "shall not apply to the design, construction, manning or equipment of foreign ships unless they are giving effect to generally accepted international rules or standards" (Article 211 (4), Article 21 (2) UNCLOS, with an exception in Article 211 (6) UNCLOS). It is widely accepted that this refers to environmental regulations of MARPOL and the IMO (Ringbom (2011), p. 21, 22). According to Article 211 (3) UNCLOS even the Port State's law-making competence to set out "particular requirements for the prevention, reduction and control of pollution of the marine environment" is limited. Thus, the right to innocent passage and the right of free entry into a port and the internal waters limits the State's competences for unilateral environmental regulation on their territorial seas.

However, these restrictions of national sovereignty do not affect the jurisdiction for the establishment of an EUMETS. Art. 211 (3) UNCLOS and the MARPOL only cover measures against pollution "of the marine environment" as defined by Article 1 Nr. 1 (4) UNCLOS: the introduction by man of substances or energy into the marine environment which results or is likely to result in deleterious effects. Even if a measure that purports climate protection might as well have an indirect influence on the marine environment, it is not within the scope of these provisions. Furthermore and even more importantly, the provisions of Article 211 (3), (4) and Article 21 (2) UNCLOS refer only to requirements directly concerning the vessel's technical characteristics including construction and equipment (Ringbom (2011), p. 613, 621). This interpretation takes account of the objective of UNCLOS to establish international acknowledged rules and standards, which cannot be amended unilaterally, thereby enabling the free movement of vessels without the need to adapt to different standards for maritime navigation (Ringbom (1999), p. 21, 22). Thus, Article 211 (3) and (4) UNCLOS merely hinder the implementation of protective measures as the technical characteristics of a vessel are concerned. Since a maritime ETS does, however, not impose the duty to comply with specific technical requirements it does not interfere with the legal interest protected by Article 211 UNCLOS.

As a result, on the basis of the territorial principle the EU could, in principle, establish a maritime ETS for emissions transmitted in the territorial seas of its Member States including emissions resulting from vessels sailing under foreign flags.

7.4.2.3 Prescriptive jurisdiction for extra-territorial emissions from EU-vessels

It is comprehensible that the EU would go one step further and implement an EU-METS that calculates GHG emissions on the basis of shipping activities not only on the territorial seas, but also on the high seas and on foreign territorial seas.

Under international law there are several principles giving law-making competences as to the regulation of extra-territorial behaviour. Of relevance in the model at hand is the personality principle that allows states to exercise jurisdiction over their nationals. As ships have the nationality of the state flag they are entitled to fly (Article 91 (1) UNCLOS), they fall within the scope of the prescriptive jurisdiction of that state (Article 92 (1) and 94 (1) UNCLOS, cf. Molenaar (1998), p. 83)). This flag state jurisdiction does not cease to exist when a vessel sails into the territorial seas of another state. Therefore, EU-Member States would have jurisdiction to regulate extra-territorial emissions attributable to ships sailing under their own flags. If the EU were to limit the personal scope of an EUMETS to EU-vessels, this would not raise any legal concerns.

7.4.2.4 Prescriptive jurisdiction for extra-territorial emissions from Non-EU- vessels

However, in order to avoid flagging out by European ship operators and competitive disadvantages to EU-companies, a comprehensive EUMETS would in all probability include extra-territorial emissions of ships sailing under foreign flags. Such a regulation could constitute an infringement of the flag-state principle and the freedom of the high sea, i.e. the prohibition to all States to subject any part of the high seas to its sovereignty (Article 87, 89 UNCLOS).

7.4.2.4.1 Incompatibility with flag-state-principle

According to Article 92 (1) UNCLOS there is an exclusive rule-making competence of the flag state for all shipping activities on the high seas as defined in Article 86 UNCLOS (Graf Vitzthum (2006), chap. 4 para. 30; Proelß (2010), para. 64). International Sea Law provides exceptions from these basic provisions in just a few cases, such as the cooperation in the suppression of illicit traffic in narcotic drugs and psychotropic substances engaged in by ships on the high seas (Article 108 UNCLOS).

Apart from these clearly defined exemptions States are not allowed to regulate shipping activities of foreign vessels on the high seas – including the EEZ (Article 58 (2) UNCLOS) – and a fortiori (Article 2 (1) UNCLOS) in parts of the sea that are included in the territorial sea of another State. The EU, which exercises – from the international law perspective – the national sovereignty of their Member States, does interfere with the flag-state-principle when imposing legal duties on ships sailing under foreign flags in the high seas.

7.4.2.4.2 EUMETS as "extra-territorial" regulation

Furthermore, it has to be considered whether and to what extent a comprehensive EUMETS model that calculates fuel consumption on the basis of sea voyages without geographical limitation has to be regarded a "regulation" of activities on the high seas and therefore beyond the limits of national jurisdiction.

One has to keep in mind that as long as vessels do not enter a port of an EU-Member State, an EUMETS does not impose any legal duties on vessels sailing on the high seas. The decision to sail into the territorial sea and to enter a port therein remains free from legal restrictions. Thus, contrary to the legal situation for emissions from permanent installations such as factories falling within the scope of the existing ETS (cf. Article 4 EU Directive 2003/87), vessel's operators would presumably not need a special permission for emitting GHG in the EU's territorial seas. The allowance trading scheme is only activated when a vessel factually enters a Member State's port for the first time.

At first glance, any activity on the high seas, in the EEZ, and on foreign territorial seas, remains legally unrestricted. The same applies if the operator fails to comply with his obligation to surrender emissions allowances. European Law would provide penalties (cf. Article 16 (3) EU Directive 2003/87) and attribute the competence to the European Commission to decide on the imposition of an operating ban on the shipping operator as the last resort (cf. Article 16 (5) EU Directive 2003/87). In any case, in accordance to international law, the geographical scope of an operating ban would be limited to the territorial seas of the EU-Member States. Once again, in sensu strictu the freedom of navigation on the high seas seems to be unlimited. However, further examination reveals that even when vessels are sailing on the high seas and on foreign territorial seas, operators are directly affected by EU legal provisions. An EUMETS would entail the duty to monitor the emissions of the vessel and report them to the administration (cf. Article 14 (3) and Part B of Annex IV to EU Directive 2003/87) for the purpose of determining the number of allowances to be surrendered (cf. Article 12 (2a) EU Directive 2003/87). In this respect EU law governs extra-territorial behaviour. Beside this, one must not only take legal duties into account. When adopting a rather material approach one has to admit that the obligation to surrender emissions allowances for parts of any sea voyage performed outside the EU territorial seas has consequences for behaviour that is as such not subject to the prescriptive jurisdiction exercised by the EU Member States (cf. Pache (2008), p. 65). Although extra-territorial activities are not directly addressed by legal duties, they are subject to the steering effects of the trading scheme. The legal duties of vessels' operators set out by an EUMETS Directive are designed to influence shipping activities on the high seas in order to reduce GHG emissions. It purports vessels' operators to react to the regulation with operational measures such as slow steaming or different route planning, and possibly with technical measures such as alternative fuels. Furthermore, ship operators would be encouraged to reduce the distance of direct sea voyages to or from an EU port to an absolute minimum (for example via intermediate stops in North Africa).

The question whether to factor the economic effects when deciding on the EU's jurisdiction depends on the interpretation of the UNCLOS. It follows from Article 24 (1) lit. a UNCLOS that beyond legal restrictions international sea law also inhibits measures that have the "practical effect of denying or impairing" the freedom of navigation. Although Article 24 applies directly only to the right to innocent passage, its rationale can be transposed by analogy to the freedom on the high seas as defined in Article 87 UNCLOS. Hence, "freedom of navigation" (Article 87 (1) lit. a UNCLOS) means not only freedom from legal restrictions but also the effective freedom to navigation by absence of all influences not authorized under the UNCLOS regime. If read as a guarantee of legal freedom only, the provision of Article 87 (1) UNCLOS would – aside the flag-state principle (Article 92 UNCLOS) and the prohibition to purport to subject any part of the high seas to national sovereignty (Article 89 UNCLOS) – be superfluous.

This interpretation is in conformity with the Convention's provisions on environmental protection. Though – in accordance with customary international law – UNCLOS does not provide state competences for investigations in respect of any activities carried out on the high seas in general, concerning pollution offences Article 218 (1) UNCLOS provides for an exception forming an "universal" port state jurisdiction (Boyle (2006), p. 15, 24). According to this provision the port state shall have the limited competence to undertake investigations and institute proceedings in respect of any illegal discharge from that vessel on the high seas whenever a vessel is voluntarily within the port. The fact that UNCLOS does explicitly empower the legal authority of a state to exercise such competences suggests that states may not tie any administrative consequences as to activities outside the territorial sea (cf. Graf Vitzthum (2006), chap. 4 para. 88).

The ECJ did not share the foregoing opinion in its Judgment of 2011, concerning the inclusion of aviation activities in the Scheme for GHG emission trading, however:

"It follows that the European Union had competence, [...] to adopt Directive 2008/101, in so far as the latter extends the allowance trading scheme laid down by Directive 2003/87 to all flights which arrive at or depart from an aerodrome situated in the territory of a Member State." (ECJ (2011), para. 130)

In its reasoning, the ECJ adopted an extremely limited point of view stating that Directive 2008/101 would not infringe the principle of territoriality or the sovereignty of third states, being only applicable to aircraft flights which depart from or arrive at an aerodrome situated in the territory of one of the Member States. While aircrafts are "physically in the territory" of the European Union, they are, according to the Court, subject to the "unlimited jurisdiction of the European Union". And while flying over the high seas, they are not subject to the allowance trading scheme (ECJ (2011), para. 125 et seq.).

This argument of the ECJ disregards the legal duties for monitoring and reporting as well as the economic impacts of the ETS. As follows from the foregoing, a purely formal approach is not convincing in the light of international law, especially in the field of navigation. Moreover, it does not fit in the European legal framework as the European fundamental rights (cf. ChFREU) as well as the Basic Freedoms of the TFEU as interpreted by the ECJ protect against any measures enacted by the Union itself or its Member States which are – not only by imposing legal obligations but also de facto – capable of hindering the usage of freedom (cf. ECJ, Case 8/74 – Dassonville [1974], ECR 837, para. 5). It is therefore not surprising that the ECJ Judgment on the Air transport sector faces criticism (cf. Athen (2012), p. 337, 339 et seq.; Mayer (2012), p. 1113, 1128 et seq.).

Hence, it is more convincing to interpret UNCLOS as not allowing, in principle, any state to generate considerable economic impacts on navigation on the high sea as an EUMETS purports and would probably have.

7.4.2.4.3 No Justififaction of "extra-territorial" regulation by the effects principle

There exist, however, principles of customary international law establishing extra-territorial jurisdiction over non-nationals that our analysis should consider in order to examine a possible justification of the implementation of an EUMETS. In particular, the so called "effects principle" may allow exceptions from the basic principles of national sovereignty, exclusive flag-state-authority and freedom of the high seas. In core terms, according to the effects principle a state may have jurisdiction to rule on extra-territorial behaviour in order to prevent the occurrence of significant and foreseeable effects for a state, its population or its territory (Molenaar (1998), p. 71; Ringbom (2011), p. 630). In this context the effects principle authorizes states to defend its economic interests against interference caused by foreign public authorities or private companies situated in a foreign country (e.g. cartel agreements concluded extra-territorially but affecting the competition interests of national companies) (Doehring (2004), para. 823). However, in the practice of the Courts the application of the effects principle has always been limited to competition and antitrust law (König and Morgenstern (2009), 181, 189; Ringbom (2011), 630). Whether it could and would be applied in the field of international environmental law and in particular the combat against global warming is left to speculation (cf. Ringbom (2011), 613, 630). Apparently, little legal basic research has been dedicated to this topic. A "handbook" of the law of the Sea does not even mention the effects principle as being capable of justifying interference with the freedom of the high seas with regard to environmental protection (Graf Vitzthum (2006), chap. 2 paras. 82¬–93). As far as legal literature has explicitly touched the question, most authors are nevertheless in favour of the application of the effects principle as a justification of a maritime ETS (König and Morgenstern (2009), 181, 189; Lassen (2010), 570, 574; with regard to the aviation sector Pache (2008), 75 et seq.; Bräuerle et al. (2010), 85 et seq.; Athen (2012), 337, 340; Mayer (2012), 1113, 1130). For this purpose, they argue that the goal of climate protection is a common good that is of essence for individual states as well as the international community. On the further premise that all states and their population would suffer under the effects of a global climate change, it is then argued that all states have a sufficient interest to pass legislation that combats GHG emissions.

While initially plausible, at second glance this motivation is not convincing. The mere fact that climate change is a global phenomenon and does therefore affect national interests of all states cannot be sufficient to extend national legislation on all extra-territorial activities producing GHG emissions. The exceptional nature of the effects principle prompts a narrow interpretation. Thus the effects principle gives jurisdiction to regulate such activities that are only formally performed outside its territory, but having consequences exclusively or at least primarily inside that territory. It is persuasive from a more material point of view to regard such activities "territorial". Insofar effects of GHG emissions on the high seas or on foreign territorial seas cannot specifically attributed to EU-Member States. Obviously, effects of gas emissions are different from the pollution of a State's coast caused by the average of an oil tanker within the EEZ (Mayer (2012), 1113, 1130 et seq.). Due to the high complexity of the climate change process, a chain of causes and effects that would clearly link GHG emissions from vessels anywhere in the world with specific environmental outcome, can scarcely be identified.

But even if the outcome could be described precisely, the effects of climate change would be tangible world-wide and would not lead to particular and extraordinary significances for EU-Member states. Member States and their population are not affected by shipping emissions as "individuals", but only as part or constituents of the international community. With regard to the effects principle, their interests ought not be considered sufficient to establish extra-territorial jurisdiction. Where all states are affected the same way, there is no reason to allow for an exception from the basic principles of national sovereignty and of the freedom of the high seas in favour of specific states. Giving up these basic principles would cause severe risk of overlapping and contradictory regulation, of duplication of measures and costs, and the prospect of uncontrolled addition of interferences within the scope of fundamental rights. The international community of states has reasonably placed the environmental protection regards shipping emissions in the hands of the IMO; a global ETS should be implemented on this basis and not under the jurisdiction of a single player as the EU.

Moreover, even if the effects principle covered measures against global warming, that does not necessarily mean establishing jurisdiction for the inclusion of emissions of foreign flagged vessels outside the territorial seas of the EU-Member States. The effects principle is limited by the principle of proportionality. In its broadest sense this principle entails three criteria, i.e. suitability, necessity, and proportionality in the narrow sense. When it comes to balancing (principle of proportionality in the narrow sense) the interests that are to be taken into account are to be confined precisely. As the effects principle exceptionally provides law-making competences for extra-territorial behaviour, the proportionality-test does not include a free balancing of advantages and disadvantages of a maritime ETS as a measure against global warming (different point of view: Lassen (2010), 570, 575). It is not decisive whether a maritime ETS is an appropriate measure, but merely whether the EU-Member States shall have the jurisdiction for its implementation. For this purpose, it is necessary to examine whether the legislation-interests of EU-Member States, namely the importance of regulation for the regulating state, the extent to which other states regulate such activities and the degree to which the desirability of such regulation (cf. Ringbom (2011), 613, 631 f.), prevail over the sovereignty of the countries affected by EUMETS (Molenaar (1998), 82). Other aspects to consider are the extent to which the regulation is consistent with traditions of international law, the likelihood of conflicts with regulation imposed by other states, and finally the importance of regulation for the international political, legal or economic system should be considered. As GHG emissions affect EU interests neither directly nor specifically the EU would by establishing a maritime ETS act rather as a procurator in behalf of global than of own interests. In other words, the specific importance of the regulation for the regulating player can be seen as relatively low. An EUMETS would aim to subject the high seas to the Union's sovereignty in order to achieve a political goal that other states – exercising their sovereignty – do not share or do not try to achieve via the implementation of a maritime ETS or other regulatory means.[5] The lack of an IMO agreement demonstrates the controversy on a global emission allowance trading scheme. The decision a political goal such as the reduction of GHG emissions is set, and which measures are taken to its achievement should remain in the realm of national sovereignty.

The analysis concludes that a comprehensive EUMETS would not meet the requirement of proportionality in the narrow sense as set out by the effects principle.

7.4.2.5 Results

One has to state as a result that international law does not hinder the EU to implement an EUMETS that encompasses emissions produced within the territorial seas of EU-member states. Likewise, an EUMETS designed to capture territorial as well as extraterritorial emissions of EU vessel does not raise deep concerns as to its compatibility with international law. A comprehensive EUMETS model, however, that includes emissions of non-EU vessels irrespective of their local production would have relevant extra-territorial effects incompatible with the flag-state principle (Article 92 UNCLOS). Furthermore, it would disregard the prohibition to all states to subject any part of the high seas to its sovereignty (Article 89 UNCLOS) as well as the national sovereignty over the territorial sea (Article 2 UNCLOS).

7.5 Summary and conclusion

On the basis of a joint economic and legal analysis, we evaluate in this paper the effects of a "regional" (European) emission trading scheme aiming at reducing emissions of international shipping. The focus lies on the question which share of emissions from maritime transport activities to and from the EU can and should be included in such a system.

Our findings suggest that the attempt to implement an EUMETS runs into a dilemma. It is impossible to design a scheme that achieves the goal of emission reductions in a cost efficient manner and is compatible with international law:

[5] Cf. for the aviation sector Mayer (2012), 1113 (1138): "[...] an attempt by 27 States to concert and use their sovereign rights to promote the aims of international law".

From an *economic point of view*, the EU should choose a comprehensive definition of the scope and include all emissions arising on the whole route that is travelled by a ship. This result is in line with the main findings of the existing literature even though none of the reports so far has analysed this research question using a general equilibrium approach. Franc and Sutto (2014) and the MEDDE (2012) findings suggest that an ETS restricted to Europe will lead to a loss of competitiveness of French and European ports. Faber et al. (2009) proposes to regulate all emissions of voyages to and from the EU because of the suggested large environmental effectiveness and the little scope for avoidance. We have shown, that limiting the scope of the ETS would put a disproportional burden on routes featuring a high share of regulated emissions, i.e. short routes traveling mainly within EU territorial waters, and impede cost-efficient emission abatement among regulated ships. From a *legal point of view*, however, deep concerns as to the compatibility of a comprehensive scheme regulating all emissions arising on voyages to and from the EU with international law arise. A comprehensive scheme would have extra-territorial effects in conflict with the flag-state principle (Article 92 UNCLOS) and disregard the prohibition to all states to subject any part of the high seas to its sovereignty (Article 89 UNCLOS).

The aforementioned dilemma does not arise in a situation with an ETS applied to shipping activities on a global basis. As a consequence, although the effects of such a global maritime ETS remains to be studied in detail, policy makers should continue working on an international agreement to reduce maritime emissions instead of resorting to regional schemes.

Chapter 8

Effects of unilateral environmental regulation on multi-stage production processes

Abstract

In the last decades supply chains emerged that stretch across many countries. Decreasing trade and communication costs have been identified as main drivers of this process. We extend the literature by analyzing if and how unilateral environmental regulation induces offshoring of parts of the supply chain to unregulated jurisdictions. We first apply an analytical partial-equilibrium model of a two-stage production process that can be distributed between two countries and investigate the effects of unilateral emission pricing and its supplementation with border carbon taxes. We find that unilateral reductions force emission-intensive producers to offshore a greater proportion of their supply chain to unregulated jurisdictions. Border taxes are successful in mitigating this. However, whereas medium-emission intensive upstream production can be protected successfully, downstream industries from regulated countries lose competitiveness on foreign markets. We subsequently apply a new multi-sector multi-region computable general equilibrium model (CGE) of the world economy that in particular has additional structure with regard to sectoral supply chains. Using input-output data from the World Input-Output Database to calibrate the model, we find mixed effects of a unilateral carbon emission reduction by the European Union (EU) on the degree of vertical specialisation of European industries. If the mitigation policy is complemented with border carbon taxes, vertical specialisation decreases particularly in carbon-intensive upstream sectors.

This chapter is based on the following paper:

Schenker, Oliver, Simon Koesler and Andreas Löschel (2014), On the Effects of Unilateral Environmental Regulation on Offshoring in Multi-Stage Production Processes, ZEW Discussion Paper No. 14-121, Mannheim, Germany.

8.1 Introduction

Actuated by decreasing trade, transportation and communication costs, in the last decades supply chains have emerged that stretch across many countries. Dietzenbacher et al. (2012) for example report that exports of processed goods, where the major part of intermediates are imported from abroad and then assembled for re-exporting, accounted for more than 50 percent of China's exports in the period 1996-2007. Much has been written about the emergence of off-shoring and vertical specialisation. Grossman and Rossi-Hansberg (2006) even argued that this fundamentally changed the nature of international trade, claiming that "[i]ts not wine for cloth anymore".

As denoted by Hummels et al. (2001), who used input-output data for the years 1970 to 1990 to compute international trade induced by vertical specialisation, most supply chains in these timespan integrated only industries from industrialized countries. But in a process Baldwin and Lopez-Gonzalez (2014) termed "globalization's second unbundling" less developed countries have been integrated in these supply chains as well. Grossman and Rossi-Hansberg (2008; 2012) and Costinot et al. (2012) explain the evolution of such supply chains with decreasing costs of managerial efforts to supervise and assure the quality of processed intermediate goods.

Although it is indisputable that the technological advancements that reduced communication and trade costs are the most important driver of the emergence of global supply chains, we argue that differences in regulation between countries provide additional incentives to offshore certain production stages to countries with lower regulation costs. An evident example are differences in environmental regulation. Developed countries have often more stringent environmental regulations compared to developing ones. The well-known pollution haven hypothesis argues that polluting industries escape from environmental regulation in the developed countries by moving to unregulated developing countries. This in turn makes unilateral environmental regulation less effective. The most prominent example is the so-called "carbon leakage effect" which proposes that a unilateral regulation of greenhouse gas (GHG) emissions may rise production costs of carbon-intensive goods and reduce the competitiveness of producers in regulated countries, leading to a shift of production to unregulated ones.

But industries may respond to regulation not only with a complete change of the production location but also with the offshoring of single production stages along the vertical supply chain and thereby contribute to the "second unbudling". Albeit of the large literature on how international trade affects the effectiveness of environmental regulation, almost all studies assess the topic through the lens of "horizontal specialisation", i.e. specialisation in final goods. Exceptions are the papers of Benarroch and Weber (2006) and McAusland (2004) which study trade in intermediates and their environmental consequences in industries with increasing returns to scale, but focus rather on the economies of scale than on the disentangling of the effects on the supply chain.

Including the supply chain effects in the analysis has also important implications for policy conclusions. Most proposals to cure the competitiveness of industries from the unintended sided effects of unilateral carbon emission regulation focus on so called "energy intensive, trade exposed" industries. These industries are mostly classified by the energy use of their final production stage and export shares as well as the substitutability of their final output but ignoring the vulnerability from upstream supply chain disruptions and the emissions embodied in the supply chains. Since a large fraction of international trade volumes is trade in intermediates this may have important consequences for policy design.

This paper aims to close this gap by analyzing the effects on the supply chain composition of two unilateral environmental policy measures, a sole carbon price on domestic emissions and a carbon price in combination with a tax on imported embodied emissions.

In order to understand the basic effects those regulations have on offshoring decisions, we use in a first step a partial equilibrium model of a two stage production process with two regions. The model blends Ricardian international trade in a continuum of goods Dornbusch et al. (1997) and multi-stage production as in Yi (2003) with a model of a pollutant-emitting production as in Copeland and Taylor (1994). Not surprisingly, we find that emission pricing polices force more emission-intensive producers to shift a greater share of their supply chain to the unregulated region and thereby increasing vertical specialisation. Border taxation in turn fetches these stages home that are offshored due to the unilateral regulation. However, this comes with the cost of losing market shares in emission-intensive goods that depend on emission-intensive upstream intermediates.

In reality, supply chains are a much more complex interweaved network of sectoral relationships. For this reason, we extend eventually the simple partial equilibrium model and apply a new full fledged computable general equilibrium (CGE) model which features for the first time an explicit specification of international trade flows between sectors in different regions. This clarification is vital for studying changes in global supply chains as it allows to trace intermediate flows through the global economy. The CGE model is calibrated to the multi-regional input-output data of the World Input-Output Database (WIOD) that maps trade flows between sectors and regions. We solve this model numerically to analyse the effect of a twenty percent carbon emission reduction through an emission trading scheme in the European Union (EU) - a stylized representation of the EU's emission reduction targets for 2020 - on the supply chains of European industries. As in the analytical model and counterfactual, we supplement this policy with a border tax on imported carbon emitted in unregulated regions. The simulated results show that a unilateral twenty percent emission reduction in the EU has differentiated impacts on the vertical specialisation of sectors depending on the emission-intensity of their supply chain. The main driver of a change in the imported value-added content of production is thereby the switch away from emission intensive energy inputs. In general, all sectors increase their degree of vertical specialisation. The pattern of change is however more divers than in the analytical model. Eventually sectoral differences can be explained by heterogeneity in input intensities and substitution elasticities. If the domestic carbon pricing is complemented with a border carbon tax, vertical specialisation decreases in virtually all sectors with the largest impacts on emission-intensive sectors. What is more, almost all European sectors that are subject to the border carbon tax regime loose a small share of their market in foreign regions.

The remainder of this paper is structured as follows: In the next section, we lay out the analytical model and illustrate the basic effects of unilateral regulation on vertical specialisation. Subsequently we enlarge the model and include further aspects of economic activity. Before applying the CGE model, we briefly elaborate the situation of vertical specialisation in Europe and give an indication of the importance of foreign emission embodied in European output. Next, we investigate the implication of the two unilateral policies and contrast our findings to the insights derived on the basis of our theoretical model. Finally, we summarise our results and conclude.

8.2 An analytical framework of offshoring

In this section, we lay out an analytical model that provides intuition how environmental regulation can affect offshoring decisions of certain stages along the supply chain and how these decisions affect the efficiency of environmental regulation. The model blends Ricardian international trade in the tradition of Dornbusch et al. (1997) and multi-stage production as in Yi (2003) with a model of different emission-intensive industries as in Copeland and Taylor (1994). This provides a tool to examine the effects of environmental policy on the vertical organization of industries. However, the analysis is kept as simple as possible and neglects several mechanisms of interaction such as general equilibrium effects on factor prices and on final demand. For analytical tractability, the analysed supply chains contain only two stages where a single upstream good is used in the downstream industry and emission-intensity varies between supply chains but not within. As already pointed out above, these limitations will be addressed below with a more inclusive calibrated general equilibrium model. Nevertheless, this simplified analytical framework provides important insights on how environmental regulation can influence offshoring decisions.

8.2.1 Firms and technology

We consider a world with two regions r, called North (N) and South (S). Following Dornbusch et al. (1997), there is a continuum of goods, indexed by $z \in [0, 1]$. Each good z is produced with a single production factor in two stages, a upstream (stage 1) and a downstream stage (stage 2) and differs in its emission-intensity of production. These emissions have a not further defined negative effects on welfare and thus are going to be regulated by an exogenous policy maker. The upstream good is a required intermediate input in the downstream industry which eventually produces the final good. We assume constant returns to scale on both stages of production and zero profit in all industries. Further, we assume constant factor prices and no factor mobility across countries but between sectors.

8.2.1.1 Upstream firms

As in Copeland and Taylor (1994) the upstream production of any good z combines factor l and emissions d in a Cobb-Douglas fashion.[1]

$$y_r^1(d_r^1, l_r^1; z) = \begin{cases} \left(A_r^1 l_r^1\right)^{1-\alpha(z)} d_r^{1\,\alpha(z)} & \text{if } d_r^1 \leq \lambda l_r^1 \\ 0 & \text{if } d_r^1 > \lambda l_r^1, \end{cases} \tag{8.1}$$

where $0 \geq 1 - \alpha(z) \leq 0$ is the value share of factor l that varies across goods. A_r^1 can be interpreted as a stage specific, factor augmenting technology used by region r at stage 1. $\lambda > 0$ is a technology efficiency parameter that limits the substitution between factor input and emissions because output must be bounded above for a given factor input. Therefore, production sets where $d_r^1 > \lambda l_r^1$ are not feasible (see Copeland and Taylor (1994)). In order to avoid corner solutions we focus on cases where $d_r^1 \leq \lambda l_r^1$. In those cases, the unit costs of a upstream firm in region r can be characterized by

$$c_r^1(\tau_r, w_r, A_r^1; z) = \phi(z)\tau_r^{\alpha(z)} \left(\frac{w_r}{A_r^1}\right)^{1-\alpha(z)}, \tag{8.2}$$

where $\phi(z) = (1-\alpha(z))^{\alpha(z)-1}\alpha(z)^{-\alpha(z)}$ is an industry specific constant, τ_r describes the input costs of a unit emissions and w_r is the price of the factor. Note that in order to avoid corner solutions τ_r has to be strictly positive but can be infinitesimal.

8.2.1.2 Downstream firms

The upstream output $y_r^1(z)$, is a required intermediate input in the downstream production of good z. Upstream products from N and S are perfect substitutes and trade costs are zero. Following Yi (2003), emissions, the factor input, and the upstream intermediate input are compounded in a nested Cobb-Douglas production function.

$$y_r^2(x_r^2, d_r^2, l_r^2; z) = \begin{cases} \left[\left(A_r^2 l_r^2\right)^{1-\alpha(z)} d_r^{2\,\alpha(z)}\right]^{1-\theta} x_{r,s}^{2\;\theta} & \text{if } d_r^2 \leq \lambda l_r^2 \\ 0 & \text{if } d_r^2 > \lambda l_r^2, \end{cases} \tag{8.3}$$

where $x_{r,s}^2$ is region r's use of the upstream good from region s and, similar to stage 1, A_r^2 is a stage- and region-specific technology that determines factor productivity of stage 2 in region r. θ is the value share of upstream goods in the downstream industry. We assume a constant upstream value share across all sectors. Similar to the upstream stage, production sets where $d_r^2 > \lambda l_r^2$ are not feasible. Downstream output of industry z in region r has unit costs of

[1] Although a joint product of output in most production processes, we follow Copeland and Taylor (1994) and model emissions as input. This requires that the joint production technologies satisfy certain regularity conditions. See the Appendix of Copeland and Taylor (1994) for a detailed derivation.

$$c_r^2(\tau_r, w_r, p_s^1; z) = \psi(z) \left[\tau_r^{\alpha(z)} \left(\frac{w_r}{A_r^2} \right)^{1-\alpha(z)} \right]^{1-\theta} p_s^1(z)^{\theta}, \tag{8.4}$$

where $\psi(z) = (1-\theta)^{\theta-1}\theta^{-\theta}\phi(z)^{1-\theta}$ is a downstream industry specific constant and $p_s^1(z)$ is the input cost of the upstream intermediate from region s faced by the downstream producer that minimizes her costs.

8.2.2 Offshoring due to unilateral environmental regulation

After introducing the production technologies we turn our attention to the effects of two types of policy measures that have been discussed widely in the literature on environmental regulation in open economies. First, a unilateral increase in the input costs of emissions by North - either caused through a tax on emission or through a tightened cap in an emission trading scheme that reduces the supply of emission permits and thus increases emission costs - is examined. Practiced examples are the European Union Emissions Trading System (EU ETS) that regulates carbon emission in some sector of the EU or the SO_2 Reductions and Allowance Trading in the United States. Subsequently we analyse the implications of complementing the unilateral emission pricing scheme with a border tax by the North on imported embodied emissions from the South. Although it has so far not been applied, a border tax on carbon has been widely debated, both among academics and policy makers, as a supplement to climate policy measures in order to respond to the losses in comparative advantages and effectiveness that accompany such measures if implemented unilaterally. The idea was incorporated into the Waxman/Markey bill (H.R. 2454 "The American Clean Energy and Security Act of 2009"), an in the end unsuccessful attempt to regulate U.S. carbon emission, but has also been discussed in Europe in addition to the EU ETS.[2] Both instruments are challenged with the questions (i) how the respective instrument affects the vertical organizational structure of emission-emitting industries and (ii) how the adjustment of supply chains affects the effectiveness of the policy instrument. Note that although we acknowledge that offshoring decisions of stages in the supply chain are (mainly) driven by many factors such as reductions in communication and trade costs,[3] in this paper we are agnostic about those other factors and focus on effects of environmental regulation as an offshoring-inducing factor.

Following Copeland and Taylor (1994), we rank goods according to their emission-intensity which is a strictly increasing function of α and assume that every good z is produced with the same emission intensity $\alpha(z)$ all along its value chain. In order to structure our economy further, a minimal set of additional assumptions are required.

[2] See Markusen (1975) and Copeland (1996) for an early analysis. They find that a border tax belongs to the optimal policy portfolio in case of an unilateral regulation of trans-boundary pollutants. More recently, Fischer and Fox (2012) provide an numerical analysis of specific climate policy schemes, showing that these schemes can support domestic competitiveness but have almost no effect on global carbon emissions.

[3] See for example Baldwin and Lopez-Gonzalez (2014) for an excellent overview to this regard.

In the following, we assume that $1 \leq \left(\frac{w_N}{w_S}\right) \leq \left(\frac{A_N^1}{A_S^1}\right) \leq \left(\frac{A_N^2}{A_S^2}\right)$, meaning that N's relative wage is lower than its relative technology used in both production stages. This implies that in the absence of any unilateral environmental policy (so that $\tau_N = \tau_S$) up- and downstream production take both place in the North. The third inequality $\left(\frac{A_N^1}{A_S^1}\right) \leq \left(\frac{A_N^2}{A_S^2}\right)$ implies that North has a relative comparative advantage in the downstream stage. Since Ricardian comparative advantage forces determine the composition of the supply chain in equilibrium, a unilateral increase in production costs in N – e.g. induced by an increase in emission costs – affects at the margin first the location of upstream production before the downstream production is offshored. This situation defines the baseline for our analysis.

8.2.2.1 Unilateral emission pricing

Our starting point is our baseline scenario, where we assume that $\tau_N = \tau_S = \epsilon$ and ϵ is infinitesimal, but positive. Now suppose that a policy action in N unilaterally increases the costs of emissions, either by an increasing emission tax or by a reduced supply of emission permits under a constant demand of such permits, and therefore $\tau_N > \tau_S$.

A purchasing manager in the downstream (stage 2) industry has to decide where to source its intermediate input. She buys the intermediate upstream good used in sector z from region S if $c_S^1(\tau_S, w_S; z) \leq c_N^1(\tau_N, w_N; z)$. The input costs of the upstream good in the downstream industry is thus $p^1(z) = \arg\min[c_S^1(\tau_S, w_S; z), c_N^1(\tau_N, w_N; z)]$. This leads to same condition for downstream production in the South as in the one-stage model of Copeland and Taylor (1994):

$$A^1 \equiv \frac{A_N^1}{A_S^1} \leq \frac{w_N}{w_S}\left(\frac{\tau_N}{\tau_S}\right)^{\frac{\alpha(z)}{1-\alpha(z)}} \equiv \omega T(z). \tag{8.5}$$

Conversely, the upstream good will be sourced from N if $A^1 \geq \omega T(z)$. With $\tau_N > \tau_S$ and $\alpha(z) > 0$, $T(z)$ is increasing in z. Because of North's relatively higher emission prices, its relative cost advantage in producing the upstream part of good z declines as expenditures for emissions become a larger share of total costs.

The cut-off emission intensity $\alpha(z)$ of the upstream sector $\underline{z}$ where the purchasing manager is indifferent between offshoring its upstream production to S or remain in N can be be found by equalizing the inequality (8.5) and solving for $\alpha(z)$. This leads to

$$\alpha(\underline{z}) = \frac{\ln\left(\frac{A^1}{\omega}\right)}{\ln\left(\frac{\tau_N}{\tau_S}\right) + \ln\left(\frac{A^1}{\omega}\right)} = \underline{\alpha}. \tag{8.6}$$

Note that the greater the difference between τ_N and τ_S, the lower is the cut-off emission intensity. The same calculus is then used by the final consumers in both regions. Goods of different origin are perfect substitutes and there are no trade costs. Thus, they source the final good z from S if $c_S^2(\tau_S, w_S, p^1; z) \leq c_N^2(\tau_N, w_N, p^1; z)$. We can rewrite this purchase decision as:

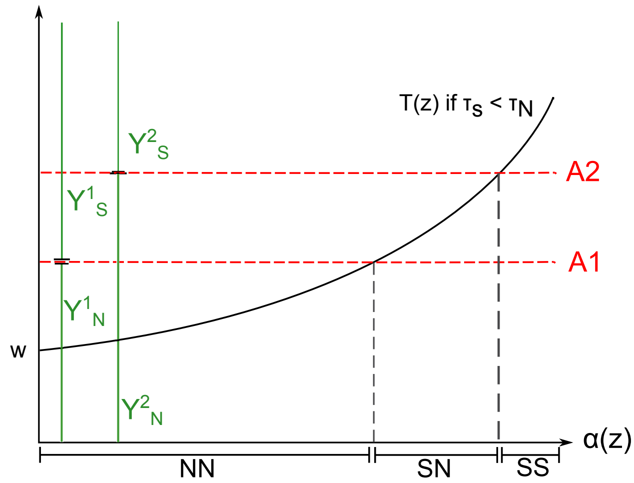


Figure 8.1: Vertical specialisation at the extensive margin

$$A^2 \equiv \frac{A_N^2}{A_S^2} \leq \frac{w_N}{w_S}\left(\frac{\tau_N}{\tau_S}\right)^{\frac{\alpha(z)}{1-\alpha(z)}} \equiv \omega T(z). \tag{8.7}$$

The final good is purchased from North if $A^2 \geq \omega T(z)$. From $A^1 < A^2$ and Ricardian comparative advantage forces it follows that in equilibrium the final good is never produced in South if the upstream good is sourced in North. The cut-off emission intensity $\alpha(z)$ of industry $\overline{z}$, such that the final consumer is indifferent between purchasing the final good z from S or N, has the same structure as Equation (8.6):

$$\alpha(\overline{z}) = \frac{\ln\left(\frac{A^2}{\omega}\right)}{\ln\left(\frac{\tau_N}{\tau_S}\right) + \ln\left(\frac{A^2}{\omega}\right)} = \overline{\alpha}. \tag{8.8}$$

Thus, every industry with an emission intensity equal or higher that $\overline{\alpha}$ is shifting its whole supply chain to S. Combining (8.5) and (8.7) allows to study the industry structure for given emission prices. Three different production patterns are possible. A good z can either (i) be produced entirely in N, it can (ii) be produced entirely in S, or (iii) it can consist of a Southern upstream good that is processed in North to a final good. The latter is a situation with a vertically specialised production setup.

Vertical specialisation at the extensive margin

We define vertical specialisation at the *extensive* margin as a production setting where upstream and downstream production are located in different regions. That is, in our analytical framework the production setups South-North and North-South feature vertical specialisation at the extensive margin. Industry z produces vertically specialized and offshores its upstream production from the North to the South if

$$A^1 \leq \omega T(z) \leq A^2. \tag{8.9}$$

The offshoring decision at the extensive margin of the different emission-intensive industries are illustrated in Figure 8.1. The supply chains of industries with emission intensity $\alpha(z) \leq \underline{\alpha}(z)$ are not affected by relative increase of N's emission prices. The production of both stages still takes place in N. When emission costs account only for a small share of overall costs, comparative advantages based on relative production technologies determine the supply chain. But $\omega T(z)$ has an upward slope. With increasing emission intensity and thus increasing share of emission costs, the $\omega T(z)$ locus cuts A^1 at $\underline{\alpha}$ from below. We know from condition (8.5) that if $A^1 < \omega T(z)$ the upstream production stage is off-shored to S. But below the A^2-line, the final good processing remains in N. With increasing emission-intensity $\omega T(z)$ cuts the A^2-line and the technological comparative advantage of N's downstream production stage is dominated by the disadvantage in emission costs for $\alpha(z) \geq \overline{\alpha}$. Thus, the final good processing is shifted to S as well.

Insight 1. *A unilateral relative increase in emission costs fragments the supply chain and induces vertical specialisation at the extensive margin for medium emission-intensive industries between $\underline{\alpha}$ and $\overline{\alpha}$. While industries with emission-intensities below $\underline{\alpha}$ do not alter the supply chain, industries with high emission-intensities above $\overline{\alpha}$ shift the complete supply chain to regions with lower relative emission costs.*

The offshoring of upstream process has also implication on emissions from the respective industries. While initially the discontinuation of production in the North has positive effects on emissions, establishing the upstream production in the South comes along with additional emissions there. So eventually the shift of emission-intensive production to less regulated regions reduces the effectiveness of the unilateral emission pricing policy and results in so-called carbon leakage. We will asses the magnitude of this problem later and calculate carbon leakage rates with the help of a calibrated computable general equilibrium model in the next section.

Vertical specialisation at the intensive margin

Having examined how unilateral environmental regulation can induce offshoring and the fragmentation of supply chains (vertical specialisation at the extensive margin), we turn now our attention to the effects of the policy on the intensity of upstream intermediate use in downstream production. Since we are interested in offshoring and vertical specialisation effects, we focus in the subsequent analysis on industries with emission-intensities between $\underline{\alpha} < \alpha < \overline{\alpha}$ where environmental regulation results in vertically specialised supply chains. We define the increased substitution of downstream production with offshored upstream output as vertical specialisation at the *intensive* margin. That is vertical specialisation at the intensive margin increases the share of used upstream intermediates in the final good.

The upstream intensity of a fragmented produced final good is $I_N^2(z) = y_S^1(z)/y_N^2(z)$. Combining this with Hicksian demand derived from the cost function (8.4) leads to:

$$I_N^2(z) = \left[\frac{\theta}{1-\theta}\left(\frac{\tau_N}{\tau_S}\right)^{\alpha(z)}\left(\frac{w_N A_S^1}{w_S A_N^2}\right)^{1-\alpha(z)}\right]^{1-\theta} \quad \forall\ \underline{\alpha}(z) < \alpha(z) < \overline{\alpha}(z) \tag{8.10}$$

The derivation of equation (8.10) by τ_N shows that a marginal increase in North's emission costs causes a marginal increase in the intensity of used upstream goods produced in S. The marginal effect is also increasing in $\alpha(z)$.

Insight 2. *A marginal unilateral rise in the emission costs of N increases the intensity of used foreign upstream goods in N's final good production and therewith vertical specialisation at the intensive margin. The marginal rise in upstream-intensity is increasing with the emission-intensity $\alpha(z)$.*

Changes in vertical specialisation at the intensive margin also have effects on emissions of the respective industries. While the existing literature on carbon leakage mainly focuses on changes in the location of production of final goods. Here, we observe leakage through another channel. As fragmented industries increase the content of offshored parts in their supply chain and, thus, shift a larger share of their supply chain to unregulated and more emission intensive regions, the overall production of a good becomes more emission intensive. Again, we will investigate the magnitude of this "within-value chain" carbon leakage using the calibrated CGE model later in this paper.

8.2.2.2 Unilateral emission pricing with border emission taxes

Suppose that the policy makers in N want to tackle the adverse effects on competitiveness and policy efficiency that N's unilateral environmental policy causes and add a border tax on embodied emissions imported from S to the domestic emission regulation set. The border tax is aiming at leveling the playing field on the domestic market and taxes each unit of imported carbon emissions that has been used in the production of the good with the difference in its respective emission price $(\tau_N - \tau_S)$.

Border carbon taxes on intermediate good markets

A unit of a upstream good in industry z produced in S contains the following amount of embodied emissions:

$$\begin{aligned} E_S^1(z) &= \frac{d_S^1}{y_S^1} \\ &= \left(A_S^1 l_S^1\right)^{\alpha(z)-1} {d_S^1}^{1-\alpha(z)} \\ &= \left(\frac{\alpha(z)}{1-\alpha(z)}\frac{w_S}{\tau_S A_S^1}\right)^{1-\alpha(z)}. \end{aligned} \tag{8.11}$$

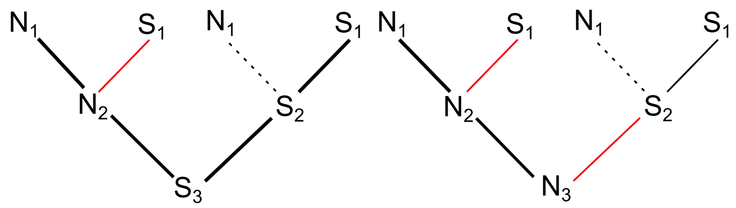


Figure 8.2: Purchase decision tree of N and S consumers and downstream industries purchase managers. Red lines mark trade links that are affected by N's border tax on imports from S. Since it is by assumption about comparative advantages not profitable for a final good producer in S to outsource its upstream intermediate production to N (dotted line) and since border taxes prevent the profitability of offshoring upstream stage for N's downstream producer vertical specialisation is eliminated

The border emission tax applied on N's import in industry z of S's upstream good is thus $t_N^1(z) = (\tau_N - \tau_S) \times E_S^1(z)$. This term is positive and increases the sourcing costs of intermediates in the N's downstream industry. A border carbon tax affects the offshoring decision of N's final good industries and puts a wedge between the prices N and S downstream purchasing managers face. The intermediate sourcing decision of final good producers in S are not affected and are still described by condition (8.5). This, however, is different for a downstream purchasing manager in N.

She faces additional costs when sourcing the intermediate input from S. Intermediate input costs in N's downstream industry z are now $p_N^{1*}(z) = \arg\min[c_S^1(\tau_S, w_S; z) + t_N^1(z), c_N^1(\tau_N, w_N; z)]$, where the asterisk indicates the border carbon tax regime and the subscript the importing region. With some algebra we can derive the following condition: Industry z, located in N, sources its intermediate input from S if

$$A^1\Gamma(z) \equiv \frac{A_N^1}{A_S^1}\left(\frac{\alpha(z)\tau_N + (1-\alpha(z))\tau_S}{\tau_S}\right)^{\frac{1}{1-\alpha(z)}} \leq \frac{w_N}{w_S}\left(\frac{\tau_N}{\tau_S}\right)^{\frac{\alpha(z)}{1-\alpha(z)}} \equiv \omega T(z). \tag{8.12}$$

Since $\tau_S < \tau_N$, S produces the same good z at least not less emission-intensive than N. Thus, with border taxes the emission costs per unit imported to N are not lower for any good z produced in S relative to N. As a consequence, under a border tax regime in N, $A^1\Gamma(z) > \omega T(z)$ holds for all $\alpha(z)$ if $\tau_N > \tau_S$. This implies that baseline Ricardian comparative advantage forces dominate again and offshoring due to environmental regulation is not a profitable motivation any more. Figure 8.2 summarises the underlying logic and a formal proof is given in the Appendix F.1. So eventually downstream producers of good z in N never offshore their upstream production to S.

Insight 3. *Border emission taxes eliminate offshoring of upstream production stages and fragmentation of supply chains that has been induced by unilateral emission pricing policies, both at the extensive and intensive margin.*

Border emission taxes on final good markets

Since border taxes drive a wedge between N and S good markets, also final consumers in N and S face different purchase problems. As showed above, the supply chain of industry z is under a border tax regime either completely based in S or N. Thus, no parts of final goods that are traded on the S market crossed the border to N and are hence not affected by the border tax. However, on Northern markets final goods are potentially available that are entirely produced in S and hence taxed accordingly when reaching N markets.

By exploiting separability the unit cost function of a final good z produced entirely in S is $c_S^2 = \psi(z)\tau_S^{\alpha(z)} w_S^{1-\alpha} \left({A_S^2}^{1-\theta} {A_S^1}^{\theta} \right)^{\alpha(z)-1}$. Shepard's Lemma shows that one unit of the final good z produced completely in S includes

$$E_S^2(z) = \left(\frac{\alpha(z)}{1-\alpha(z)} \frac{w_S}{\tau_S {A_S^2}^{1-\theta} {A_S^1}^{\theta}} \right)^{1-\alpha}, \tag{8.13}$$

units of emissions and the tax on imported final goods from S is thus $t_S^2 = (\tau_N - \tau_S) E_S^2(z)$. The final consumer in the *North* purchases final good z from N if $c_N^2(\tau_N, w_N; z) \leq c_S^2(\tau_S, w_S; z) + t_S^2$. Rearranging this condition provides:

$$(A^1)^{\theta} (A^2)^{1-\theta} \leq \omega T(z) \chi^{\frac{1}{1-\alpha(z)}} \Gamma(z), \tag{8.14}$$

where $\chi = (1-\theta)^{1-\theta}\theta^{\theta}$. So again baseline Ricardian comparative advantages dominate and the North relies only on domestic final goods.

Insight 4. *If N implements a border tax on imported embodied emissions, all trade to N's final good market induced by unilateral emission pricing is prevented.*

In the *South*, the situation looks slightly different. There, the consumers are not directly confronted with the border tax. But indirectly, since under the border tax regime no goods are available that are produced in a vertically specialised manner. Ultimately, a final consumer in S will source the final good from N if $c_N^2(z) \leq c_S^2(z)$, that is if:

$$(A^1)^{\theta} (A^2)^{1-\theta} \leq \omega T(z). \tag{8.15}$$

This points out that consumers in S switch from final goods produced in N to goods produced in S emission-intensive industries if the $\omega T(z)$-locus cuts the $(A^1)^{\theta}(A^2)^{1-\theta}$-line from below. Thus, in contrast to a regime with unilateral domestic emission pricing where only fragmented supply chains emerged for industries with an emission intensity between $\underline{\alpha}$ and $\overline{\alpha}$, in a border tax regime all industries produce within a single region.

Figure 8.3 shows the consequences for the industry structure over the good space z for N industries that are active on S markets. The effects are ambiguous. On the one hand, the border tax regime in N makes more integrated industries competitive and

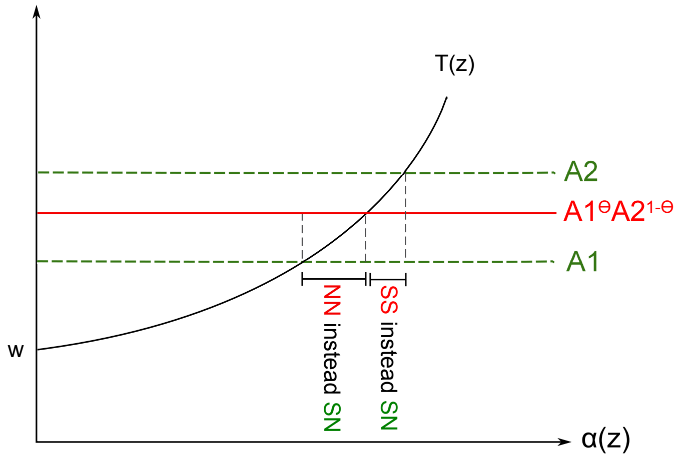


Figure 8.3: Purchase decision of consumers in the South in the presence of a border tax

reverses the offshoring of upstream production and fetches them back to N. But on the other hand, the North looses competitiveness due to higher costs on intermediates for some of the more energy-intensive final goods.

Insight 5. *On final good markets in unregulated S, the introduction of a tax on imported embodied emissions as a supplement to a unilateral emission pricing has ambiguous effects. On the one hand, it enables N to retrieve some of the upstream production stages that were lost to S due to N's unilateral emission regulation. On the other hand, the border tax cause in cases where relative emission-intensive industries have already offshored their upstream production stages due to the unilateral emission pricing a dislocation also of the downstream industries to the South.*

With the change in the production setup, the presence of a border carbon tax also has effects on emissions from production. For markets in the regulated North the implications are straightforward: offshoring due to emissions regulation is not a profitable strategy anymore and leakage becomes irrelevant. But the situation is different for markets in the South. Here on the one hand, border taxes reduce emissions because some upstream processes are brought back to N and N produces cleaner than S due to higher emission costs. On the other hand, other industries now also move their downstream stages S and thus increase the emissions. Depending on which of the effects is greater, the border carbon tax can also have a negative effect on carbon leakage. Although the effects are of course limited to goods sold in Southern final goods markets.

Insight 6. *Although the border carbon tax reduces carbon leakage for most production setups, by inducing a transfer of parts of the downstream production to the unregulated South, the border tax can also induce some new carbon leakage.*

8.3 Quantitative assessment of complex supply chains

The above described analytical partial equilibrium framework revealed several important insights about the effect of environmental regulation on offshoring and fragmentation of supply chains. However, the model offered only a stylized representation of supply chain management under environmental regulation and ignored at least five important dimensions due to trade-offs with analytical tractability. In this section, we extend the illustrative framework first and foremost to a general equilibrium representation that includes repercussions on factor and good markets. Thus, supply chains may interact. Second, we study trade and offshoring relationships in a universe consisting of more than two regions. Third, final goods are produced in more than two stages and can span over multiple regions. Fourth, an intermediate good may be used in several industries, so supply chains are not straight lines but complex interweaved networks of sectoral relationships. Fifth, also the representation of industries is more complex. They vary in more dimensions than only their emission-intensity and may also differ in their ability to change the source of their upstream intermediates, their ability to substitute in the production process the intermediates with factor input, and their intensity of upstream intermediate goods use.

8.3.1 Model structure

To account for the aforementioned additional aspects and to quantify the effects of unilateral regulation on vertical specialisation, we apply for the first time a unique CGE model with an explicit specification of the origin as well as the recipient of intermediate flows on a regional and sectoral level (for a general model description see Koesler and Pothen (2013)). The rich bilateral and bi-sectoral trade structure is calibrated on WIOD (World Input Output Data).

Similar to our analytical model, production is modeled using constant elasticity of substitution (CES) functions, although more nuanced with heterogeneity among regions and industries regarding value shares and elasticities. The production of final sectoral output is described by:

$$y_{r,i} = \left[\theta_{r,i} x_{r,i}^{\rho_{r,i}^{ldx}} + (1-\theta_{r,i}) \left[(1-\alpha_{r,i}) l_{r,i}^{\rho_{r,i}^{ld}} + \alpha_{r,i} d_{r,i}^{\rho_{i,r}^{ld}}\right]^{\frac{\rho_{r,i}^{ldx}}{\rho_{r,i}^{ld}}}\right]^{\frac{1}{\rho_{r,i}^{ldx}}}. \tag{8.16}$$

Note that industries are no longer distributed continuously but are discrete and of finite number, indexed by i. Final output $y_{r,i}$ in industry i from region r is produced in a similar structure as in the analytical model. On the first stage, a production factor composite $l_{r,i}$ consisting of capital and labour is blended with a carbon-emitting energy input $d_{r,i}$, where $\sigma_{r,i}^{ld} = 1/(1-\rho_{r,i}^{ld})$ denotes the elasticity of substitution between these two inputs. Each sector uses a fixed mix of energy sources, each with a specific carbon emissions coefficient. Note that in contrast to the analytical model, also process emissions – a fixed byproduct of sectoral production – are taken into account and affect the emission

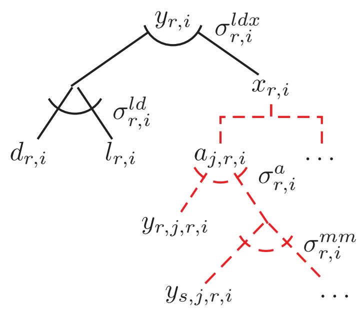


Figure 8.4: Structure of the numerical model, dashed lines indicate extensions to the analytical model

intensity of a sector. On the second stage, the composite of factors of production and energy is combined with a bundle of intermediate goods $x_{r,i}$ sourced from other sectors, where $\sigma^{ldx}_{r,i} = 1/(1-\rho^{ldx}_{r,i})$ denotes the elasticity of substitution between these two inputs. In contrast to the analytical model, we account now for more complex production structures and consider intermediates from various sectors. However, we assume that the mix of intermediates remains constant.

Each intermediate good $a_{j,r,i}$ used in sector i in region r consists of a combination of domestic and foreign final inputs from sector j. While assuming in the analytical model above that goods from different regions are perfect substitutes, it its now assumed that goods of different origin are only imperfect substitutes Armington (1969), with an elasticity of substitution parameter between domestic and foreign output $\rho^a_{r,i}$ and between different foreign regions $\rho^{mm}_{r,i}$. Eventually, each intermediate input $a_{j,r,i}$ arises from

$$a_{j,r,i} = \left(\beta_{j,r,i} {m_{r,j,r,i}}^{\rho^a_{r,i}} + (1-\beta_{j,r,i}) \left(\sum_{s \forall s \neq r} \gamma_{s,j,r,i} (m_{s,j,r,i})^{\rho^{mm}_{r,i}} \right]^{\frac{\rho^a_{r,i}}{\rho^{mm}_{r,i}}} \right)^{\frac{1}{\rho^a_{r,i}}}, \tag{8.17}$$

where $\beta_{j,r,i}$ indicates sector $y_{r,i}$'s share of domestic intermediates from sector j and $\gamma_{s,j,r,i}$ with $\sum_{s \forall s \neq r} \gamma_s = 1$ is the respective share of intermediate j sourced from region s.

Note that in contrast to most other CGE models, WIOD enables to model Armington bundles specific for each sourcing sector. This additional structure does not only allow to trace sectoral supply chains more detailed but also creates additional variation in sectoral supply chain adjustments as responses to the examined policy interventions. The overall production structure of the CGE model and an illustration of how this relates to the analytical model is presented in Figure 8.4. Further details on the CGE model can be taken from the general model description in Chapter 2 and Appendix A.1.

Similar to the analytical model, a purchasing manager has two responses if emissions become more costly – e.g. due to unilateral climate policy regulation: On the one hand, she can substitute energy, which became more costly due to the policy, for domestic production factors. We might call this 'direct abatement action', which increases the intensity of domestic production factors of final output and therewith indirectly reduces vertical specialisation. On the other hand, she can increase the use of foreign, non-regulated intermediates and implicitly offshore production to non-regulated regions. This mirrors what has been defined as 'vertical specialisation and offshoring at the intensive margin' in the analytical discussion. The magnitude of theses two substitution effects depends on the respective input intensities and elasticities of substitution. If the input intensities or the elasticities of either production stage are particularly high, then one of two substitution responses dominates and thus governs changes in the composition of the supply chain. As can be seen from Table 8.1, industries vary substantially in their pre-policy input intensity of foreign intermediate use. Later in our deliberations we identify this as the main source in sectoral heterogeneity of the reaction to policies with regard to vertical specialisation.

8.3.2 Data, calibration and aggregation

The model is calibrated with the novel WIOD dataset.[4] WIOD provides an annual consistent representation of the world economy for the period 1995 to 2009. The dataset contains production, trade and emissions data for 35 sectors of 27 member states of the European Union plus 13 other major economies.

The originally 40 economies included in WIOD are aggregated to eight regions. Table F.1 in the Appendix shows the regional aggregation in detail. Some are large countries, such as China or the United States; others are multi-country regions such as the European Union (EU). The primal 35 sectors are aggregated to 18 sectors, details are given in Table F.2 in the Appendix. We focus on sectors were a higher embodiment into cross-border supply chains is expected, such as manufacturing sectors. Thereby we broaden the picture generally drawn by the literature and not only consider the output side when assessing the trade exposure of sectors but also the input side and the sourcing of upstream intermediates. Since service sectors have neither a high emission intensity nor are expected to have particular intense cross-border supply chains, several service sectors have been aggregated. Furthermore we distinguishes between three types of energy which are sourced from the three WIOD sectors "coke, petroleum, nuclear fuel" (COPN), "mining and quarrying" (MINI), and "electricity, gas, water supply" (ELGW).

For substitution elasticities determining the flexibility of production with regard to inputs, estimates from Koesler and Schymura (2015) are applied which are derived from the same data the model is also calibrated to. The average of the elasticity of substitution between value-added and energy ($\sigma^{\mathrm{ld}}_{(r,i)}$) is 0.4, the minimum is 0.1 and the maximum is 1.1.[5] The average substitutability between the value-added-energy composite and

[4]See Timmer et al. (2012) and Dietzenbacher et al. (2013) for an extensive description of the dataset, which can be downloaded for free at http://www.wiod.org. Data downloaded on the 17th of April 2013 has been used for this analysis.

[5]Note, Koesler and Schymura (2015) do not provide a reliable substitution elasticity between value-added and energy for the Coke Refined Petroleum and Nuclear Fuel (CPN) sector, here we assume that

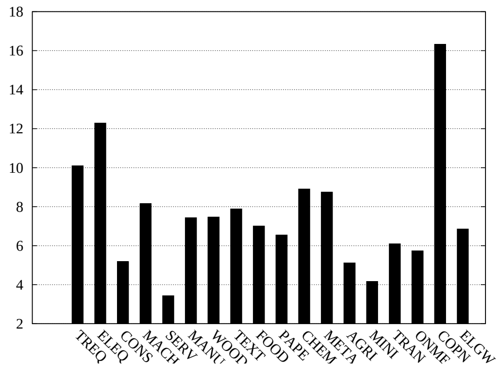


Figure 8.5: Share of foreign non-energy value added content in 2005 for 18 European sectors [%]

material ($\sigma^{\mathrm{ldx}}_{(r,i)}$) is 0.6 and varies from 0.1 to 2.3. An overview of the different elasticities is also given in Table 8.1. The Armington elasticities required by the model are taken from GTAP7 Badri and Walmsley (2008); Hertel et al. (2007, 2008) and are mapped to WIOD sectors prior to the implementation into the model. The average elasticity for the choice between domestic and foreign goods ($\sigma^{\mathrm{a}}_{r,i}$) is 3.1 and varies between 1.6 and 4.4, while the elasticity for the regional allocation of inputs ($\sigma^{\mathrm{mm}}_{r,i}$) is 6.2 and ranges from 3.1 to 8.8.

8.3.3 Benchmark situation

The model has been calibrated to the year 2005 to avoid drawing conclusions from latter periods of economic turmoil where international trade and the related supply chains may have been distorted. Accordingly the benchmark for our counterfactual analysis will build on production as WIOD describes them for the year 2005.

We define the degree of vertical specialisation of an industry by calculating the share of foreign value added that is not related to energy consumption per unit of output. This corresponds to what we defined as vertical specialisation at the intensive margin above. Note that due to the Armington trade structure a discrete offshoring of entire production stages to non-regulated regions – defined in the analytical model as vertical specialisation at the extensive margin – is ruled out. To compute the quantity of value added embodied in sectoral output we follow Leontief's input output concept Leontief (1970) and construct a Leontief inverse from the aggregated World Input-Output Table provided by WIOD. This provides us with an input coefficient matrix which includes all necessary information of global intermediate input use along the supply chain for all considered sectors. Subsequently combining this matrix with the value added or carbon intensity of foreign sectoral production also available from WIOD results in estimates for the amount of non-regulated value added or carbon embodied in domestic output.

Figure 8.5 shows the share of foreign value added in the production of European

this elasticity is equal to the corresponding elasticity for the chemical and chemical products sector (0.717).

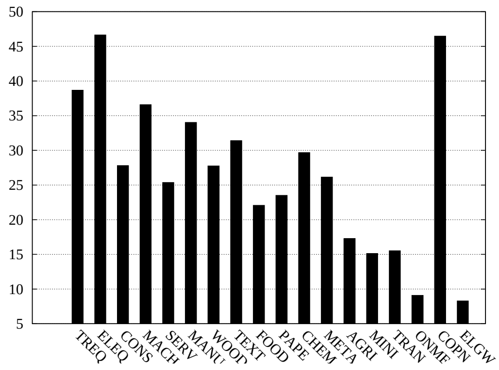


Figure 8.6: Share of non-European carbon embodied on European sectoral output [%]

sectors in the year 2005. The content varies from 3.4 percent in the service sector (SERV) to 16.3 percent in the energy intensive sector of coal, petroleum and nuclear (COPN) production. Apart from services, sectors with a low degree of fragmentation are upstream sectors covering mining and quarrying (MINI), agriculture (AGRI) and construction (CONS). More fragmented with more non-European value added embodied in its output are on the one hand manufacturing sectors such as the production of electronic equipment (ELEQ), transport equipment (TREQ), and machinery (MACH). On the other hand, also European basic material sectors such as metals (META) and chemicals (CHEM) are characterised with a high content of foreign value added. But the two groups differ in their emission intensity: Whereas ELEQ, TREQ, and MACH are sectors with low emission intensity, META and CHEM emit plenty of carbon during their production process.

Obviously, not only value added has been added along the supply chain but often also emissions. Figure 8.6 illustrates the amount of foreign carbon embodied in EU sectoral output. Its foreign carbon share ranges from 10.7 (ELGW) percent to 56.4 (ELEQ) percent. In particular the European sectors that produce coke, petroleum and nuclear fuel, but also electrical equipment – the most fragmented sector – contain high shares of foreign embodied carbon. But note that both sectors feature very different absolute values in embodied carbon. Sectors with only little foreign carbon embodied in their production are the sectors associated to electricity gas and water supply (ELGW) as well as non-metallic minerals such as cement where in contrast a large part of emission is added during the last production stage.

8.3.4 Simulation results

To quantify the magnitude of the effects identified in the analytical model, we study two policy scenarios that correspond to those evaluated in the simplified framework. In the first examined policy regime we assume that the EU commits itself to unilaterally reduce its carbon emissions by 20 percent relative to baseline of 2005. Thereby we assume that the required emission reductions within the EU are granted by an emission trading scheme with full auctioning encompassing emissions in all sectors. This can be seen as a

Table 8.1: Input content and elasticities of European production in benchmark

Sector	CO_2 $[\frac{g}{USD}]$	VA [%]	E[%]	NEG[%]	FNEG[%]	σ^{ld}	σ^{ldx}	σ^{a}	σ^{mm}
TREQ	15.36	23.49	1.50	75.01	6.38	0.16	0.38	3.55	7.10
ELEQ	17.70	33.77	1.54	64.69	10.42	1.06	0.64	4.40	8.80
CONS	21.36	40.19	2.03	57.78	2.44	0.15	0.61	1.90	3.80
MACH	23.53	36.01	1.76	62.22	5.43	0.20	0.55	4.05	8.10
SERV	26.78	61.01	1.57	37.42	2.02	0.27	1.48	1.57	3.13
MANU	39.66	34.50	2.23	63.27	4.72	0.18	0.53	3.75	7.50
WOOD	53.07	32.48	2.98	64.54	4.43	0.21	0.71	3.40	6.80
TEXT	61.25	32.28	2.73	64.98	5.36	0.26	0.58	3.79	7.58
FOOD	62.86	26.77	2.67	70.56	3.93	0.19	0.63	3.00	6.00
PAPE	82.14	37.86	3.42	58.72	4.08	0.25	0.66	2.95	5.90
CHEM	168.55	32.57	6.50	60.94	6.64	0.57	0.87	3.30	6.60
META	272.96	32.53	6.64	60.83	6.02	1.01	0.11	3.75	7.50
AGRI	217.97	49.51	4.67	45.82	2.83	0.40	0.98	2.50	5.00
MINI	338.43	61.95	11.02	27.00	2.16	0.42	0.22	4.12	8.25
TRAN	348.12	43.76	5.38	50.85	3.42	0.48	0.45	1.90	3.80
ONME	940.16	37.45	12.70	49.85	2.82	0.25	0.81	2.90	5.80
COPN	533.54	12.25	59.47	28.27	9.81	0.72	0.42	2.10	4.20
ELGW	1948.75	40.55	35.03	24.42	3.10	0.46	0.68	2.80	5.60

Input content from WIOD and elasticities from Koesler and Schymura (forthcoming) (σ^{ld}, σ^{ldx}) and Badri and Walmsley (2008) (σ^{a}, σ^{mm}).

VA: value-added, E: energy, NEG: non-energy intermediates, FNEG: foreign non-energy intermediates, σ^{ld}: substitution elasticity between factor input and energy, σ^{ldx}: substitution elasticity between factor-energy composite and intermediate composite, σ^{a}: Armington elasticity between domestic and foreign goods, σ^{mm}: Armington elasticity between goods from different foreign regions.

stylized replication of EU 2020 climate policy, that aim at reducing GHG emissions by 20 percent relative to the 1990 level by 2020.[6] In other regions, no emission reduction regulations are in place. Ultimately, this results in a positive emission price in the EU, while in all other regions emitting carbon does not imply any direct costs.

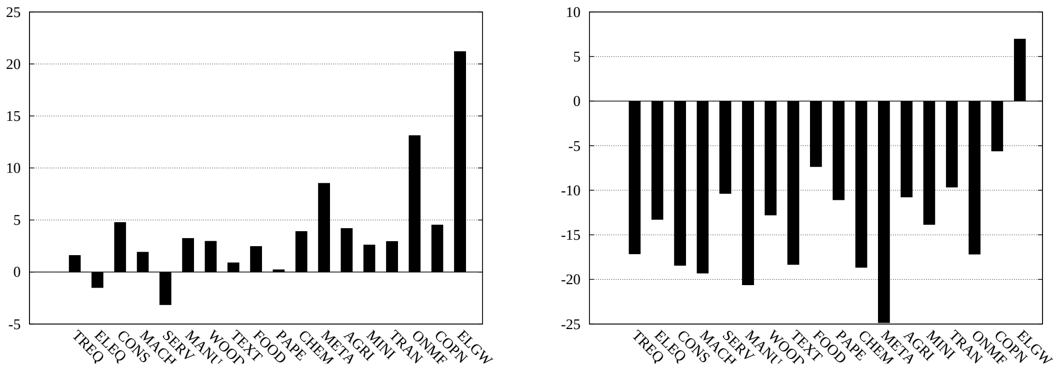
In a further policy scenario, we supplement the unilateral domestic climate policy of the EU by a border tax on all carbon that is embodied in imports to the EU. Embodied carbon is calculated by taking into account the carbon emitted along the supply chain when entering the jurisdiction of the EU. The tax is on carbon embodied along the supply chain descending from non-regulated regions. Thus, we account for a possible multi-regulation of emissions at different production stages of a good. The imported embodied carbon is priced according to the prevailing price of carbon in the emission trading scheme regulating EU emissions. The introduction of a border tax in turn implies that now carbon emissions arising in non-EU regions also become costly if they are imported in the EU.

8.3.4.1 Unilateral carbon pricing

Figure 8.7 shows the changes in embodied foreign value added in output of European sectors under the different scenarios, the core result of the numerical model. As in the analytical framework, sectors are ranked according their emission intensity. The unilateral European policy to reduce carbon emissions by 20 percent indeed alters the sourcing of intermediates in European sectors. The median increase in vertical specialisation is 3.3 percent. In particular industries with a high emission intensity such as as electricity, gas and water supply (ELGW, +21.2%), the production of metal products (META,+8.5%) or other non-metallic minerals (ONME, +13.1%) are becoming more dependent on foreign intermediates and more vertically specialised. To a smaller extent, but due to the size of the sectors also important, the European chemical industries (CHEM, +3.9%) and manufacturing (MANU, +3.2%) offshore production capacities to non-regulated regions and increase the share of non-European value added in their final output.

But as the Figure 8.7 shows, the supply chain reactions are patchy. Several industries – such as services (SERV, -3.1%) or electrical equipment (ELEQ, -1.5%) – become less fragmented and reduce the use of foreign input. So while in general our simulation results reflect Insight 2 derived from the analytical model, here we observe more heterogeneity in the reaction of sectors to the European policy than one would have expected. To shed light upon the sectoral differences, we take a closer look at the cross-price elasticities of demand for foreign value added with regard to changes in European energy prices which are at the heart of the effects provoked by our policy scenarios. Note that thereby we only consider marginal price changes and for the moment disregard any general equilibrium effects. The respective cross-price elasticities feature two components. One describing the change induced by a change in the amount of energy directly used in the

[6] For an more comprehensive assessment of this policy, see Böhringer et al. (2009).



(a) Unilateral carbon pricing

(b) Unilateral carbon pricing and border tax

Figure 8.7: Changes in vertical specialisation for European sectors relative to benchmark scenario [%]

production of a European sector and another one describing the change in the amount of European energy used to produce intermediates required for the production of the European sector. Most importantly, the cross-price elasticities are composed of input intensities and substitution elasticities. If sectors differ only in their energy respectively emission intensity – as is the case in out analytical model where sectors feature different α but are otherwise alike – the demand for foreign value added induced by a change in local energy prices follows a linear function which is increasing in the energy/emission intensity (c.f. Insight 2). But accounting for additional sectoral heterogeneity in input intensities and substitution elasticities leads to a more complex pattern of changes. The graphs in Figure 8.8 illustrates how the reaction evolves when taking more and more sectoral specifications into account and moving step-by-step from the illustrative specification of the analytical model to our simulation exercise which is informed by WIOD data.[7] Graph 8.8a only accounts for WIOD data for energy intensities and otherwise uses a setup as in the analytical model. Graph 8.8b additionally accounts for WIOD data for intermediate intensities. Graph 8.8c accounts further for informed shares for the origin of intermediates (domestic vs. foreign).

Although all graphs feature a rather clear positive trend in emission intensity, sectoral differences become clearer as additional information from WIOD is used. With an increase in vertical specialisation of 4.5 percent in the full simulation exercise, the coke, petroleum and nuclear fuel sector (COPN) for example features a lower change then one would have expected given its relatively high level of energy respectively emission intensity. Studying the associated cross-price elasticity then reveals that its relatively high original share in foreign intermediate use decreases the impact of the policy on this

[7]For parameters that are originally not part of the analytical model or have not been explicitly specified we assume the following: $\theta = 0.5, \beta = 0.2, es_a = 10$. We choose these values as they are fairly close the values supplied by WIOD and Koesler and Schymura (2015).

sector. Accordingly, when moving from Graph 8.8b to Graph 8.8c the corresponding cross-price elasticity drops. The opposite can be observed for construction (CONS), for which the increase in vertical specialisation is higher (+4.8) than expected on the basis of Insight 2. Also for this sector, Figure 8.8 reveals that additional heterogeneity with regard to input intensities and their implication on the cross-price elasticity can explain parts of the variability of the overall simulation results presented in Figure 8.7.

The decrease in vertical specialisation of the service and electrical equipment sector however cannot directly be explained by differences in the reaction to energy price changes. Both sectors are characterized by a particular low energy and emission intensity and are thus initially not affected much by the energy price change. In addition to this, both sectors are comparatively value added intensive and can benefit from the decrease in the price of value added (-4.7%) that follows the implementation of the policy in Europe. So eventually also general equilibrium effects that resonate throughout the economy after the policy implementation can have an important impact on the production setup of sectors and should therefore also be considered when studying vertical specialisation.

Obviously, changes in the vertical structure of an industry and the respective supply chain adjustments also cause changes in the amount and source of emissions embodied in an industries' output. We measure the change in the origin of carbon that is embodied in a unit of output as:

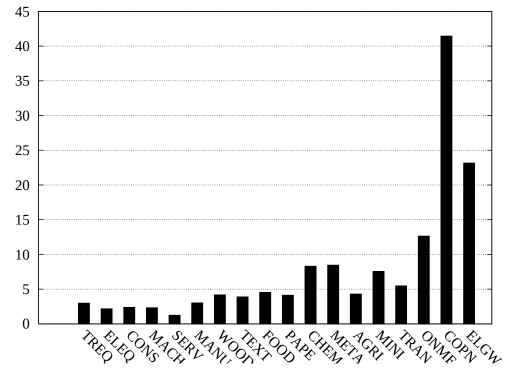
$$\Delta C_i^{\mathrm{EUR}} = \frac{\Delta ec_i^{\mathrm{NoEUR}}}{\Delta ec_i^{\mathrm{EUR}}}, \tag{8.18}$$

where $\Delta ec_i^{\mathrm{NoEU}}$ is the change in embodied carbon from non-European sources and $\Delta ec_i^{\mathrm{EUR}}$ the change in embodied carbon from European sources, both in output of industry i relative to the Bechmark. Note that an increase of non-European carbon embodied in European output due to lower prices of non-European energy intensive intermediates is one part of what generally encompasses carbon leakage. The change in the origin of carbon in non-European industries' supply chains is presented in Table 8.2. All sectors apart of the transportation sector (TRAN) increase the amount of embodied carbon from non-EU regions and therewith contribute to leakage. Transportation is an exception because although it reduces its output and in Europe, this is not accompanied by a comparatively large expansion of production and related emissions abroad. The main contributor is the coke, petroleum and nuclear fuel sector.

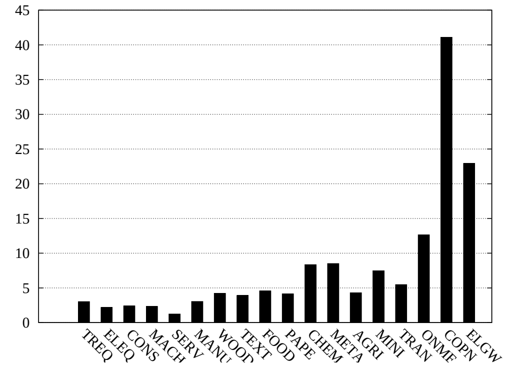
8.3.4.2 Unilateral emission pricing with border emission taxes

Changes in the degree of vertical specialisation if the domestic emission reduction policy in the EU is complemented by a border tax on all carbon that is embodied in imports to the EU are also illustrated in Figure 8.7. With a median decrease of 18.9 percent, vertical specialisation drops significantly for virtually all sectors. The strongest drop takes place in the metal production sector (META, -28.7%), a sector which in Europe

(a)



(b)



(c)

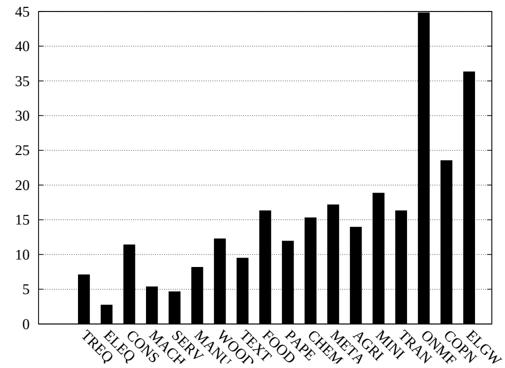


Figure 8.8: Cross-price elasticities of demand for foreign value added with regard to changes in European energy prices parameterised with different values for input intensities and substitution elasticities. Graph (a) accounts for WIOD data for energy intensities and otherwise uses a setup as in the analytical model. Graph (b) additionally accounts for WIOD data for intermediate intensities. Graph (c) accounts further for informed shares for the origin of intermediates (domestic vs. foreign).

Table 8.2: Change in the origin of embodied carbon in output of European sectors [%]

Sector	Unilateral carbon pricing	Unilateral carbon pricing and border tax
ELEQ	5.43	-56.74
CONS	27.35	-52.89
MACH	15.94	-52.81
SERV	3.67	-35.98
MANU	16.30	-51.83
WOOD	11.93	-39.13
TEXT	7.77	-45.62
FOOD	6.82	-29.52
PAPE	7.83	-33.22
CHEM	8.40	-44.44
META	5.97	-36.28
AGRI	0.78	-22.62
MINI	1.46	-25.24
TRAN	-3.52	-17.18
ONME	17.10	-30.04
COPN	88.85	-78.95
ELGW	0.43	-12.72

relies heavily on now more costly carbon intensive intermediate inputs from abroad. The sector with the smallest but still very much noticeable drop of 7.0 percent is the sector related to the supply of coke, petroleum and nuclear products (COPN). This sector also uses carbon intensive inputs, but these tend to be very upstream intermediates and have thus not yet collected as much now taxed embodied carbon along the value chain. For the same reasons and the fact that because the non-energy intermediates it imports feature a relatively low emission intensity, the electricity, gas and water sector (ELGW, +3.6%) increases its share of vertical specialisation and indeed offshores parts of its production despite the border tax.

According to Insight 5 from the analytical model, the introduction of a border carbon

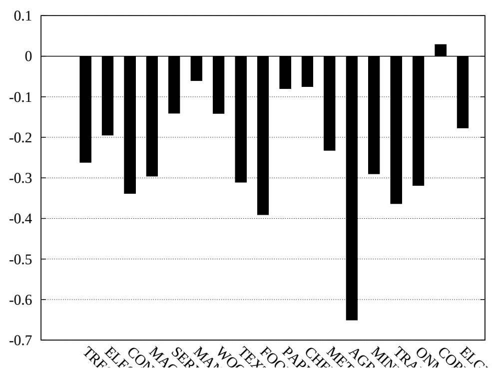


Figure 8.9: Changes of final demand served by European sectors in non regulated regions relative to REDO [%]

tax will results in the offshoring of some parts of the production originally supplying non-European final demand and thus will also have an effect on the market share of European sectors in the non-regulated regions. Figure 8.9 shows the simulation results to this regard. Virtually all European sectors see the demand for their final goods reduced in the non-regulated regions, the median decrease is -0.25 percent. While the most affected sector is agriculture (AGRI, -0.65%), the coke, petroleum and nuclear fuel sector (COPN, +0.03%) is an exception and experiences a slight increase in foreign demand. The effect can be expected to be stronger for sectors where more non-European carbon is embodied in the European final good, that is for example electrical or transport equipment (ELEQ, -0.19%; TREQ, -0.26%). However, there is a multitude of factors such as relative factor abundancy, productivity or trade elasticities that also play a role. Eventually we observe a picture that is low in magnitude and rather divers. Further research should be directed in the specific drivers of the shifts in market share. Note also that in our setting and in contrast to the theoretical potential mentioned in Insight 6 we do not observe any additional leakage (c.f. Table 8.2).

Overall, in the setting with a border carbon tax, our simulation exercise comes to the same results as our theoretical deliberations summarised in Insight 4. Although in the numerical model, owing to the more complex setup of value chains, the Armington structure of trade, and the lack of clear cut comparative advantages, we still observe some vertical specialisation in the presence of a border tax on carbon.

8.3.4.3 General results

After having presented details on how vertical specialisation is affected by environmental policy in the last section, the following section presents more general implications of reducing emissions in the EU. Table 8.3 summarizes the change in key economic indicators for the EU following the European emission reduction efforts under the both policy scenarios. If the EU reduces its emissions unilaterally, GDP in the EU falls by 0.48 percent and welfare, measured in Hicksian equivalence, drops by 0.50 percent. Imports and exports are are affected to a stronger degree and reduce by 4.63 percent and 4.25 percent respectively. From a sectoral perspective the impact is yet rather minor and output reduces generally between 0 and 5 percent. For sectors with a low CO_2 intensity it might even lead to an increase in output. The electrical equipment sector (ELEQ) for example slightly raises its output in the unilateral carbon pricing scenario as it makes use of reduced factor prices. As is to be expected, energy intensive sectors such as coke and petroleum production (COPN), mining and quarrying (MINI), and electricity and gas supply (ELGW) belong to the most affected sectors under a regime with domestic reduction policy only (REDO). Particulary mining and quarrying suffers under a policy that addresses only domestic emissions and a 20 percent reduction of CO_2-emissions leads to a decrease in output by about 27 percent. With 39.46 percent carbon leakage is relatively high, although this rate is consistent with findings from Bednar-Friedl et al. (2012) who also account process emissions. Besides the EU, in particular Russia and the

Table 8.3: Change in key economic indicators in the EU [%]

	Unilateral carbon pricing	Unilateral carbon pricing and border tax
GDP	-0.48	-0.38
Exports	-4.25	-21.79
Imports	-4.63	-22.08
Welfare	-0.50	-0.31
Carbon leakage	39.46	25.75

'Rest of the World' are negatively affected by the EU policy and they see their GDP fall by 0.40 percent and 0.19 percent while their welfare decreases by 0.40 percent and 0.14 percent respectively. This relates mainly to a drop in energy exports of these regions as the EU reduces it energy use to cut emissions.

The implementation of a border carbon tax on imports from unregulated countries eases the effect of the reduction policy on the EU economy and GDP losses amount 0.38 percent only while welfare falls by 0.31 percent. But it comes at the cost of strong reductions in exports (-21.79%) and imports (-22.08%). This also gives an indication that the effect that the border tax regime limits all trade induced by unilateral climate policy as described by Insight 4 can be observed in our simulation exercise. What is more, the border carbon tax redistributes the climate policy costs among EU sectors. Sectors such as electrical equipment (ELEQ) or machinery (MACH) that were less hit under REDO have now to cope with stronger output losses of up to 5 percent. An explanation might be the dependence on carbon-intensive intermediate imports such as steel that are becoming more costly with a border carbon tax. The tariff however effectively reduces the comparative advantage of non-regulated sectors beyond EU borders and carbon leakage is reduced by almost 14 percentage points. Thus, in our modelling framework and with regard to overall effects, the issue of an increase in carbon leakage because of a large scale relocation of parts of the supply of goods consumed in non-regulated regions to these regions described in Insight 5 does not arise. The likely reason for this is that in our numerical exercise comparative advantages are not as clear cut as in the small scale theoretical model and because of the Armington structure of trade, even in the benchmark all sectors are active in all regions. The border carbon tax leads also to a different burden sharing of the costs of climate policy between regions. Under regulation of only domestic carbon emissions, the EU has to bear the majority of the climate policy costs, the effects for other regions are negligible and only Russia and 'Rest-of-the-World' are confronted with relevant reductions. But the carbon tax results in a shift of the costs to the main trading partners, in particulary of energy intensive goods, of the EU. As a result, if expressed in terms of welfare loss, a EU policy with a border carbon tax has costs for Russia of more than 4 percent and of nearly 1 percent for 'Rest-of-the-World'. But also China is significantly affected, coping with costs of now 1 percent.

8.4 Summary and conclusion

The evolution of global value chains reshapes the economic landscape. This paper investigates the effects of unilateral regulation, more specifically a unilateral carbon pricing on domestic emitters and a border tax on imported embodied carbon, on vertical specialisation. We first analyse the general economics of vertical specialisation on the basis of an analytical partial equilibrium model of a two stage production process with two countries.

In the process we distinguish between vertical specialisation on the extensive margin, that is the implementation of a fragmented production structure by offshoring one production step, and vertical specialisation at the intensive margin, which indicates by how much a sector relies on intermediates produced in earlier production steps abroad. We find that unilateral emission reduction polices force more emission-intensive producers to shift a greater share of their supply chain to the unregulated region and thereby increasing vertical specialisation at the extensive as well as at the intensive margin. Border carbon taxation in turn is successful in fetching these stages back home. But by shifting parts of the final good production to unregulated regions may also have negative implications, such as a loss of market shares and the shift of emissions to unregulated jurisdictions.

In reality though, the production setup of sectors is far more complex and interweaved with other sectors. Because of this, we next make use of a full fledged CGE model that is calibrated to WIOD data and investigate the implications of unilateral emission reduction policies by the EU. Overall, the findings of the CGE model corroborate the results of the theoretical analysis. However, as intermediate intensities and elasticities of substitution define how well offshoring can be a response to unilateral policies, the magnitude of the effects on vertical specialisation vary across sectors.

When the EU unilaterally implements a 20 percent reduction in emissions, sectors increase vertical specialisation by up to 21 percent, whereas the median sector increases its degree of vertical specialisation by about 3 percent. While overall carbon leakage amounts to 39 percent, changes in the supply chain of sectors result in an increase in the amount of embodied carbon from non-European sources for most industries. The median increase to this regard equals 8 percent. If the EU complements its policy with a border tax on all carbon that is embodied in imports, the policy no longer results in more vertical specialisation. On the contrary, in such a situation supply chains shrink notably and the median sector reduces its level of vertical specialisation by almost 19 percent compared to the benchmark setup. What is more due to the border tax, EU sectors loose market share in foreign final demand markets.

Overall, our results indicate that unilateral regulation can have effects on the production structures of industries and complement other drivers such as transportation costs in shaping the value change of sectors. It also has implications on the overall emission intensity of production. This implies that researchers and policy makers alike should not only consider direct effects such as export potentials of sectors when discussing unilateral policy measures but also less tangible but as important changes in vertical specialisation.

However, in order to be able to assess these effects comprehensively more research is necessary. It is particularly important to better understand the substitution possibilities and the flexibility to adjust the value chains. In addition, the interaction of drivers of the different vertical specialisation such as unilateral policy and transportation costs needs further research in order to be able to derive better indications of how value chains may change in future.

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Appendix A

The Basic WIOD CGE Model

A.1 Short description

The Basic WIOD CGE model is a static, multi-region, multi-sector computable general equilibrium (CGE) model. It has been developed within the project 'WIOD World Input-Output Database: Construction and Applications' funded by the European Commission, Research Directorate General as part of the 7th Framework Programme and has been designed deliberately as flexible as possible in order to allow researchers to use the World Input-Output Database (WIOD) in the framework of a CGE model in various applications. While a comprehensive description of the Basic WIOD CGE Model and the data it uses is provided by Koesler and Pothen (2013), the following provides a concise description of the model.

The model distinguishes between two groups of commodities in region r: energy commodities $Y_{(eg,r)}$ and non-energy commodities $Y_{(neg,r)}$. The production of these goods is characterised by production functions with constant elasticities of substitution (CES) and constant returns to scale. Nested CES functions with three levels are employed to specify the substitution possibilities between capital $K_{(r)}$, labour $L_{(r)}$, energy inputs $A_{(eg,r)}$ and non-energy intermediate inputs $A_{(neg,r)}$ of sectoral production. A KLEM production structure is applied for all sectors i, thus capital and labour enter the production function on the lowest level, on the second level value added is combined with energy and finally on the top level of the CES function the energy-value-added composite is combined with a non-energy material aggregate. An overview of the production structure is given in Figure A.1 and the corresponding zero-profit condition is given in Equation A.1. Thereby and for all following CES functions, π denotes profits and CES stands for a constant elasticity of substitution function. The arguments of the CES function is given in parentheses and the corresponding elasticity of substitution in the upper index. Small p's are prices of commodities and factors.

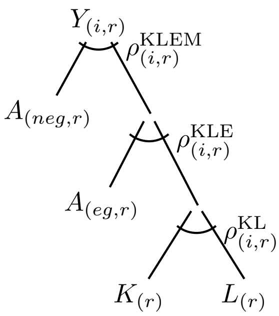

Figure A.1: Structure of commodity production

$$\begin{aligned}\pi^{Y}_{(r,i)} \leq & CES^{0}_{(r,i)}\Big[CES^{0}_{(r,i)}(pem_{(em,ETSGroup)}), CES^{\sigma^{klem}_{(r,i,t)}}_{(r,i)}\big[CES^{\sigma^{ms}_{(r,i,t)}}_{(r,i)}(pa_{(neg,r,i)}),\\ & CES^{\sigma^{kle}_{(r,i,t)}}_{(r,i)}\big[CES^{\sigma^{e}_{(r,i,t)}}_{(r,i)}(pe\_em_{(eg,r,i)}),\\ & CES^{\sigma^{kl}_{(r,i,t)}}_{(r,i)}(pl_{(r)}, pk_{(r)})\big]\big]\Big].\end{aligned} \tag{A.1}$$

Sectoral output can be used for intermediate use and/or final consumption domestically and/or exported to other regions. Perfect competition is assumed in all markets. Interregional trade is fully flexible and need not be balanced as long as the agent's overall budget is balanced.

As is the case for many other models, the choice among imports and domestically produced commodities is based on Armington's idea of regional product differentiation (Armington, 1969), i.e. domestic and foreign goods are not necessarily perfect substitutes and in combination form an Armington aggregate. However, in the Basic WIOD CGE Model, Armington goods are not only region specific to account for regional differences in preference for domestic and foreign goods, but also sector specific in order to allow intermediates to be traced from their origin to their destination. Figure A.2 gives an overview of the underlying Armington structure and Equations A.2 and A.3 present the zero-profit and market clearance conditions for international commodity markets. $Y_{(r,i)}$ is domestic production, $Y_{(rr,i)}$ is production by foreign regions, small p's are prices and $M_{(i,rr,mkt)}$ are imports of commodity i of market mkt (final demand and sectors) in region rr. While the Armington elasticity $\sigma^{es\_a}_{(r,i)}$ governs the substitutability between domestic and foreign goods, $\sigma^{es\_mm}_{(r,i)}$ controls the substitution between the same good from different regions. Apart from this, the basic model abstracts from other potential trade distortions.

$$\pi^{A}_{(i,r,mkt)} \leq CES^{\sigma^{es\_a}_{(r,i)}}_{(i,r,mkt)}\Big[py_{(r,i)}, CES^{\sigma^{es\_mm}_{(r,i)}}_{(i,r,mkt)}(py_{(rr,i)})\Big] \text{ with } rr \neq r, \tag{A.2}$$

$$M_{(i,r,mkt)} \geq \sum_{rr;rr\neq r}\left(\frac{\partial \pi^{A}_{(i,r,mkt)}}{\partial py_{(rr,i)}} A_{(i,r,mkt)}\right), \tag{A.3}$$

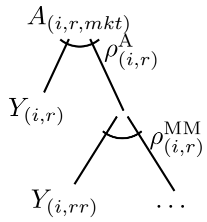

Figure A.2: Structure of Armington aggregate

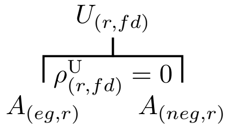

Figure A.3: Structure of utility of representative agents

Each region may be represented by up to five aggregated representative agent who embraces all final demand types available in WIOD. The representative agents maximise their utility by purchasing bundles of consumption goods subject to their budget constraint. Utility of representative agents $U(fd, r)$ is given as a Leontief composite of energy $A_{(eg,r)}$ and a non-energy commodities $A_{(neg,r)}$. The structure of the utility functions is given in Figure A.3 and the related zero-profit condition is given in Equation A.4.

$$\pi^{U}_{(r,fd)} \leq CES^{0}\left[CES^{0}(pa_{(neg,r)}), CES^{0}(pa_{(eg,r)})\right]. \tag{A.4}$$

As described exemplarily for households and a government agent in Equation A.5 and A.6, the budget is determined by factor and tax income along with (intertemporal and interregional) borrowing or saving. In the basic version, agents supply a fix amount of capital and labour. Factors are mobile across sectors within regions but not across regions and therefore the model in its basic version abstracts from interregional factor mobility and investment.

$$\begin{aligned} B_{(r,FC\_HH)} =& pk_{(r)} \sum_{i} \left(K_{(r,i)}\right) + pl_{(r)} \sum_{i} \left(L_{(r,i)}\right) \\ & - Saving_{(r,FC\_HH)} + Borrowing_{(r,FC\_HH)}, \end{aligned} \tag{A.5}$$

$$B_{(r,GOV)} = Tax(r) - Saving_{(r,GOV)} + Borrowing_{(r,GOV)}. \tag{A.6}$$

Besides standard economic activity, the model makes provisions for the accounting of CO_2 and other air emissions (N_2O, CH_4, NO_X, SO_X, NH_3, NMVOC, CO) caused by economic activity. For CO_2, the model distinguishes between energy related emissions and process emissions from sectoral production as well as consumption. Because the

WIOD dataset does currently not allow to tie any of the other air emissions to particular inputs, these emissions are considered only as process emissions from production and consumption. From a modelling perspective, when emissions are related to energy, they occur during the production process parallel to the use of energy. That is they are associated with the second nest of the production structure outlined in Figure A.1 and the first branch of Figure A.3 depicting the structure of utility. Process emission in turn are understood as a byproduct of production and consumption and are thus tied to sectoral output and final demand. If required, an emission trading system or a taxing scheme can be applied to all types of emissions.

Following Rutherford (2005) and Böhringer et al. (2003), the equilibrium in our model is characterised through three types of equilibrium conditions, namely market clearance conditions for all commodities and factors (supply = demand), income balances (net income = net expenditure) and zero profit conditions (cost of inputs = value of output). The variables defining the equilibrium are activity levels for the constant-returns-to-scale production, commodity and factor prices, and the price of final consumption. The market clearance condition related to the production of commodities is illustrated in Equation A.7.

$$\begin{aligned} Y_{(r,i)} \geq & \sum_{ii} \left(\frac{\partial \pi^{Y}_{(r,ii)}}{\partial py_{(r,i)}} Y_{(r,ii)} \right) + \sum_{fd} \left(\frac{\partial \pi^{U}_{(r,fd)}}{\partial py_{(r,i)}} U_{(r,fd)} \right) \\ & + \sum_{rr;r \neq rr} \sum_{mkt} \left(\frac{\partial \pi^{A}_{(i,rr,mkt)}}{\partial py_{(r,i)}} A_{(i,rr,mkt)} \right). \end{aligned} \tag{A.7}$$

The market clearance condition for final demand is given in Equation A.8.

$$B_{(r,fd)} \geq U_{(r,fd)}. \tag{A.8}$$

For factor markets the following market clearance conditions must hold.

$$K_{(r,i)} \geq \sum_{ii} \left(\frac{\partial \pi^{Y}_{(r,ii)}}{\partial pk_{(r)}} Y_{(r,ii)} \right), \tag{A.9}$$

and

$$L_{(r,i)} \geq \sum_{ii} \left(\frac{\partial \pi^{Y}_{(r,ii)}}{\partial pl_{(r)}} Y_{(r,ii)} \right). \tag{A.10}$$

Numerically, the model is formulated as a mixed complementarity problem (MCP) in the mathematical optimization program GAMS, a program that is frequently used to develop and run CGE models. It is written in GAMS using the MPSGE syntax (c.f. Rosenthal, 2010; Rutherford, 1999). The model is solved using the PATH algorithm (c.f. Dirkse and Ferris, 1993).

Regarding the basic economic structure and information on emissions, the model builds on data from the World Input-Output Database (WIOD) (Timmer et al., 2012;

Dietzenbacher et al., 2013) and can be calibrated to any year WIOD covers (currently 1995 to 2009). The required Armington elasticities are taken from GTAP7 (Badri and Walmsley, 2008; Hertel et al., 2007, 2008) and are mapped to WIOD sectors prior to the implementation into the model. For substitution elasticities determining the flexibility of production with regard to inputs, estimates from Koesler and Schymura (2015) are applied.

A.2 Additional tables

Table A.1: List of data sources used to generate WIOD.gdx

Short	Data Source
WIOT Analytics	World Input-Output Tables
SEA	Socio-Economics Accounts
AIR	Emissions to Air
CO2	CO_2 Emissions
EU	Energy Use
EM	Energy Use Emission Relevant
KS	Koesler and Schymura (2015)

Table A.2: List of regions, sectors and final demand types

Short	Region	Short	Sector or Final Demand
AUS	Australia	AtB	Agriculture, Hunting, Forestry and Fishing
AUT	Austria	C	Mining and Quarrying
BEL	Belgium	15t16	Food, Beverages and Tobacco
BGR	Bulgaria	17t18	Textiles and Textile Products
BRA	Brasil	19	Leather, Leather and Footwear
CAN	Canada	20	Wood and Products of Wood and Cork
CHN	China	21t22	Pulp, Paper, Paper , Printing and Publishing
CYP	Cyprus	23	Coke, Refined Petroleum and Nuclear Fuel
CZE	Czech Republic	24	Chemicals and Chemical Products
DEU	Germany	25	Rubber and Plastics
DNK	Denmark	26	Other Non-Metallic Mineral
ESP	Spain	27t28	Basic Metals and Fabricated Metal
EST	Estland	29	Machinery, Nec
FIN	Finland	30t33	Electrical and Optical Equipment
FRA	France	34t35	Transport Equipment
GBR	Great Britain	36t37	Manufacturing, Nec; Recycling
GRC	Greece	E	Electricity, Gas and Water Supply
HUN	Hungaria	F	Construction
IDN	Indonesia	50	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
IND	India	51	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
IRL	Ireland	52	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
ITA	Italia	H	Hotels and Restaurants
JPN	Japan	60	Inland Transport
KOR	South Korea	61	Water Transport
LTU	Lithuania	62	Air Transport
LUX	Luxemburg	63	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies

Short	Region	Short	Sector or Final Demand
LVA	Latvia	64	Post and Telecommunications
MEX	Mexico	J	Financial Intermediation
MLT	Malta	70	Real Estate Activities
NLD	The Netherlands	71t74	Renting of M&Eq and Other Business Activities
POL	Poland	L	Public Admin and Defence; Compulsory Social Security
PRT	Portugal	M	Education
ROM	Romania	N	Health and Social Work
RUS	Russia	O	Other Community, Social and Personal Services
SVK	Slovakia	P	Private Households with Employed Persons
SVN	Slovenia		
SWE	Sweden	FC_HH	Final consumption expenditure by households
TUR	Turkey	FC_NP	Final consumption expenditure by non-profit organisations serving households (NPISH)
TWN	Taiwan	FC_GOV	Final consumption expenditure by government
USA	United States of America	FC_CF	Gross fixed capital formation
RoW	Rest of the World	FC_IV	Changes in inventories and valuables

Table A.3: Elements in core data file WIOD.gdx

Element	Description	Source	Unit
$CiffobAdj_{(r,mkt,t)}$	Cif fob adjustments on exports	WIOT Analytics	current mio. US Dollar
$Capital_{(r,i,t)}$	Computed absolute values for capital compensation	WIOT Analytics	current mio. US Dollar
$Labor_{(r,i,t)}$	Computed absolute values for labor compensation	WIOT Analytics	current mio. US Dollar
$DirPur_{(r,fd,t)}$	Direct purchases abroad by residents	WIOT Analytics	current mio. US Dollar
$FinalDemand_{(r,i,rr,fd,t)}$	Final demand inputs and outputs	WIOT Analytics	current mio. US Dollar
$Intermed_{(r,i,rr,ii,t)}$	Intermediate inputs and outputs	WIOT Analytics	current mio. US Dollar
$IntTransMa_{(r,mkt,t)}$	International Transport Margins	WIOT Analytics	current mio. US Dollar
$TotOutputCol_{(r,mkt,t)}$	Output at basic prices in columns	WIOT Analytics	current mio. US Dollar
$TotOutputRow_{(r,i,t)}$	Output at basic prices in rows	WIOT Analytics	current mio. US Dollar
$PurNonRes_{(r,fd,t)}$	Purchases on the domestic territory by non-residents	WIOT Analytics	current mio. US Dollar
$TaxFinalDemand_{(r,fd,t)}$	Taxes less subsidies on final demand	WIOT Analytics	current mio. US Dollar
$TaxOutput_{(r,i,t)}$	Taxes less subsidies on products	WIOT Analytics	current mio. US Dollar
$TotIntermed_{(r,mkt,t)}$	Total intermediate consumption	WIOT Analytics	current mio. US Dollar
$ValueAdded_{(r,i,t)}$	Value added compensation at basic price	WIOT Analytics	current mio. US Dollar
$es\_kl\_KS_{(r,i,t)}$	Elasticity of substitution between K and L	KS	
$es\_kle\_KS_{(r,i,t)}$	Elasticity of substitution between KL and E	KS	
$es\_klem_{K}S_{(r,i,t)}$	Elasticity of substitution between KLE and MS	KS	
$es\_ms\_KS_{(r,i,t)}$	Elasticity of substitution between M and S	KS	
$EM\_Sec_{(eg,r,i,t)}$	Emission relevant energy use of industries	EM	Terajoules
$EM\_FD_{(eg,r,fd,t)}$	Emissions relevant energy use of final demand	EM	Terajoules
$EM\_Total_{(eg,r,t)}$	Total emissions relevant energy use per energy carrier	EM	Terajoules
$EU\_Sec_{(eg,r,i,t)}$	Energy use of industries	EU	Terajoules
$EU\_FD_{(eg,r,fd,t)}$	Energy use of final demand	EU	Terajoules
$EU\_Total_{(eg,r,t)}$	Total energy use per energy carrier	EU	Terajoules
$CO2FD_{(co2source,r,fd,t)}$	CO_2 emissions per final demand	CO2	Kilotons
$CO2Sec_{(co2source,r,i,t)}$	CO_2 emissions per sector	CO2	Kilotons

Element	Description	Source	Unit
$CO2Total_{(co2source,r,t)}$	Total CO_2 emissions per source	CO2	Kilotons
$AirSec_{(em,r,i,t)}$	Air emissions of sector	AIR	Tons (CO_2 in Kilotons)
$AirFD_{(em,r,fd,t)}$	Air emissions of final demand	AIR	Tons (CO_2 in Kilotons)
$TotAirFD_{(em,r,t)}$	Total air emissions of final demand	AIR	Tons (CO_2 in Kilotons)
$TotAirSec_{(em,r,t)}$	Total air emissions of sector	AIR	Tons (CO_2 in Kilotons)
$TotAir_{(em,r,t)}$	Total air emissions of sectors and final demand	AIR	Tons (CO_2 in Kilotons)
$LABShare_{(origR,origSec,t)}$	Labor share		
$SecShare_{(origR,origSec,r,i,t)}$	Output share		
$aggE_{(origE,eg)}$	Set – Aggregation of energy carriers		
$aggFD_{(origFD,fd)}$	Set – Aggregation of final demand		
$aggMKT_{(origMKT,mkt)}$	Set – Aggregation of markets		
$aggR_{(origR,r)}$	Set – Aggregation of regions		
$aggSec_{(origSec,i)}$	Set – Aggregation of sectors		
$aggco2src_{(co2src,co2source)}$	Set – Aggregation of sources for CO_2 emission		
mkt	Set – All markets - sectors plus final demands		
em	Set – Emissions to Air		
$eg(mkt)$	Set – Energy goods		
$fd(mkt)$	Set – Final demand		
r, alias rr, s	Set – regions		
$i(mkt)$, alias ii, j	Set – sectors to be used in the model		
$co2source$	Set – Sources of CO_2 emissions		
t	Set – time		

Table A.4: Elements in core data file WIOD_PreAgg.gdx

Element	Description	Source	Unit
$CAP\_SEA\_PreAgg_{(origR,origSec,t)}$	Absolute values for capital compensation from YL files	SEA	current mio. local currency
$LAB\_SEA\_PreAgg_{(origR,origSec,t)}$	Absolute values for labor compensation from YL files	SEA	current mio. local currency
$VA\_SEA\_PreAgg_{(origR,origSec,t)}$	Absolute values for value added from YL files	SEA	current mio. local currency
$CiffobAdj\_PreAgg_{(r,mkt,t)}$	Cif fob adjustments on exports	WIOT Analytics	current mio. US Dollar
$DirPur\_PreAgg_{(r,fd,t)}$	Direct purchases abroad by residents	WIOT Analytics	current mio. US Dollar
$FinalDemand\_PreAgg_{(r,i,rr,fd,t)}$	Final demand inputs and outputs	WIOT Analytics	current mio. US Dollar
$Intermed\_PreAgg_{(r,i,rr,ii,t)}$	Intermediate inputs and outputs	WIOT Analytics	current mio. US Dollar
$IntTransMa\_PreAgg_{(r,mkt,t)}$	International Transport Margins	WIOT Analytics	current mio. US Dollar
$TotOutputCol\_PreAgg_{(r,mkt,t)}$	Output at basic prices in columns	WIOT Analytics	current mio. US Dollar
$TotOutputRow\_PreAgg_{(r,i,t)}$	Output at basic prices in rows	WIOT Analytics	current mio. US Dollar
$PurNonRes\_PreAgg_{(r,fd,t)}$	Purchases on the domestic territory by non-residents	WIOT Analytics	current mio. US Dollar
$TaxFinalDemand\_PreAgg_{(r,fd,t)}$	Taxes less subsidies on final demand	WIOT Analytics	current mio. US Dollar
$TaxOutput\_PreAgg_{(r,i,t)}$	Taxes less subsidies on products	WIOT Analytics	current mio. US Dollar
$TotIntermed\_PreAgg_{(r,mkt,t)}$	Total intermediate consumption	WIOT Analytics	current mio. US Dollar
$ValueAdded\_PreAgg_{(r,i,t)}$	Value added compensation at basic price	WIOT Analytics	current mio. US Dollar
$es\_kl_{K}S\_PreAgg_{(r,i,t)}$	Elasticity of substitution between K and L	KS	
$es\_kle_{K}S\_PreAgg_{(r,i,t)}$	Elasticity of substitution between KL and E	KS	
$es\_klem_{K}S\_PreAgg_{(r,i,t)}$	Elasticity of substitution between KLE and MS	KS	
$es\_ms_{K}S\_PreAgg_{(r,i,t)}$	Elasticity of substitution between M and S	KS	
$EM\_Sec\_PreAgg_{(eg,r,i,t)}$	Emission relevant energy use of industries	EM	Terajoules
$EM\_FD\_PreAgg_{(eg,r,fd,t)}$	Emissions relevant energy use of final demand	EM	Terajoules
$EM\_Total\_PreAgg_{(eg,r,t)}$	Total emissions relevant energy use per energy carrier	EM	Terajoules
$EU\_Sec\_PreAgg_{(eg,r,i,t)}$	Energy use of industries	EU	Terajoules
$EU\_FD\_PreAgg_{(eg,r,fd,t)}$	Energy use of final demand	EU	Terajoules
$EU\_Total\_PreAgg_{(eg,r,t)}$	Total energy use per energy carrier	EU	Terajoules
$CO2FD\_PreAgg_{(co2source,r,fd,t)}$	CO_2 emissions per final demand	CO2	Kilotons

Element	Description	Source	Unit
$CO2Sec\_PreAgg_{(co2source,r,i,t)}$	CO_2 emissions per sector	CO2	Kilotons
$CO2Total\_PreAgg_{(co2source,r,t)}$	Total CO_2 emissions per source	CO2	Kilotons
$AirSec\_PreAgg_{(em,r,i,t)}$	Air emissions of sector	AIR	Tons (CO_2 in Kilotons)
$AirFD\_PreAgg_{(em,r,fd,t)}$	Air emissions of final demand	AIR	Tons (CO_2 in Kilotons)
$TotAirFD\_PreAgg_{(em,r,t)}$	Total air emissions of final demand	AIR	Tons (CO_2 in Kilotons)
$TotAirSec\_PreAgg_{(em,r,t)}$	Total air emissions of sector	AIR	Tons (CO_2 in Kilotons)
$TotAir\_PreAgg_{(em,r,t)}$	Total air emissions of sectors and final demand	AIR	Tons (CO_2 in Kilotons)
em	Set – Emissions to Air		
$origFD(origMKT)$	Set – Original final demand of goods in WIOD		
$origSec(origMKT)$	Set – Original industries in WIOD (35 industry level)		
$origMKT$	Set – Original markets in WIOD (industries and final consumption)		
$origR$	Set – Original Regions		
$origE$	Set – Original types of energy in WIOD		
$co2src$	Set – Original sources of CO_2 emission		
t	Set – time		

Table A.5: Notation in Basic WIOD CGE Model

Element	Description
$A_{(i,r,mkt)}$	Armington composite production
$es\_a_{(r,mkt,t)}$	Armington elasticity of substitution between import composite and domestic commodity
$es\_mm_{(r,mkt,t)}$	Armington elasticity of substitution between imports of different countries
$Borrowing_{(r,fd,t)}$	Borrowing of final demand agents
$Saving_{(r,fd,t)}$	Saving of final demand agents
$Y_{(r,i)}$	Commodity production
$C_{(r,fd)}$	Consumption good production
$EmissionRdcTarget_{(em,ETSGroup,t)}$	Emission reduction target
$EmissionPerUnit_{(em,co2energy,r,mkt,t)}$	Emissions per unit of energy use (energy related emissions) or per unit of output (process emissions)
$GOV_{(r)}$	Final demand agent – government
$FC\_HH_{(r)}$	Final demand agent – representative household
$flaggAggR$	Flag used in the regional aggregation process
$flaggAggSec$	Flag used in the sectoral aggregation process
$pa_{(i,r,mkt)}$	Price of Armington good
$pk_{(r)}$	Price of capital
$py_{(i,r)}$	Price of commodity
$pem_{(em,ETSGroup)}$	Price of emission
$pe_em_{(eg,r,fd)}$	Price of energy good
$pc_{(r,fd)}$	Price of final demand
$pl_{(r)}$	Price of labour
$pstock_{(r,i,rr,'FC\_HH')}$	Price of old stock
$RA_{(r,fd)}$	Representative agent
mkt	Set – All markets - sectors plus final demands
$co2energy(co2source)$	Set – CO_2 sources related to energy emissions
$ETSGroup$	Set – Emission trading groups
em	Set – Emissions to Air
$eg(mkt)$	Set – Energy goods

Element	Description
$fd(mkt)$	Set – Final demand
$neg(mkt)$	Set – Non-energy goods
r, alias rr, s	Set – regions
$i(mkt)$, alias ii, j	Set – sectors
$co2source$	Set – Sources of CO_2 emissions
$Process$	Set – Sources related to process emissions
t	Set – time
$es\_kl_{(r,i,t)}$	Substitution elasticity between capital and labour in commodity production
$es\_kle_{(r,i,t)}$	Substitution elasticity between capital-labour composite and energy in commodity production
$es\_klem_{(r,i,t)}$	Substitution elasticity between capital-labour-energy composite and other intermediated goods in commodity production
$es\_e_{(r,i)}$	Substitution elasticity between different energy goods in commodity production
$es\_ce_{(r,t)}$	Substitution elasticity between different energy goods of final demand agents
$es\_ms_{(r,i,t)}$	Substitution elasticity between different non-energy Armington goods in commodity production
$es\_c_{(r,t)}$	Substitution elasticity between energy and other goods of final demand agents
$es\_stock_{(r,i,t)}$	Substitution elasticity between newly produced commodities and old stock in commodity production
$t\_f_{(r,i,t)}$	Tax – factor
$t\_i_{(r,i,t)}$	Tax – input
$TotIntermed_{(r,i,t)}$	Vale of total intermediates used in benchmark
$capital_{(r,i,t)}$	Value of capital used in production of commodity
$emAllowance_{(em,ETSGroup,r)}$	Value of emission allowances
$GrossFinalDemand_{(r,fd,t)}$	Value of gross final demand
$GrossTotOutputCol_{(r,i,t)}$	Value of gross total output
$labour_{(r,i,t)}$	Value of labour employed in production of commodity
$stock_{(rr,i,r,fd,t)}$	Value of old stock of final demand agent fd in region r used in production of commodity i in region rr in benchmark t
$InputDemand_{(i,r,mkt,t)}$	Value of the sum of all intermediates employed in the commodity production or final demand

Appendix B

Substitution elasticities in a CES framework

B.1 Additional tables

Table B.1: List of regions included in the analysis

Region	Region Code	Region	Region Code
Australia	AUS	Italy	ITA
Austria	AUT	Japan	JPN
Belgium	BEL	Latvia	LVA
Brazil	BRA	Lithuania	LTU
Bulgaria	BGR	Luxembourg	LUX
Canada	CAN	Malta	MLT
China	CHN	Mexico	MEX
Cypres	CYP	Netherlands	NLD
Czech Republic	CZE	Poland	POL
Denmark	DNK	Portugal	PRT
Estonia	EST	Republic of Korea	KOR
Finland	FIN	Romania	ROU
France	FRA	Russia	RUS
Germany	DEU	Slovakia	SVK
Great Britain	GBR	Slovenia	SVN
Greece	GRC	Spain	ESP
Hungary	HUN	Sweden	SWE
India	IND	Taiwan	TWN
Indonesia	IDN	Turkey	TUR
Ireland	IRL	United States of America	USA

Table B.2: List of sectors included in the analysis

Sector	NACE Code	Group
Agriculture, hunting, forestry and fishing	AtB	Basic Materials
Mining and quarrying	C	Basic Materials
Food, beverages and tobacco	15t16	Manufacturing
Textiles and textile	17t18	Manufacturing
Leather, leather and footwear	19	Manufacturing
Wood and products of wood and cork	20	Basic Materials
Pulp, paper, printing and publishing	21t22	Manufacturing
Coke, refined petroleum and nuclear fuel	23	Energy
Chemicals and chemical	24	Manufacturing
Rubber and plastics	25	Manufacturing
Other non-metallic mineral	26	Manufacturing
Basic metals and fabricated metal	27t28	Manufacturing
Machinery, nec	29	Manufacturing
Electrical and optical equipment	30t33	Manufacturing
Transport equipment	34t35	Manufacturing
Manufacturing nec; recycling	36t37	Manufacturing
Electricity, gas and water supply	E	Energy
Construction	F	Manufacturing
Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel	50	Services
Wholesale trade and commission trade, except of motor vehicles and motorcycles	51	Services
Retail trade, except of motor vehicles and motorcycles; repair of household goods	52	Services
Hotels and restaurants	H	Services
Inland transport	60	Transport
Water transport	61	Transport
Air transport	62	Transport
Supporting and auxiliary transport activities activities of travel agencies	63	Transport
Post and telecommunications	64	Services
Financial intermediation	J	Services
Real estate activities	70	Services
Renting of m&eq and other business activities	71t74	Services
Public admin and defence; compulsory social security	L	Services
Education	M	Services
Health and social work	N	Services
Other community, social and personal services	O	Services
Total industries	TOT	Total

Appendix C

Catching the rebound

C.1 Additional tables

Table C.1: List of regions

Short	Regions	Associated WIOD Regions
GER	Germany	DEU
ROW	Rest of the World	AUT, BEL, BGR, CYP, CZE, DNK, ESP, EST, FIN, FRA, GBR, GRC, HUN, IRL, ITA, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROM, SVK, SVN, SWE, AUS, BRA, CAN, CHN, IDN, IND, JPN, KOR, MEX, ROW, RUS, TUR, TWN, USA

Table C.2: List of sectors

Short	Sectors	Associated WIOD Sectors
AGWO	Agriculture and Wood	AtB, 20
ATRN	Air Transport	62
CHEM	Chemicals and Plastics	24, 25
CONS	Construction	F
ELEQ	Eletrical Equipment	30t33
ENER	Energy	C, 23, E
FOOD	Food, Beverages, Tobacco	15t16
ITRN	Inland Transport	60
MACH	Machinery	29
MANU	Manufacturing	36t37
META	Metal	27t28
ONME	Other Non-metallic Minerals	26
PAPE	Paper	21t22
SERV	Services	51, 52, H, 63, 64, J, 70, 71t74, L, M, N, O, P
STRN	Services for Private Transport Equipment	50
TEXT	Textiles and Leather	17t18, 19
TREQ	Transport Equipment	34t35
WTRN	Water Transport	61

Table C.3: Overview of scenarios

Short	Scenario	Habit	Substitution		
		θ	σ^{Umetrns}	$\sigma^{\text{TRNpropriv}}$	$\sigma^{\text{TRNetrnma}}$
NP-MIN	no persistence inflexible consumption	0.00	0.00	0.00	0.00
MP-MIN	medium persistence inflexible consumption	0.50	0.00	0.00	0.00
HP-MIN	high persistence inflexible consumption	0.90	0.00	0.00	0.00
NP-FLEX	no persistence flexible consumption	0.00	1.00	1.00	0.42
MP-FLEX	medium persistence flexible consumption	0.50	1.00	1.00	0.42
HP-FLEX	high persistence flexible consumption	0.90	1.00	1.00	0.42

Appendix D

Beyond national economy-wide rebound effects

D.1 Quantifying rebound in a multi-regional setting

To consider the full economy-wide rebound effect in the domestic economy, d, we must also consider the impact on energy use on the (final) consumption side of the economy, which generally equates to household energy consumption. Thus, the own-country economy-wide rebound formulation, R_d is given as:

$$R_d = \left(1 + \frac{\delta E_d}{\beta\gamma}\right) \times 100, \tag{D.1}$$

where β is the initial (base/reference year) share of sector i energy use in total energy use (in both production and consumption) in the domestic economy d. The term $\frac{\dot{E}_d}{\beta\gamma}$ can be expressed as:

$$\frac{\dot{E}_d}{\beta\gamma} = \frac{\delta E_d}{\gamma E_i} = \frac{\delta E_i + \delta E_p^{-i} + \delta E_c}{\gamma E_i} = \frac{\dot{E}_i}{\gamma} + \frac{\delta E_p^{-i}}{\gamma E_i} + \frac{\delta E_c}{\gamma E_i}, \tag{D.2}$$

where the c subscript indicates 'consumption' (households) and the $-i$ superscript all production excluding sector i. Substituting Equation (D.2) into Equation (D.1) and using equations (6.1) and (6.4) gives:

$$R_d = R_p + \left(\frac{\delta E_c}{\gamma E_i}\right) \times 100, \tag{D.3}$$

which is Equation 6.5 in the main text.

The global rebound rebound effect, R_g, defining the total impact on energy use in all countries resulting from increased efficiency in the use of energy in sector i within the home economy, d:

$$R_g = \left(1 + \frac{\delta E_g}{\chi\gamma}\right) \times 100, \tag{D.4}$$

where χ is the initial (base/reference year) share of sector i (within country d) energy use in total energy use (in both production and consumption in all countries) in the global economy, g. The term $\frac{\dot{E}_g}{\chi\gamma}$ can be expressed as:

$$\frac{\dot{E}_g}{\chi\gamma} = \frac{\delta E_g}{\gamma E_i} = \frac{\delta E_i + \delta E_p^{-i} + \delta E_c + \delta E_g^{-d}}{\gamma E_i} = \frac{\dot{E}_i}{\gamma} + \frac{\delta E_p^{-i}}{\gamma E_i} + \frac{\delta E_c}{\gamma E_i} + \frac{\delta E_g^{-d}}{\gamma E_i}, \tag{D.5}$$

where the $-d$ superscript indicates global energy use without the domestic economy where the efficiency shock occurs (i.e. not including sector i or any other production, p, or consumption activity, c, in country d). Substituting Equation (D.4) into equation (D.5) and using equations (6.1), (6.4) and (D.3) gives:

$$R_g = R_d + \left(\frac{\delta E_g^{-d}}{\gamma}\right) \times 100, \tag{D.6}$$

which is Equation 6.6 in the text.

D.2 Additional tables

Table D.1: List of sectors

Short	Sectors	Associated WIOD Sectors
E	Electricity and Gas	E
SER	Services	50, 51, 52, H, 63, 64, J, 70, 71t74, L, M, N, O, P
TRN	Transport	60, 61, 62
CON	Construction	F
MAN	Manufacturing	17t18, 19, 21t22, 24, 25, 26, 27t28, 29, 30t33, 34t35, 36t37
CPN	Coke Refined Petroleum and Nuclear Fuel	23
FOB	Food Beverages and Tobacco	15t16
PRI	Primary Goods	AtB, C, 20

Table D.2: List of regions

Short	Regions	Associated WIOD Regions
AUT	Austria	AUT
BEL	Belgium	BEL
BGR	Bulgaria	BGR
CYP	Cypress	CYP
CZE	Czech Republic	CZE
DNK	Denmark	DNK
ESP	Spain	ESP
EST	Estonia	EST
FIN	Finland	FIN
FRA	France	FRA
GBR	Great Britain	GBR
GER	Germany	DEU
GRC	Greece	GRC
HUN	Hungary	HUN
IRL	Ireland	IRL
ITA	Italia	ITA
LTU	Lithuania	LTU
LUX	Luxembourg	LUX
LVA	Latvia	LVA
MLT	Malta	MLT
NLD	The Netherlands	NLD
POL	Poland	POL
PRT	Portugal	PRT
ROM	Romania	ROM
SVK	Slovakia	SVK
SVN	Slovenia	SVN
SWE	Sweden	SWE
REU	Rest of Europe	AUT, BEL, BGR, CYP, CZE, DNK, ESP, EST, FIN, FRA, GBR, GRC, HUN, IRL, ITA, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROM, SVK, SVN, SWE

Table D.3: Stylised facts on Germany economy and German manufacturing - Authors' calculations based on WIOD

	German Production		German Manufacturing	
Main Export Partner (Share of Export)	REU Final Demand	21.01%	REU Final Demand	21.06%
	ROW Final Demand	18.70%	ROW Final Demand	20.56%
	REU MAN	15.45%	REU MAN	18.92%
	ROW MAN	15.55%	ROW MAN	17.10%
	REU SER	7.77%	REU SER	6.32%
	ROW SER	7.31%	ROW SER	4.52%
Main Import Partner (Share of Imports)	REU MAN	38.97%	REU MAN	53.8%
	ROW MAN	22.75%	ROW MAN	30.12%
	REU SER	9.08%	REU SER	3.39%
	ROW SER	8.62%	ROW SER	3.8%
Main Input (Share of total Inputs)	SER	25.82%	MAN	37.15%
	MAN	13.66%	SER	22.32%
	Energy	2.69%	Energy	2.88%
Share of Energy Use in German Production (α)	NA		28.58%	
Share of Energy Use in German Economy (β)	57.99%		16.57%	
Share of Energy Use in EU (ψ)	10.81%		3.09%	
Share of Energy Use Worldwide (χ)	2.95%		0.84%	
Share of Output in German Economy	NA		26.73%	

Table D.4: Results of sensitivity analysis with regard to consumption structure - Scenario 1: 10% increase in energy efficiency in all German sectors, but assuming different elasticities of substitution for consumption (es_c) and fixed national labour and capital supply

	Own-country production R_p	Own-country total R_d	EU R_g	World R_g
Leontief composite				
Rebound [%]	46.60	50.18	47.28	46.58
Change [percentage points]		3.58	-2.90	-0.70
es_c = 0.5				
Rebound [%]	47.57	55.87	53.50	53.03
Change [percentage points]		8.30	-2.37	-0.47
Cobb-Douglas composite				
Rebound [%]	48.55	61.58	59.74	59.50
Change [percentage points]		13.3	-1.84	-0.24
Change of household energy use		Germany	REU	ROW
Leontief composite		0.4948%	0.0005%	-0.0003%
es_c = 0.5		11454%	0.0141%	0.0027%
Cobb-Douglas composite		17991%	0.0274%	0.0057%

Table D.5: Results of sensitivity analysis with regard to consumption structure - Scenario 3: 10% increase in energy efficiency in German manufacturing, but assuming different elasticities of substitution for consumption (es_c) and fixed national labour and capital supply

	Own-sector R_i	Own-country production R_p	Own-country total R_d	EU R_g	World R_g
Leontief composite					
Rebound [%]	56.44	47.63	51.31	50.22	48.11
Change [percentage points]		-8.81	3.68	-1.09	-2.11
es_c = 0.5					
Rebound [%]	57.05	48.29	52.22	50.96	48.86
Change [percentage points]		-8.76	3.93	-1.26	-2.10
Cobb-Douglas composite					
Rebound [%]	57.63	48.93	53.12	51.68	49.63
Change [percentage points]		-8.70	4.19	-1.44	-2.05
Change of household energy use			Germany	REU	ROW
Leontief composite			0.1453%	0.0004%	-0.0004%
es_c = 0.5			0.1551%	-0.0017%	-0.0008%
Cobb-Douglas composite			0.1653%	-0.0038%	-0.0013%

Appendix E

Sailing into a dilemma

E.1 Additional tables

Table E.1: List of regions included in the analysis

Short	Region	Associated WIOD Region
EU	Europe	AUT, BEL, BGR, CYP, CZE, DNK, ESP, EST, FIN, FRA, GBR, GER, GRC, HUN, IRL, ITA, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROM, SVK, SVN, SWE
NAM	North America	CAN, MEX, USA
FEA	Far East	CHN, JPN, KOR, TWN
MID	Middle Distance	RUS, TUR
ROW	Rest of the World	AUS, BRA, IDN, IND, ROW

Table E.2: List of sectors included in the analysis

Short	Sector	Associated WIOD Sector
INLAND	Inland Transport	60
WATER	Water Transport	61
AIR	Air Transport	62
NTR	No Transport Costs	F, 50, 51, 52, H, 63. 64, J, 70, 71t74, L, M, N, O, P
HIGH	High Ad-valorem Transport Costs	AtB, 15t16, 20, 21t22, 34t35, 36t37
LOW	Low Ad-valorem Transport Costs	17t18, 19, 24, 25, 26, 27t28, 29, 30t33
ENERGY	Energy	C, 23, E

Table E.3: List of scenarios included in the analysis

Reduction Target of ETS (w.r.t. 2009 Emission Levels)	Scope of ETS Whole Route (WR)	European Economic Zone plus Territorial Waters (EEZp)	European Territorial Waters (ETW)
0%	WR0	EEZp0	ETW0
5%	WR5	EEZp5	ETW5
10%	WR10	EEZp10	ETW10
20%	WR20	EEZp20	ETW20
30%	WR30	EEZp30	ETW30

Table E.4: Share of regulated emissions

Route	Whole Route (WR)	European Economic Zone plus Territorial Waters (EEZp)	European Territorial Waters (ETW)
EU-NAM / NAM-EU	100%	9.0%	2.2%
EU-FEA / FEA-EU	100%	3.2%	0.8%
EU-MID / MID-EU	100%	22.5%	5.6%
EU-ROW / ROW-EU	100%	4.9%	1.2%

Table E.5: Overview of legal framework

Short	Description
Directive 2003/87/EC	Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC, as last amended by Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009
GATS	World Trade Organization - General Agreement on Trade in Services
GATT	World Trade Organization - General Agreement on Tariffs and Trade
Kyoto Protocol	Kyoto Protocol to the United Nations Framework Convention on Climate Change
MARPOL	International Maritime Organization: International Convention for the Prevention of Pollution From Ships, 1973 as modified by the Protocol of 1978
MRV-Proposal	Proposal for a Regulation of the European Parliament and of the Council on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport and amending Regulation (EU) No 525/2013, COM(2013) 480 final
UNCLOS	United Nation - Convention on the Law of the Seas

Appendix F

Unilateral regulation and multi-stage production processes

F.1 Proof Insight 3

The cut-off determining the outsourcing of upstream production to S as in condition (8.12) is:

$$A^1\Gamma(z) \equiv \frac{A_N^1}{A_S^1}\left(\frac{\alpha(z)\tau_N + (1-\alpha(z))\tau_S}{\tau_S}\right)^{\frac{1}{1-\alpha(z)}} \leq \frac{w_N}{w_S}\left(\frac{\tau_N}{\tau_S}\right)^{\frac{\alpha(z)}{1-\alpha(z)}} \equiv \omega T(z). \tag{F.1}$$

By assumption $A^1 \geq \omega$. Thus, it becomes clear that $\Gamma(z) \leq T(z)$ must hold for (8.12) to hold. Since $0 < \alpha(z) < 1$, $\Gamma(z)$ can attain values in the interval $\lim_{\alpha(z)\to 0}\Gamma(z) = 1$ and $\lim_{\alpha(z)\to 1}\Gamma(z) = \frac{\tau_N}{\tau_S}$.

At the lower bound of $\alpha(z)$,

$$\lim_{\alpha(z)\to 0}\Gamma(z) = 1 < \lim_{\alpha(z)\to 0}T(z) = 1 \tag{F.2}$$

must hold.

Since $\tau_N > \tau_S$, (F.2) never holds, at the upper bound of $\alpha(z)$

$$\lim_{\alpha(z)\to 1}\Gamma(z) = \frac{\tau_N}{\tau_S} < \lim_{\alpha(z)\to 1}T(z) = \frac{\tau_N}{\tau_S} \tag{F.3}$$

must hold.

Since $\tau_N > \tau_S$, (F.3) never holds for $\alpha(z) < 1$, (8.12) can never hold either. □

F.2 Additional tables

Table F.1: Regional aggregation

Short	Region	Associated WIOD Region
BRA	Brazil	BRA
CHN	China	CHN
EAS	Other East Asia	JPN, KOR, TWN
EU	European Union (EU27)	AUT, BEL, BGR, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, GBR, GRC, HUN, IRL, ITA, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROM, SVK, SVN, SWE
IND	India	IND
RUS	Russia	RUS
USA	United States of America	USA
ROW	Rest of the World	AUS, CAN, IDN, MEX, ROW, TUR

Table F.2: Sectoral aggregation

Short	Sectors	Associated WIOD Sectors
FOOD	Food, Beverages, Tobacco	15t16
TEXT	Textiles, Leather, Footwear	17t18, 19
WOOD	Wood Products	20
PAPE	Pulp, Paper, Printing, Publication	21t22
COPN	Coke, Petroleum, Nuclear Fuel	23
CHEM	Chemicals, Rubber, Plastic	24, 25
ONME	Other Non-metalic mineral	26
META	Basic Metals, Fabric. Met.	27t28
MACH	Machinery Nec.	29
ELEQ	Electrical & Optical Equi.	30t33
TREQ	Transport Equipment	34t35
MANU	Manufacturing Nec., Recycling	36t37
TRAN	Transport Activities	60, 61, 62, 63
AGRI	Agriculture, Forestry, Fishing	AtB
MINI	Mining and Quarrying	C
ELGW	Electricity, Gas, Water	E
CONS	Construction	F
SERV	Sale, Tourism, Financial Services, Health	50,51,52,H,64,J,70,71t74,L,M,N,O,P