Essays on the Economics of Regional Climate Policy

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To my parents, Monika & Torsten, and to Raphaela.

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION TO THE DISSERTATION

Climate policy usually takes place at the regional level following individual targets. Although economists urge for collective greenhouse gas emission targets which protect against free-riding, global climate policy has been marked by individual targets or a national 'pledge-and-review' approach since the mid-1990s. In the Kyoto Protocol from 1997, countries pledged individual emission reductions relative to 1990 levels. In the Paris Agreement from 2015, countries pledged almost anything and the national review processes are still ongoing (Cramton et al., 2017).

This also applies to Germany who successfully reduced its emissions by around 22% below 1990 levels by the year 2008, thereby fulfilling its individual commitment made under the Kyoto Protocol (Umweltbundesamt, 2010). One of the key drivers behind the successful reduction has been the rapid expansion of renewable energies under the Renewable Energy Sources Act (EEG) (Umweltbundesamt, 2010). From its commencement in 2000 to the target year of the Kyoto pledge 2008, the EEG lead to a successful market penetration of renewables in the electricity generation mix through the provision of a feed-in tariff. As a result of the subsidy, renewables began to substitute coal-fired and gas power stations and thus lead to significant emission reductions in the energy sector (Klobasa and Sensfuß, 2016). This transition from conventional to renewable energy sources also leads to changes in the economy. In this regard, policymakers often promote renewables as an opportunity to reduce emissions while at the same time fueling economic growth and employment.

Since decision-making on the deployment of renewables often takes place at the regional level, the potential economic benefits should be evaluated rather on a regional than on a national scale. The German states (Bundesländer) usually set up their individual expansion targets, in addition to the federal ones. Moreover, planning law at the state and municipal level significantly affects the regional allocation of renewables, especially of wind energy (Strunz et al., 2016). Finally, renewables depend on the elements of nature, which are scarce in some regions and plentiful in others.

Against this background, the third chapter of my dissertation analyzes the regional economic impacts of renewable energies by means of a computable general equilibrium (CGE) model. In order to do so, we need to regionalize a national Input-Output (I-O) table which serves as the main data input for the model. An I-O table provides detailed information on the economy's production activities, the supply and demand of goods and services, intermediate consumption, primary inputs and foreign trade for a given year. Therefore, the accuracy of the regionalization is crucial for model applications. Alas, the available regionalization techniques in the literature are unsatisfying because they lack a clear theoretical foundation and are often inconsistent with regard to the region's economic accounts. Therefore, the second co-authored chapter of my dissertation (with Johannes Bröcker), entitled *Estimating Trade in a Regional Input-Output Table*, provides a new method which is both theory based and consistent. I have contributed to this paper at almost every stage of the research process. While the analytical model and formal derivations stem from my supervisor, I conducted the empirical analysis and wrote the paper, which is about to be resubmitted to the *Economic Systems Research* journal.

The state of Schleswig-Holstein (S-H) in northern Germany is one of the leading states in expanding renewables, especially wind energy. The local government plans to more than double renewable electricity production by the year 2030 (MELUND, 2016). Therefore, the third chapter of my dissertation, entitled *Regional Economic Impacts of Renewable Energies*, contributes the first regional general equilibrium analysis of the expansion of renewables in Germany (cf. Jenniches, 2018, Table 8). Existing studies either focus on the national scale or estimate regional effects by means of supply chain and (or) regional I-O analysis which both show considerable disadvantages compared to a general equilibrium approach.[1] In this regard, Bröcker et al. (2014, 2016) were the first to combine the supply chain approach with a regional I-O model as part of a research project funded by the *Gesellschaft für Energie und Klimaschutz Schleswig-Holstein (EKSH) GmbH*. The results of the successful project had a direct impact on the policy debate. Therefore, this chapter builds upon the work of Bröcker et al. (2014, 2016), but extends its methodology to a more consistent general equilibrium framework. I thereby hope to shed further light on the ongoing policy debate about the economic benefits of renewable energies.

The EEG has led to a successful market penetration of renewables in Germany. However, it did not lead to a sufficient phase out of high carbon emitting conventional technologies such as coal-fired power stations in order to meet the post-Kyoto targets of reducing emissions by 40% below 1990 levels until the year 2020. Most importantly, the EEG collides with the European Union Emissions

1 For national CGE approaches, see e.g. Böhringer et al. (2013, 2017). For supply chain and regional I-O studies, see the overview by Jenniches (2018), Table 6 and 7.

Trading System (EU ETS) because while it reduces, ceteris paribus, emissions in the electricity sector, the excess emission allowances can be sold to other industry sectors (potentially outside Germany) that are also involved in the EU ETS. As a result, the EEG's true effect is merely a shift rather than a reduction of emissions. Therefore, shortly before the Paris conference in December 2015, Germany initiated a so-called 'Climate Action Programme 2020' which resulted in a proposal for a climate levy for old coal-fired power stations. Since the design of the climate levy included the retirement of emission allowances, it was the first policy option that showed the potential to reconcile EU and national climate policy in an effective manner.

Therefore, the final co-authored chapter of my dissertation (with Sonja Peterson), entitled *National Climate Policy under the European Union Emissions Trading System*, explores the potential scope and optimal design of additional regional climate policy under the EU policy framework. It includes a theoretical and empirical review of the climate levy as well as two suggestions for an efficient and effective national carbon price floor design. I thereby hope to contribute to the ongoing policy debate about effective and economically efficient regional climate policy against the background of overlapping regulation. I have contributed substantially to this paper at every stage of the research process, including the design of the research question, empirical modeling as well as writing and revising the paper. A previous version of this chapter has appeared as *Kiel Working Paper 2052*.

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2 ESTIMATING TRADE IN A REGIONAL INPUT-OUTPUT TABLE

This chapter is under revision and will be resubmitted to the 'Economic Systems Research' journal. It may be referenced as:

Bröcker, Johannes and Johannes Burmeister (2018). Estimating Trade in a Regional Input-Output Table. Mimeo, University of Kiel.

Abstract: This paper provides a new hands-on recipe for regionalizing national Input-Output (I-O) tables. While the theoretical grounds of existing non-survey techniques are shaky, our method is theoretically well-founded, consistent with accounting constraints and takes reasonable account of cross-hauling. By formulating a theoretical gravity equation in the functional form of a doubly-constrained gravity model for two regions, the region under study and the rest of world, and solving for the region's internal flow, we derive an *internal trade equation*. This trade equation can be readily applied to scale down the *national technical input coefficients* in order to estimate the *regional input coefficients* for a single region. It depends on the economic size of the region as well as the region's ability to buy from and sell to the world market. We extend our approach to three regions in order to explicitly account for the geographical size of the region and the distance effect on trade. We call our approach 'Gravity Regionalization of Trade Approach' (GRETA). GRETA does not tend to overestimate regional output multipliers, which is a common critique of existing techniques and crucial for model applications.

Keywords: Regional input-output tables, non-survey methods, gravity regionalization of trade, internal trade equation

2.1 INTRODUCTION

The construction of regional Input-Output (I-O) tables has a long history because they provide valuable information about regional economic interdependencies and are the main data input for regional I-O or Computable General Equilibrium (CGE) models. The modeler can either rely on survey-based tables provided by statistical offices or construct regional tables with existing non-survey or semi-survey regionalization methods. Ready-made survey tables are rare because they are very expensive to produce (Hewings, 1985). Hence, the usual procedure is regionalizing national I-O tables with a non-survey technique, which is less accurate but also less expensive. Alas, we find that existing techniques lack a theoretical foundation, show inconsistencies with regard to accounting constraints, and do not take reasonable account of cross-hauling. Therefore, this paper introduces a new non-survey method called 'Gravity Regionalization of Trade Approach' (GRETA). It is derived from the gravity model of trade and thus based on well-established theory. Moreover, our approach is consistent and takes reasonable account of cross-hauling.

Our point of departure is that the only data at hand is a symmetric, industry-by-industry I-O table for the nation to which the region under study belongs to. Further, we assume to have some proxies for the region's local output and final use by industry. We then follow a top-down approach and estimate the *regional input coefficients* for a single region by adjusting the *national technical input coefficients*. The former indicate the inputs supplied from firms within the region for outputs of firms in that region (R. Miller and Blair, 2009). The latter indicate the inputs supplied from all firms, either within or outside the nation, for outputs of firms in the nation. Therefore, the general assumptions are the same as for the most frequently applied non-survey techniques in the literature, namely location quotient (LQ) and supply-demand pool (SDP) approaches.

However, these techniques suffer from considerable shortcomings. First of all, both lack a theoretical foundation. The LQ simply uses output (or employment) by industry ratios of the region compared to the nation to scale down the national table. Because of rather poor estimation performance and the preclusion of cross-hauling in the original LQ formula, ad hoc manipulations led to numerous variants of the technique. However, neither did these provide much theoretical improvement, nor do they necessarily perform better (Harrigan et al., 1981; Riddington et al., 2006; Smith and Morrison, 1975). Most importantly, LQ approaches are not consistent, which has been already pointed out by Schaffer and Chu (1969). There is no guarantee, for example, that estimates of the region's exports are non-negative. In that case, the formula relies on ad hoc adjustments.

The SDP approach, originating from work by Isard (1953), estimates the region's 'commodity balance' (CB) as the difference between regional supply and demand of a commodity in order to scale down the national table.[1] There is no theoretical motivation for this technique either, but it is at least consistent. However, as the simplest LQ, the original SDP formula does not allow for cross-hauling. Therefore, it has been adjusted for cross-hauling by Kronenberg (2009). But also this technique is not explicitly derived from theory and proves to be inconsistent without further ad hoc manipulation of its original formula (cf. Többen and Kronenberg, 2015). Nevertheless, our approach has a point in common with it, namely the idea that product heterogeneity is behind the cross-hauling of commodities.

Given these shortcomings and the data requirements of semi-survey approaches such as the econometric approach by Stevens et al. (1983), we contribute the first non-survey gravity approach for a single region. Gravity approaches have been initially suggested in an I-O context by Isard and Bramhall (1960), Leontief and Strout (1963) and Theil (1967). More recent applications of the gravity approach in I-O studies are Horridge et al. (2005), Lindall et al. (2006) and Riddington et al. (2006). In contrast to the techniques above, the gravity approach usually estimates trade flows between regions within a multi-regional I-O (MRIO) framework. If one has a complete set of within and between regional trade flows available, the *regional input coefficients* can be observed directly. However, this requires a large amount of data such that existing gravity approaches are rather expensive and do not provide an easy to use regionalization formula for a single region. Moreover, they do not invoke the theoretical underpinning of the gravity equation, which we will draw upon to derive our non-survey method.

The rest of this paper is structured as follows. The next section presents the theoretical foundation of our approach. Based on a gravity model for two regions, we derive a trade equation that allows us to estimate *regional input coefficients*. In Section 2.3, we extend our approach to three regions in order to explicitly account for the geographical size of the region and the effect of distance on trade flows. We then discuss and compare our approach with the existing non-survey alternatives in Section 2.4, followed by an empirical test in Section 2.5. Finally, we conclude.

1 Therefore, the SDP approach is also referred to as the CB approach.

2.2 GRAVITY REGIONALIZATION OF TRADE APPROACH

In this section, we lay the theoretical foundation for our approach. It is based on the gravity model of trade which is a major workhorse for analyzing the determinants of bilateral trade flows. The most important characteristic of the gravity model is that it is consistent with a variety of trade theories. We begin by presenting the general assumptions of our regionalization approach, which do not differ from the existing non-survey techniques. We then review the gravity model of trade and show that the first theoretical gravity equation by Anderson (1979) can be formulated as what has been called the 'doubly-constrained gravity model' (DCGM) in the transport and urban modeling traditions (Wilson, 1967, 1971). By solving the theoretical DCGM with only two regions, the region under study r and the rest of world w, we derive a regional trade equation that can be readily applied to scale down the *national technical input coefficients*. As a result, our approach is rich in theory but inexpensive in data collection. Finally, we conclude by summarizing the main properties of the derived trade equation and show that it exhibits desirable properties that are in line with economic theory.

2.2.1 *Regionalization*

A typical regionalization technique distributes domestic output and final use by industry according to proxies such as employment and income shares. This yields region r's local output in industry j, x_r^j, and region r's local final use, u_r^i, of commodities from industry i. Furthermore, *technical input coefficients* a_r^{ij} in the region r are assumed to be the same as in the nation n, $a_r^{ij} = a_n^{ij}$. Total local use for commodities from industry i in region r is thus

$$y_r^i = \sum_j a_n^{ij} x_r^j + u_r^i. \tag{2.1}$$

Hence, the final question is how to estimate region r's external trade, i.e. exports e_r^i to and imports m_r^i from the rest of world w, respectively. In this regard, w comprises the rest of the nation as well as foreign countries. For later use, we denote the rest of the nation as s and foreign countries as c, i.e. $w = \{s, c\}$. The question reduces to determining the internal trade flow t_{rr}^i since, by definition, the difference between local output and internal trade is exports,

$$e_r^i = x_r^i - t_{rr}^i, \tag{2.2}$$

and the difference between local use and internal trade is imports,

$$m_r^i = y_r^i - t_{rr}^i \tag{2.3}$$

(cf. Wei, 1996, p. 3). In this paper, the term 'internal' defines flows with the identical origin and destination. Hence, internal trade t_{rr}^i is the amount of commodities that is bought for intermediate and final use from within the region.[2] Any estimation method for t_{rr}^i should make sure that t_{rr}^i is non-negative and does not exceed either x_r^i or y_r^i. Given estimates of t_{rr}^i, we are able to obtain *regional input coefficients*

$$a_{rr}^{ij} = \frac{t_{rr}^i}{y_r^i} a_n^{ij} \tag{2.4}$$

which are the basis for regional I-O models. The term t_{rr}^i / y_r^i is what R. Miller and Blair (2009) define as the *regional supply proportion* ρ_r^i, since it is the 'proportion of the total amount of commodity i available in region r that was produced in r'. This is exactly what the LQ and SDP approaches estimate. For simplicity, we make the common assumption that this proportion is uniform across purchasing industries j (cf. R. Miller and Blair, 2009, p. 348). Further, by assuming t_{rr}^i / y_r^i also to be uniform across final customers, we obtain local internal final use by

$$u_{rr}^i = \frac{t_{rr}^i}{y_r^i} u_r^i. \tag{2.5}$$

2.2.2 *The Basic GRETA Model*

The gravity model of trade estimates bilateral trade flow values between origins k and destinations l in industry i, t_{kl}^i, based on the economic sizes of and trade costs between trading partners. The following relations are valid for each industry; so we omit index i up to the next section. The traditional form inspired by Newton's equation is

$$t_{kl} = A \frac{M_k N_l}{d_{kl}^{\zeta}}, \tag{2.6}$$

2 Intraregional trade would be an alternative and more precise, though very cumbersome expression.

where A is a constant and M_k and N_l are the relevant economic activity masses in the origin and destination, respectively. Depending on whether we work on the aggregate level or, as here, on the industry level, these masses are aggregate activities such as GDP or available industry-specific activities such as output. Trade costs are assumed to correspond roughly with the geographical distance d_{kl} between trading partners. The parameter to be estimated is the distance parameter ζ.[3] The traditional form stemming from Tinbergen (1962) is not consistent with economic structure because trade flows are obtained independently from one another such that adding up constraints are not satisfied by (2.6). That is, (2.6) does not guarantee that the sum of flows from origin k to each destination l equals the origin's total economic activity M_k. A similar argument applies to the destination. However, the traditional form has been widely used as a statistical relationship. In fact, it explains a large fraction of the variation in observed bilateral trade flows. It has been also widely applied in the I-O literature to estimate interregional trade flows in MRIO frameworks (see Leontief and Strout, 1963; Polenske, 1970; Theil, 1967, among others).

So far, the gravity equation is just an intuitive and empirically well performing relationship. Anderson (1979) offered the first theoretical derivation of a gravity equation under the assumptions of product differentiation by place of origin, i.e. based on the Armington (1969) trade model. Armington's assumption was that each origin is specialized in the production of a unique commodity for which it is the only source and that customers would like to buy at least some of each origin's commodity. The preferences (or technologies in case of intermediate consumption) for buying these commodities in each destination are assumed to be of the CES form and thus completely specified by the CES price index

$$P_l = \left(\sum_k \alpha_k \left(p_k \tau_{kl} \right)^{1-\sigma} \right)^{1/(1-\sigma)} . \tag{2.7}$$

It is the minimum unit expenditure of destination l on composite commodities from all origins k. The distribution parameter α_k is an exogenous measure of product heterogeneity in origin k. The factory-gate price in origin k is denoted by p_k. Trade costs are assumed to raise the delivered price of a good in destination l by an 'iceberg melting' factor $\tau_{kl} > 1$. Then, under perfect competition it follows that $p_{kl} = p_k \tau_{kl}$ is the price of origin k's commodity for buyers in l. In the following, we call τ_{kl} the trade barrier. In empirical studies, τ_{kl} is usually approximated not only by the geographical distance as in (2.6) but by further

3 In Newton's form, $\zeta = 2$.

observable barriers such as adjacency, trade agreement memberships and so forth. The elasticity of substitution between commodities from different origins is denoted by σ. Ordinarily, it is assumed in accordance with the data that $\sigma > 1$. Though, in principle it is possible to allow for $\sigma < 1$ in the model (cf. Armington, 1969, p. 168).

Applying Hotelling's theorem, Anderson (1979) proceeded to derive the expenditures on commodities shipped from origin k to destination l as

$$t_{kl} = \alpha_k \left(\frac{p_k \tau_{kl}}{P_l} \right)^{1-\sigma} y_l, \tag{2.8}$$

where y_l is total expenditures in destination l. This is the first theoretical gravity equation derived from a rather simple trade theory. Different from the traditional form (2.6), all flows are mutually interdependent due to price effects and substitution possibilities. Equation (2.8) also covers intuitive relationships. First, trade flows t_{kl} are proportional to total expenditures y_l. That is, the larger destination l's economic size, the higher the value of commodities it buys, including the one from origin k. Secondly, the higher the prices for delivering varieties from k to l including the costs for shipping the good, $p_k \tau_{kl}$, the lower are trade flows. Thirdly, the higher the CES price index P_l, the higher are trade flows t_{kl}. That is, the relatively more expensive the commodities from all origins are on average, the more consumers in destination l will substitute them with commodities from origin k. Lastly, the higher σ, the higher the aforementioned substitution effect.

The general equilibrium structure of the trade model imposes that markets for commodities from each origin must clear, i.e. that

$$x_k = \sum_l t_{kl} = \sum_l \alpha_k \left(\frac{p_k \tau_{kl}}{P_l} \right)^{1-\sigma} y_l \qquad \forall k \tag{2.9}$$

holds. This is the accounting constraint for each origin k, which guarantees that the total value of output in origin k, x_k, equals the sum of sales to all destinations l, including sales to k itself. In the I-O context, (2.9) is equivalent to (2.2), since internal trade are sales of origin k to itself, t_{kk}, and exports are the sum of sales to all other destinations l except to k itself, $e_k = \sum_{l \neq k} t_{kl}$. The accounting constraint for each destination l is implicitly given by (2.7)-(2.8) and guarantees that total expenditures are equal to the sum of purchases from all origins k:

$$y_l = \sum_k t_{kl} = \sum_k \alpha_k \left(\frac{p_k \tau_{kl}}{P_l}\right)^{1-\sigma} y_l \qquad \forall l. \tag{2.10}$$

In the I-O context, (2.10) is equivalent to (2.3), since internal trade are purchases of destination l from itself, t_{ll}, and imports are the sum of purchases from all origins k except from l itself, $m_l = \sum_{k \neq l} t_{kl}$.

Therefore, conditional on totals x_k and y_l, trade flows from (2.8) can be formulated as a 'doubly-constrained gravity model' (DCGM), with

$$t_{kl} = a_k f_{kl} b_l \tag{2.11}$$

and constraints

$$\sum_l t_{kl} = x_k, \quad \sum_k t_{kl} = y_l. \tag{2.12}$$

The balancing factors a_k and b_l guarantee the fulfillment of the constraints. The DCGM formulation (2.11)-(2.12) is a specific functional form which is also known in the I-O literature from Wilson (1971), who integrated different multiregional I-O models with entropy-maximizing techniques by treating the interregional I-O equations as constraints for the underlying gravity equation. Here, balancing factors $a_k = \alpha_k p_k^{1-\sigma}$ and $b_l = y_l P_l^{\sigma-1}$ contain only origin and destination specific characteristics from the Armington model, respectively. The factor a_k indicates the 'capabilities' of origin k as a supplier to all destinations. The factor b_l indicates the 'potential' of destination l as a consumer for commodities from all origins. Given that $\sigma > 1$, $f_{kl} = \tau_{kl}^{1-\sigma}$ is a trade cost decay function. That is, the lower τ_{kl}, the higher is f_{kl} and therefore trade flows t_{kl}. We thus call f_{kl} the trade freeness.

The DCGM formulation (2.11)-(2.12) does not only apply to the Armington model but to a large set of trade theories as long as the underlying gravity equation is multiplicatively separable in the a_k, b_l and f_{kl} terms. For instance, the Ricardian comparative advantage framework by Eaton and Kortum (2002) differs from the Armington model in almost every respect and yet can be formulated as a DCGM. Further examples include a Heckscher-Ohlin framework (Bergstrand, 1985; Deardorff, 1998) and more recent trade theories with heterogeneous firms selecting into markets (Chaney, 2008; Helpman et al., 2008; Melitz and Ottaviano, 2008).[4]

It is known from Darroch and Ratcliff (1972) that there exist unique flows t_{kl} solving the bi-proportional system (2.11)-(2.12), if $\sum_k x_k = \sum_l y_l$ and, for all k, l, $x_k \geq 0$, $y_l \geq 0$ and $f_{kl} > 0$. The solution is usually obtained by means of iterative techniques such as the RAS procedure. However, in the following we derive an analytical solution for the internal flow t_{rr}, i.e. $k = r$ and $l = r$, for the two-regions case which can then be readily plugged into (2.4) in order to estimate *regional input coefficients*.

2.2.3 *Model Solution*

Let us consider the DCGM (2.11)-(2.12) for the region under study r and the rest of world w. The trade flow matrix between r and w then reads

$$T = \begin{pmatrix} t_{rr} & t_{rw} \\ t_{wr} & t_{ww} \end{pmatrix} = \begin{pmatrix} a_r f_{rr} b_r & a_r f_{rw} b_w \\ a_w f_{wr} b_r & a_w f_{ww} b_w \end{pmatrix}. \tag{2.13}$$

As introduced above, internal trade t_{rr} is the amount of commodities that is bought from within the region and the flow we are looking for. Trade flows t_{rw} and t_{wr} are exports to and imports from the rest of world w, respectively. Recall that w includes the rest of the nation s as well as foreign countries c. The corresponding accounting constraints according to (2.12) for each origin and destination are

$$t_{rr} + t_{rw} = x_r, \tag{2.14}$$
$$t_{wr} + t_{ww} = x_w, \tag{2.15}$$
$$t_{rr} + t_{wr} = y_r, \tag{2.16}$$
$$t_{rw} + t_{ww} = y_w. \tag{2.17}$$

The bi-proportional system (2.13)-(2.17) can be solved analytically as a function of the economic size of the region, x_r and y_r, and a new variable $z_r = t_{rw} t_{wr} / t_{rr}$. This leads to a quadratic equation

$$t_{rr}^2 - t_{rr} \left(x_r + y_r + z_r \right) + x_r y_r = 0 \tag{2.18}$$

4 For a thorough review of the conformity of the gravity model with a variety of trade theories, we refer to Anderson (2011), Arkolakis et al. (2012) and Head and Mayer (2014).

with two real solutions. The smaller one applies, yielding a surprisingly simple formula

$$t_{rr} = \frac{(x_r + y_r + z_r)}{2} - \sqrt{\frac{(x_r + y_r + z_r)^2}{4} - x_r y_r}. \tag{2.19}$$

This is shown in Appendix A.1. Equation (2.19) is the *internal trade equation*, the key to our non-survey gravity approach. Local output x_r and use y_r are approximated as described at the beginning of this section. But where to get z_r from? The variable z_r measures the size of the world market, scaled by trade freeness factors measuring its relevance for the region under study. It can be written as

$$z_r = \frac{t_{rw} t_{wr}}{t_{rr}} = \frac{a_r a_w f_{rw} f_{wr} b_r b_w}{a_r f_{rr} b_r} = t_{ww} \frac{f_{rw} f_{wr}}{f_{rr} f_{ww}}. \tag{2.20}$$

The variable z_r indicates region r's ability to sell to and buy from the world market. We thus call z_r the *relevant world market* for region r, shortly written as

$$z_r = t_{ww} R_r \tag{2.21}$$

with

$$R_r = \frac{f_{rw}}{f_{ww}} \frac{f_{wr}}{f_{rr}} = \left(\frac{\tau_{rw}}{\tau_{ww}} \frac{\tau_{wr}}{\tau_{rr}} \right)^{1-\sigma}. \tag{2.22}$$

The size of the world market is measured by the internal trade value within the rest of world, t_{ww}, and its relevance for region r by the factor R_r. In the trade literature, $\sqrt{R_r}$ is known as an average measure of bilateral trade integration (cf. Head and Ries, 2001, p. 863; Chen and Novy, 2011, p. 208). This factor is decreasing in the relative trade barriers to flows between the region and the rest of world. According to (2.22), what matters for the relevance of sales to the rest of world are not trade barriers τ_{rw} themselves but relative trade barriers τ_{rw}/τ_{ww} to procurements within the rest of world. Similarly, what matters for the relevance of purchases from the rest of world are not trade barriers τ_{wr} themselves but relative trade barriers τ_{wr}/τ_{rr} to procurements within the region under study. Output x_r, use y_r and internal trade t_{ww} are all measured in values of the corresponding I-O table (e.g. million dollars). The factor R_r only consists of trade cost mark-up factors and is thus dimensionless. Hence, z_r is measured in values as well. This is as it should be, otherwise one could not add up x_r, y_r and z_r in the *internal trade equation* (2.19). One might be worried about measuring the size of the world market by t_{ww}, which is itself an endogenous variable in the DCGM (2.13)-(2.17), rather than by x_w or y_w. This is a valid objection as long as the rest of world is not large compared to the region under study. If the rest of world is large, then $z_r = t_{ww}R_r$ and $\tilde{z}_r = x_w R_r$ tend to produce identical results, which we show in Appendix A.2.

We still lack an estimate of z_r. Though our approach is quite different from the widely used 'cross-hauling adjusted regionalization method' (CHARM) by Kronenberg (2009), we have a point in common with it, namely the idea that product heterogeneity is behind the cross-hauling of commodities. In our case, the *relevant world market* is an indirect measure of cross-hauling. As we will show in the next section, if there is no *relevant world market* for the region, there is no cross-hauling of commodities but only internal trade. In contrast, if the *relevant world market* for the region is infinitely large, there is only cross-hauling of commodities but no internal trade. Similar to CHARM, we find that cross-hauling at the national level is the best source we have for quantifying it as long as no further geographical information is incorporated (see Section 2.3 below). Thus, the most inexpensive way is to assume that the *relevant world market* for the region and nation coincides, i.e. $z_r = z_n$. This implies that the average trade integration with the rest of world of the region and nation coincides, which is a rather strict assumption that we will discuss at the end of this section. The national value can be obtained by solving (2.18) for z_n, i.e. with $r = n$. This leads to

$$z_r = z_n = t_n - (x_n + y_n) + \frac{x_n y_n}{t_n}. \tag{2.23}$$

All values on the right hand side of (2.23) are easily obtained from the national I-O table.[5] Finally, plugging values z_r into (2.19) leads to internal trade t_{rr} and thereby estimates of *regional input coefficients*.

Let us summarize GRETA's two-regions recipe for industry i:

1) Estimate x_r^i and u_r^i with employment and income shares of the region and national I-O data.

2) Calculate $y_r^i = \sum_j a_n^{ij} x_r^j + u_r^i$.

3) Calculate $z_r^i = z_n^i = t_n^i - (x_n^i + y_n^i) + x_n^i y_n^i / t_n^i$ with national I-O data.

4) Plug x_r^i, y_r^i and z_r^i into (2.19) to obtain t_{rr}^i.

5) Finally, calculate $a_{rr}^{ij} = \rho_r^i a_n^{ij}$ with $\rho_r^i = t_{rr}^i / y_r^i$.

5 Recall that $t_n = x_n - e_n = y_n - m_n$.

2.2.4 *Properties*

The main ingredient of the above recipe is the *internal trade equation*. In the following, we show how it depends on its determinants, i.e. the region's economic sizes and its *relevant world market*. We find that (2.19) is consistent with accounting constraints, cross-hauling, and economic theory in general. Relations are valid for each region-industry pair; so we omit also index r up to the next section.

First of all, our approach fulfills the accounting constraint that internal trade is non-negative and cannot exceed the minimum of the region's local output and use,

$$0 \leq t(x, y, z) \leq \min(x, y). \tag{2.24}$$

This is a minimal consistency requirement any regionalization approach should fulfill. However, this is not the case for all existing LQ techniques as well as the original CHARM, which we will show in the discussion. The proof of (2.24) is given in (2.45) and (2.46) of Appendix A.1.

Next, we show how t responds to its determinants x, y and z. Internal trade t is increasing in local output x and use y,

$$\frac{\partial t(x, y, z)}{\partial x} = \frac{m}{m + e + z} \geq 0 \tag{2.25}$$

and

$$\frac{\partial t(x, y, z)}{\partial y} = \frac{e}{m + e + z} \geq 0. \tag{2.26}$$

In other words, the larger the economic size of the region is, the higher are internal trade flows. This is an intuitive relationship that we already pointed out regarding the trade flows of the underlying gravity model. The proof is given in Appendix A.3.

The most important feature of our approach is that a simultaneous increase in local output and use causes a more than proportional increase of internal trade, i.e. if $\lambda > 1$, then

$$t(\lambda x, \lambda y, z) > \lambda t(x, y, z). \tag{2.27}$$

We show this in Appendix A.4. Say, local output and use in the region double, then internal trade t more than doubles. This is a desirable property which is directly related to the occurrence of cross-hauling and product heterogeneity. Imagine a region that only produces one variety within an industry of the I-O table such that its economic size is small. Due to product differentiation, cross-hauling in this industry is expected to be high since the producer sells to the large rest of world market and customers only have one variety to buy. In other words, the *regional supply proportion* is expected to be low. Now, imagine the region's economic size increases. The more it covers the size of the world market, the more varieties it will be able to produce and supply to itself. Thus, less cross-hauling occurs and the *regional supply proportion* is supposed to increase. In the extreme case, the region itself is the world market producing all of the varieties within the industry. Then, everything will be traded internally and no cross-hauling takes place. If, in contrast, internal trade increases proportionally to local output and use, the *regional supply proportion* remains constant regardless of the economic size of the region. This is implausible, but indeed the property of e.g. the widely used CHARM as discussed below.

Moreover, internal trade t is decreasing in the *relevant world market* z,

$$\frac{\partial t(x,y,z)}{\partial z} = -\frac{t}{m+e+z} \leq 0. \tag{2.28}$$

Though not obvious from (2.19), this is suggestive, given that the *relevant world market* is increasing in the internal trade barrier τ_{rr}. If the *relevant world market* for the region increases, local firms trade more with firms from the rest of world than with other local firms.

In particular, if on the one hand the *relevant world market* is zero, internal trade equals the minimum of local output and use,

$$t(x,y,0) = \min(x,y). \tag{2.29}$$

Without any *relevant world market* to trade with, the region trades the maximum possible amount internally. If $t = x \leq y$, internal trade increases proportionally to output and is independent of use. If $t = y \leq x$, internal trade increases proportionally to use and is independent of output. In this extreme case, our method reduces to the original SDP approach which precludes cross-hauling.

On the other hand, if the *relevant world market* becomes infinitely large, internal trade approaches zero,

$$\lim_{z\to\infty} t(x,y,z) = 0. \tag{2.30}$$

In this case, all output x is exported and all use y is imported. Both limiting cases are proven in A.5 of the appendix. All of the above inequalities also hold strictly for $x, y, z > 0$.

To sum up, the *internal trade equation* is consistent, takes reasonable account of cross-hauling and exhibits desirable properties that are in line with economic theory. However, the low data requirements of our approach come at the cost of geographical inaccuracy. By assuming that the *relevant world market* of the region and nation coincides, we assume that the size of the world market as well as the average trade integration coincide. As long as the region's economy is small, the former is a valid assumption. However, the average trade integration of the region and nation are likely to differ. In particular, we assume that both face the same external trade barriers, i.e. $\tau_{rw} = \tau_{nc}$ and $\tau_{wr} = \tau_{cn}$, as well as internal barrier within themselves, i.e. $\tau_{rr} = \tau_{nn}$. Regarding external barriers, from the regional perspective w includes the rest of the nation as well as other countries. Trade barriers with other municipalities, counties or federal states, however, are likely to differ from trade barriers with other countries, which may involve tariffs, different currencies and so forth. Regarding internal barriers, the main impedance is geographical distance for shipping commodities from one local firm to another, because barriers such as border tariffs usually do no exist within a nation. Hence, if the geographical size of the region significantly differs from the nation's, internal barriers are likely to differ. That is, distance matters, which we will take into account by extending our approach to three regions.

2.3 DISTANCE IN GRAVITY REGIONALIZATION OF TRADE APPROACH

Let us consider the CES gravity model from the previous section for three regions: the region under study r, the rest of the nation s and foreign countries c. There are thus nine flows to be determined, but we need to consider only those eight flows that affect the nation to which the region under study belongs to. The trade matrix to be set up then reads

$$T = \begin{pmatrix} t_{rr} & t_{rs} & t_{rc} \\ t_{sr} & t_{ss} & t_{sc} \\ t_{cr} & t_{cs} & - \end{pmatrix}, \tag{2.31}$$

where internal trade flows within the rest of world are not of interest. Again, we are looking for the internal trade flow t_{rr} in order to estimate *regional input coefficients* for a single region. The corresponding accounting constraints are row totals x_r, x_s and m_n, and column totals y_r, y_s and e_n, where m_n and e_n denote national imports and exports, respectively. We again assume trade flows as in (2.8) such that there might potentially be eight different trade barriers, but for the sake of data parsimony we reduce them to three different barriers, namely

$$\tau_1 = \tau_{rr}, \tag{2.32}$$

$$\tau_2 = \tau_{rs} = \tau_{sr} = \tau_{ss}, \tag{2.33}$$

$$\tau_3 = \tau_{rc} = \tau_{sc} = \tau_{cr} = \tau_{cs}. \tag{2.34}$$

Barrier τ_2 implies symmetric trade barriers within the nation, which is a common assumption in the gravity trade literature. It means that trade costs for shipping cars from the region to the rest of the nation coincide with costs for shipping cars from the rest of the nation to the region. More importantly, we assume that the barrier between region r and rest of the nation s coincides with the barrier within the rest of the nation s. Finally, besides symmetry, we assume that the trade barrier between region r and foreign countries c coincides with the barrier between the rest of the nation s and foreign countries c.

Given trade flows of the form

$$t_{kl} = \alpha_k \left(\frac{p_k \tau_{kl}}{P_l} \right)^{1-\sigma} y_l$$

and trade barriers (2.32)-(2.34), we may rewrite trade matrix (2.31) as

$$T = \begin{pmatrix} a_r \gamma b_r & a_r b_s & a_r b_c \\ a_s b_r & a_s b_s & a_s b_c \\ a_c b_r & a_c b_s & - \end{pmatrix}, \tag{2.35}$$

with $\gamma = (\tau_1/\tau_2)^{1-\sigma}$,

$$a_r = \alpha_r \left(p_r \tau_2\right)^{1-\sigma},$$

$$a_s = \alpha_s \left(p_s \tau_2\right)^{1-\sigma},$$

$$a_c = \alpha_c \left(p_c \tau_3\right)^{1-\sigma},$$

and

$$b_r = y_r / P_r^{1-\sigma},$$
$$b_s = y_s / P_s^{1-\sigma},$$
$$b_c = \left(\frac{\tau_3}{\tau_2 P_c} \right)^{1-\sigma} y_c.$$

The factor γ is the internal barrier of the region relative to the internal barrier of the rest of the nation. In the following, we call it the *relative geographical barrier*. Given that $\sigma > 1$, the higher τ_{ss} relative to τ_{rr}, the higher γ and thus internal trade t_{rr}. In other words, if it is relatively cheaper to trade with local firms rather than with firms in the rest of the nation, the higher is trade with the former.

In order to obtain t_{rr}, the bi-proportional system in (2.35) can be solved by iterative proportional fitting i.e. the RAS procedure with the mentioned row and column totals from above and balancing factors a_r, a_s, a_c and b_r, b_s, b_c. The solution is positive and unique, if the data is strongly consistent, meaning if there exists a matrix with the lower right entry equal to zero and all other entries strictly positive, such that the row and column constraints are fulfilled. For this to be the case, the row and column totals must obviously be positive, and the row totals and column totals must sum up to the same amount, i.e. national output plus imports must equal national use plus exports, $x_r + x_s + m_n = y_r + y_s + e_n$. This is necessary, but not sufficient. For sufficiency it must also hold that domestic output exceeds exports, $x_r + x_s > e_n$ (or equivalently $y_r + y_s > m_n$). The case $x_r + x_s = e_n$ (or equivalently $y_r + y_s = m_n$) is also allowed. It is called 'just consistent'. The solution is in this case trivial: it implies all domestic flows, including t_{rr}, to vanish.

Thus, we only lack an initial value for the *relative geographical barrier*

$$\gamma = \left(\frac{\tau_{rr}}{\tau_{ss}} \right)^{1-\sigma} \tag{2.36}$$

that we can plug into the RAS procedure. In empirical gravity studies, trade barriers are approximated by various bilateral geographical and trade policy variables. Regarding the internal barrier, the main impedance is geographical distance. We assume the general form $\tau_{kk} = d_{kk}^{\zeta}$ for $k = r$ or s, with distance parameter ζ and average internal distance d_{kk}. This is a commonly assumed though not the only possible functional form. Alternative representations include the exponential or a step function, among many others. For a thorough discussion of trade costs we refer to Anderson and van Wincoop (2004). The internal distance is the average distance a local firm faces when shipping commodities to another local firm within the region. A useful but obviously expensive measure would be a weighted average of the distance between all cities in the region under study. Less expensive measures for the internal distance are one-quarter of the distance to the nearest foreign center as in Wei (1996), the distance between the two largest cities as in Wolf (2000), or the square root of the region's area multiplied by a proportionality factor as in Leamer (1997), Nitsch (2000) and Head and Mayer (2000). Here, we assume the general form $d_{kk} = F_k^{\phi}$, with parameter ϕ and area size F_k. Inserting the general form above into (2.36) leads to

$$\gamma = \left(\frac{F_r^{\phi\zeta}}{F_s^{\phi\zeta}} \right)^{1-\sigma} . \tag{2.37}$$

Finally, by taking the natural log of (2.37), the *relative geographical barrier* can be reformulated to

$$\ln \gamma = \eta \left(\ln F_s - \ln F_r \right) , \tag{2.38}$$

with $\eta = \phi\zeta\,(\sigma - 1)$. Area sizes of the region and rest of the nation are easily available. Thus, we only need an estimate of η, which is the elasticity of trade with respect to distance of a standard gravity estimation at commodity level where $\phi = 1$. It can, for example, be obtained from Leamer (1974), Möhlmann et al. (2009) and Anderson and Yotov (2010a,b). For the sake of user friendliness, we also provide $\hat{\eta}$'s for 18 commodities in the first column of Table 2.2, Section 2.5 based on the estimation by Meier (2018). Further, we provide the RAS procedure for solving system (2.35) in the supplementary material to this paper.

Let us summarize GRETA's three-regions recipe for industry i:

i) Step 1)-2) from the previous section.

ii) Calculate $x_s^i = x_n^i - x_r^i$ and $y_s^i = y_n^i - y_r^i$.

iii) Obtain F_r, F_s, and distance parameter η^i from the literature or Table 2.2 in order to calculate γ^i by (2.38).

iv) Plug x_r^i, x_s^i, m_n^i, y_r^i, y_s^i, e_n^i and γ^i into the RAS program in order to obtain t_{rr}^i.

v) Finally, calculate $a_{rr}^{ij} = \rho_r^i a_n^{ij}$ with $\rho_r^i = t_{rr}^i / y_r^i$.

This recipe is almost as easy to use as the *internal trade equation*, though a little more expensive. Its main ingredient is the *relative geographical barrier* which depends on estimates of the distance parameter. The literature on such estimates is rich but diverse. In general, there is strong empirical evidence for the negative impact of distance on trade and that it is persistent since the middle of the last century (Disdier and Head, 2008). The magnitude, however, depends on various factors such as the underlying functional form, the distance measurement technique, the regression method and the level of commodity aggregation, among others. Moreover, there is little or no empirical evidence for the distance effect on trade in services due to the lack of data (Larch et al., 2017). If in fact there is no distance barrier for trade in services, we may simply use our two-regions approach from the previous section for regionalizing the service industries of the I-O table, which we will explore further in the empirical test of our approach.

2.4 DISCUSSION

The I-O regionalization approach developed in the course of this paper shows considerable advantages compared to existing techniques, which are summarized in Table 2.1 below. First of all, given the low data requirements, we consider both our approaches to be pure non-survey methods which can otherwise only be said about LQ and SDP techniques.

In contrast, the econometric approach by Stevens et al. (1983) as well as the gravity approaches by Lindall et al. (2006) and Riddington et al. (2006) can be considered as semi-survey approaches. Stevens et al. (1983) estimate what are essentially the *regional supply proportions* ρ_r^i, which the authors termed *regional purchase coefficients* (RPCs). The RPCs are assumed to depend on the LQ, but also on further ratios of regional to national values such as relative wages and land area. The relationships of the RPCs and these ratios have been fitted by different regression techniques to a unique set of transportation data of the US census and thus require a large amount of data (Stevens et al., 1988; Treyz and Stevens, 1985). This is why the approach has never found widespread application, although it is both a theoretical and empirical improvement to LQ and SDP approaches (Kronenberg, 2007; Stevens et al., 1988). Besides, the RPC approach does not guarantee consistent estimation results regarding accounting constraints which is a further disadvantage of the technique. Lindall et al.

(2006) provide an alternative approach to obtain RPCs by estimating trade flows between thousands of US counties with a DCGM. Similarly, Riddington et al. (2006) estimate trade flows between 40 Scottish regions by a DCGM and find that their approach produces more reasonable output and expenditure multipliers for a single region than LQ approaches. However, also these studies require a large amount of data and do not provide an easy to use regionalization recipe for a single region.

Hence, our main competitors are LQ and SDP techniques. The LQ is the most prominent and frequently used regionalization technique in applied analysis. For instance, the Bureau of Economic Analysis of the US Department of Commerce sells regional multipliers produced by their 'Regional Impact Modeling System (RIMS II)' which uses LQs to estimate *regional input coefficients*. Despite its frequent application, the technique shows considerable theoretical and empirical deficiencies which the I-O literature is well aware of. First of all, LQs do not guarantee consistent results. On a national scale, we have by definition

$$e_n^i = x_n^i - t_{nn}^i = x_n^i - \sum_j a_{nn}^{ij} x_n^j - u_n^i. \tag{2.39}$$

If we scale (2.39) down to a region that has a significantly different production structure than the nation, it is not guaranteed that exports e_r^i are non-negative, i.e. that t_{rr}^i is smaller or equal to local output x_r^i. A similar argument holds for imports. In that case, LQ techniques require ad-hoc balancing corrections which has been already criticized by Schaffer and Chu (1969). We showed in (2.24) that this cannot happen with our approach. Further, the simple LQ assumes product homogeneity and thus precludes the possibility of cross-hauling a priori. Tackling this theoretical as well as other empirical issues led to numerous variants of the simple LQ such as the Cross-Industry LQ and its commonly used modification, the FLQ by Flegg and Webber (1997). These do not preclude cross-hauling, but neither do they add much theory to the mechanics of the technique, nor necessarily perform better (Harrigan et al., 1981; Riddington et al., 2006; Smith and Morrison, 1975). A case for LQ techniques that has been made in the literature (Flegg and Tohmo, 2013; Kronenberg, 2012) is its applicability if only *national input coefficients* a_{nn}^{ij} rather than *national technical input coefficients* a_n^{ij} are known. However, we find that national I-O tables that only include information about the former are rare. Usually, tables that are based on the System of National Accounts (SNA) like the ones provided by Eurostat or the World Input-Output Database (Dietzenbacher et al., 2013) include information about both. Nevertheless, in the unlikely event that the modeler has a table containing only information about a_{nn}^{ij}'s, and given the disadvantages of the LQ approach, we rather recommend to construct the a_n^{ij}'s by expanding the I-O table with a column of foreign imports by industry and applying the RAS method.[6]

The SDP technique, although being very similar to the LQ as shown by Robison and J. Miller (1988), is less present in applied regional analysis. The main advantage compared to the LQ is that it is at least consistent or 'self-balancing' (Schaffer and Chu, 1969). However, as the simplest LQ, it also precludes cross-hauling. Therefore, Kronenberg (2009) adjusts the original technique by a measure of product heterogeneity as the main reason for the cross-hauling of commodities. To discuss it more deeply, we again omit industry index i. This 'cross-hauling adjusted regionalization method' (CHARM) can, in an intuitive way, be rewritten as a an *internal trade equation* like (2.19) as

$$t_{rr} = \min(x_r, y_r) - h_r \frac{x_r + y_r}{2}, \tag{2.40}$$

which we show in Appendix A.6. It says that t_{rr} equals the maximum internal flow $\min(x_r, y_r)$, downward corrected by the cross-hauling share $h_r \in [0, 1]$ of the mean between x_r and y_r. This share is assumed to be a measure of product heterogeneity. One obtains the nation's cross-hauling share h_n by solving (2.40) for h_n with national data, i.e. with $r = n$,

$$h_n = \Big(\min(x_n, y_n) - t_n\Big) \frac{2}{x_n + y_n}.$$

Assuming that product heterogeneity is independent of location, it is supposed to be the same in the region and the nation so that $h_r = h_n$. Inserting this for h_r into (2.40) yields the estimates for t_{rr} which can then be plugged into (2.4) in order to estimate *regional input coefficients*.

Alas, (2.40) is inconsistent. Obviously, $t_{rr} \leq \min(x_r, y_r)$, as it should, with equality in case of $t_n = \min(x_n, y_n)$. But unfortunately, t_{rr} might well become negative. As an extreme example, let $t_n = 0$, $x_n = y_n$, $y_r > 0$ and $x_r = 0$, then $t_{rr} = -y_r/2 < 0$. This shortcoming of the initial approach is corrected ad-hoc while presenting a multi-regional approach in Többen and Kronenberg (2015).[7] The mean in (2.40) is replaced by the minimum which makes the technique consistent again. In addition, the corrected version of CHARM follows a three-

6 Data on foreign imports by industry is usually available at country level in the national external trade statistics.

7 Without explicitly correcting Kronenberg (2009).

regions approach (region r, rest of the country s and rest of world w). In general, CHARM is an improvement compared to the existing LQ and SDP techniques because it includes a measure of product heterogeneity. It is, however, not explicitly derived from theory which is the main reason for its consistency issue in the first place.

Moreover, (2.40) is proportionally increasing in the region's local output and use, i.e. if $\lambda > 1$, $t(\lambda x, \lambda y, h) = \lambda t(x, y, h)$. That is, if output and use in the region under study double, internal trade also doubles. In other words, a simple scaling up of the regional economy has no effect on its *regional supply proportions* (cf. Kronenberg, 2009, requirement 2 on page 50). However, we argued that if the region's economic size increases, it should be able to produce and supply relatively more varieties to itself. Thus, if taking product heterogeneity seriously, we do not find this a desirable property of the CHARM formula.

To sum up, all the existing regionalization methods show disadvantages compared to our approach. All of them lack a clear theoretical foundation. The existing gravity approaches (DREAM and Lindall et al. (2006)) are expensive and focus on the multi-regional level. The LQ techniques are not consistent. The original SDP technique is consistent but precludes cross-hauling. Finally, CHARM does not take reasonable account of cross-hauling by assuming that it is proportional to the economic size of the region.

Given these disadvantages, we also expect to outperform the existing techniques empirically. However, also our approaches rely on strong assumptions. Our two-regions approach assumes that the *relevant world market* of the region and nation coincides. Therefore, we expect the estimates of our two-regions approach to be upward biased in the way that it overestimates internal and underestimates external trade. This is because we assume national external trade barriers that are likely to be too high in order to apply them to the regional level. This has been taken care of by our three-regions approach whose estimates, however, depend on the accuracy of the distance parameters which the modeler is free to choose from the literature. Therefore, we provide a sensitivity analysis with respect to the distance elasticity of trade within the next section. It remains to take our approach to the data and test its performance.

Table 2.1: Comparison of different I-O regionalization methods

Method	Non-survey	Single-region	Theory based	Consistent	Cross-hauling	Geographical size
LQ	×	×				
CILQ	×	×			×	
FLQ	×	×			×	
SDP	×	×		×		
CHARM1	×	×			×	
CHARM2	×	×		×	×	
RPC		×				×
DREAM				×	×	×
Lindall et al. (2006)				×	×	×
GRETA1	×	×	×	×	×	
GRETA2	×	×	×	×	×	×

Note: LQ, Location Quotient; CILQ, Cross-Industry Location Quotient; FLQ, Flegg's Location Quotient by Flegg and Webber (1997); SDP, Supply Demand Pool; CHARM1, Cross-Hauling Adjusted Regionalization Method by Kronenberg (2009); CHARM2, Corrected CHARM1 formula from Többen and Kronenberg (2015); RPC, Regional Purchase Coefficients by Stevens et al. (1983); DREAM, Detailed Regional Economic Accounting Model by Riddington et al. (2006); GRETA1, Two-regions Gravity Regionalization of Trade Approach; GRETA2, Three-regions Gravity Regionalization of Trade Approach.

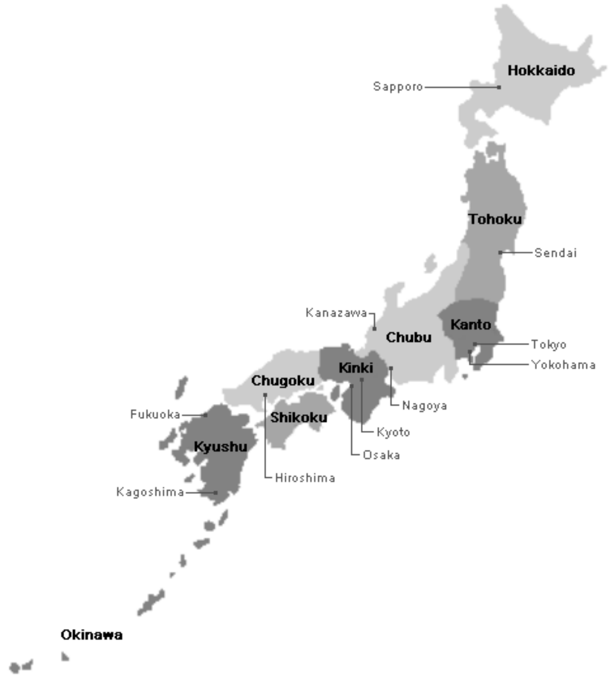
2.5 EMPIRICAL TEST

In the following, we present a first empirical test for estimating internal trade with our approach. It is based on comprehensive Japanese multi-regional I-O survey data for the year 2005 provided by the Ministry of Economy, Trade and Industry (METI), Japan.[8] Japan has a long history in constructing regional I-O tables. Since 1960, every five years the METI has carried out a joint project with various prefectural Bureaus of Economy, Trade and Industry, among others, in order to construct regional I-O tables. The tables were constructed, inter alia, with comprehensive survey information. In the manufacturing industries, trade estimates are based on commodity distribution and regional movement of freight surveys. In the service industries, these estimates rely on interregional traveler fares, passengers carried tables, and headquarters office expenses. The latest table for the year 2005 includes nine Japanese regions depicted in Figure 2.1 and 53 industries. For ease of comparison, we aggregate the table

8 For a full description of the data and construction methodology, we refer to the 'debrief report' (Ministry of Economy, Trade and Industry, 2010).

to 18 industries according to the classification of the gravity estimation from Table 2.2.

Figure 2.1: The nine regions of the multi-regional I-O table of Japan in 2005



Source: www.japan-guide.com

Based on the survey table, we calculate for each region and industry the benchmark internal trade value as the difference between local output and exports, i.e. $t^i_{rr} = x^i_r - e^i_s - e^i_c$, and compare them with estimates $\hat{t}^i_{rr}$ of our approach as well as CHARM. Given the theoretical and empirical issues of the LQ, we refrain from applying the technique here. It is important to note that we do not estimate local output x^i_r and use y^i_r. Instead, we use the survey data because the main objective is to evaluate the performance of estimating the regional trade pattern.

The summary statistics are shown in Table 2.3, Appendix A.7. The square root of the weighted mean squared error (Root wMSE) shows the average deviation from the survey data in billion Yen. We weight the MSE by each industry's share in the region's total local output. GRETA1, our two-regions approach, outperforms CHARM1 in all regions except Okinawa. However, the comparison is biased because CHARM1 produces inconsistent estimates ($\hat{t}^i_{rr} < 0$) for the 'Pharmaceuticals' and 'Computer' industries in Okinawa.[9] Compared to the corrected version which we denote CHARM2, GRETA1 outperforms CHARM2

9 In fact, if we estimate internal trade for the original 53 industries, CHARM1 does not only produce inconsistent estimates in Okinawa but in all other regions as well.

in six out of nine regions. According to the summary statistics, our three-regions approach, GRETA2, performs worse than the other approaches. However, this is only due to the fact that our three-regions approach is not suitable to estimate trade in service industries which we will discuss in the following.

In general, GRETA1 and both versions of CHARM significantly overestimate internal trade in manufacturing industries (industries 1-13), but perform rather well in service industries (industries 14-18). In contrast, GRETA2 performs fairly well in manufacturing industries, but significantly underestimates internal trade in service industries. This is depicted in the more detailed sectoral results for each region in Figure 2.2-2.10 of Appendix A.8 in which the bars show the natural logarithm of deviations from the survey data, $\ln(\hat{t}^i_{rr}/t^i_{rr})$. Except for the regions Hokkaido and Okinawa (Figure 2.2 and 2.10), our two-regions approach systematically overestimates internal trade in manufacturing industries because of the assumption that the *relevant world market* of the region and nation coincides. In the survey data, we observe that regions trade heavily with the rest of the nation which our two-regions approach does not take reasonably into account due to the geographical inaccuracy of the above assumption. That is, trade barriers between Japanese regions are in fact lower compared to barriers between Japan and the rest of the world. Regarding the service industries, the Japanese regions are highly self sufficient i.e. *regional supply proportions* are observed to be high. The average regional proportions range from 0.75 in Chubu to 0.93 in Kanto. The national average is 0.99. For GRETA1, the latter implies that the nation's *relevant world market* z^i_n for service industries is close to zero. Therefore, GRETA1, which assumes $z^i_r = z^i_n$, results in internal trade estimates that are very close to the survey data. That is, with no relevant world market to trade with, most of the regions trade the maximum possible amount internally (recall (2.29)). Similar arguments hold for product heterogeneity in CHARM, i.e. $h^i_r = h^i_n$.

In contrast, our three-regions approach accounts for the geographical sizes of the regions as well as the effect of distance on trade flow values. However, it depends on the availability and accuracy of the distance parameter estimates $\hat{\eta}$, which we provide in the first column of Table 2.2 below. The estimates are based on a gravity estimation with international trade data and indicate the elasticity of trade with respect to distance.[10] For instance, a 1% increase in the average distance between trading partners leads to a 1.6% decrease in the average trade value of agricultural products. The larger the parameter is in absolute terms, the less the region trades with the rest of the nation and thus the higher are internal

10 A brief description of the gravity estimation is provided in Appendix A.9.

trade values estimated by GRETA2. Regarding the manufacturing industries, the approach shows no systemic bias and performs fairly well in estimating internal trade, especially in economically more important regions such as Kanto (in which Tokyo is located), Chubu, and Kinki (Figure 2.4-2.6). All are located on the main island of Japan and constitute more than two thirds of Japan's total domestic output. This is also indicated by the last columns of Table 2.2 which show the distance parameters inferred from the survey data for four selected regions. We find that the parameters inferred from international trade data are fairly suitable for applying GRETA2 to the manufacturing sectors of the above regions, whereas less suitable for more self sufficient regions such as Hokkaido where the distance effect is expected to be larger.

Regarding the service industries, we find strong indication that the survey data, in which regions trade heavily with the nearby rest of Japan, show a larger distance effect as what can be inferred from international trade data. This is plausible because anyway under long distances those commodities self select into long distance trade if they are more easily tradable. This means that commodities with higher obstacles to trade self select into short distance trade which suggests that for short distances the distance parameter should be larger in absolute terms. Therefore, we find that especially for the service industries the distance parameter should be much larger than the ones inferred from international trade data. In fact, if we would let the parameter go to infinity, we expect GRETA2 to yield similar results as GRETA1 with a relevant world market close to zero for the service industries. Therefore, we suggest the modeler to apply GRETA2 to manufacturing industries and GRETA1 to the service industries of the underlying I-O table.

Table 2.2: Poisson Quasi-Maximum Likelihood estimation results for the elasticity of trade with respect to distance η

Industries	$-\hat{\eta}$	Std. Err.	p-value	$-\eta^*$ Hokkaido	$-\eta^*$ Kanto	$-\eta^*$ Chubu	$-\eta^*$ Kinki
Manufacturing							
1 Agriculture, forestry, fishing	-1.60**	0.54	0.003	-3.36	-1.27	-2.61	-1.64
2 Mining and quarrying	-2.28***	0.33	0.000	-2.77	-1.01	-1.87	-1.04
3 Food, beverages, tobacco	-1.26***	0.35	0.000	-2.69	-0.94	-2.01	-0.96
4 Textiles, clothing, leather	-1.17**	0.43	0.007	-2.91	-0.71	-0.87	-0.27
5 Wood, Paper, Printing	-0.91*	0.38	0.017	-3.30	-0.46	-1.89	-1.10
6 Coke, refined petroleum	-2.93**	0.90	0.001	-2.72	-1.11	-2.16	-1.41
7 Chemicals	-1.35***	0.29	0.000	-3.63	-0.58	-1.13	-0.61
8 Pharmaceuticals	-0.69	0.58	0.236	-0.71	-0.19	-0.73	-0.12
9 Rubber, Plastic	-1.35**	0.45	0.003	-4.83	-0.81	-1.59	-0.65
10 Metals	-1.25***	0.33	0.000	-4.20	-1.03	-1.59	-1.05
11 Computer	-1.00***	0.20	0.000	-2.17	-0.13	-0.88	-0.37
12 Machinery	-0.88**	0.28	0.002	-2.85	-0.36	-0.91	-0.45
13 Motor Vehicles	-0.44	0.28	0.123	-2.23	-0.70	-1.15	-0.75
Services							
14 Electricity, gas, water, waste	-1.72	1.10	0.120	-10.14	-3.28	-6.12	-3.74
15 Accomodation	-0.90	2.93	0.758	-4.36	-1.28	-2.00	-1.41
16 IT and communications	-1.29	1.49	0.385	-5.43	-1.52	-3.64	-2.20
17 Real estate	-1.11	0.59	0.061	-7.94	-4.01	-7.30	-4.94
18 Business services	-0.69	3.49	0.843	-6.14	-2.03	-4.18	-2.47

Note: The estimates $\hat{\eta}$ are provided by Meier (2018).

Regarding output multipliers, GRETA1, CHARM1 and CHARM2 rather overestimate whereas GRETA2 underestimates multipliers (see Table 2.3, Appendix A.7). The latter result is biased because it includes the service industries for which our three-regions approach is not suitable as explained above. However, we find that even if we exclude the service industries, GRETA2 still rather underestimates multipliers. The systematic overestimation of regional multipliers has been a common critique in the non-survey I-O literature (cf. Jackson, 1998; Richardson, 1985; Robison and J. Miller, 1988; Többen and Kronenberg, 2015). The reason is that it leads to model results which inflate regional economic impact assessments. We may thus conclude that GRETA2 is the first non-survey approach which does not systematically overestimate multipliers but rather provides more conservative estimates.

To sum up, the first empirical test of our approach is promising. It is, of course, far from being conclusive because survey-based models are not necessarily the best standards for comparison in the first place because they may partly rely on non- or semi-survey techniques themselves. However, the test provides some interesting insights into our approach. In particular, GRETA2 tackles the ongoing critique of overestimating internal trade and output multipliers. While estimation results of GRETA1 seem the most accurate at first glance, the detailed results on the industry level show the systemic overestimation of internal trade in manufacturing sectors. Therefore, accounting for the geographical size of the region and the distance effect on trade is important and leads to more accurate estimates of internal trade in manufacturing sectors. Most importantly, the estimates do not seem to be systematically biased. Finally, since distance matters less for trade of services compared to manufactured goods, we recommend the modeler to apply GRETA1 to service industries and GRETA2 to manufacturing industries of the underlying I-O table.

2.6 conclusion

In this paper, we provided a new hands-on recipe for regionalizing national I-O tables. Our non-survey 'Gravity Regionalization of Trade Approach' (GRETA) does not differ from other regionalization techniques in estimating local output and use, but it differs in estimating regional trade. Most importantly, our approach is theory based. By formulating a theoretical gravity equation in the functional form of a doubly-constrained gravity model for two regions, the region under study and the rest of world, and solving for the region's internal flow, we derive a closed form *internal trade equation*. This trade equation can be readily applied to scale down the *national technical input coefficients* in order to estimate the *regional input coefficients* for a single region. It depends on the region's economic size as well as its ability to buy from and sell to the world market, or in short, the region's *relevant world market*. We further showed that, as long as the underlying theoretical gravity equation is multiplicatively separable, it is consistent with our *internal trade equation*. This requirement applies to a large set of modern trade theories which makes our approach theoretically very attractive.

We showed that our trade equation exhibits desirable properties. Internal trade is non-negative and increasing in both, output and use, without exceeding either. As shown, other non-survey techniques violate this consistency requirement by allowing for both, negative internal trade as well as internal trade exceeding output or use. Internal trade is furthermore decreasing in the *relevant world market*, with the two sensible limits of no internal trade for an infinite *relevant world market* and internal trade equal to the smaller one of either output or use for a vanishing *relevant world market*. Finally internal trade exhibits a desirable scaling property: scaling output and use up leads to a more than proportional increase of internal trade, reflecting the fact that scaling does not only affect output and use per commodity, but also product heterogeneity.

Since distance matters for estimating trade flows, we have also extended our gravity approach to three regions in order to explicitly account for the region's geographical size and the distance effect on trade. By doing so, the solution for the internal trade flow cannot be easily derived in closed form any more, but can be found by e.g. the RAS procedure. In our three-regions approach, internal trade depends on the region's economic size as well as its internal trade barrier relative to the internal trade barrier within the rest of the nation. The latter, which we call the region's *relative geographical barrier*, can be approximated by the region's and nation's land area and the distance parameters of a standard gravity estimation at commodity level.

We showed that existing non-survey techniques show disadvantages compared to our approach. All of them lack a clear theoretical foundation. The existing gravity approaches are rather expensive and focus on the multi-regional level. The LQ techniques are not consistent. The original SDP technique is consistent but precludes cross-hauling. Finally, our approach can be best compared with the CHARM by Kronenberg (2009) because we share the idea that product heterogeneity is behind the cross-hauling of commodities. However, neither is this technique explicitly derived from theory nor does it exhibit the desirable scaling property of our approach mentioned above.

Finally, in order to evaluate the performance of our approach, we conducted an empirical test with survey data for nine Japanese regions. We find that it generally performs fairly well in estimating internal trade, although the performance significantly differs across industries and regions. Most importantly, the estimates of our three-regions approach do not seem to be systematically biased, which is a common critique of existing non-survey techniques. However, since distance parameters for service industries are usually not available from international gravity studies, we suggest modelers to apply our three-regions approach to manufacturing industries only and to rely on our two-regions approach for the service industries. Last but not least, we have also compared estimates with the commonly used SDP technique CHARM and find that we generally perform better.

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A APPENDIX TO CHAPTER 2

For ease of notation, we define $V_r := (x_r + y_r + z_r)/2$ and $S_r := \sqrt{V_r^2 - x_r y_r}$, such that (2.19) reads $t_{rr} = V_r - S_r$.

A.1 *Proof of the internal trade equation (2.19)*

In the following, we omit the industry index i up to Appendix A.5. The bi-proportional system (2.13)-(2.17) can be solved analytically for t_{rr} by the following manipulations. By multiplying (2.14) and (2.16), we obtain

$$x_r y_r = t_{rr}^2 + t_{rr}(t_{rw} + t_{wr}) + t_{rw}t_{wr}. \tag{2.41}$$

Further, adding up (2.14) and (2.16), and multiplying both sides with t_{rr}, results in

$$t_{rr}(x_r + y_r) = 2t_{rr}^2 + t_{rr}(t_{rw} + t_{wr}). \tag{2.42}$$

Then, solving (2.42) for $t_{rr}(t_{rw} + t_{wr})$ and inserting into (2.41) yields

$$t_{rr}^2 - t_{rr}\,(x_r + y_r + z_r) + x_r y_r = 0, \tag{2.43}$$

with $z_r = t_{rw}t_{wr}/t_{rr}$. Finally, solving the quadratic equation (2.43) for t_{rr} leads to two possible solutions

$$t_{rr_{1,2}} = V_r \pm \sqrt{V_r^2 - x_r y_r}. \tag{2.44}$$

For the expression under the square-root in (2.44) we get

$$V_r^2 - x_r y_r \geq \frac{(x_r + y_r)^2}{4} - x_r y_r = \frac{(x_r^2 - 2x_r y_r + y_r^2)}{4} = \frac{(x_r - y_r)^2}{4} \geq 0. \tag{2.45}$$

Both solutions are thus real. As $V_r \geq (x_r + y_r)/2 \geq \min(x_r, y_r)$, the larger solution (the one with ('+') yields $t_{rr} > \min(x_r, y_r)$ if $z_r > 0$ or $x_r \neq y_r$. Hence, the larger solution cannot apply. For the smaller solution we obtain $t_{rr} \geq 0$, because $S_r \leq V_r$. Furthermore,

$$t_{rr} \leq \min(x_r, y_r) \tag{2.46}$$

is immediate from $t_{rr} = \min(x_r, y_r)$ for $z_r = 0$ (see A.5) and $\partial t_{rr}/\partial z_r = 1/2 - V_r/2S_r \leq 0$ (see A.3). Thus, the smaller solution of (2.44) (the one with '$-$') applies, leading to *internal trade equation* (2.19).

A.2 *Measuring the size of the world market*

Let us consider the economic size of the world market increases while the region's remains small. The question is what happens to the *relevant world market* z_r. Thus, we consider the limit of $z_r = t_{ww}R_r = (x_w - t_{wr})R_r$ for x_w tending to infinity, while both, x_r and y_r remain finite. Then, $t_{ww} = x_w - t_{wr}$ also tends to infinity, because $t_{wr} \leq y_r$ remains finite. But regarding R_r, we need to consider two cases of a limiting process: 1) When x_w tends to infinity, R_r tends to some positive constant. Then, z_r tends to infinity and t_{rr} thus tends to zero. The same holds true if we plug in $\tilde{z}_r$ rather than z_r. And 2), when x_w tends to infinity, R_r tends to zero. Then, $\tilde{z}_r - z_r = (x_w - t_{ww})R_r = t_{wr}R_r$ also tends to zero, because $t_{wr} \leq y_r$ remains finite. To summarize, in both cases $\tilde{z}_r$ or z_r deliver the same result in the limit i.e. if the region under study is small compared to the rest of world. A similar argument holds for measuring the size of the world market by y_w.

A.3 *Proof of the general scaling properties (2.25),(2.26) and (2.28)*

In the following, we also omit the region index r up to Appendix A.6. The change of t due to a change of x is given by

$$\frac{\partial t}{\partial x} = \frac{1}{2} - \frac{V - y}{2S} = \frac{S - V + y}{2S} = \frac{m}{m + e + z} \geq 0. \tag{2.47}$$

Similar operations yield $\partial t/\partial y$ and $\partial t/\partial z$. We disregard the case $m + e + z = 0$ that can only occur if $z = 0$ and $x = y$, as is immediate from A.5 below.

A.4 *Proof of the simultaneous scaling property (2.27)*

If $\rho > 1$, then

$$t(\rho x, \rho y, z) \geq t(\rho x, \rho y, \rho z) = \rho t(x, y, z).$$

The inequality follows from $\partial t/\partial z \leq 0$, the equality is obvious from *internal trade equation* (2.19) which is jointly linear homogenous in x, y and z.

A.5 *Proof of the limit properties (2.29)-(2.30)*

For $z = 0$, trade equation (2.19) reads

$$\begin{aligned} t &= (x+y)/2 - \sqrt{(x+y)^2/4 - xy} \\ &= (x+y)/2 - \sqrt{(x^2 - 2xy + y^2)/4} \\ &= (x+y)/2 - |x-y|/2 \\ &= \min(x,y). \end{aligned}$$

As to the other end, let t and t^* be solutions for z and $z^* \leq z$ and given x and y. Hence, $t^* \geq t$ due to $\partial t/\partial z \leq 0$. Thus,

$$t = \frac{xy}{x+y+z-t} \leq \frac{xy}{x+y+z-t^*}. \tag{2.48}$$

Taking the limit of (2.48) for $z \to \infty$ yields $t \to 0$.

A.6 *Rewriting CHARM as an internal trade equation*

In its original form, CHARM estimates the sectoral trade volume v_r^i by

$$v_r^i = \left|x_r^i - y_r^i\right| + h_r^i(x_r^i + y_r^i), \tag{2.49}$$

with $v_r^i := e_r^i + m_r^i$, which is supposed to also hold for the nation, i.e. $r = n$. In the following, we again omit industry index i. $h_r \in [0,1]$ is a factor representing sectoral product heterogeneity that accounts for cross-hauling and is obtained from the national I-O table as

$$h_r = h_n = \frac{v_n - |b_n|}{x_n + y_n},$$

where b_n is the trade balance such that the nominator is the amount of cross-hauling. Using $v_r = e_r + m_r = (x_r - t_r) + (y_r - t_r) = x_r + y_r - 2t_r$ and $x_r + y_r - |x_r - y_r| = 2\min(x_r, y_r)$, (2.49) can be rewritten as

$$t_{rr} = \min(x_r, y_r) - h_r \frac{x_r + y_r}{2}. \tag{2.50}$$

A.7 *Internal trade estimates for Japan*

	Survey	GRETA1	GRETA2	CHARM1	CHARM2	Survey	GRETA1	GRETA2	CHARM1	CHARM2	Survey	GRETA1	GRETA2	CHARM1	CHARM2
	Hokkaido					**Tohoku**					**Kanto**				
	Internal trade $\hat{t}^i_r$ in bn Yen					Internal trade $\hat{t}^i_r$ in bn Yen					Internal trade $\hat{t}^i_{rr}$ in bn Yen				
Mean	1,479	1,619	273	1,790	1,705	2,130	2,561	562	2,856	2,670	17,350	19,806	12,730	20,211	19,242
Root wMSE	-	589	7,378	977	720	-	1,313	9,211	1,675	1,342	-	6,334	21,202	6,685	4,837
	Regional Output Multipliers $\hat{\mu}^j_{rr}$					Regional Output Multipliers $\hat{\mu}^j_{rr}$					Regional Output Multipliers $\hat{\mu}^j_{rr}$				
Mean	1.56	1.50	1.07	1.65	1.58	1.48	1.54	1.12	1.71	1.60	1.83	1.82	1.59	1.87	1.76
wMSE	-	0.026	0.196	0.035	0.025	-	0.018	0.107	0.070	0.029	-	0.024	0.055	0.039	0.021
	Chugoku					**Chubu**					**Kinki**				
	Internal trade $\hat{t}^i_{rr}$ in bn Yen					Internal trade $\hat{t}^i_{rr}$ in bn Yen					Internal trade $\hat{t}^i_{rr}$ in bn Yen				
Mean	2,135	2,624	628	2,943	2,764	4,134	5,386	1,873	5,757	5,401	5,799	7,149	2,724	7,600	7,240
Root wMSE	-	1,207	6,850	1,695	1,372	-	3,068	11,226	3,524	2,916	-	3,435	14,388	4,226	3,637
	Regional Output Multipliers $\hat{\mu}^j_{rr}$					Regional Output Multipliers $\hat{\mu}^j_{rr}$					Regional Output Multipliers $\hat{\mu}^j_{rr}$				
Mean	1.63	1.68	1.29	1.88	1.75	1.60	1.70	1.21	1.83	1.71	1.61	1.72	1.41	1.88	1.75
wMSE	-	0.070	0.172	0.171	0.108	-	0.073	0.149	0.152	0.071	-	0.038	0.04	6 0.096	0.044
	Shikoku					**Kyushu**					**Okinawa**				
	Internal trade $\hat{t}^i_{rr}$ in bn Yen					Internal trade $\hat{t}^i_{rr}$ in bn Yen					Internal trade $\hat{t}^i_{rr}$ in bn Yen				
Mean	913	1,096	143	1,301	1,220	3,230	3,758	964	4,164	3,888	274	247	11	300	292
Root wMSE	-	578	4,006	811	660	-	1,383	12,197	2,128	1,567	-	240	1,359	171	114
	Regional Output Multipliers $\hat{\mu}^j_{rr}$					Regional Output Multipliers $\hat{\mu}^j_{rr}$					Regional Output Multipliers $\hat{\mu}^j_{rr}$				
Mean	1.46	1.51	1.22	1.79	1.67	1.58	1.60	1.24	1.81	1.67	1.49	1.32	1.19	1.48	1.46
wMSE	-	0.046	0.077	0.135	0.081	-	0.028	0.102	0.122	0.045	-	0.061	0.110	0.036	0.041

Table 2.3: Summary statistics for estimating internal trade and output multipliers in a multi-regional I-O table for Japan (2005)
Source: Authors' calculations. The survey data is from the Ministry of Economy, Trade and Industry (2010).
Note: GRETA1, Two-regions Gravity Regionalization of Trade Approach; GRETA2, Three-regions Gravity Regionalization of Trade Approach; CHARM1, Cross-Hauling Adjusted Regionalization Method by Kronenberg (2009); CHARM2, Corrected CHARM1 formula from Többen and Kronenberg (2015).

A.8 *Sectoral internal trade estimates for Japan*

Figure 2.2: Sectoral internal trade estimates for the province of Hokkaido as the natural logarithm of deviations from the survey data, $\ln(\hat{t}^i_{rr}/t^i_{rr})$.

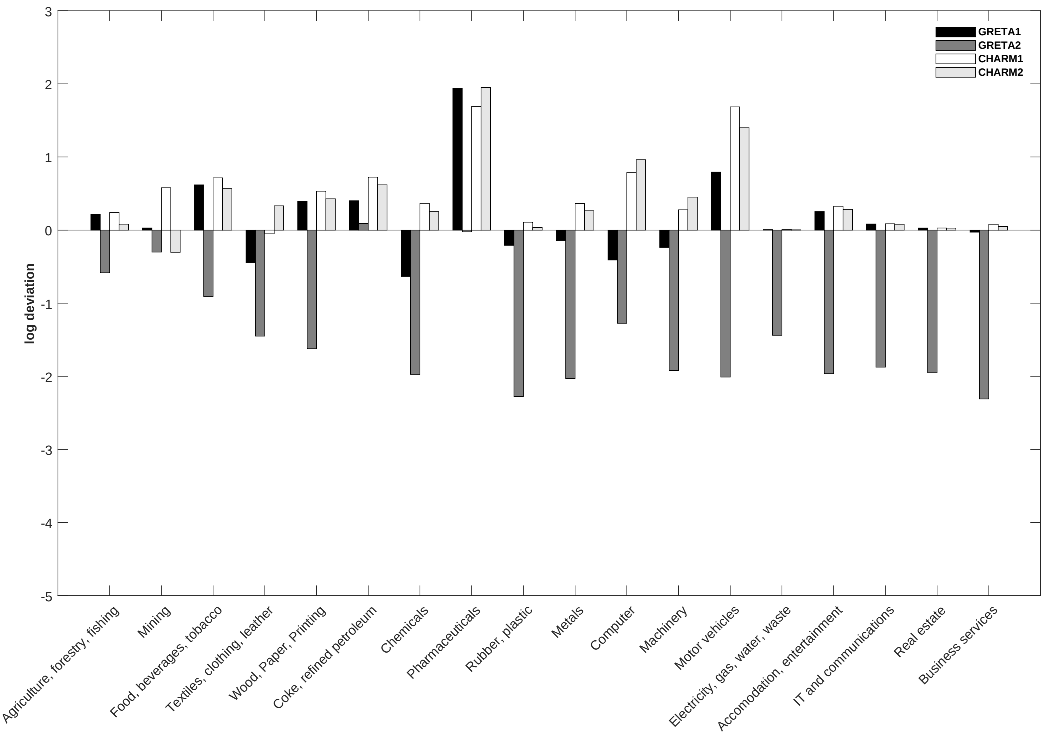


Figure 2.3: Sectoral internal trade estimates for the province of Tohoku as the natural logarithm of deviations from the survey data, $\ln(\hat{t}^i_{rr}/t^i_{rr})$.

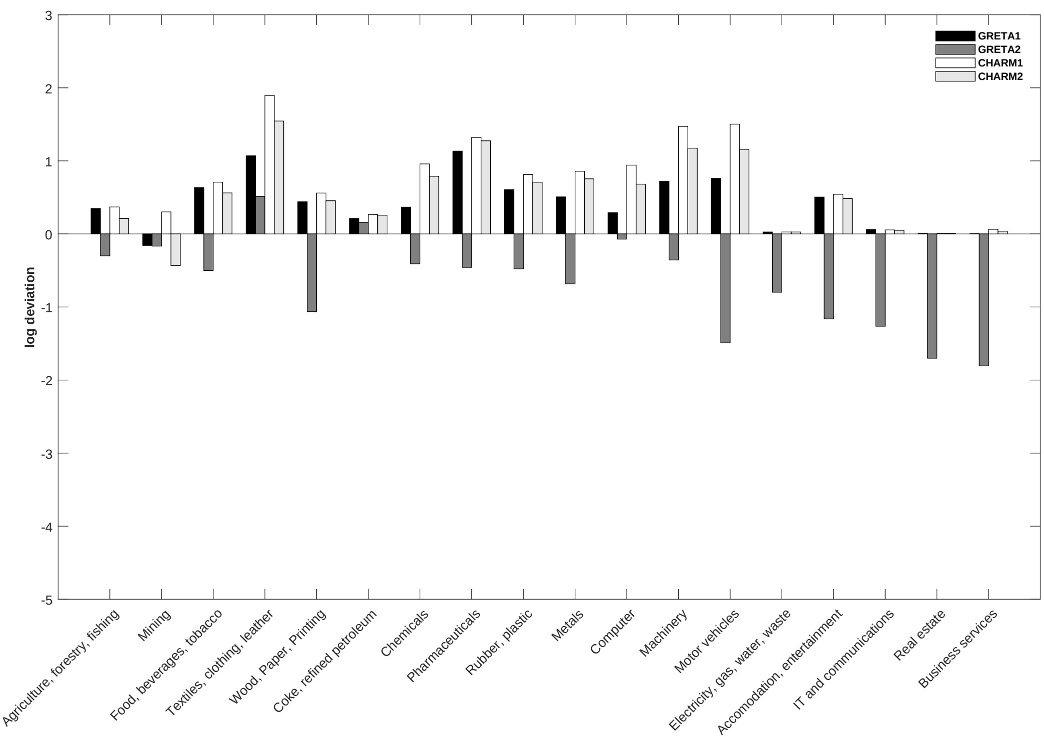


Figure 2.4: Sectoral internal trade estimates for the province of Kanto as the natural logarithm of deviations from the survey data, $\ln(\hat{t}^i_{rr}/t^i_{rr})$.

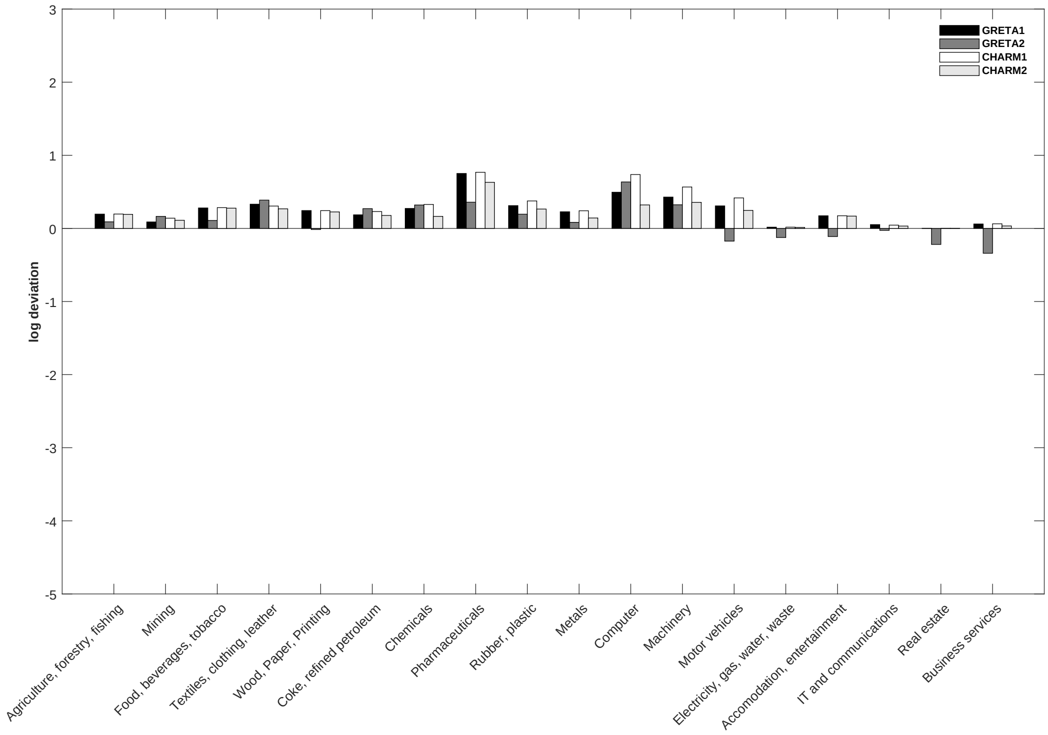


Figure 2.5: Sectoral internal trade estimates for the province of Chubu as the natural logarithm of deviations from the survey data, $\ln(\hat{t}^i_{rr}/t^i_{rr})$.

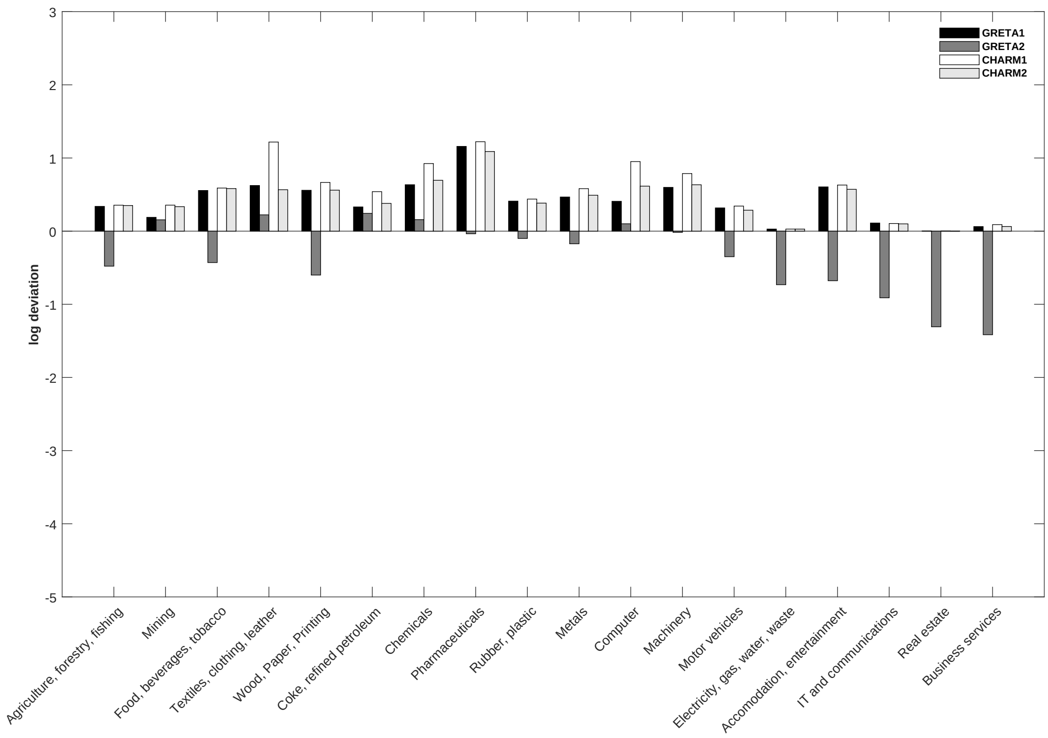


Figure 2.6: Sectoral internal trade estimates for the province of Kinki as the natural logarithm of deviations from the survey data, $\ln(\hat{t}^i_{rr}/t^i_{rr})$.

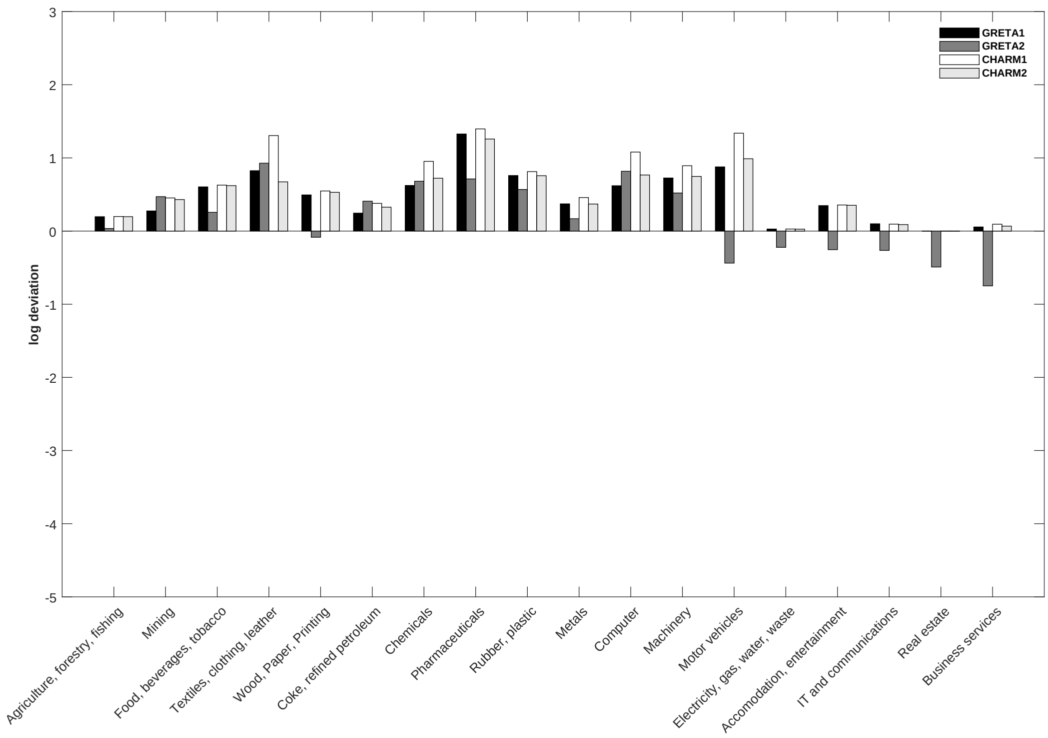


Figure 2.7: Sectoral internal trade estimates for the province of Chugoku as the natural logarithm of deviations from the survey data, $\ln(\hat{t}^i_{rr}/t^i_{rr})$.

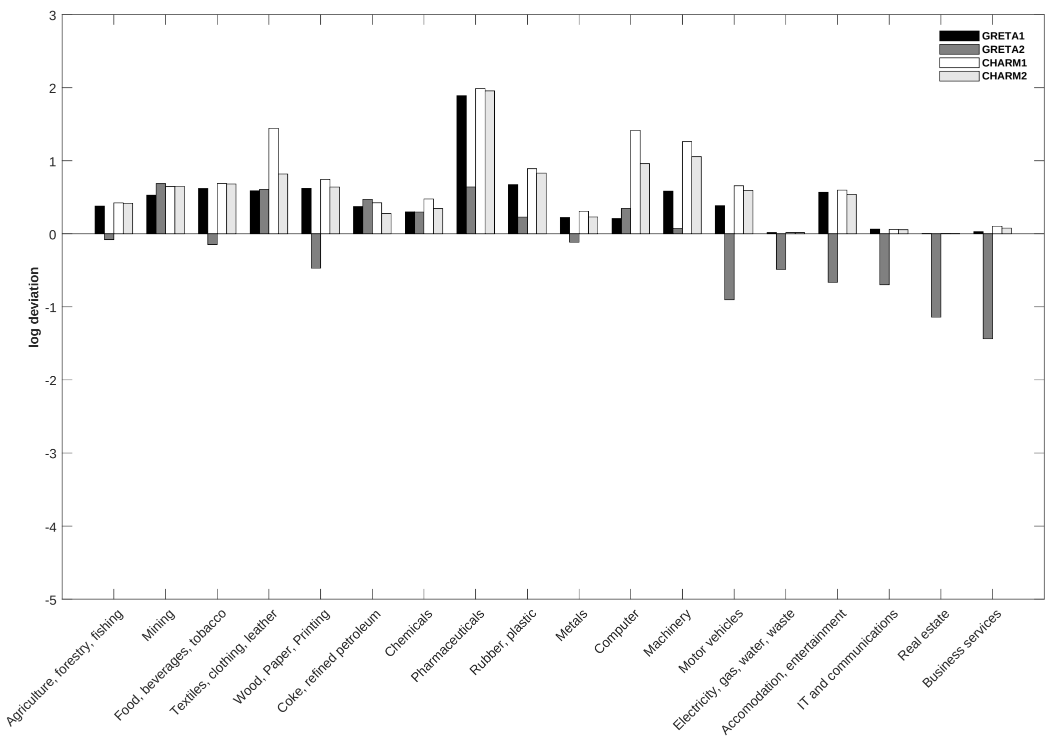


Figure 2.8: Sectoral internal trade estimates for the province of Shikoku as the natural logarithm of deviations from the survey data, $\ln(\hat{t}^i_{rr}/t^i_{rr})$.

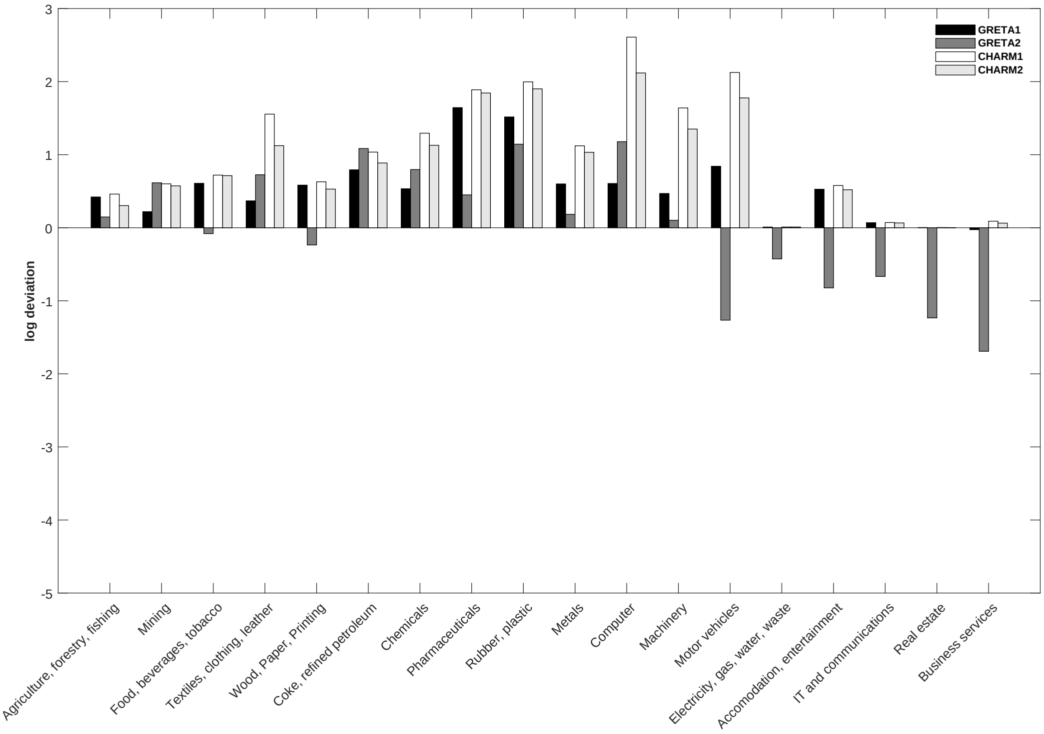


Figure 2.9: Sectoral internal trade estimates for the province of Kyushu as the natural logarithm of deviations from the survey data, $\ln(\hat{t}^i_{rr}/t^i_{rr})$.

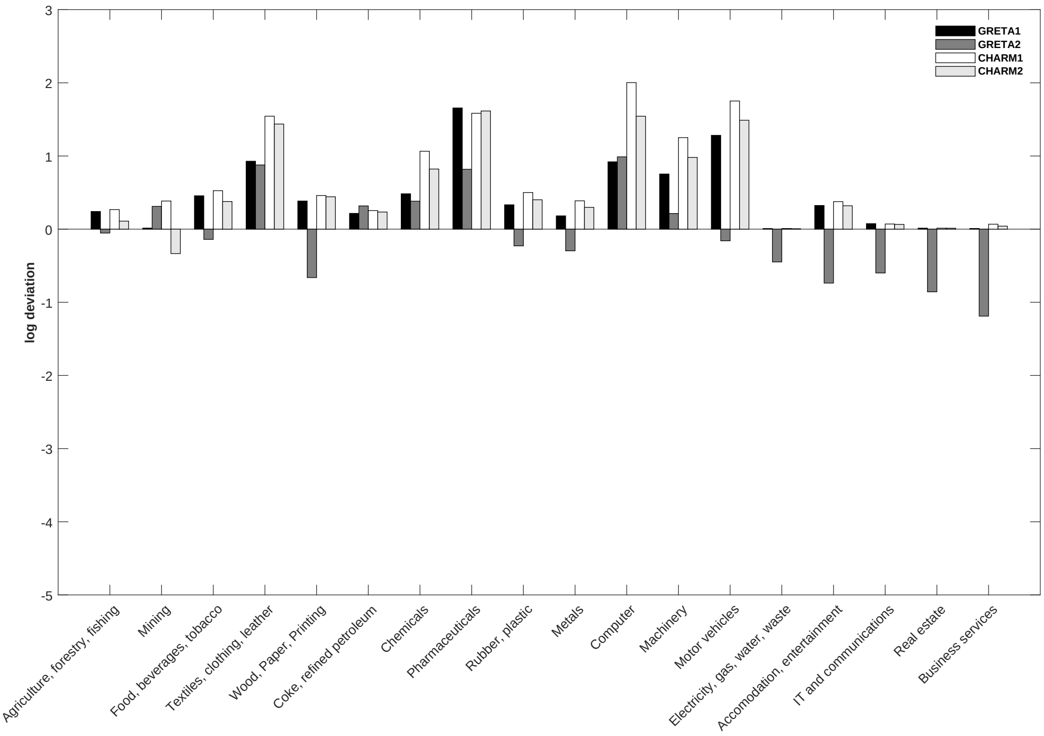
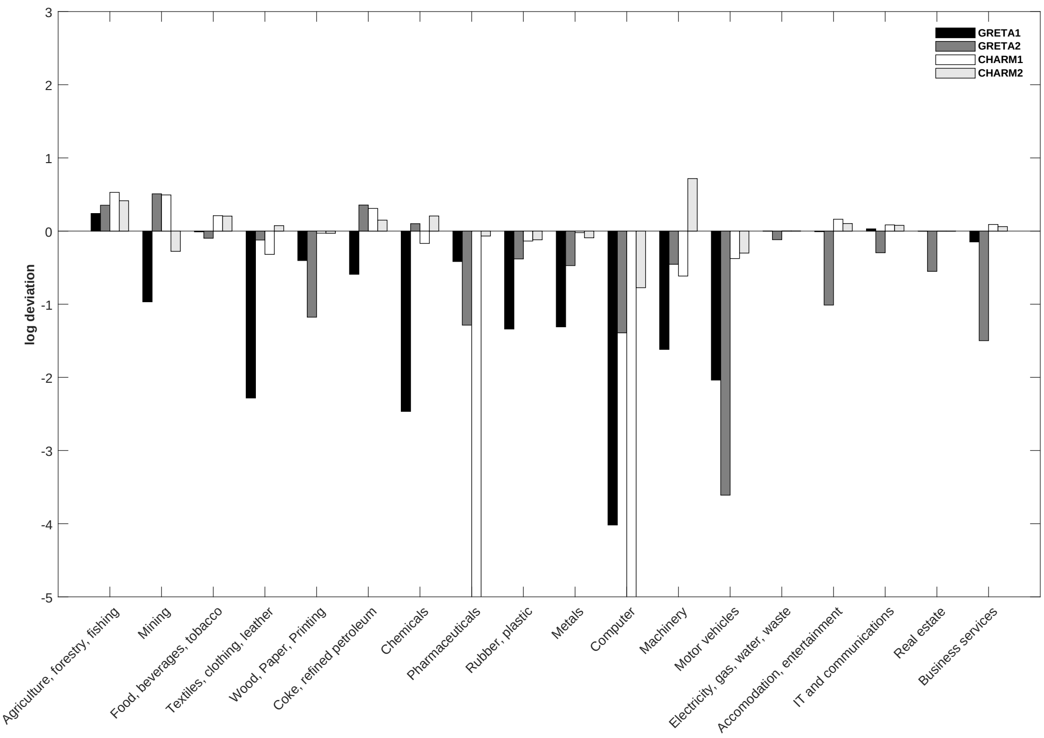


Figure 2.10: Sectoral internal trade estimates for the province of Okinawa as the natural logarithm of deviations from the survey data, $\ln(\hat{t}^i_{rr}/t^i_{rr})$.



A.9 *Poisson Quasi-Maximum Likelihood gravity estimation with fixed effects*

The distance parameters provided in Table 2.2 are obtained from a gravity estimation at commodity level with international trade data by Meier (2018). The natural procedure would be to log-linearize (2.8) or any other gravity model, add a disturbence term, and fit the resulting equation by ordinary least squares (OLS). But this procedure is not compatible with the observed data which includes a significant amount of zero trade flows. Therefore, an alternative and nowadays standard procedure in the gravity trade literature is to apply a Poisson Quasi-Maximum Likelihood (PQML) estimation as suggested by e.g. Bröcker and Rohweder (1990). In the following, we omit industry index i. The estimation equation reads

$$t_{kl} = \exp(\beta_k + \theta_l - \eta \ln d_{kl} + x_{kl}\delta) + \epsilon_{kl} \quad \forall\, k, l; \;\; l \neq k \tag{2.51}$$

with $k, l = 1, ..., N$ countries.

The bilateral trade flow values t_{kl} from exporter k to importer l are obtained from the United Nations Commodity Trade Statistics Database (UN Comtrade) for $N = 207$ countries in the year 2014. The parameters β_k and θ_l are N exporter and importer fixed effects, respectively. The distance d_{kl} in 1000km is the cheapest route over land and sea between trading partners.[11] The parameter of interest is $\eta = \phi\zeta(\sigma - 1)$. In international gravity studies, it is usually assumed that $l \neq k \;\forall\; k, l$ such that there are no internal distances that need to be approximated by e.g. area sizes, i.e. $\phi = 1$. Thus, applying our three-regions approach with the distance parameters inferred from (2.51) implies that the region under study is of longitudinal ($\phi = 1$) rather than of circular shape ($\phi = 0.5$). This is suitable for our empirical test of Japan where geography looks more like a narrow band rather than a circle. However, in the case of geographically more compact regions, the η's are expected to be smaller than inferred from (2.51). Besides geographical distance, trade barriers are assumed to depend on K further variables defined by the $1 \times K$ row vector x_{kl} with $K \times 1$ column parameter vector δ. It includes dummy variables for neighbouring countries, colonial relationships, and membership in preference areas (i.e. a free trade agreement, a customs union or a common market). Finally, ϵ_{kl} is a random disturbance.

11 For further information, I refer to Meier (2018).

3

REGIONAL ECONOMIC IMPACTS OF RENEWABLE ENERGIES

This chapter has not been published yet. It may be referenced as:

Burmeister, Johannes (2018). Regional Economic Impacts of Renewable Energies. Mimeo, University of Kiel.

Abstract: This paper quantifies the regional income and employment effects of the renewable electricity expansion plans of the state of Schleswig-Holstein (S-H), Germany for the year 2030 by means of a computable general equilibrium (CGE) model. Methodologically, the model is based on supply and use tables which allow for introducing multi-output firms into the model. Renewable electricity producing firms are modeled with survey information on regional component-wise input costs. The labor market allows for unemployment via the wage curve, and tax income results take into account the German tax revenue sharing scheme such that we present net results. We find that the general equilibrium effects on the economy of S-H are rather small. The main income effects result from feed-in compensations and land ownership. Under the old feed-in scheme, the expansion leads to a 0.95% (or 715mn € p.a.) higher regional GDP, a wage increase of 0.2% and 1,424 new jobs from 2030 onwards. Under the new tender scheme, income effects are considerably lower because competition between renewable firms drives profits to zero. However, the labor income, rents from land ownership, as well as wage and employment effects remain stable under both schemes.

Keywords: Renewable energy, computable general equilibrium, regional economic impacts, feed-in tariff, tender scheme

3.1 INTRODUCTION

Germany is often considered as a role model for a successful transition from conventional to renewable energy sources. In fact, during the last two decades the German Renewable Energies Act (EEG) led to a successful expansion and market penetration of renewable energies. Regarding the electricity market, the production more than quadrupled from 36 TWh in 2000 to 188 TWh in 2017. However, the economic efficiency of expanding renewables has caused ongoing and controversial debates in politics, businesses, academia and the media. Therefore, the EEG has been revised five times since its introduction in 2000.

The latest revision in 2017 introduced a fundamental change in the compensating scheme of renewable electricity. It replaced the *feed-in* by a *tender scheme* and thus changed from a price to a quantity mechanism in which the government issues a fixed, technology-specific quantity of installed capacity which the most favorable bidders win and build. Primarily, the *tender scheme* is supposed to increase cost efficiency by preventing over-subsidization through competitive pricing. Moreover, the introduction of a quantity mechanism aims to better control the further expansion because the ramped construction of wind energy, biogas and photovoltaic plants also implies negative externalities such as falling house prices, noise, and impairments of the landscape and wildlife (Drewitt and Langston, 2006; Dröes and Koster, 2016; Gibbons, 2015; Knopper and Ollson, 2011; Sunak and Madlener, 2016).

In fact, although 93% of the German population are in favor of renewables, only 52% would accept a wind turbine in their direct neighborhood (AEE, 2016). These 'not in my backyard' positions cannot be ignored by regional policy makers. Therefore, in the past citizen-owned wind farms have been an important regional profit-sharing scheme which constitute strong arguments for policy makers to back the further expansion in their communities. Also at the national level, the German government reaffirmed that the transition from conventional to renewable energy can only succeed with citizens' involvement. Therefore, the EEG 2017 facilitates the tender participation of citizen-owned wind farms. However, the latest tenders have been mainly won by large project developers disguised as citizen projects (Wetzel, 2017). Whether these projects will be realized and citizens involved adequately thus remains an open issue.

The transition from conventional to renewable energy sources also requires the transition from a centralized to a more decentralized energy generation infrastructure because renewables are dependent on the elements of nature, which are scarce in some regions and plentiful in others. The state of Schleswig-Holstein (S-H) in northern Germany, surrounded by the North and Baltic Sea, has plenty of wind and is one of the leading states in expanding renewable electricity, especially wind energy. In 1983, 'GROWIAN', at that time with 3MW installed capacity the world's largest wind turbine, was built in S-H. Thirty-three years later in 2016, 19 TWh or 10% of total national renewable electricity was produced in S-H whereas the state only constitutes 2.8% of national GDP. The share of produced renewable electricity to total gross electricity consumption is 122% compared to 32% nationwide. Therefore, most of the electricity is directed to southern parts of Germany via the continuously expanded grid.

The local government aims to more than double renewable electricity production by the year 2030. The political tenor is that renewables do not only mitigate CO_2 emissions but also lead to regional income and employment. Many wind farms in S-H are citizen-owned, which increases acceptance due to regional profit-sharing.[1] In addition, landowners profit from rents. As an income example, in 2013 the average income in the village 'Reußenköge' in the county North Frisia was 109,387 € per person compared to 35,443 € statewide because most citizens are shareholders of the local wind farm (Statistikamt Nord, 2017). In the past, wind farms have generated high profits due to much lower levelized costs of electricity (lcoe) than revenues from government-guaranteed feed-in compensations. Therefore, the question is how large the income (and employment) effects of the ambitious government expansion targets until 2030 will be and whether income effects will change significantly under the new *tender scheme*. The aim of this paper is thus to quantify the income and employment effects by means of a regional computable general equilibrium (CGE) model as well as to compare the results of the old *feed-in* with the new *tender scheme*.

This paper is, to the best of our knowledge, the first to quantify the regional income and employment effects of the renewables expansion in Germany in a CGE framework.[2] Several previous studies with similar objectives show certain methodological disadvantages. In a series of studies for German states, Hirschl et al. (2010, 2015, 2012) quantify the regional value added and employment effects of the construction and operation of renewable plants by means of supply chain analysis and find significant effects for the states of Berlin, Sachsen-Anhalt, Hessen and Baden-Württemberg. Ulrich et al. (2012) quantify the employment effects for all states by means of a regional allocation model

1 For example, in the county of 'North Frisia' 90% of wind farms are citizen-owned (windcomm, 2010).
2 For an overview, see Jenniches (2018), Table 8

combined with a national input-output (I-O) model. Finally, Bröcker et al. (2014, 2016) quantify income and employment effects of the expansion targets of S-H until 2020 by means of supply chain analysis combined with a regional I-O model. However, the main disadvantage of all aforementioned studies is that they only quantify gross income and employment effects. Thus, they do not take into account crowding-out effects in other industries as well as offsetting effects due to price changes. An exception is the work of Többen (2017), who quantifies the regional net impacts of promoting renewable energies by means of a multi-regional price and quantity I-O model. However, the modeling approach also shows certain disadvantages to a CGE approach by assuming fixed technology input coefficients and no supply constraints. Therefore, the following paper contributes to the existing literature by extending the methodology of Bröcker et al. (2014, 2016) to a CGE approach. The major advantage of a CGE compared to an I-O model is that it is based on microeconomic general equilibrium theory and thus captures all quantity and price adjustments, for example due to an energy or climate policy intervention, in a closed and theoretically consistent framework. Finally, compared to previous studies, the following paper also contributes to research on the acceptance of renewable energy by comparing income effects under different compensating schemes. As mentioned above, regional profit-sharing schemes are important for regional policy makers in order to back up future expansion targets. However, since the latest EEG revision buried the *feed-in scheme*, the question is whether the new *tender scheme* leads to significantly smaller income effects and thus dampens the acceptance of renewables expansion.

The remainder of this paper is organized as follows. Section 3.2 gives an overview of the modeling setup. After describing the basic ideas of the regional model, we introduce the formal structure. The basic presentation of technologies and preferences mainly follows Bröcker (2015). The section closes by describing the data and its regional break down for the state of S-H. In Section 3.3, the general equilibrium conditions are described. In order to account for unemployment in S-H, we then extend the model by introducing an imperfect labor market. An important part of static CGE modeling is to define how the model is closed with respect to parts of the economy which would usually incorporate dynamic behaviour such as investment and saving decisions. These 'closure rules' are described in Section 3.3.2. Finally, the reference equilibrium is solved with benchmark data for S-H in 2014. Since this paper aims at quantifying regional income and employment effects of the renewables expansion, we design counterfactual equilibria which reflect the expansion plans of the local government for the year 2030 at the end of Section 3.3. The model is solved for these counterfactual equilibria in Section 3.4, presenting comparative static income and employment results of the local expansion plans. In order to check for the robustness of the results, it follows a sensitivity analysis with respect to various substitution elasticities as well as one of the closure rules. Finally, Section 3.5 concludes.

3.2 THE MODEL

3.2.1 *Basic ideas*

We set up a model for a small open economy that represents the region of S-H. It is based on a standard SHOVEN-WHALLEY CGE framework with a static economy, constant returns to scale, perfect competition and taxes in the data (Shoven and Whalley, 1984). The main advantages of a CGE compared to an I-O approach is that we are able to take into account supply constraints of the economy, substitution possibilities of firms and households and price changes on all markets of S-H. We follow a single-region approach in which the region of S-H is trading goods with the rest of the world (ROW), whereby the ROW is not explicitly modeled. Therefore, external trade of the region with the ROW comprises flows to and from the rest of Germany as well as foreign countries. We assume that there is two-way trade of any good i.e. cross-hauling and that local goods and externally traded goods, although having the same commodity classification, are imperfect substitutes. Thus, we follow the so-called Armington assumption (Armington, 1969). Given that the economy of S-H is small compared to the ROW, prices in the ROW for the externally traded goods are assumed to be given. This means that S-H imports and exports goods at a fixed price. The exchange of goods with the ROW leads to corresponding capital flows, namely capital exports and imports. In our model, we summarize these flows as well as all other potential capital flows (e.g. portfolio investments and social transfers) as the net flow of funds, which can be either positive or negative depending on S-H's trade balance, debt position and so forth.

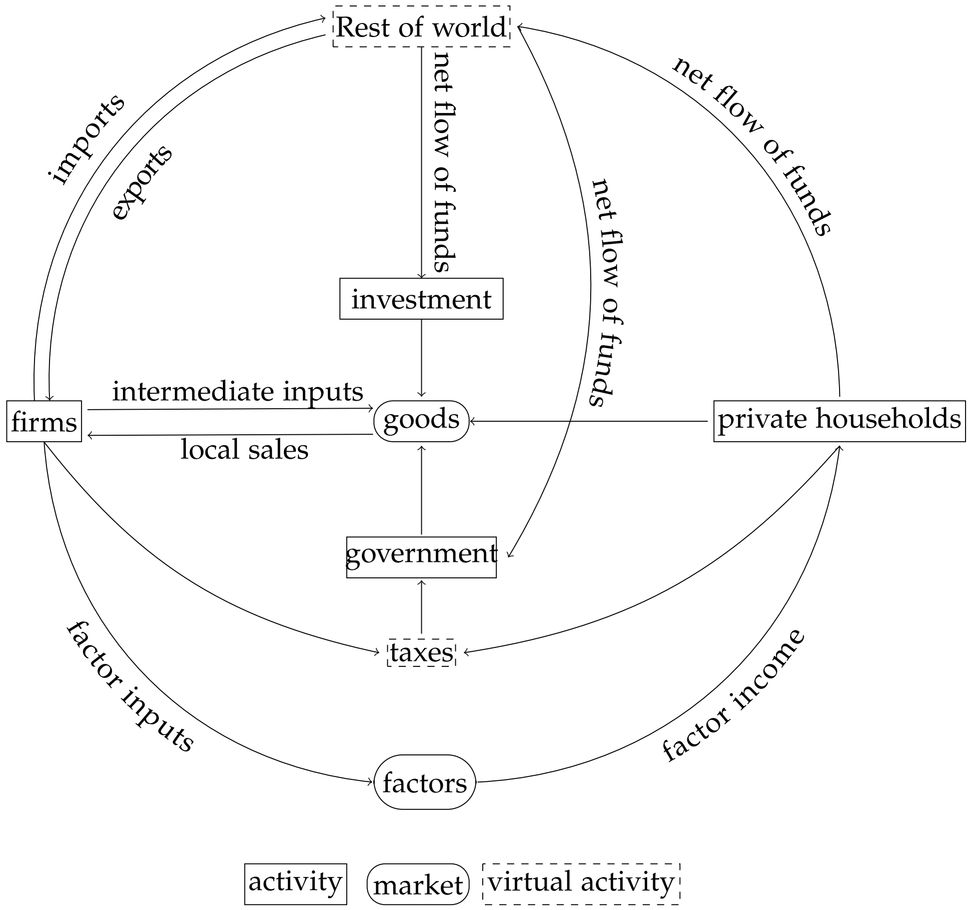
Figure 3.1 summarizes the economic interactions in the model of S-H where the arrows point in the direction of the financial flow. We assume two types of activities in the region, production, which is done by a number of representative firms, and final use, which is the activity of a number of representative households. The latter include private households, the government, and investment. The activities take place on markets as follows.

Firms buy intermediate and factor inputs on which they both pay marginal taxes. Further, they import goods from the ROW. They earn revenue from selling goods to local markets and to the ROW. Firms maximize profits, which implies that in equilibrium prices equal minimal unit cost and no profits are left.

Private households consume goods on which they pay value added tax. They earn income by selling primary factors to firms. The local government of S-H consumes goods and earns income by collecting taxes. Any differences between consumption expenditures and earnings indicate either positive or negative net flow of funds with the ROW. Both private households and the local government maximize utility under their budget constraint. In contrast, local investment demand is assumed to be exogenous.

In the reference situation, the economy of S-H in the year 2014 is assumed to be in equilibrium, meaning that supply equals demand on all markets, unit revenue equals unit cost for all firms, and the budgets of all households are balanced. In case of an external shock to the regional economy such as the renewables expansion, we calculate the resulting counterfactual equilibrium. By comparing the reference situation with the counterfactual i.e. comparative statics, we then quantify the resulting output, income and price changes due to the shock. Given that we model the economy of S-H in a single-region framework, we do not capture any feedback effects of the regional expansion on the rest of the German economy.

Figure 3.1: Economic interactions in the CGE model of Schleswig-Holstein



Source: Own illustration.

3.2.2 *Formal structure*

We begin by introducing the subscripts of activities and markets appearing in the model. There are $y \in Y = \{1, \ldots, 146\}$ activities taking place on $m \in M = \{1, \ldots, 240\}$ markets. The activities Y comprise production of firms $j \in J = \{1, \ldots, 142\} \subseteq Y$ and final use of households $h \in H = \{143, \ldots, 146\} \subseteq Y$. For the purpose of the paper, firms and households are further sub-categorized into three types of firms and four types of households as follows.

Firms $f \in F = \{1, \ldots, 61\} \subseteq J$ represent all major industries of S-H such as agriculture, shipping, construction, tourism and financial services (see Table 3.2). Firms $a \in A = \{62 : 139\} \subseteq J$ are 'Armington composing firms', which incorporate external trade with the ROW into the model. Finally, firms $z \in Z = \{140 : 142\} \subseteq J$ represent the renewable electricity producing firms wind onshore, wind offshore and photovoltaic. Since the local government does not plan to expand electricity production from biogas, it is not considered in the model.

The four types of households are defined as follows. Household $o = 143$ represents the average household living in S-H. Most importantly, this household is characterized as a 'wind *o*utsider' with no possibility to invest in a citizen-owned wind farm in S-H because it lives in a municipality with no suitable land or other restrictions for wind or photovoltaic farms.[3] In contrast, household $w = 144$ is a '*w*ind insider'. The share of wind insiders in the total population of S-H and thus in consumption and endowments is $\omega = 1\%$. This is roughly the share of people living in municipalities with citizen-owned wind farms. Household w has the same consumption patterns and endowments as household o, but, in addition, earns profits of renewable firms Z as well as rents from land ownership. The public sector of S-H is treated as another household $g = 145$ representing the local government, which consumes goods and earns tax income. Finally, a household $v = 146$ represents investment demand.

The markets M comprise local and foreign markets. Local markets and corresponding goods and factors are the following. Local goods $d \in D = \{1, \ldots, 78\} \subseteq M$ are locally produced goods for the local market. Commodities $i \in I = \{79, \ldots, 156\} \subseteq M$ are a composite of a local good d and an imported good im, which are bought by firms as intermediate inputs and by households as final use. Factor markets are labor $l = 157$ and capital $k = 158$. Finally, foreign markets $fm \in FM = \{159, \ldots, 240\} \subseteq M$ are either exports EX to the ROW in the use table or imports IM from the ROW in the supply table, which both serve as the main data input for the model.

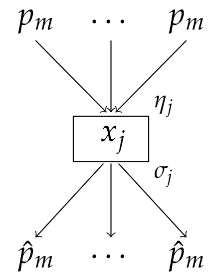
3.2.2.1 *Firms*

The production side of the economy of S-H is represented by firms F comprising all major industries and services, Armington firms A and renewable firms Z. One can think of a representative firm as the aggregation of several production plants operating in the same industry. For instance, the shipping firm represents the production of all shipyards in S-H because the aggregate profit obtained by each price-taking shipyard that maximizes profits separately is the same as if all shipyards were to coordinate their actions in a joint profit maximizing decision (cf. Mas-Colell et al., 1995, Proposition 5.E.1). This applies irrespective of the individual shipyard's production technology. The separation of firm activities and commodities in the underlying supply and use (S-U) tables

3 For ease of presentation, I refer the outsider and insider to the technology wind.

permits any activity to produce multiple commodities and any commodity to be produced by multiple activities.[4] This is a major advantage compared to other CGE models, which usually assume single-output firms. The input-output structure of a firm is shown in Figure 3.2. Again, the arrows point in the direction of the financial flow. For the sake of simplicity, we begin by assuming non-nested functional forms. Later, we introduce and apply nested functions. A representative firm j producing at activity level x_j buys multiple inputs $a_{m,j}x_j$ in order to transform them into x_j units of a throughput. The throughput is in turn the only input to produce multiple outputs $b_{m,j}x_j$. The input and output coefficients $a_{m,j}$ and $b_{m,j}$ indicate the cost-minimal input m per unit of throughput and the revenue-maximal output m per unit of throughput, respectively. Inputs are bought at customer prices $\hat{p}_m = p_m(1+\hat{\tau}_m)$, where p_m are market prices and $\hat{\tau}_m$ are commodity specific tax rates. Outputs are sold at market prices p_m.

Figure 3.2: Input-output structure of a firm



The throughput assumption is necessary because there is no information which of the inputs relate to the multiple outputs of a firm. Thus, in order to increase the output of a certain good m, firm j minimizes costs with respect to the price vector of all inputs which are necessary for the production of the throughput. We assume CES unit cost functions for firms J,

$$c_j(\hat{\boldsymbol{p}}) = \left(\sum_m \alpha_{m,j}\hat{p}_m^{1-\sigma_j}\right)^{\frac{1}{1-\sigma_j}} \qquad \forall\, j \in J, \tag{3.1}$$

4 A comprehensive description of the database for the CGE model, especially the S-U tables, will be given at the end of this section.

with constant elasticity of substitution $\sigma_j \geq 0$ and position parameter $\alpha_{m,j}$. If the cost function is differentiable at $\hat{\boldsymbol{p}}$, and $\hat{p}_m \geq 0 \; \forall \; m$, SHERPHARD's lemma implies that cost-minimizing input coefficients are given by

$$a_{m,j} = \frac{\partial c_j(\hat{\boldsymbol{p}})}{\partial \hat{p}_m} = \alpha_{m,j} \left(\frac{\hat{p}_m}{c_j} \right)^{-\sigma_j}. \tag{3.2}$$

Analogously, on the output side we assume CET unit revenue functions for firms J,

$$r_j(\boldsymbol{p}) = \left(\sum_m \beta_{m,j} p_m^{1+\eta_j} \right)^{\frac{1}{1+\eta_j}} \qquad \forall \; j \in J, \tag{3.3}$$

with constant elasticity of transformation $\eta_j \geq 0$ and position parameter $\beta_{m,j}$. The CET form depicts a firm's optimal unit revenue given the output prices of goods M. As above, revenue-maximizing output coefficients are given by

$$b_{m,j} = \frac{\partial r(\boldsymbol{p})}{\partial p_m} = \beta_{m,j} \left(\frac{p_m}{r_j} \right)^{\eta_j}. \tag{3.4}$$

The only difference to the input side is the reversed sign before the η_j in (3.3) and (3.4). Hence, η_j determines the degree of transformability between multiple outputs instead of substitutability between inputs. Say, relative output prices increase by 1%. Then, firm j increases relative output quantities by η_j%. Finally, we assume zero profits[5] for all firms J, i.e.

$$P_j = r_j(\boldsymbol{p}) - c_j(\hat{\boldsymbol{p}}) = 0 \qquad \forall \; j \in J \setminus Z, \tag{3.5}$$

where P_j denotes unit profits.

In order to apply the input-output structure of firms as above, we lack estimates of position parameters $\alpha_{m,j}$ and $\beta_{m,j}$ as well as elasticities σ_j and η_j. In the following, we only refer to the input side because similar operations apply to the output side. Since it is not possible to estimate σ_j based on a single observation of S-H's economy in 2014, elasticities are taken from empirical estimates in the literature. Once elasticities are determined in this way, we are able to fix position parameters $\alpha_{m,j}$ such that (3.1) reproduces the unit cost benchmark data. This procedure is called calibration, assuming the benchmark data to be an initial observable equilibrium. In other words, given σ_j, unit cost

5 The zero profit assumption does not apply to renewable firms z under the *feed-in scheme* which we will describe at the end of this section.

functions are completely specified by the benchmark data which we denote by the superscript ^{0}. This becomes more obvious from the calibrated form of (3.1), which is commonly used in applied modeling. It is obtained by rearranging (3.2) to

$$\alpha_{m,j} = a^0_{m,j} \left(\frac{c^0_j}{\hat{p}^0_m} \right)^{-\sigma_j}, \tag{3.6}$$

with benchmark input coefficients

$$a^0_{m,j} = \frac{V^0_{m,j} / \hat{p}^0_m}{V^0_j / c^0_j}, \tag{3.7}$$

where $\hat{p}^0_m$ are benchmark input prices, $V^0_{m,j}$ is the value of input m bought by firm j, and V^0_j is the total value of inputs bought by firm j. The latter two can be obtained from the benchmark use table. The benchmark cost per unit of activity of firm j, c^0_j, is the benchmark CES price index. Plugging (3.6) into (3.1) leads to

$$c(\hat{\boldsymbol{p}}) = c^0_j \left(\sum_m v^0_m \left(\frac{\hat{p}_m}{\hat{p}^0_m} \right)^{1-\sigma_j} \right)^{\frac{1}{1-\sigma_j}} \tag{3.8}$$

(see Appendix A.2). As obvious from (3.8), the calibrated form is completely specified by benchmark data, whereas $\alpha_{m,j}$ is only implicitly given in (3.8). The term $v^0_{m,j} = a^0_{m,j} \hat{p}^0_m / c^0_j$ is the benchmark value cost share of input m. Taking the derivative of (3.8) with respect to input prices leads to input coefficients

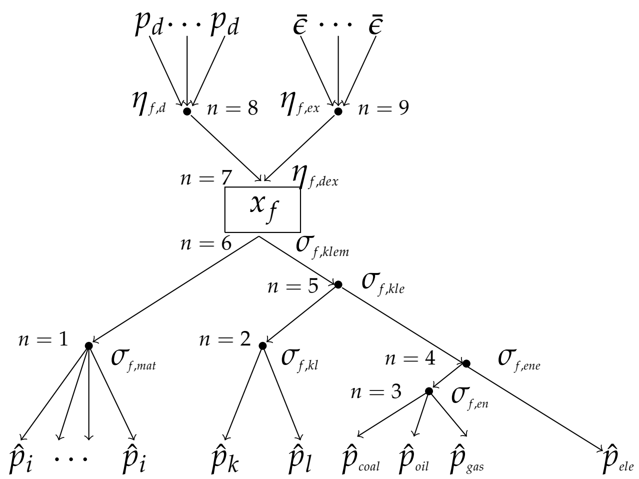
$$a_{m,j} = \frac{\partial c(\hat{\boldsymbol{p}})}{\partial \hat{p}_m} = a^0_{m,j} \left(\frac{c_j / c^0_j}{\hat{p}_m / \hat{p}^0_m} \right)^{\sigma_j}, \tag{3.9}$$

which is shown in Appendix A.3.

The CES technology assumed so far is more flexible than the Cobb-Douglas or Leontief technology but still not very flexible because we can choose only one σ_j. Therefore, we assume a yet more flexible nested CES form (Sato, 1967). The general idea is that a CES unit cost function with, say, three inputs can be formulated as the combination of the CES unit cost function of the first two inputs (first nest) which is then nested into a CES unit cost function combining it with the third input (second nest). In this way, more flexibility comes with the nest specific elasticity of substitution σ_j at each nest n.

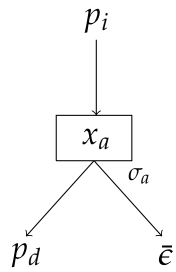
The nested input-output structure of a local firm f is depicted in Figure 3.3. Firm f buys multiple inputs in order to transform them into multiple outputs which are either sold to local markets D or to export markets EX. Given that the economy of S-H is small compared to the ROW, we assume that prices in the ROW are fix. Therefore, all exported goods EX are sold at a fixed price which we denote by $\bar{\epsilon}$, i.e. $p_{ex} = \bar{\epsilon}$ for all EX. All elasticity parameter values are given in Table 3.2. On nest $n = 1$, firm f buys material (and service) inputs with substitutability $\sigma_{f,mat}$. Factor inputs k and l are substituted with $\sigma_{f,kl}$ at $n = 2$. Fossil energy inputs coal, oil and gas are substituted with $\sigma_{f,en}$ at $n = 3$. Nest $n = 4$ combines electricity with the fossil energy aggregate with substitutability $\sigma_{f,ene}$. The capital-labor aggregate and energy-electricity aggregate is combined with substitutability $\sigma_{f,kle}$ at $n = 5$. Finally, the most upper nest on the input side, $n = 6$, combines material inputs and the capital-labor-energy aggregate with $\sigma_{f,klem}$. The transformability between multiple outputs of local and export goods is given by the CET's $\eta_{f,d}$ and $\eta_{f,ex}$ at nest $n = 8$ and $n = 9$, respectively. The most upper nest on the output side, $n = 7$, indicates the transformability between local and export goods by $\eta_{f,dex}$. It indicates the percentage change in the supply ratio of local good d to exported good ex given a percentage change in the ratio of the local price p_d to the ROW price $\bar{\epsilon}$. The larger $\eta_{f,dex}$ in absolute value, the more sensitive is the supply ratio to a change in relative prices. For example, if the relative price of local to exported ships decreases, shipyards in S-H are more flexible to sell their ships to export markets if $\eta_{f,dex}$ is high and vice versa.

Figure 3.3: CES nesting structure of a local firm f



The input-output structure of a firm a is depicted in Figure 3.4. Firm a buys a local and an imported good in order to transform them into a commodity i, which is in turn bought by firms and households for intermediate and final use. Thus, for each commodity i, we introduce a corresponding 'Armington composing firm' a. Analogously to the exported goods of firms F, the imported goods are bought at the fixed ROW price $p_{im} = \bar{\epsilon}$ for all IM. The so-called Armington trade elasticity σ_a describes the substitutability between a local and an imported input and is taken from Aguiar et al. (2016). It indicates the percentage change in the demand ratio of a local good d to an imported good im given a percentage change in the ratio of the local price p_d to the ROW price $\bar{\epsilon}$.

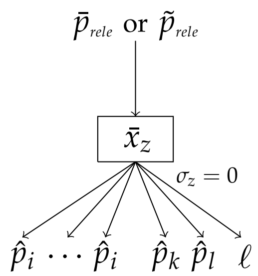
Figure 3.4: Input-output structure of an Armington firm a



3.2.2.2 *Renewables*

So far, firms are assumed to act on perfectly competitive input and output markets. However, this applies only partly to renewable electricity producing firms Z acting on the regulated electricity market of S-H. The input-output structure of a firm z is shown in Figure 3.5.

Figure 3.5: Input-output structure of a renewable firm z



A renewable firm z buys multiple inputs with LEONTIEF technology in order to export electricity to the ROW. Besides buying intermediate and factor inputs, it pays a lumpsum rent to landowners denoted by ℓ. According to survey data from Bröcker et al. (2014), this rent is considerably higher than the average rent for agricultural land because land which is suitable for wind farms is scarce and stipulated by the government. Suitable land is restricted to so-called 'priority areas' which account for only around 2% (31,353 ha) of the total land area in S-H.[6] Therefore, agricultural land cannot simply be transformed into land for wind farms; whether farmers are able to supply suitable land is rather a lottery. Moreover, in contrast to the land requirements for biogas plants, wind farms require relatively little land of around 4 ha per wind turbine. These include a compensation measure of around 1.4 ha for intervening in the landscape and nature according to the Nature Conservation Act. Henning et al. (2014) find that this compensation measure has only little effect on average rents for agricultural land in S-H. Thus, given the lack of a settlement mechanism for wind land as well as the negligible effects of the compensation measure on rents for agricultural land, we do not assume land as an additional factor input with associated market price but assume a lumpsum rent ℓ directly paid to the wind insider household w. The exported electricity is either remunerated at exogenous compensations $\bar{p}_{rele}$ under the *feed-in scheme* or at endogenous mill prices $\tilde{p}_{rele}$ under the *tender scheme*. The subscript *rele* denotes the respective technology wind onshore, wind offshore, or photovoltaic.

Under the *feed-in scheme*, the output side is non-competitive because a firm z sells at a fixed, technology-specific compensation $\bar{p}_{rele}$ stipulated by the government. In practice, $\bar{p}_{rele}$ is stipulated by the German government and usually much higher than the electricity spot price at the European Power Exchange (EPEX). The difference is a technology-specific Renewable Energies Act levy (EEG-Umlage) to be paid by households. Thus, households pay a levy (or subsidy) $\bar{s}_{rele} = \bar{p}_{rele} - \bar{e}$. This levy is partly paid by households in S-H and the ROW, whereby households in S-H pay only a small share.[7] In addition to a fixed compensation, a firm z produces at a fixed activity level $\bar{x}_z$. Thus, the government does not only stipulate $\bar{p}_{rele}$, but also sets a cap $\bar{x}_z$ on renewable electricity production. Given $\bar{p}_{rele}$ and $\bar{x}_z$, the zero profit condition from (3.5) does no longer hold. Suppose that $\bar{x}_z$ is fix but p_{rele} is flexible. If input prices $\hat{\boldsymbol{p}}$ would decrease due to an external shock, p_{rele} would adjust accordingly such that (3.5) holds. If, by contrast, x_z is flexible but $\bar{p}_{rele}$ is fix and input prices $\hat{\boldsymbol{p}}$ would decrease, x_z would adjust accordingly such that (3.5) holds. But with both price and output fixed, unit profits of renewable firms P_z are endogenous and either less or greater than zero, i.e.

$$P_z = r_z(\bar{p}_{rele}) - c_z(\hat{\boldsymbol{p}}) \neq 0 \qquad \forall\, z \in Z. \tag{3.10}$$

6 The restrictions include minimum distances to residential areas and nature reserves, among many others.

7 In practice, a part of the total levies are paid by the rest of Germany which is, however, not differentiated from the ROW in this single-region model for S-H.

Under the *tender scheme*, both the output and input side are competitive. In practice, the German government tenders a total amount of renewable electricity and firms bid on producing a share of this amount at a certain bid price. The firms that offer the lowest prices win the bids. If a firm's bid price is higher than its unit cost, it makes a profit. The scheme is competitive if the total cumulated electricity production that is being offered in the bids exceeds the electricity production that is being tendered by the government. The scheme is supposed to increase competition among renewable electricity producers. Here, we do not model the technology-specific tender markets explicitly, but assume that a tender market is represented by a firm z that bids at an endogenous price $\tilde{p}_{rele}$ to which it covers its unit cost. That is, a firm z is willing to produce a stipulated output level $\bar{x}_z$ if it is able to break even such that the zero profit condition

$$P_z = r_z(\tilde{p}_{rele}) - c_z(\hat{\boldsymbol{p}}) = 0 \qquad \forall\, z \in Z \tag{3.11}$$

holds. The break even is attained by a corresponding unknown levy $s_{rele} = \tilde{p}_{rele} - \bar{e}$ to be paid by households.

3.2.2.3 *Households*

The consumption side of the economy is represented by a wind outsider household o, a wind insider household w, the local government g, and investment demand v. In contrast with the theory of aggregate production, the aggregation of individual consumers to representative households underlies a very restrictive condition on preferences. That is, aggregate demand must be independent of the income distribution among individual consumers i.e. depend solely on prices and aggregate income. This property holds if and only if consumers' indirect utility can be represented by functions of the Gorman form (cf. Mas-Colell et al., 1995, Proposition 4.B.1). One special case of this general form arises when consumers have identical preferences that are homothetic, as assumed in the following.

Again, we begin by assuming non-nested functional forms. Household preferences are completely specified by the expenditure function which we assume to be of the CES form

$$e_h(\hat{p}_i, u_h) = u_h \pi_h = u_h \left(\sum_i \gamma_{i,h} \hat{p}_i^{1-\sigma_h} \right)^{\frac{1}{1-\sigma_h}}, \tag{3.12}$$

with constant elasticity of substitution $\sigma_h \geq 0$ and shift parameter $\gamma_{i,h}$. The CES price index π_h is the cost per unit of utility.

Thus, a sensible measure for a citizen's consumer price index (CPI) in S-H would be her cost per unit of utility, i.e. π_h / N_h, where N_h is the number of citizens represented by household h. Then, the overall local CPI in S-H can be represented by a weighted sum of these individual CPI's. If we choose as weights the relative share of citizens N_h in the total population of S-H denoted by N, i.e. N_h/N, the overall local CPI can simply be defined as $\Pi = \sum_h \pi_h$.

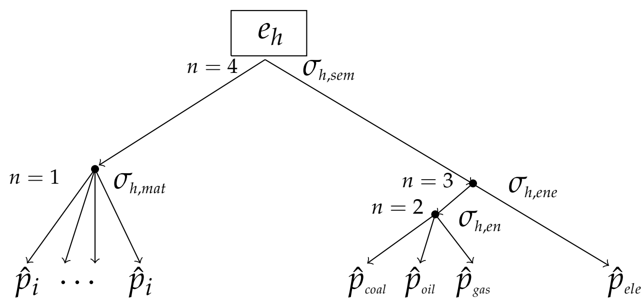
If (3.12) is differentiable in $\hat{\boldsymbol{p}}$, and $\hat{p}_i \geq 0 \;\forall\; i$, HOTELLING's lemma implies that a consumer's HICKSIAN demand for commodity i is given by

$$d_{i,h} = \frac{\partial e(\hat{\boldsymbol{p}}, u_h)}{\partial \hat{p}_i} = u_h \gamma_{i,h} \left(\frac{\hat{p}_i}{\pi_h} \right)^{-\sigma_h}. \tag{3.13}$$

By choosing a benchmark utility level of $u_h^0 = 1$, the calibration of (3.12) is similar to the calibration of the unit cost function (3.8).

The nesting structure of households is shown in Figure 3.6. Households o, w and g substitute between material and service commodities with $\sigma_{h,mat} = 2$ at nest $n = 1$. Regarding energy consumption, fossil fuels cannot be substituted i.e. $\sigma_{h,en} = 0$ at nest $n = 2$. The fossil fuel aggregate is nested into the consumption of electricity with substitutability $\sigma_{h,ene} = 0.1$ at nest $n = 3$. The most upper nest combines the materials and services aggregate and the energy aggregate with $\sigma_{h,sem} = 1$. Finally, a household v represents investment demand by buying commodities i with LEONTIEF preferences at exogenous utility level $\bar{u}_v$.

Figure 3.6: CES nesting structure of a household h



On the income side, we assume balanced budgets for private households o and w such that expenditures equal endowments. The budget constraint of household o is

$$e_o(\hat{\boldsymbol{p}}, u_o) = \boldsymbol{E}_o \tilde{\boldsymbol{p}} + q \bar{S}_{l,o} \bar{p}_q - (1-\omega)\nu L - \bar{F}_o, \tag{3.14}$$

where we denote variables that are not affected by the renewables expansion by a bar. The first income component $\boldsymbol{E}_o\tilde{\boldsymbol{p}}$ is the factor income of employed wind outsiders in S-H. It is the scalar product of factor endowments $E_{l,o}$ and $E_{k,o}$ with respective tax excluding factor prices $\tilde{p}_l = p_l(1-\tilde{\tau}_l)$ and $\tilde{p}_k = p_k(1-\tilde{\tau}_k)$, where $\tilde{\tau}_l$ and $\tilde{\tau}_k$ are average labor and capital income tax rates, respectively. The second income component $q\bar{S}_{l,o}\bar{p}_q$ is the income of unemployed wind outsiders in S-H, where q is the unemployment rate, $\bar{S}_{l,o} = E_{l,o}/(1-q)$ is the labor supply of wind outsiders in the case of full employment, and $\bar{p}_q$ is a fixed unemployment compensation rate.[8] The term $(1-\omega)\nu L$ are total levies to be paid by wind outsiders in S-H, where L is the endogenous total value of EEG levies for the additional renewable electricity production in S-H due to the expansion plans. Under the *feed-in scheme*, it is the difference between feed-in revenues and revenues at the price in the ROW,

$$L = \sum_{rele}\sum_{z} \bar{\epsilon}\bar{s}_{rele} b_{rele,z}\bar{x}_z, \tag{3.15}$$

whereas under the *tender scheme* between total electricity production costs and revenues at the price in the ROW,

$$L = \sum_{rele}\sum_{z} \bar{\epsilon} s_{rele} b_{rele,z}\bar{x}_z. \tag{3.16}$$

We denote the share of EEG levies to be paid by private households in S-H by ν which we assume to be equal to the share of gross electricity consumption in S-H according to AEE (2017), i.e. $\nu = 3.5\%$. Finally, the net flow of funds $\bar{F}_o$ summarizes all residual external flows with the ROW which we assume to remain constant. These may include portfolio investments and social transfers, among others. If $\bar{F}_o > 0$, wind outsiders make a net payment to the ROW, whereas if $\bar{F}_o < 0$, wind outsiders receive a net payment from the ROW.

The budget constraint of wind insider w is similar to (3.14) but with two additional sources of income, namely profits from renewables and rents from landownership. It is given by

$$e_w\left(\hat{\boldsymbol{p}}, u_w\right) = \boldsymbol{E}_w\tilde{\boldsymbol{p}} + q\bar{S}_{l,w}\bar{p}_q + (1-\kappa)(\tilde{P}_z + \ell) - \omega\nu L - \bar{F}_w, \tag{3.17}$$

8 We assume that the unemployment benefits are paid entirely by the ROW. The expansion of renewables leads to a decrease of the unemployment benefits. Thus, we do not take into account the hypothetical savings in expenditures for unemployment benefits in S-H. However, the savings are small and would only occur in the long-run via a premium adjustment for citizens in S-H.

where $\tilde{P}_z$ denotes unit profits of renewables after the deduction of municipal business taxes. The specific treatment of taxes will be described in the following section. We denote the flat tax on capital income by κ such that $(1-\kappa)\tilde{P}_z$ are net returns on investments in citizen-owned wind farms and $(1-\kappa)\ell$ are net rents of landowners. The budget constraint under the *tender scheme* is equivalent to (3.17) with $\tilde{P}_z = 0$.

3.2.2.4 *Government*

The local government of S-H is assumed to act like a household, consuming commodities i in order to maximize utility under its budget constraint. It earns revenue by collecting taxes from firms and households. The budget constraint of local government g is given by

$$e_g\left(\hat{\boldsymbol{p}}, u_g\right) = (1-\theta)R_g - \bar{F}_g. \tag{3.18}$$

The local tax revenue $(1-\theta)R_g$ takes into account the German tax revenue sharing scheme. This scheme stipulates the distribution of tax revenues as follows. First, the tax revenue is lumped together in a national tax account and then split between the federal government and the sum of state governments according to fixed shares (vertical distribution). These shares vary across tax types. Secondly, the sum of the state governments' tax revenues is distributed among the individual states according to the location where the tax was collected (horizontal distribution). Finally, a balancing mechanism redistributes tax revenues between financially stronger and weaker states (the so-called 'Länderfinanzausgleich'). According to Hentze (2015), this balancing mechanism leads to a marginal burden rate of $\theta = 85.5\%$ for S-H in 2014. It indicates how much of one additional Euro tax income is redistributed from S-H to the rest of Germany. Thus, R_g in (3.18) comprises tax revenue that accrues to the state of S-H including municipalities after the vertical but before the horizontal tax distribution. It is given by

$$R_g = \phi\Big[\sum_h (E_{l,h}\tilde{\tau}_{l,h}p_l + E_{k,h}\tilde{\tau}_{k,h}p_k)\Big] + \Big[\mu P_z \psi\Big] + \phi\Big[\kappa(\tilde{P}_z + \ell)\Big]. \tag{3.19}$$

The first bracket contains revenues from factor income taxes. The second bracket contains revenues from business taxes which accrue to the municipalities in which the citizen-owned wind farms are located. Business taxes are calculated based on earnings which we approximate by the renewable profits P_z. Then, by applying the base rate of $\mu = 3.5\%$ and an average, municipality-specific assessment rate of $\psi = 358\%$, we obtain total business taxes of renewables in S-H. The last bracket contains revenues from income taxes on profits and land rents, where $\kappa = 25\%$ is the flat tax on capital income. Finally, $\phi = 57.5\%$ is the fixed share of income tax revenue that accrues to the state of S-H according the vertical tax revenue distribution scheme (BMF, 2019).

As for the private households, $\bar{F}_g$ in (3.18) summarizes all residual external flows with the ROW which are not affected by the renewables expansion. These may include tax revenues which accrue to the federal government of Germany and new borrowing of the local government of S-H, among others. The budget constraint (3.18) is attained by the unknown utility level u_g. This means that a marginal change in tax revenues R_g due to the renewables expansion leads to an equal marginal change in local government consumption expenditures.

3.2.3 *Data*

In order to apply the model, we need various local benchmark data on firms' output, intermediate inputs, factor inputs, external trade, final use, factor income and taxes. Most of this data are obtained from the latest national supply and use (S-U) tables for Germany in 2014 provided by Destatis (2018), which we regionalize by applying the non-survey I-O method presented in chapter 2. The general structure of the S-U tables is shown in Table 3.1.

The S-U tables show values in million € which we denote by V. The supply table shows values of supply of commodity i by firm f at mill prices, $\tilde{V}^0_{i,f}$, as well as total imports of commodity i, $V^0_{i,im}$. The tilde denotes values at mill prices. It further includes values of trade margins $V^0_{i,tm}$ and commodity taxes $V^0_{i,t}$. Total supply of commodity i is defined as the sum over all columns denoted by V^0_i.

The use table shows values of intermediate use of commodity i by firm f, $\hat{V}^0_{i,f}$, as well as final use both at customer prices denoted by the hat. Final use comprises consumption of commodity i by private households, $\hat{V}^0_{i,ph}$, the government, $\hat{V}^0_{i,g}$, gross investments, $\hat{V}^0_{i,v}$, and total exports of commodity i, $V^0_{i,ex}$. The total input expenditure of a firm is defined as $\hat{V}^0_f := \sum_i \hat{V}^0_{i,f}$. Total use of commodity i equals total supply V^0_i.

Table 3.1: General structure of the S-U tables for Germany in 2014

S	$\cdots f \cdots$	im	tm	t	$\sum$
$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
i	$\tilde{V}^0_{i,f}$	$V^0_{i,im}$	$V^0_{i,tm}$	$V^0_{i,t}$	V^0_i
$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$\sum$	$\cdots \tilde{V}^0_f \cdots$	V^0_{im}	V^0_{tm}	V^0_t	

U	$\cdots f \cdots$	ph	g	v	ex	$\sum$
$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
i	$\hat{V}^0_{i,f}$	$\hat{V}^0_{i,ph}$	$\hat{V}^0_{i,g}$	$\hat{V}^0_{i,v}$	$V^0_{i,ex}$	V^0_i
$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
l	$\cdots \hat{V}^0_{l,f} \cdots$					$\hat{V}^0_l$
k	$\cdots \hat{V}^0_{k,f} \cdots$					$\hat{V}^0_k$
$\sum$	$\cdots \hat{V}^0_f \cdots$	$\hat{V}^0_{ph}$	$\hat{V}^0_g$	$\hat{V}^0_v$	V^0_{ex}	

Compared to a symmetric industry-by-industry I-O table, which is usually used as data input for CGE models, the non-symmetric commodity-by-industry S-U tables allow for introducing multi-output firms into the model. For instance, car producers do not only sell cars but also other vehicles and possibly financial services. This fact is not included in I-O tables since they are constructed from S-U tables by, among other assumptions, assuming 'homogeneous branches' that only produce one type of commodity i.e. single-output firms (Eurostat, 2008). In order to feed the S-U tables into the model, some data manipulation and extensions are necessary which will be described briefly in the following.

First, we need to regionalize the national S-U tables for S-H because regional survey tables for Germany are not available. Therefore, we apply GRETA from chapter 2, where GRETA1 is applied to service sectors and GRETA2 to manufacturing sectors. Total local supply of each commodity i is obtained by distributing domestic supply – given by $V^0_i - V^0_{i,im}$ from the national supply table – with regional employment shares of S-H according to Statistik der Bundesagentur für Arbeit (2017b). Total local final use over all commodities i for household and government consumption and for gross investments, $\hat{V}^0_{ph}$, $\hat{V}^0_g$ and $\hat{V}^0_v$, is obtained from the national accounts of the states according to Statistische Ämter des Bundes und der Länder (2017). Final local use for each commodity i, $\hat{V}^0_{i,ph}$, $\hat{V}^0_{i,g}$ and $\hat{V}^0_{i,v}$, is obtained by applying the relative consumption shares of the national use table, e.g. $\hat{V}^0_{i,ph}/\hat{V}^0_{ph}$. Thus, we assume that consumers in S-H spend the same relative amount on commodity i than the average consumer in Germany. Intermediate use of commodity i by firm f, $\hat{V}^0_{i,f}$, is obtained by assuming the same technical input coefficients in the nation and region as in Section 2.2.1 of the previous chapter. The sum of intermediate and final use subtracted by exports leads to total local use for each commodity i, i.e. $V_i^0 - V_{i,ex}^0$. Given total local supply and use for each commodity i, we estimate internal trade and thereby exports and imports in order to complete the regional S-U tables for S-H.

Secondly, we need to align the prices of the S-U tables because we want to solve the model for market prices p_m. However, the original S-U tables are valued at mill and customer prices, respectively. The difference between selling a commodity i at mill price

$$\tilde{p}_i^0 = p_i^0/(1+\mu_i) \tag{3.20}$$

in the supply table and buying a commodity i at customer price

$$\hat{p}_{i,y}^0 = p_i^0(1+\hat{\tau}_{i,y}) \tag{3.21}$$

in the use table are trade margin rates μ_i and tax rates $\hat{\tau}_{i,y}$, respectively. Trade margin rates are only introduced at this point in order to align prices but will not be modeled explicitly. We distribute the trade margins for commodity i uniformly across firms. Therefore, in the supply table, the market value of commodity i supplied by firm f is obtained as

$$V_{i,f}^0 = \tilde{V}_{i,f}^0(1+\mu_i),$$

where $\mu_i = V_{i,tm}^0/V_{tm}^0$. In the use table, we distribute the commodity tax data from the supply table, $V_{i,t}^0$, across households and firms as follows. We assume that all households, including the government and investment, pay value added tax $\hat{\tau}_{i,h}$ of either 7 or 19%. This leaves a residual (either positive or negative) of the original tax data $V_{i,t}^0$ which we distribute uniformly across firms F as intermediate input taxes (or subsidies) $\hat{\tau}_{i,f}$. Therefore, in the use table, the market value of commodity i used by activity y is obtained as

$$V_{i,y}^0 = \tilde{V}_{i,y}^0/(1+\hat{\tau}_{i,y}).$$

As a result, both tables are valued at benchmark market prices p_i^0.

The benchmark market prices cannot be observed from the data because the S-U tables are in value data (here mn €) and one cannot collect price data for all industries of the S-U tables. Therefore, we need to separate the price and quantity data in order to calibrate cost functions (3.1), revenue functions (3.3), and expenditure functions (3.12). A common way is to fix benchmark market prices as well as activity and utility levels to unity, i.e. $p_m^0 = 1 \; \forall \; m \in M$, $x_j^0 = 1 \; \forall \; j \in J$, and $u_h^0 = 1 \; \forall \; h \in H$. Further, we also fix the price in the ROW to one, i.e. $\bar{\epsilon}^0 = \bar{\epsilon} = 1$. Setting all the benchmark prices to unity is known as normalizing prices and implies that the initial value data from Table 3.1 becomes the quantity per unit of currency in the benchmark.

Regarding firms, setting the benchmark activity level x_f to one implies that the benchmark unit cost of firm f is equal to the total input expenditures of firm f from the use table, i.e. $c_f^0 = \hat{V}_f^0$. Further, given that benchmark prices are equal to one, the benchmark input coefficient (3.7) are the input quantity of commodity i per unit of activity level of firm f, i.e. $a_{i,f}^0 = V_{i,f}^0$. Similarly, benchmark unit revenue is equal to the output market value, i.e. $r_f^0 = V_f^0$. Thus, the benchmark output coefficient is the output quantity of a good d or ex per unit of activity level.

Regarding Armington firms A, the benchmark activity level $x_a = 1$ imply that benchmark unit cost and revenue are equal to total local use of commodity i, i.e. $c_a^0 = r_a^0 = V_i^0 - V_{i,ex}^0$.

Regarding renewable firms Z, the benchmark data for calibrating cost and revenue functions are summarized in Table 3.3 of the appendix. The benchmark unit cost are given by $c_z^0 = \hat{V}_z^0$, where the total value of input costs of firm z, $\hat{V}_z^0$, is obtained as the product of the electricity production in KWh in 2030 and the levelized cost of electricity (lcoe) in € per KWh. The regional input costs differentiated by cost components, $\hat{V}_{i,z}^0$, are obtained from interviews in Bröcker et al. (2014, 2016). The benchmark revenue under the *feed-in scheme* is given by $r_z^0 = \bar{V}_{rele}^0$, where the total value of EEG compensations per technology, $\bar{V}_{rele}^0$, is obtained as the product of the electricity production in KWh in 2030 and the average technology-specific EEG compensation in € per KWh in 2014. Given that we fix the electricity spot market price i.e. price in the ROW to one, a renewable firm exports a quantity of $b_{rele,z}^0 = V_{rele}^0$ to the ROW, where the total market value of electricity per technology, V_{rele}^0, is obtained as the product of the electricity production in KWh in 2030 and the average electricity spot market price at the European Power Exchange (EPEX) in 2014. Choosing the benchmark quantity in this way implies that the benchmark feed-in compensation is given by $\bar{p}_{rele}^0 = \bar{V}_{rele}^0 / V_{rele}^0$. Under the *tender scheme*, the benchmark revenue of firm z is given by $r_z^0 = V_{rele}^0$.

Regarding households, setting the benchmark utility level to one implies that the benchmark cost per unit of utility equals the total benchmark expenditures from the use table, i.e. $e(\hat{\boldsymbol{p}}^0, 1) = \pi_h^0 = \hat{V}_{ph}^0$. This also means that the overall local benchmark CPI in S-H is given by total household expenditures, i.e. $\Pi^0 =$

$\sum_h \pi_h^0$. On the income side, total benchmark factor income of employed private households in (3.14) and (3.17), $\boldsymbol{E_o^0}$ and $\boldsymbol{E_w^0}$, are obtained as the total factor inputs of firms f distributed by the wind insider share ω, i.e. $\boldsymbol{E_o^0} = (1-\omega)(V_l^0 + V_k^0)$ and $\boldsymbol{E_w^0} = \omega(V_l^0 + V_k^0)$. The benchmark income of unemployed households, $q^0 \bar{S}_l^0 \bar{p}_q$, is obtained with the benchmark unemployment rate $q^0 = 0.068$ and the benchmark unemployment compensation rate which is given by $\bar{p}_q^0 = (\bar{S}_l^0 - E_l)\tilde{p}_l^0(1-q^0)/E_l q^0$. As a last step, the benchmark net flows of funds $\bar{F}_o^0$ and $\bar{F}_w^0$ are obtained as residuals. Finally, the benchmark tax income of the local government, R_g^0, is obtained with benchmark factor income $E_l^0 = \sum_f V_{l,f}^0$ and $E_k^0 = \sum_f V_{k,f}^0$ and marginal income tax rates $\bar{\tau}_l = \bar{\tau}_k = 0.3$. The government's net flow of funds $\bar{F}_g^0$ is obtained as a residual. The resulting flow of -16.4bn€ indicates the local government's budget deficit.

3.3 GENERAL EQUILIBRIUM

The zero profit conditions for firms, market clearing conditions for goods and factors, and budget constraints for households yield a system of simultaneous equations which can be solved for the general equilibrium of the economy with the benchmark data above. In modern CGE models, this system is usually formulated as a (nonlinear) mixed complementarity problem (MCP) consisting of weak inequalities with complementary variables as well as additional equations. The MCP for the model of S-H can be summarized as follows:

$$r_j(\tilde{\boldsymbol{p}}) - c_j(\hat{\boldsymbol{p}}) \leq 0 \quad \perp \quad x_j \geq 0 \quad \forall\, j \in J \setminus Z, \tag{3.22}$$

$$\sum_j x_j \left(b_{m,j} - a_{m,j}\right) \geq \sum_h \left(d_{m,h} - E_{m,h}\right) \quad \perp \quad p_m \geq 0 \qquad \forall\; m \;\in M \setminus FM. \tag{3.23}$$

The zero profit conditions (3.22) are complementary to non-negative activity levels x_j.[9] If a particular zero profit condition holds as an equality, the associated activity level is allowed to be strictly positive. If it holds as a strict inequality, the associated activity level is zero. Market clearing conditions (3.23) are complementary to non-negative prices p_m. If supply of a certain good or factor equals its demand, the associated price is allowed to be strictly positive. If there exists excess supply, the associated price is zero. Thus, in principle it is

9 The $\perp$ symbol is used as a mathematical shorthand for expressing complementarity, meaning that not both inequalities can be strict.

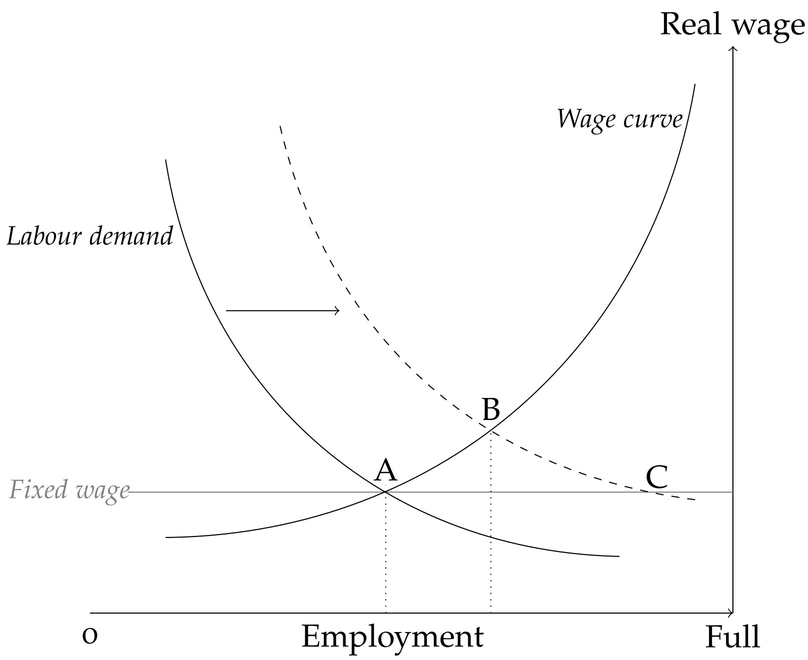
possible that a firm runs out of business because it does not break-even and that a good is for free because there is excess supply of it. However, it does not happen in our model analysis. Finally, households are supposed to have a balanced budget with associated unknown utility level u_h according to (3.14), (3.17), and (3.18).

The system of simultaneous equations described above represents a static framework which does not allow for true neoclassical modeling of e.g. saving and investment which would be dynamic by nature. Therefore, we have to choose how we close our model with regard to decision variables that are not strictly determined by the static framework above. These so-called closure rules are presented in Section 3.3.2. Moreover, we relax one of the market clearing assumptions in (3.23) in order to allow for a more realistic market imperfection in the form of unemployment in the labor market.

3.3.1 *Labor market*

In the basic model presented so far, we assumed a perfectly competitive labor market which is cleared by a fully flexible wage. Of course, this is a very unrealistic representation of the regional labor market. In 2014, S-H had an unemployment rate of 6.8%. Therefore, we account for unemployment by introducing the so-called wage curve of Blanchflower and Oswald (1995b) into the model. For advantages of implementing the wage curve approach into a CGE model compared to other models of wage rigidity such as efficient bargaining (McDonald and Solow, 1981) or search and matching (Pissarides, 1984), we refer to Korzhenevych (2010). The wage curve describes a negative relationship between the real wage and the unemployment rate. As shown in Figure 3.7, the expansion of renewables leads to an increase in labor demand. The new labor market equilibrium moves from point A to B, resulting in higher employment but also a higher wage. In contrast to assuming a fixed wage as in Bröcker et al. (2014, 2016), here only part of the adjustment is done by employment. The rest of the adjustment is accomplished by an increase in the wage level. Thus, we assume that both employment and the wage respond to the external shock such that the renewables expansion will potentially lead to much lower employment effects compared to the equilibrium point C in the case of a fixed wage.

Figure 3.7: Labour market response of the renewables expansion



The wage curve is given by

$$\frac{p_l}{\Pi} = \vartheta q^{\zeta}, \tag{3.24}$$

where the wage p_l is corrected by the local CPI to obtain the real wage, ϑ is a position parameter, q is the unemployment rate, and ζ is the unemployment elasticity of wages. The latter shows by which percentage the real wage changes due to a 1% increase in the unemployment rate. The labor market clearing condition is now given by

$$\bar{S}_l (1 - q) = \sum_j x_j a_{l,j}. \tag{3.25}$$

The labor supply in the case of full employment is denoted by $\bar{S}_l$. It is obtained from the benchmark data as $\bar{S}_l = \sum_h E^0_{l,h}/(1 - q^0)$. The wage curve (3.24) is calibrated with benchmark unemployment rate $q^0 = 0.068$ from Statistik der Bundesagentur für Arbeit (2017a), price level $\Pi^0 = \sum_h \pi^0_h = \sum_h \hat{V}_h$ from the benchmark use table, benchmark wage $p^0_l = 1$, and $\zeta = -0.1$ from Blanchflower and Oswald (1995a).

3.3.2 *Model closures*

The general equilibrium model developed in the course of this paper only provides a snapshot view of the economy of S-H. It is based on standard neoclassical microeconomics where e.g. households maximize their utility at a given point in time, here the year 2014. The effects of an external shock to the economy is then evaluated by comparative statics. Therefore, we have to make assumptions on parts of the economy which would usually be modeled in a dynamic framework. These include saving and investment decisions of households and fiscal policies of the local government which both would include forward looking behaviour regarding e.g. risks and price expectations. Since we do not model any intertemporal efficiency and equilibrium, we thus define ad hoc adjustment rules for these otherwise dynamic economic behaviors as follows.

The state of S-H is assumed to be a small open economy, which takes the price for any good in the ROW as given. Therefore, we introduced only one ROW price denoted by $\bar{e}$. The local prices relative to this ROW price are then determined endogenously by the system of simultaneous equations introduced above. Thus, we assume that there does not exist any exchange rate mechanism to influence the local price level. In fact, if all zero profit, market clearing and budget constraints are fulfilled, the external balance of payments of the small open economy of S-H is also fulfilled as per Walras' law. The balance of payments would include all net flows of funds appearing in the model, which we denoted by F_h for all $h \in H$. For instance, the renewables expansion in S-H leads to an improvement of the state's current account since the additional electricity is exported to the ROW. Thus, in order to attain a simultaneous equilibrium on all markets, the local price level increases such that exports become relatively more expensive and imports relatively cheaper vis-à-vis local goods, which ensures the equilibrium of S-H's balance of payments in our modeling framework.

Regarding saving and investment, we assume that investors would like to achieve certain investment goals in real terms. These investment goals are represented by the utility level of the investment household v which we fix at $\bar{u}_v$. In case of an external shock to the economy, the exogenous investment level $\bar{u}_v$ is maintained by an endogenous net flow of funds F_v from the ROW.

Regarding the state's fiscal policy, we assume that the local government debt and tax transfers remain constant. Recall that according to (3.18), the local government consumption expenditures only depend on tax revenues that accrue to the state and municipalities after the vertical and horizontal tax revenue distribution. The remainder are the government debt and tax revenue transfers i.e. exogenous net flow of funds $\bar{F}_g$. The government's budget balance is attained by its unknown utility level u_g. This means that any additional local tax revenue due to the renewables expansion is used for government consumption and not for e.g. the reduction of debt.

Further, we assume that saving and investment of private households remains constant. Thus, similar to the local government, we assume the net flow of funds $\bar{F}_o$ and $\bar{F}_w$ to be exogenous such that any additional income due to the renewables expansion is spent for private consumption and not for savings or other external flows with the ROW.

Finally, by letting the price for capital p_k be endogenous according to (3.23), we assume that capital is mobile across firms F, but immobile across regions i.e. between S-H and the ROW. The underlying S-U tables of our static model only show value flows and we have no information on the capital stock of S-H. Therefore, we implicitly assume that the capital stock in S-H is fix and 'jumps' from one firm (or sector) to the other but not to or from the ROW.

It is important to note that the choice of closure rules is crucial for the model results and especially welfare analysis. Suppose that we let the net flow of funds of private households be endogenous. Then, part of the additional income due to the expansion of renewables will be transferred to the ROW instead of consumed locally such that households' utility levels decrease. Thus, an increase of lending to the ROW without taking into account future periods would lead to a decrease in welfare in our static framework.

3.3.3 *Solution and counterfactual equilibria*

Given the equilibrium conditions (3.14), (3.17), (3.18), (3.22)-(3.23), and the labor market clearing condition (3.25), we compute the reference equilibrium in order to verify that all model equations hold and benchmark values are being reproduced, if benchmark market prices $p_m^0 = 1 \; \forall \; m \in M$, activity levels $x_j^0 = 1 \; \forall \; j \in J$, utility levels $u_h = 1 \; \forall \; h \in H$, and unemployment rate $q^0 = 0.069$ are inserted. The system has 300 equations with corresponding unknowns.

In order to analyze the income and employment effects of the renewables expansion in S-H, we need to define a policy scenario for comparing the reference equilibrium with counterfactual equilibria. The static nature of the model only allows for one-period shocks i.e. comparative statics. Therefore, in the reference no additional renewable electricity is produced, whereas in the counterfactual equilibrium the government's expansion plans for the year 2030 have been implemented.

The expansion plans are shown in the first columns of Table 3.3. In total, renewable electricity production is supposed to be more than doubled until 2030. The major share with 88% of total renewable electricity production in 2030 will be produced by wind energy. Note that there is no need to account for the already existing renewable electricity production since we are only interested in the equilibrium effects of the expansion plans. The shock variables are the exogenous activity levels $\bar{x}_z \; \forall \; z \in Z$. In the reference equilibrium, the activity levels are $\bar{x}_z = 0 \; \forall \; z \in Z$ such that there is no expansion. In the counterfactual equilibria, the stipulated amount of renewable electricity in value terms for the year 2030 from Table 3.3 is produced at activity levels $\bar{x}_z = 1 \; \forall \; z \in Z$. Under the *feed-in scheme* the values are given by the EEG compensations $\bar{V}^0_{rele}$. Under the *tender scheme* the values are given by the market values V^0_{rele} (cf. last columns of Table 3.3).

Bröcker et al. (2014, 2016) differentiate between income and employment effects during the construction and operation phase. Here, we merge the effects. For instance, besides buying intermediate service and factor inputs for operating the wind farms, renewable firm $z = 140$ buys 152 onshore wind turbines as an additional intermediate input representing the yearly construction phase. One can also think of it as the yearly depreciation of wind turbines. Cost and revenue functions are calibrated with regional information on commodity-wise input costs $V^0_{i,z}$ and total input costs V^0_z from interviews in Bröcker et al. (2014, 2016) as well as with the feed-in compensation and market price data from Table 3.3. Demand for intermediate and factor inputs due to the construction and operation of new plants amount to 1.9bn €. Revenues under the *feed-in* and *tender scheme* are 2.6bn € and 0.7bn €, respectively.

3.4 SIMULATION RESULTS

The main income results are summarized in Figure 3.8. Under the *feed-in scheme* the renewables expansion leads to a 0.94% (or 715mn € p.a.) higher regional GDP from 2030 to as long as the plants operate. Thereof, the labor income effect of factor l is 86mn € p.a., the capital income effect of factor k is -19mn € p.a., the profit income effect of renewable firms Z is 544mn € p.a., the land rent income effect is 72mn € p.a., and the tax income effect $(1 - \theta)R_g$ is 32mn € p.a. Note that the latter takes into account the German tax revenue sharing scheme. The decrease in capital income indicates that the expansion shifts production from capital to more labor intensive firms. Since the lifetime of new plants is hard to estimate and old plants are repowered constantly, we assume that the expansion results are long-term income effects. Regarding the wage and employment effects, the expansion leads to an increase of the wage by 0.2% and creates 1,424 jobs. Further, total levies L to be paid by all households in Germany due to the expansion in S-H are 1.93bn € p.a., of which only 67mn € p.a. are paid by households in S-H. This corresponds to a levy for the additionally produced renewable electricity of 7.6 Cent/KWh for households in Germany and 0.3 Cent/KWh for households in S-H, respectively. Note that this levy is only due to the expansion in S-H and does not indicate the overall levy to be paid for all the renewable electricity in Germany.

The *tender scheme* leads to significantly smaller income effects because competition between renewable firms drives profits to zero. In total, GDP is only 0.15% (or 139mn € p.a.) higher from 2030 onwards. Thereof, the labor income effect of factor l is 85mn € p.a., the capital income effect of factor k is -24mn € p.a., the land rent income effect remains at 72mn € p.a., and the tax income effect is only 6mn € p.a. The decrease of the latter compared to the *feed-in scheme* is mainly due to the loss of business tax income from profits. The wage and employment effects are with an increase of the wage by 0.2% and 1,471 new jobs very similar to the *feed-in scheme*. Recall that under the *tender scheme* levies are endogenous such that renewable firms break even. Therefore, levies are lower compared to the *feed-in scheme* in which guaranteed compensations are well above the lcoe. They amount to 1.2bn € p.a. to be paid by all households in Germany, of which only 42mn € p.a. are paid by households in S-H. This equals a levy for the additionally produced renewable electricity of 4.7 Cent/KWh for households in Germany and 0.2 Cent/KWh for households in S-H, respectively. Thus, levies decrease by roughly one third due to the change in the compensating scheme.

Detailed sectoral results of both counterfactual equilibria are presented in Figure 3.12 and following. Firm activities of 'repair and installation of machinery', 'manufacturers of electrical equipment' and 'research and development' increase the most whereas of 'manufacturers of other vehicles', 'shipping' and 'computer manufacturers' decrease the most. Local prices p_d for all $d \in D$ and p_i for all $i \in I$ only change marginally because S-H is small and fully integrated into the world market. Thus, relatively little is traded internally and export and import shares are high. All in all, the general equilibrium effects are small and the main income effects result from feed-in compensations and land ownership.

Finally, regarding the welfare effects of expanding renewables we calculate the equivalent variations (EV) of households o, w and g as

$$EV_h = e(\hat{\boldsymbol{p}}^{\mathbf{0}}, u_h) - e(\hat{\boldsymbol{p}}^{\mathbf{0}}, u_h^0) \quad \forall\, h \in H \setminus \{v\}. \tag{3.26}$$

The EVs indicate the monetary changes of benchmark income that households would need in the reference equilibrium in order to obtain the post-shock utility under benchmark prices $\hat{\boldsymbol{p}}^{\mathbf{0}}$.

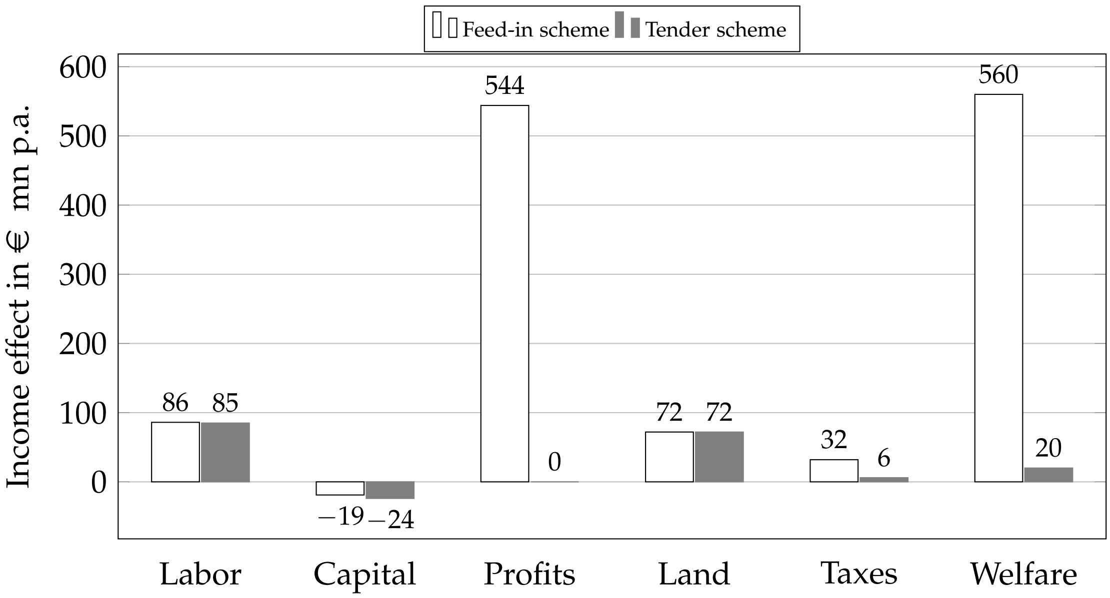
Under the *feed-in scheme*, the EVs are -47mn € p.a. for the wind outsiders, 615mn € p.a. for the wind insiders and 13mn € p.a. for the local government. This means that the wind outsiders are willing to pay 47mn € p.a. in order to avert the renewables expansion. In contrast, the wind insider and the local government are willing to accept 615mn € p.a. and 13mn € p.a. if the renewables expansion is not undertaken, respectively. Regarding the overall welfare effects in S-H, we need to consider that the expansion leads to a change in the net flow of investment funds F_v for household v due to the change in local prices p_i. Therefore, we obtain the overall welfare as

$$EV = \sum_h EV_h - \Delta F_v, \tag{3.27}$$

where $\Delta F_v = F_v - F_v^0$. The expansion of renewables leads to an inflow of investment funds of ΔF_v =20mn € p.a. The overall welfare increases by 560mn € p.a.

Under the *tender scheme*, the EVs are -21mn € p.a. for the wind outsiders, 71mn € p.a. for the wind insiders and -11mn € p.a. for the local government. The overall welfare increases by 20mn € p.a.

Figure 3.8: Income effects of renewables expansion in S-H



3.4.1 *Sensitivity analysis*

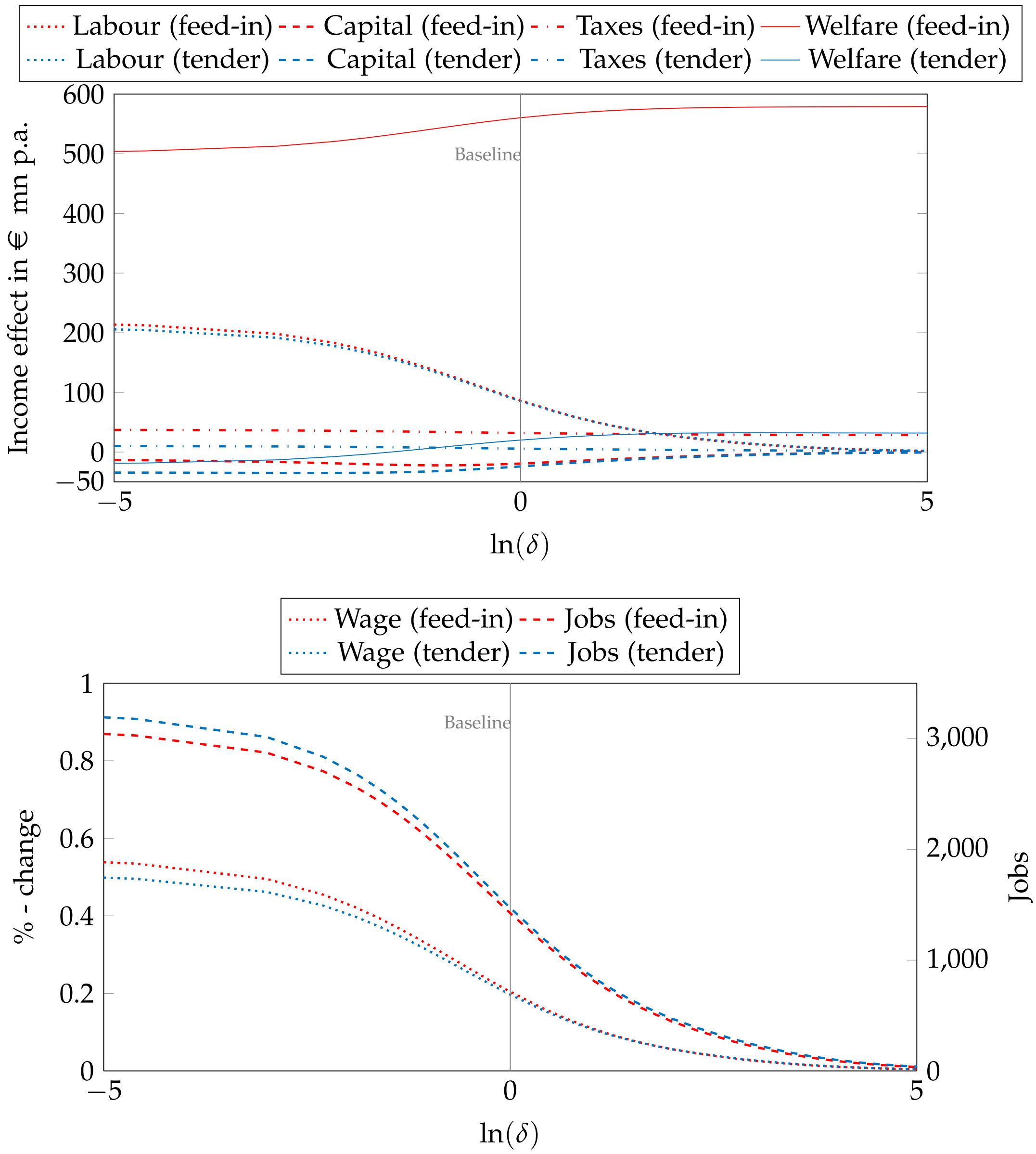
In order to assess the robustness of the results, we check the sensitivity with respect to different elasticities of substitution as well as the closure rule for the capital mobility in S-H. In the following, we refrain from presenting sensitivity results for the profit and land rent income effects because they remain stable under all scenarios.

Since the economy of S-H is small compared to the ROW and trade data for S-H is estimated by GRETA, the possibility of local firms to substitute between local and foreign inputs can be one of the key mechanism that drives the model results. Therefore, we check the sensitivity of results with respect to the Armington trade elasticities σ_a from Table 3.2.

Figure 3.9 shows the income and employment results for varying σ_a by a factor δ for all $a \in A$. For purposes of illustration, the x-axis shows the natural logarithm of this factor where the left end indicates a factor δ very close to zero i.e. assuming Leontief technology for all Armington firms and the right end a very high factor i.e. nearly perfect substitutability. The results show that the tax and capital income effects remain relatively stable under both compensating schemes. Irrespective of the magnitude, this is an important insight for regional policy makers who often promote the renewables expansion with tax benefits for the municipalities in S-H. In contrast, the labor income effect is more sensitive to trade elasticities and shows a negative relationship.

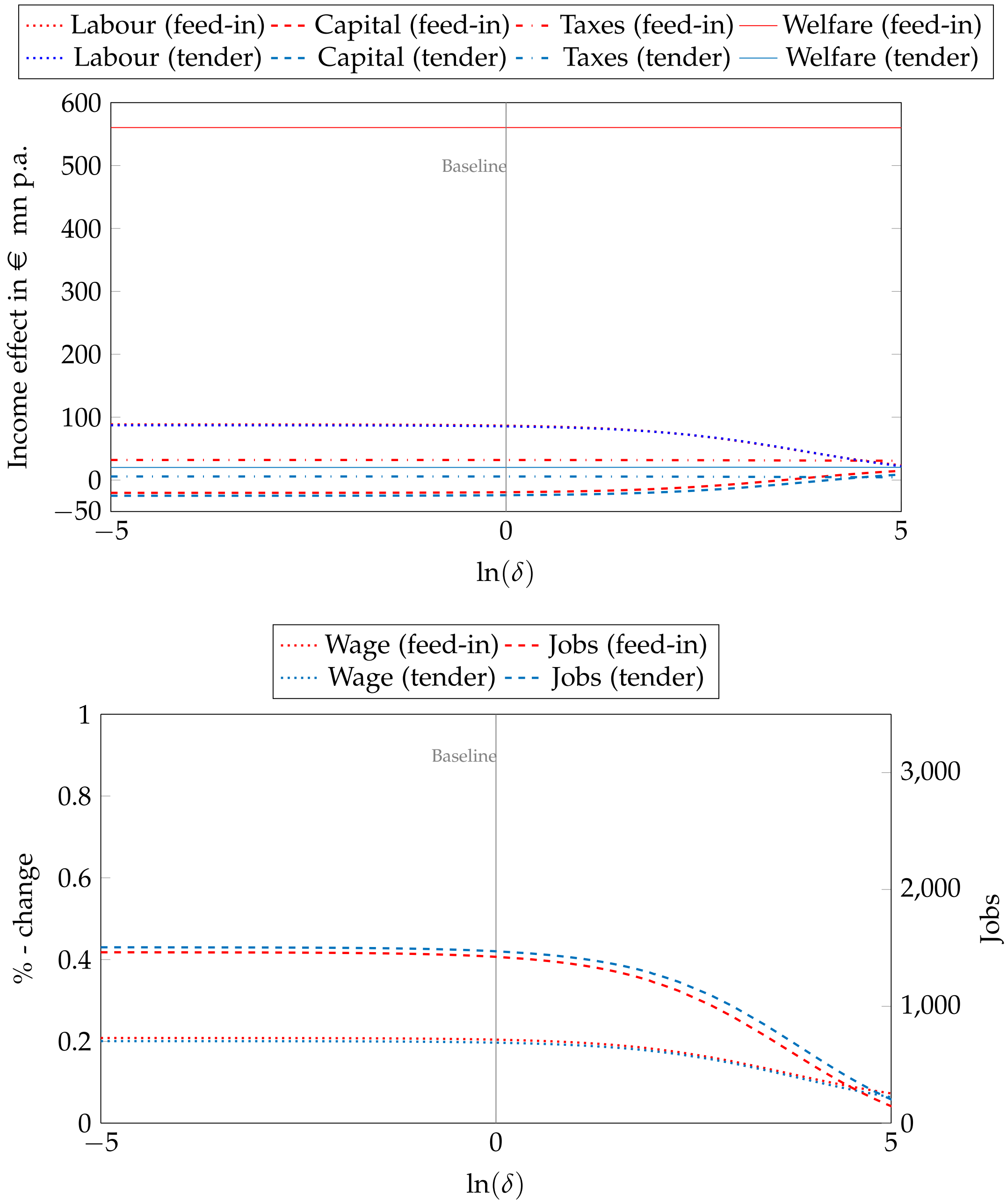
Thus, the higher the trade elasticities are the lower is the labor income effect and vice versa. In the extreme case of almost no substitution possibilities of firms A between local and imported goods, the labor income effect is 216mn € p.a. (208mn € p.a.) under the *feed-in (tender) scheme* compared to 86mn € p.a. (85 € p.a.) in the baseline, respectively. The wage and employment results depicted in the lower part of Figure 3.9 show the highest sensitivity with respect to trade elasticities. They range from 3,070 (3,222) jobs for Armington elasticities close to zero to only 570 (596) jobs for very high Armington elasticities under the *feed-in (tender) scheme*.

Figure 3.9: Sensitivity of results with respect to different Armington elasticities, where $\ln(\delta) = \ln(\sigma_a) / \ln(\sigma_a^0)\ \forall\ a \in A$



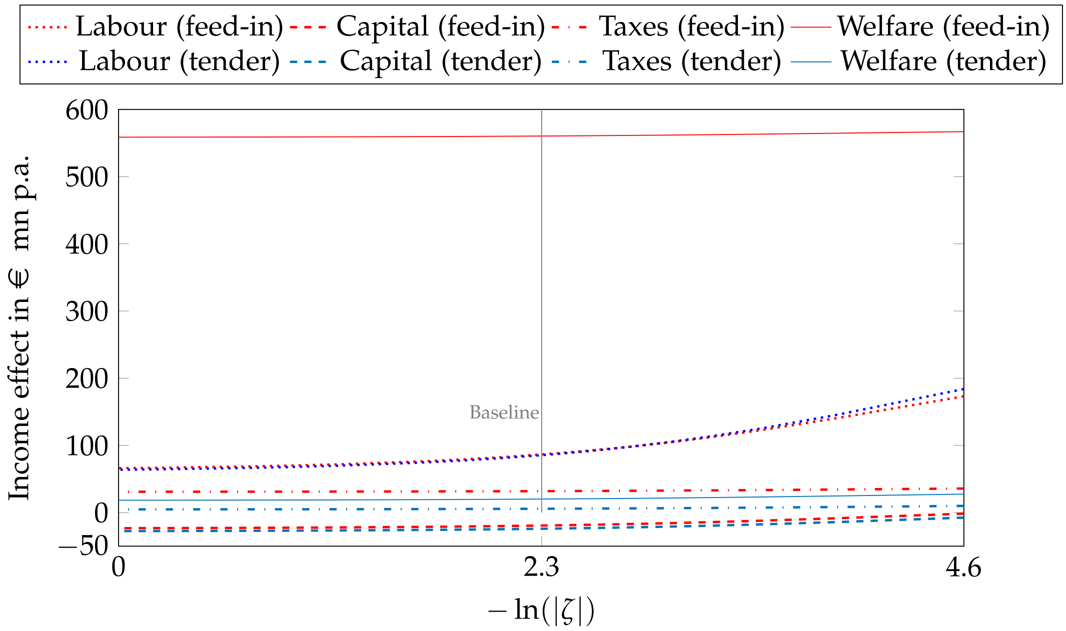
Besides Armington elasticities, we further check the sensitivity of income results to changes in the input substitution elasticities $\sigma_{f,klem}$ of firms F in the top level nest of Figure 3.3. The results depicted in Figure 3.10 show that income and employment effects are not very sensitive to changes in the input elasticities of firms.

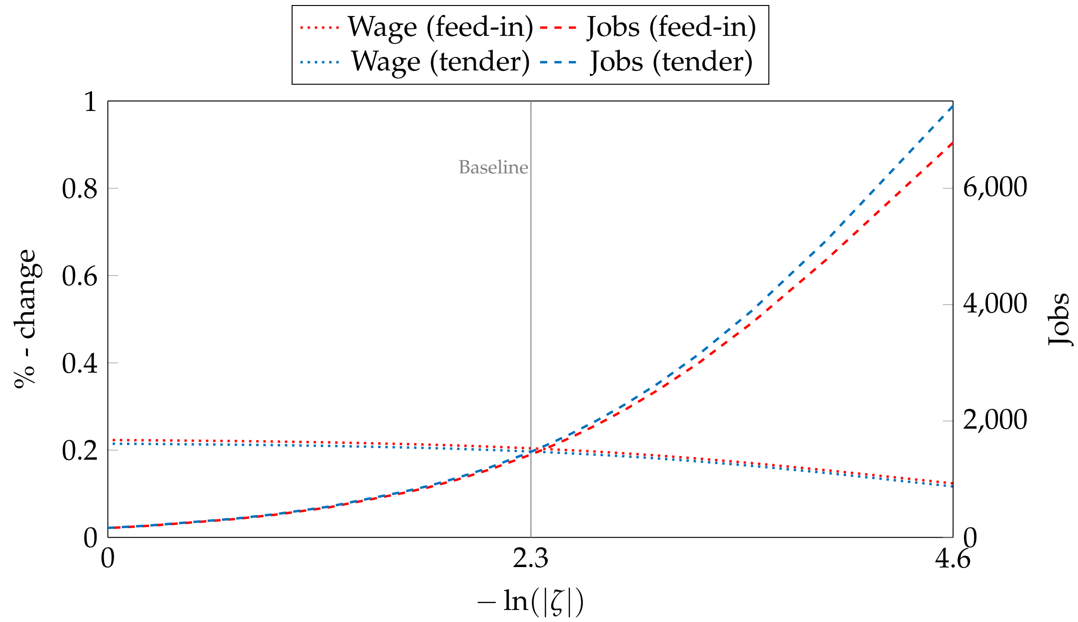
Figure 3.10: Sensitivity of results with respect to different input elasticities, where $\ln(\delta) = \ln(\sigma_{f,klem}) / \ln(\sigma^0_{f,klem})\ \forall\ f \in F$



As a last robustness check regarding elasticities, we compare the sensitivity of results with respect to the unemployment elasticity of wages ζ. In their seminal book (and paper), Blanchflower and Oswald (1995a,b) discover a statistical regularity across countries, namely that ζ is very often close to -0.1. Hence, if the unemployment rate doubles the wage falls by 10%. However, Kosfeld and Dreger (2017b) argue that this 'empirical law' does not hold for more recent multi-country as well as single-country studies which estimate ζ's that lie well below Blanchflower and Oswald's popularized average value of -0.1. For instance, Baltagi et al. (2012) and Kosfeld and Dreger (2017a) find a significantly lower ζ of -0.025 and -0.037 for (West) Germany, respectively. This would indicate a rather rigid labor market in which e.g. labor unions are able to significantly influence the wage setting. Such lower values do not influence the income effects but change the employment results significantly which is shown in Figure 3.11. Given that we vary ζ from -1 to -0.01, we approximate the corresponding natural logarithms by $-\ln(|\zeta|)$ which is again shown on the x-axis. The right end of the abscissa indicates an unemployment elasticity of wages of $\zeta = -0.01$ and the left end of $\zeta = -1$. Thus, if the labor market of S-H is becoming very rigid i.e. $\zeta = -0.01$, the expansion leads to 6,785 (7,416) new jobs under the *feed-in (tender) scheme* compared to 1,424 (1,471) jobs in the baseline.

Figure 3.11: Sensitivity of results with respect to different unemployment elasticities of wages ζ.





Finally, we check the sensitivity of results with respect to the capital mobility in S-H. So far, we have assumed that capital is totally mobile across firms F but immobile across regions i.e. between S-H and the ROW. In order to assess whether the results change if capital is allowed to jump not only across firms but also across regions, we fix the price of capital at $\bar{p}_k = 1$, thereby implicitly endogenizing the capital stock. Then, a decrease in capital inputs of firms due to the renewables expansion would indicate an increase of the capital stock financed by the ROW. In other words, if the return on capital in S-H is higher than in the ROW due to the shock, the endogenous capital stock would jump from the ROW to S-H. In fact, the shock leads to a decrease of capital inputs i.e. jump of capital stock from the ROW to S-H by the amount of 437mn €. For the welfare analysis, it is important that we do not consider this jump of capital as additional income of private households in S-H. Therefore, we keep the capital income from factor k fix at $\bar{E}_{k,h}\bar{\bar{p}}_k$ for $h = o, w$.

The results show that the tax income effect remains stable whereas the labor income effect almost halves in case of higher capital mobility. Obviously, there is no loss in income from factor k any more since endowments and the price are both fixed. The tax income effect under the feed-in (tender) scheme is 31mn € p.a. (5mn € p.a.) compared to 32mn € p.a. (6mn € p.a.) in the baseline. The labor income effect decreases from 86mn € p.a. (85mn € p.a.) to 56mn € p.a. (46mn €p.a.). The wage increases by 0.14% (0.12%) compared to 0.2% (0.2%) in the baseline. Finally, the employment effect halves to only 774 (640) new jobs compared to 1,424 (1,471) in the baseline.

3.4.2 *Discussion*

This paper provides certain methodological improvements to previous studies on regional income and employment effects of renewables expansion such as Hirschl et al. (2010, 2015, 2012), Ulrich et al. (2012), Bröcker et al. (2014, 2016), and Többen (2017).

First, we take into account factor and output supply constraints. For instance, the renewables expansion leads to an increase in labor demand by firms. While previous studies assume that these additional workers are readily available at the given wage, we assume that additional workers can only be mobilized by paying a higher wage. Thus, we assume that labor supply is constrained and represented by the upward-sloping wage curve discussed in Section 3.3.1. As a consequence, only part of the adjustment to the additional labor demand is done by employing additional workers while the rest of the adjustment is accomplished by an increase in the wage. Hence, the unconstrained models used in previous studies tend to exaggerate the size of the employment effects. In fact, we find that the renewables expansion in S-H only leads to about half as many new jobs compared to the results of Bröcker et al. (2014, 2016). Similar arguments hold for the income effects since all other markets in our model are supply-constrained as well.

Secondly, we take into account the full response of price effects and substitution possibilities of firms and households. The renewables expansion changes the relative prices of goods in S-H. Thus, households shift their consumption to goods which become relatively cheaper, and firms shift their input compositions accordingly. Similarly, firms shift their production output to goods which become relatively more expensive. The degree of these shifts in the economy is determined by various substitution elasticities (or transformation elasticities in the case of outputs). The higher these elasticities, the more flexibly the economy of S-H adjusts to the renewables expansion. This flexibility is usually not considered in previous studies because price effects are either disregarded in the first place or the underlying models assume cost-determined prices independent of demand. Although we find that the average price effects in S-H are rather small, prices for certain goods and services such as underground construction and transport equipment increase by up to 4 and 9%, respectively.

Thirdly, we take into account that part of the renewables expansion is paid by private households in S-H according to the levy. This means that any additional income is partly offset by an increase in levies. This is an improvement compared to e.g. the studies of Bröcker et al. (2014, 2016). However, given that only around 3.5% of the total levies are paid by citizens in S-H while the remainder is paid by the rest of Germany, we find that these offsetting effects are rather small. Or to put it bluntly, the income and employment effects for S-H are mainly paid by the rest of Germany.

Finally, we take into account induced income effects. That is, the additional income of households due to the renewables expansion leads to an increase in local final consumption. Therefore, production is increased to satisfy the additional demand which in turn results in additional factor income for households which again leads to an increase in local final consumption. Since we assume that any additional income is entirely spent on local final consumption and not partly on e.g. savings, we cover all these feedback effects in our welfare analysis from Section 3.4.

3.5 CONCLUSION

The objectives of this paper are twofold. First and foremost, to quantify the income and employment effects of the renewable electricity expansion plans of the state of S-H for the year 2030 by means of a static CGE model. Secondly, to compare the income results of the old *feed-in scheme* with the *new tender scheme* against the background of the future acceptance of renewable energies.

Methodologically, the model is based on the national S-U tables of Germany for 2014 which allow for introducing multi-output firms into the model. The tables are regionalized for S-H with a new non-survey regionalization technique that explicitly accounts for geography in trade relationships. We follow a single-region approach in which the state of S-H is trading goods with the large ROW, whereby the ROW is not explicitly modeled. Renewable electricity producing firms are modeled with survey information on regional component-wise input costs and feed-in compensations. Compared to previous studies, the main advantages of our CGE approach are the consideration of factor and supply constraints of the economy, the full response of price effects and substitution possibilities of firms and households, and induced income effects. Further, the labor market allows for unemployment via the wage curve, and tax income results take into account the German tax revenue sharing scheme such that we present net income and employment effects of the renewables expansion.

The results suggest that net effects for S-H are rather limited. Income effects result mainly from profits due to the stipulated compensations under the old *feed-in scheme*. Labor and land rent income effects are considerably lower than profits but remain stable under both schemes. We find that capital income decreases after the renewables expansion. However, this is partly due to the fact that we assume that capital is mobile across local firms but immobile between S-H and the ROW. Further, the tax income effect is rather low because of the German tax revenue scheme. Moreover, it is considerably higher under the *feed-in scheme* due to business tax income of the municipalities.

Under the *feed-in scheme*, the local government's expansion plans lead to a 0.94% (or 715mn € p.a.) higher regional GDP from 2030 onwards. Thereof, the income effect from renewables' profit is 544mn € p.a., the labor income effect is 86mn € p.a., the land rent income effect is 72mn € p.a., the tax income effect is 32mn € p.a. and the capital income effect is -19mn € p.a. The expansion increases the wage by 0.2% and creates 1,424 jobs which constitute 1.4% of all 100,957 unemployed persons in S-H in 2014. Competition among renewable electricity producers under the *tender scheme* lowers income effects such that the expansion leads only to a 0.15% (or 139mn € p.a.) higher GDP. Thereof, the labor income effect is 85mn € p.a., the land rent income effect is 72mn € p.a., the tax income effect is 6mn € p.a., and the capital income effect is -24mn € p.a. Thus, profits and its associated tax income effects vanish which may in fact result in lower acceptance of the renewables expansion. The wage and employment effect is very similar to the *feed-in scheme*. Local firms that benefit most from the expansion are in the field of 'repair and installation of machinery', 'manufacturers of electrical equipment' and 'research and development'. Moreover, the new *tender scheme* leads to a decrease of levies to be paid by citizens of S-H for the additionally produced electricity by roughly two thirds. The overall welfare in S-H indicated by the EV increases by 560mn € p.a. under the *feed-in scheme* and only 20mn € p.a. under the *tender scheme*. Compared to Bröcker et al. (2014, 2016) who estimated gross effects of the renewables expansion in S-H, we find that the overall income and employment results are roughly 50% lower if general equilibrium effects are taken into account.

Finally, we find that the profit, land ownership, and tax income effects remain stable under different assumptions on substitution possibilities of firms. In contrast, the labor income effect as well as wage and employment results are quite sensitive to assumptions on the ability of S-H's firms to substitute between local and foreign inputs in their production process. The better firms are able to substitute, the lower are the income and employment effects and vice versa. Thus, if firms in S-H are not able to substitute between foreign and local intermediate inputs, this might in fact have positive effects on labor income and employment generated by the renewables expansion. Further, the employment effects are very sensitive to assumptions on the level of rigidity of S-H's labor market. The more rigid i.e. bargaining power labor unions in S-H have, the higher the employment effects and vice versa.

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A APPENDIX TO CHAPTER 3

A.1 *Substitution elasticities*

Table 3.2: Substitution elasticities of firms F and A.

firm f	σ_{klem}	σ_{kle}	σ_{kl}	σ_{ene}	σ_{en}	σ_{mat}	**firm** a	σ_a
Agriculture	0.78	5.23	0.34	0.10	0.00	1.00	Products of agriculture and hunting	3.08
Forestry and logging	0.78	5.23	0.34	0.10	0.00	1.00	Products of forestry and logging	2.50
Fishery	0.78	5.23	0.34	0.10	0.00	1.00	Fish	1.25
Mining and quarrying	0.27	0.54	1.28	0.10	0.00	1.00	Oil and gas	11.20
Manufacture of food, beverages and tobacco	0.62	0.10	0.26	0.10	0.00	1.00	Mining and quarrying	0.90
Manufacture of textiles	0.63	0.12	0.42	0.10	0.00	1.00	Food products	3.21
Wood products	0.64	0.64	0.22	0.10	0.00	1.00	Beverages	1.15
Manufacture of paper and paper products	0.68	0.36	0.23	0.10	0.00	1.00	Tobacco	1.15
Printing and media	0.68	0.36	0.23	0.10	0.00	1.00	Textiles	3.75
Manufacture of coke and refined petroleum	0.31	7.86	0.31	0.10	0.00	1.00	Wearing apparel	3.70
Manufacture of chemicals products	0.77	1.15	0.52	0.10	0.00	1.00	Leather	4.05
Manufacture of pharmaceutical products	0.77	1.15	0.52	0.10	0.00	1.00	Wood	3.40
Manufacture of rubber and plastic products	0.56	0.17	0.22	0.10	0.00	1.00	Pulp and paper	2.95
Manufacture of other non-metallic minerals	0.64	0.87	0.29	0.10	0.00	1.00	Pulp and paper products	2.95
Manufacture of basic metal	0.16	0.14	0.30	0.10	0.00	1.00	Printing and media	2.95
Manufacture of fabricated metal products	0.16	0.14	0.30	0.10	0.00	1.00	Coke and refined petroleum products	2.10
Manufacture of computer, electronic and opticals	0.00	0.29	0.29	0.10	0.00	1.00	Chemical products	3.30
Manufacture of electrical equipment	0.00	0.29	0.29	0.10	0.00	1.00	Basic pharmaceuticals	3.30
Manufacture of machinery and equipment	0.79	0.00	0.82	0.10	0.00	1.00	Rubber products	3.30
Manufacture of motor vehicles	0.53	0.32	0.58	0.10	0.00	1.00	Plastic products	3.30
Manufacture of other transport equipment	0.53	0.32	0.58	0.10	0.00	1.00	Glass products	2.90
Manufacture of furniture and other products	0.54	1.27	0.59	0.10	0.00	1.00	Ceramic and minerals	2.90
Repair and installation of machinery	0.68	0.21	0.20	0.10	0.00	1.00	Basic iron and steel	2.95
Other Energy	0.00	0.00	0.00	0.10	0.00	1.00	Basic metals and other non-ferrous metals	4.20
Trade margins	0.00	0.00	0.00	0.10	0.00	1.00	Casting of metals	4.20
Water supply	1.20	0.28	0.30	0.10	0.00	1.00	Metal products	3.75
Waste management	1.20	0.28	0.30	0.10	0.00	1.00	Computer and optical products	4.40
Constructions and construction works	0.71	0.06	0.31	0.10	0.00	1.00	Electrical equipment	4.40
Land transport services	0.92	0.22	0.87	0.10	0.00	1.00	Machinery	4.05
Water transport	0.84	1.20	0.00	0.10	0.00	1.00	Motor vehicles	2.80
Air transport	0.97	0.28	0.82	0.10	0.00	1.00	Other transport equipment	2.80
Warehousing	0.71	0.70	0.36	0.10	0.00	1.00	Furniture	3.75
Postal services	1.17	0.03	2.72	0.10	0.00	1.00	Other manufacturing	3.75
Accommodation and food services	0.71	0.70	0.36	0.10	0.00	1.00	Repair and installation of machinery	1.90
Publishing services	1.17	0.03	2.72	0.10	0.00	1.00	Electricity	2.80
Media and broadcasting	1.17	0.03	2.72	0.10	0.00	1.00	Trade margins	1.90
Telecommunications	1.17	0.03	2.72	0.10	0.00	1.00	Water	2.80
Information services	1.17	0.03	2.72	0.10	0.00	1.00	Waste management services	2.80
Financial services	1.03	0.35	1.32	0.10	0.00	1.00	Waste and disposal services	3.75

Insurance services and pension funding	1.03	0.35	1.32	0.10	0.00	1.00
Other financial and insurance services	1.03	0.35	1.32	0.10	0.00	1.00
Real estate services	1.33	0.25	0.39	0.10	0.00	1.00
Legal and accounting services	0.66	1.24	0.32	0.10	0.00	1.00
Architectue and engineering services	0.66	1.24	0.32	0.10	0.00	1.00
Research and development	0.66	1.24	0.32	0.10	0.00	1.00
Advertising and market research services	0.66	1.24	0.32	0.10	0.00	1.00
Other professional, scientific and technical services	0.66	1.24	0.32	0.10	0.00	1.00
Rental and leasing services	0.66	1.24	0.32	0.10	0.00	1.00
Employment services	0.66	1.24	0.32	0.10	0.00	1.00
ravel agency, tour operator	0.66	1.24	0.32	0.10	0.00	1.00
Office and other business support activities	0.66	1.24	0.32	0.10	0.00	1.00
Public administration and defence	1.12	0.07	0.26	0.10	0.00	1.00
Education services	1.15	0.00	0.82	0.10	0.00	1.00
Human health services	0.97	0.93	0.43	0.10	0.00	1.00
Social and residential care services	0.97	0.93	0.43	0.10	0.00	1.00
Arts, culture and gambling	0.88	0.32	0.21	0.10	0.00	1.00
Sports and recreation services	0.88	0.32	0.21	0.10	0.00	1.00
Services furnished by membership organisations	0.88	0.32	0.21	0.10	0.00	1.00
Repair services of computers and personal goods	0.88	0.32	0.21	0.10	0.00	1.00
Other personal services	0.88	0.32	0.21	0.10	0.00	1.00
Services of households	0.88	0.32	0.21	0.10	0.00	1.00

Other waste management services	3.75
Building construction	1.90
Underground construction	1.90
Other construction	1.90
Land transport services	1.90
Water transport services	1.90
Air transport services	1.90
Warehousing	1.90
Postal services	1.90
Accommodation and food services	1.90
Publishing services	1.90
Audiovisual and broadcasting services	1.90
Telecommunications services	1.90
Information services	1.90
Financial services	1.90
Insurance service and pension fundings	1.90
Other financial and insurance services	1.90
Real estate activity services	1.90
Legal and accounting activities	1.90
Architecture and engineering services	1.90
Research and development	1.90
Advertising and market research	1.90
Other professional, scientific and technical activities	1.90
Veterinary activities	1.90
Rental and leasing activities	1.90
Activities of employment placement agencies	1.90
Travel agencies	1.90
Security and investigation activities	1.90
Public administration and defence	1.90
Compulsory social security service	1.90
Educational support activities	1.90
Human health activities	1.90
Residential care	1.90
Arts, culture, gambling and betting	1.90
Sports and recreation activities	1.90
Activities of membership organisations	1.90
Repair of computers and household goods	1.90
Other personal service activities	1.90
Goods and services of private households	1.90

Source: Koesler and Schymura (2012), Aguiar et al. (2016) and own assumptions.

A.2 *Calibrated share form*

In the benchmark situation, rearranging (3.2) to

$$\alpha_{m,j} = a^0_{m,j} \left(\frac{q^0_j}{\hat{p}^0_m} \right)^{1-\sigma_j} \tag{3.28}$$

and then inserting into (3.1) leads to the *calibrated share form*

$$\begin{aligned} c_j(\hat{\boldsymbol{p}}) &= \left(\sum_m a^0_{m,j} \left(\frac{q_{j^0}}{\hat{p}^0_m} \right)^{-\sigma_j} \hat{p}_m^{1-\sigma_j} \right)^{\frac{1}{1-\sigma_j}} \\ &= \left({q^o_j}^{-\sigma_j} \sum_m a^0_{m,j} \hat{p}^0_m \left(\frac{\hat{p}_m}{\hat{p}^0_m} \right)^{1-\sigma_j} \right)^{\frac{1}{1-\sigma_j}} \\ &= \left({q^o_j}^{1-\sigma_j} \sum_m \frac{a^0_{m,j} \hat{p}^0_m}{q^0_j} \left(\frac{\hat{p}_m}{\hat{p}^0_m} \right)^{1-\sigma_j} \right)^{\frac{1}{1-\sigma_j}} \\ &= q^0_j \left(\sum_m v^0_m \left(\frac{\hat{p}_m}{\hat{p}^0_m} \right)^{1-\sigma_j} \right)^{\frac{1}{1-\sigma_j}} \end{aligned} \tag{3.29}$$

with *benchmark value input cost shares* $v^0_i = a^0_{ij} \hat{p}^0_i / q^0_j$.

A.3 *Input coefficients*

Taking the derivative of (3.29) leads to input coefficients

$$\begin{aligned} a_{m,j} = \frac{\partial c(\hat{\boldsymbol{p}})}{\partial \hat{p}_m} &= \frac{1}{1-\sigma_j} q^0_j \left(\sum_m \frac{a^0_{m,j} \hat{p}^0_m}{q^0_j} \left(\frac{\hat{p}_m}{\hat{p}^0_m} \right)^{1-\sigma_j} \right)^{\frac{\sigma_j}{1-\sigma_j}} \frac{a^0_{m,j} \hat{p}^0_m}{q^0_j} {\hat{p}^o_m}^{\sigma_j - 1} (1-\sigma_j) \hat{p}_m^{-\sigma_j} \\ &= q^0_j \left(\sum_m \frac{a^0_{m,j} \hat{p}^0_m}{q^0_j} \left(\frac{\hat{p}_m}{\hat{p}^0_m} \right)^{1-\sigma_j} \right)^{\frac{\sigma_j}{1-\sigma_j}} \frac{a^0_{m,j}}{q^0_j} \left(\frac{\hat{p}^0_m}{\hat{p}_m} \right)^{\sigma_j} \\ &= {q^o_j}^{1-\sigma_j} q_j^{\sigma_j} \frac{a^0_{m,j}}{q^0_j} \left(\frac{\hat{p}^0_m}{\hat{p}_m} \right)^{\sigma_j} \\ &= a^0_{m,j} \left(\frac{q_j / q^0_j}{\hat{p}_m / \hat{p}^0_m} \right)^{\sigma_j}. \end{aligned} \tag{3.30}$$

A.4 *Regional electricity market data*

Technology	Installed capacity in GW	Electricity in TWh	Installed capacity in GW	Full load hours	Electricity production in TWh	lcoe in € per KWh	Input costs $\hat{V}_z^0$ in mn €	EEG compensation in € per KWh	EEG compensation $\bar{V}^0_{rele}$ in mn €	Spot market price in € per KWh	Spot market value V^0_{rele} in mn €
	2016	**2016**	**2030**		**2030**		**2030**		**2030**		**2030**
Wind onshore	6.3	9.1	12	2,300	27.6	0.06	1,170	0.09	1,665	0.03	535
Wind offshore	1.7	5.8	2.5	4,400	11	0.11	597	0.15	803	0.03	158
Photovoltaic	1.5	1.3	2.9	1,000	2.9	0.11	177	0.13	204	0.03	54
Total	**9.9**	**18.9**	**17.8**	-	**43.9**	**-**	**1,944**	**-**	**2,672**	**-**	**747**

Table 3.3: Renewable electricity market data and expansion targets of S-H
Source: Own representation based on data of **Broecker.2012**; Bröcker et al. (2014) and MELUND (2016).

A.5 *Sectoral results*

Figure 3.12: Change in output activity of a local firm x_f

Figure 3.13: Change in output activity of an Armington firm x_a

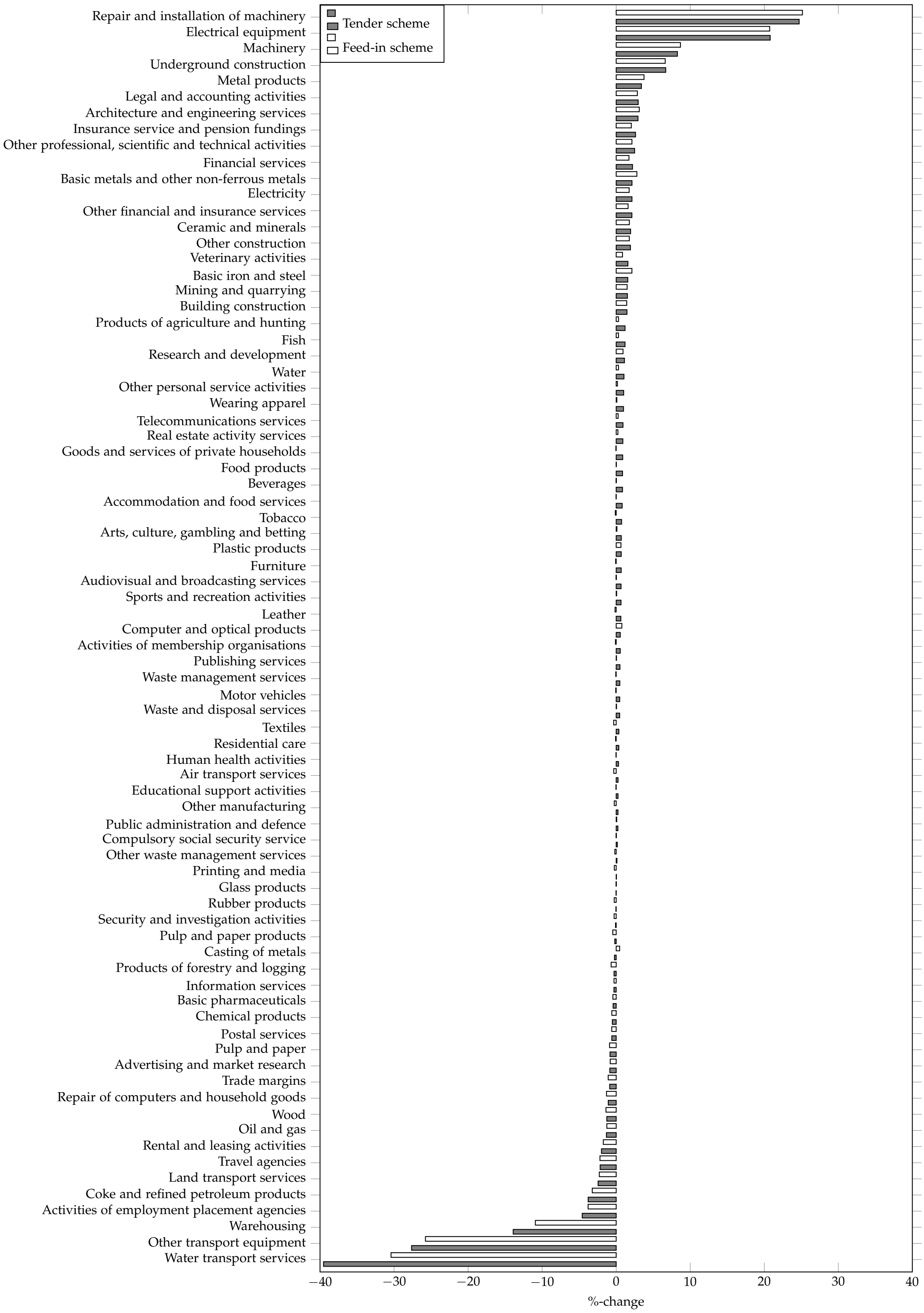


Figure 3.14: Change in local prices p_d

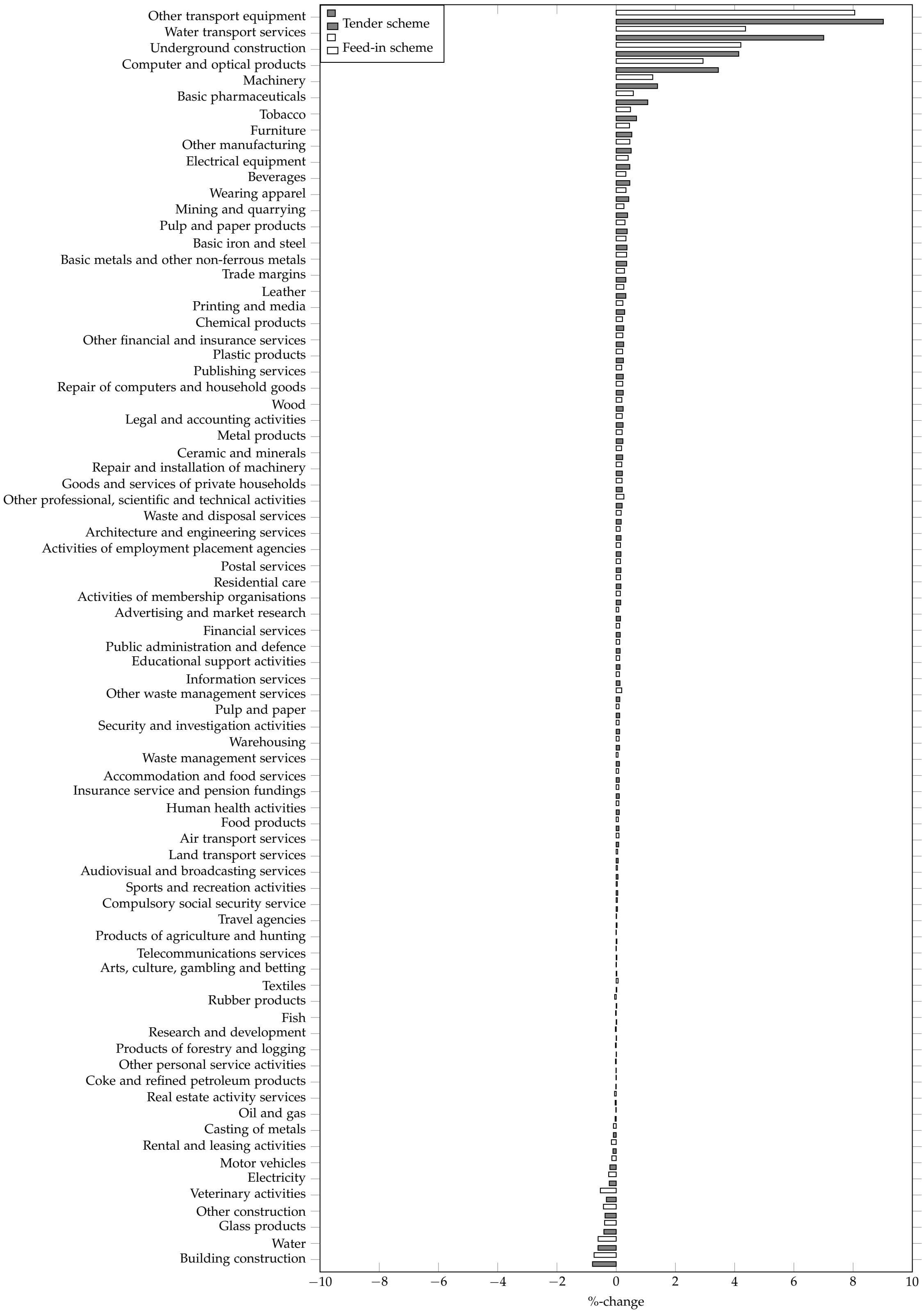
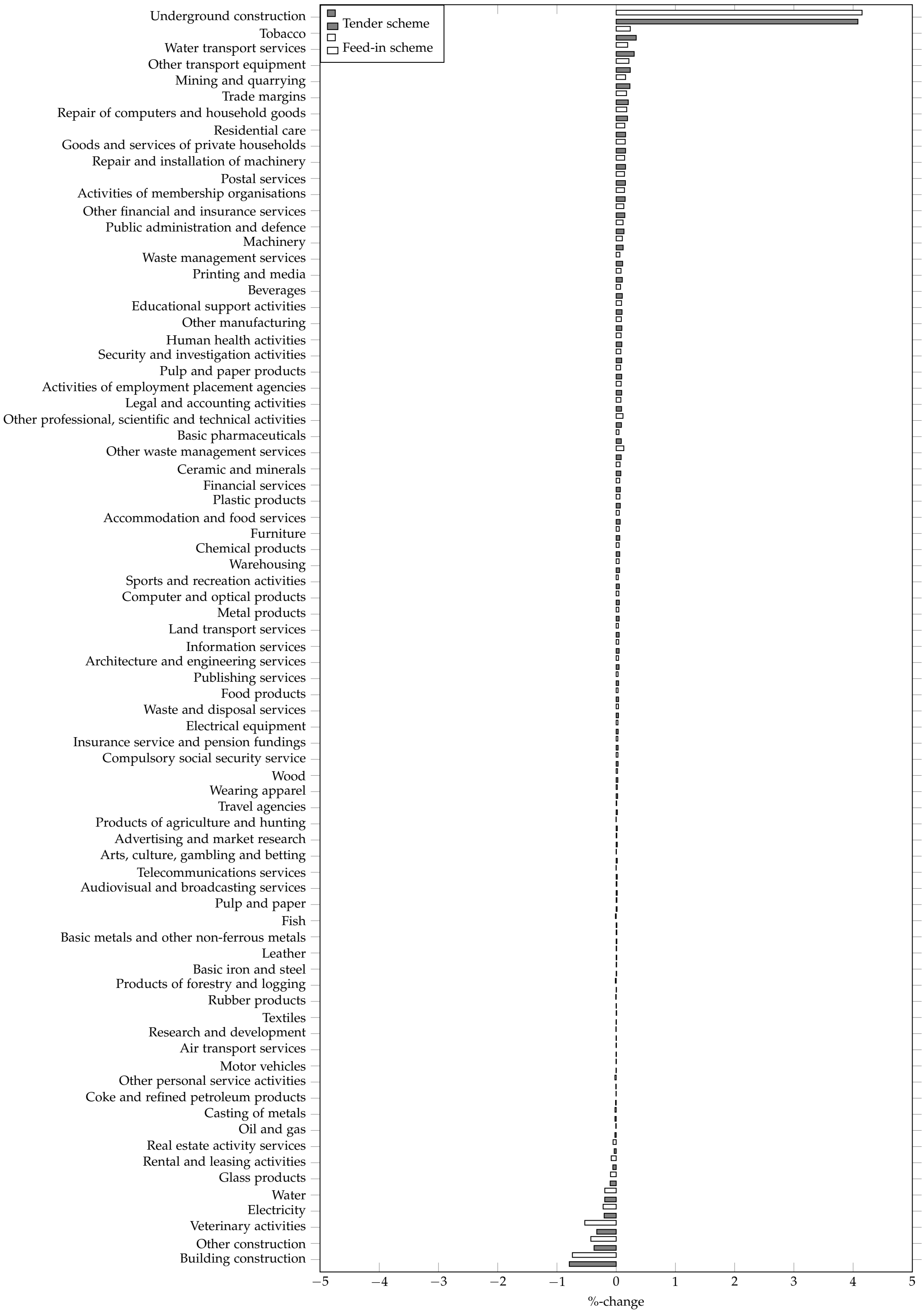


Figure 3.15: Change in commodity prices p_i



4

NATIONAL CLIMATE POLICY UNDER THE EUROPEAN UNION EMISSIONS TRADING SYSTEM

A previous version of this chapter has appeared as:

Burmeister, Johannes and Sonja Peterson (2016). National Climate Policies in Times of the European Union Emissions Trading System (EU ETS). Kiel Working Paper 2052.

Abstract: Given the low carbon price in the EU Emissions Trading System (ETS) in recent years while consensus about a more stringent EU climate policy is very unlikely in the near future, we explore the potential scope and optimal design of additional national climate policy in the current EU policy framework. We suggest to implement a type of carbon price floor in the national EU ETS sectors that allows for shifting emission targets to non-ETS sectors like housing and transportation as well as retiring EU-wide emission allowances. By doing so, countries are able to either i) achieve the same emission target at lower abatement cost or ii) achieve a lower emission target at basically no extra cost. In order to determine the empirical relevance of our policy suggestions, we conduct a partial equilibrium analysis of the EU carbon market in 2020. We find that Germany is able to either achieve the same emission target at 370mn € lower abatement cost or achieve a 11 Mt of CO_2 lower emission target at no extra costs by introducing a carbon price floor of 32 € or 36 € per ton in 2020, respectively.

Keywords: Climate policy, EU Emissions Trading System, overlapping regulation, carbon price floors, marginal abatement costs, partial equilibrium analysis

4.1 INTRODUCTION

This paper explores the potential scope and optimal design of national climate policy in the European climate policy context. We argue that certain carbon pricing policy designs have the potential to reconcile European Union (EU) and national climate policy in an effective and cost-efficient manner.

Already in the Kyoto Protocol from 1997, the EU member states made use of the provision to fulfill their greenhouse gas (GHG) emission commitments jointly. They agreed on a collective target to reduce emissions in the first commitment period of the Protocol from 2008-2012 to 8% below 1990 levels. Also for the post-Kyoto climate policy, the EU intends to fulfill its emission reduction targets jointly. One of the three main targets of the EU Climate and Energy Package adopted in 2009 is to cut GHG emissions by 20% compared to 1990 levels by the year 2020 (European Commission, 2008). Economists appreciate such a joint target since it opens the way to implement an EU-wide climate policy that aims at reaching this target at minimum costs.

A cornerstone of EU climate policy to reach the joint target is the EU Emissions Trading System (EU ETS) launched in 2005. It covers more than 11,000 power stations and industrial plants in 31 countries, as well as airlines. In principle, the EU ETS ensures cost efficiency because due to trading of emission allowances marginal abatement costs across sources equalize and thereby the exogenous joint emissions target (the so-called 'cap') is reached at minimum costs.

Yet, the system produces large inefficiencies since the EU ETS only covers about half of the EU's GHG emissions. For the remaining emissions in non-ETS sectors such as housing, agriculture and transportation, EU countries agreed to undertake individual measures to reach binding national annual targets until 2020 under the 'Effort Sharing Decision' (European Commission, 2009). Therefore, the current EU carbon market already represents a second best solution (Böhringer et al., 2006; Böhringer et al., 2016). Böhringer et al. (2009) analyze the resulting inefficiencies in the year 2020 with three computable general equilibrium (CGE) models. They show that the inefficiencies of the partitioned EU carbon market, with one EU Emission Allowance (EUA) price and 28 implicit non-ETS prices in each member state, can be significant and leading to 25-50% higher abatement costs compared to the efficient solution.[1]

1 In reality, inefficiencies are potentially even larger since the multitude of national policy measures outside the EU ETS do not ensure an equalization of marginal abatement costs in the non-ETS sectors in each country as in the models used in Böhringer et al. (2009).

One reform proposal for the EU ETS is thus to extend its scope to more sectors and regions (Böhringer et al., 2014; Edenhofer et al., 2014). It would be beneficial if there was only one carbon price in the EU in the long-run and an overall coherent European climate policy. Moreover, the hitherto political EU ETS targets have not been very ambitious and lead to a large surplus of around 1.5 billion EUAs at the end of 2017 (Graichen and Matthes, 2018). The corresponding low EUA price of only around 5 € per ton of CO_2 in recent years thus gave little incentive for technological development and structural change required to achieve the long-term targets. Therefore, the latest EU ETS reform includes an increase of the reduction rate of the emissions cap from 1.74% to 2.2% p.a. from 2021 onwards as well as the establishment of a so-called 'market stability reserve' (MSR). The MSR is a quantity-based adjustment mechanism of the annual auction volumes of allowances which aims to tackle the structural surplus problem (European Commission, 2015, 2018a). However, it is doubtful whether the MSR is the right policy measure to resolve this problem (Edenhofer et al., 2014; Hepburn et al., 2016; Holt and Shobe, 2016; Perino and Willner, 2016).

This is why a number of countries that regard EU policies as insufficient are discussing or implementing additional national measures to reduce emissions in sectors that are already covered by the EU ETS. Examples are the UK carbon price floor and several national carbon taxes (e.g. in Sweden, Finland and Denmark). In 2016, also France announced the introduction of a price floor of 30 € per ton from 2019 on (The Guardian, 2016). Germany discussed an additional *climate levy* for power stations (BMWi, 2015).

The general problem of these additional policies is that they are i) not effective in terms of additional emissions reduction because with an unchanged amount of allowances any national reductions within the EU ETS are offset elsewhere and ii) not cost-efficient since they drive further wedges between carbon prices. In this context, Böhringer et al. (2008) and Heindl et al. (2014) show that an additional national carbon tax in the ETS sector in one or more countries further increase EU-wide inefficiencies. Both papers impose a tax on top of the EUA price in one region, which is equivalent to a price floor in the ETS sector, while keeping the joint target constant. On the one hand, the higher carbon price in the taxing region leads to an increase of overall abatement costs. On the other hand, firms in the taxing region emit less and sell their excess allowances, resulting in a fall of the EUA price. This leads to a decrease of overall abatement costs in the EU ETS because non-taxing regions face a lower price and abate less emissions. Böhringer et al. (2008) and Heindl et al. (2014) find that the net effect is always an increase in overall abatement costs and thus higher inefficiencies. The non-ETS sector is disregarded because it is not affected by the policy in the ETS sector.

As a result, the only way to increase abatement efforts by single, ambitious EU countries seems to be to reduce more emissions in their non-ETS sectors that are not linked to the EU ETS. The question is whether there are no advisable possibilities to pursue more ambitious national climate policy in their ETS sectors. Motivated by the idea of the German *climate levy* proposal that included retiring EUAs as well as the general potential of additional policies to close the gap between implicit non-ETS carbon prices and the EUA price, our paper discusses two new policy options. These account for the possibility to shift emission targets between ETS and non-ETS sectors as well as to retire EUAs into the MSR and thereby reducing overall EU emissions. Therefore, we show that national climate policy – although interfering with the EU ETS – can be effective and cost-efficient.

This paper builds on the work by Böhringer et al. (2008) and Heindl et al. (2014) but adds two alternative carbon pricing policy options, thereby contradicting previous efficiency results. The general idea to allow for the adjustment of emission targets in either the ETS or non-ETS sector as motivated above is similar as in Abrell and Rausch (2016). But while Abrell and Rausch (2016) take the perspective of a social planner for the EU which would again require unanimous approval by all member states for any additional measures, we take a national perspective. Our paper is also linked to the extensive literature on price versus quantity constraints in emissions regulation and the combination of both i.e. so-called hybrid approaches to carbon pricing such as price floors within an ETS (e.g. Abrell and Rausch, 2017; Brink et al., 2016; Mandell, 2008; Roberts and Spence, 1976; Unold and Requate, 2001; Weitzman, 1974; Wood and Jotzo, 2011).

The rest of this paper is structured as follows. In Section 4.2, we revisit the Germany *climate levy* proposal from 2015 which – compared to e.g. existing price floors – showed the potential to reconcile EU and national climate policy (Peterson, 2015). In Section 4.3, we set up the stylized theoretical framework of a simple one-country, two-sector model in order to derive the optimal design of our two new policy options analytically. In Section 4.4, we test our theoretical findings empirically and conduct a numerical partial equilibrium analysis of the EU carbon market in 2020. After discussing the validity of our empirical findings for the EU, we summarize our results and conclude.

4.2 POLICY CONTEXT

In December 2014, the German Federal Ministry for Economic Affairs and Energy (BMWi) had set up a task force and agreed on a 'Climate Action Programme 2020' (BMU, 2014) because it was likely to miss the national target to reduce GHG emissions by 40% relative to 1990 until the year 2020. As part of the programme, the BMWi identified the electricity sector as the one with the highest potential to reduce emissions with a gap of at least 22 Mt of CO_2 emissions until the year 2020. In order to close this gap, the task force recommended to introduce a carbon pricing option that is consistent with the EU ETS framework in particular. The resulting *climate levy* proposal stipulated that power stations have to submit a certain amount of additional EUAs for emissions beyond a pre-defined free emission level. These additional 'penalty allowances' would then have been signed over to the government and retired. The free emission levels were designed such that especially old coal-fired power stations would have been affected by the levy. In order to reach the emission target for the power sector, it was estimated that the additional allowances will result in extra costs of 18-20 € per ton of CO_2 in 2020.

In general, the proposal was very promising because besides accelerating the fossil-fuel phase-out, the policy would have been effective due to the retirement of EUAs. How many EUAs would have been actually retired is not clear though. Only by chance, the EU emission reductions would have been equal to the German ones. Peterson (2015) showed that they can be either higher or lower depending on the free emission level compared to the hypothetical emission level of the German power sector without the policy, the development of the EUA price, and the implicit level of the levy.

Therefore, the effectiveness of the *climate levy* to reach the national targets depends – as with all price based instruments – on estimates of the marginal abatement cost curves (MACCs). From the perspective of an individual power station, the MACC indicates either the marginal loss in profits from avoiding the last unit of emissions or the marginal cost of achieving a certain emission target given some level of output (Klepper and Peterson, 2006). If targets are not reached, it would be necessary to readjust the specifics of the levy. Similarly, also the cost efficiency depends on the design of the free emission level and it is not guaranteed that marginal abatement costs equalize across German power stations which is the condition for cost efficiency. Thus, it is not guaranteed that the emission reductions within the power sector are taking place where they are cheapest.

Given these uncertainties, it would be better to implement a true national price floor for all emitters in the ETS sectors as suggested by Edenhofer and Schmidt (2018), among many others. That is, all emitters need to pay a levy as the difference between the current EUA price and the stipulated price floor. The revenues can then be used to retire EUAs.

Although the proposal has been dismissed in mid 2015 due to strong resistance from the coal lobby, the latest reform of the EU ETS from 2017 adopts the idea of retiring EUAs within the establishment of the MSR. The MSR is a quantity mechanism designed to adjust the short-term auction supply of EUAs by establishing a reserve of non-auctioned EUAs. The long-term emissions cap is not affected by the MSR. Most importantly, within the MSR it is also possible to retire EUAs if power stations shut down due to national policy measures (cf. BMU, 2018, p. 4). In addition to retiring EUAs, Germany is supposed to buy additional EUAs from other member states for missing its non-ETS targets especially in the transportation and agriculture sector (Tutt, 2018). In general, this implicitly allows for the possibility to shift emission targets between ETS and non-ETS sectors. Given both these possibilities, we show that additional national climate policy can be effective as well as cost-efficient and suggest that policymakers hedge against differences in marginal abatement costs across non-ETS and ETS sectors. This can either be done by following a *cost* or an *environmental optimization* behavior which we show in the following simple one-country, two-sector model.

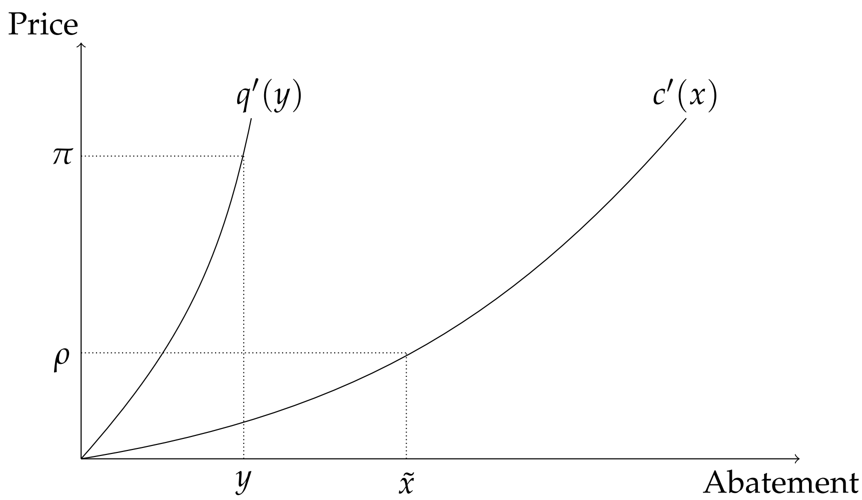
4.3 THEORETICAL ANALYSIS

We use a simple partial equilibrium framework for one country in order to evaluate the effectiveness and cost efficiency of additional national carbon pricing. The country has to abate emissions in two sectors. One sector is regulated by an ETS with a fixed overall joint target for potentially $i = 1, ..., I$ countries (ETS sector). The other sector is regulated by an individual carbon tax in order to meet a fixed national target (non-ETS sector).

The country has emission abatement possibilities associated with certain costs that can be represented by a cost function $c(a)$ with a being the abated emissions quantity (e.g. Mt of CO_2). The cost function is assumed to be strictly monotonically increasing and convex, i.e. $c'(a) > 0$ and $c''(a) > 0$. We denote $c(x)$ and $q(y)$ as the cost functions in the ETS and non-ETS sector with actual abated emission quantities x and y, respectively. Within the joint target of the ETS sector, the country of interest can trade emission allowances with other countries as needed because its actual abatement x may be either greater or less than ex-ante allocated or auctioned quantities depending on its abatement possibilities. Cost efficiency for the ETS sector is characterized by the cost-minimizing allocation of abatement between the country of interest and all other countries, which are not explicitly modeled here. Therefore, we denote $\tilde{x}$ as the equilibrium abatement quantity with respective allowance price ρ that equalizes marginal abatement costs across all countries.

Regarding the non-ETS sector, there does not exist a joint target but only a national target. For simplicity, we follow Böhringer et al. (2016) and assume that this individual target is met by a national carbon tax $\pi = q'(y)$. Therefore, the carbon market is characterized by a second best solution with two potentially different carbon prices ρ and π. This second best solution reflects, in a simplified manner, the situation of a single country in the current EU carbon market. Of course, while in the EU market there also exist only one EUA price, there exist many potentially different (shadow) prices outside the ETS in the 28 member states and their various non-ETS sectors. The general setting is summarized in Figure 4.1 where the functional form of the MACCs is chosen arbitrarily. Empirically, one expects higher costs for the same abatement quantity in the non-ETS sector because it represents sectors like transportation or housing where it is more costly to abate emissions. Thus, the non-ETS MACCs are typically left to the ETS ones. However, this does not necessarily have to be the case as we will discuss in Section 4.4.

Figure 4.1: Marginal abatement cost curves in the one-country, two-sector model

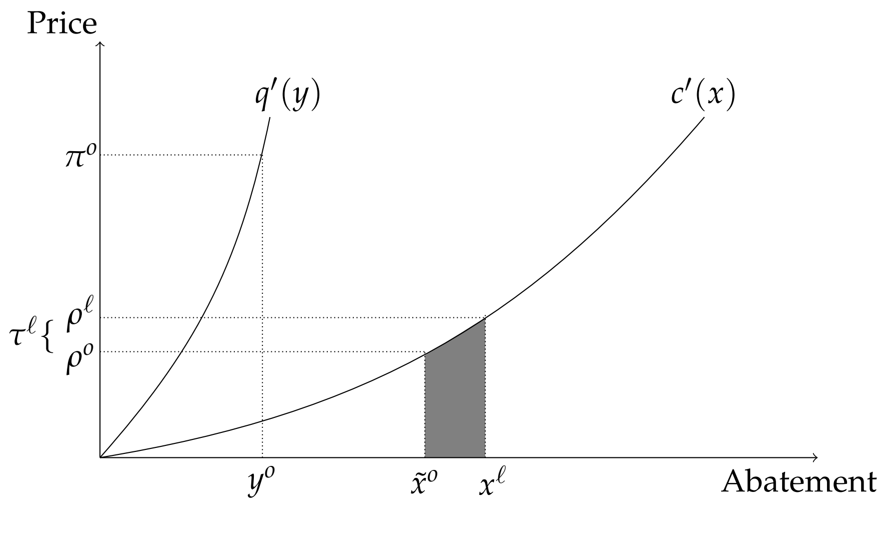


4.3.1 *The climate levy*

First, we revisit the German climate levy proposal. In contrast to the original proposal, we assume that the government introduces a true national carbon price floor. That is, the government introduces a quantity tax (or levy) on top of the allowance price for all emitters in the ETS sector instead of only for certain emitters in the power sector. If translated into our partial equilibrium framework, the country increases its abatement effort in the ETS sector due to the national price floor. Normally, this would lead to a falling allowance price ρ and higher emissions in other countries covered by the ETS i.e. to a counter-effect and overall unchanged ETS emissions since the overall ETS target remains the same. However, as stipulated in the proposal, we assume that the government buys the excess allowances and retires them. This means that other countries are not affected by the policy measure in the country of interest. The *climate levy* policy option, in the following denoted by the superscript ℓ, is depicted in Figure 4.2 below.

In the benchmark situation, denoted by the superscript o, the country abates quantities $\tilde{x}^o$ and y^o at allowance price ρ^o and tax π^o, respectively. Let $C(x, y) = c(x) + q(y)$ denote the aggregated cost function. It follows that the total national abatement costs in the benchmark situation are $C(\tilde{x}^o, y^o) = c(\tilde{x}^o) + q(y^o) = C^o$. The introduction of a tax τ^ℓ on top of the benchmark allowance price ρ^o is equivalent to introducing a national price floor $\rho^\ell = \rho^o + \tau^\ell$, which results in the increased abatement level x^ℓ.

Figure 4.2: Effectiveness of the German *climate levy* proposal



On the one hand, the retiring of allowances makes the policy effective such that national as well as overall emissions decrease. On the other hand, the additional abatement effort increases costs by the gray shaded area in Figure 4.2. The new emission target is simply met at higher costs. Since we are not able to directly measure the environmental benefits of the additionally averted pollution, the cost efficiency of the German *climate levy* cannot be easily compared with the benchmark situation because both costs and benefits increase. However, the proposal does not follow any optimization behavior and we suspect it to drive further wedges between carbon prices, thereby increasing inefficiencies of the carbon market. Therefore, we rather suggest national policymakers to use the possibility of shifting abatement efforts between sectors in order to hedge against the differences in marginal abatement costs of the non-ETS and ETS sector as follows.

4.3.2 *Cost optimization*

Given the possibility to shift emission targets, we suggest policymakers to introduce a carbon price floor that optimizes national cost efficiency. That is, the country shifts its abatement effort between the ETS and non-ETS sector such that the benchmark emission target is attained at lower total abatement costs. As before, the excess allowances resulting from the policy measure in the country of interest are retired such that other countries covered by the ETS are again unaffected. The national optimization problem is given by

$$\begin{aligned} \min_{x,y} \ & c(x) + q(y) \\ \text{s.t.} \quad & x + y = z. \end{aligned} \tag{4.1}$$

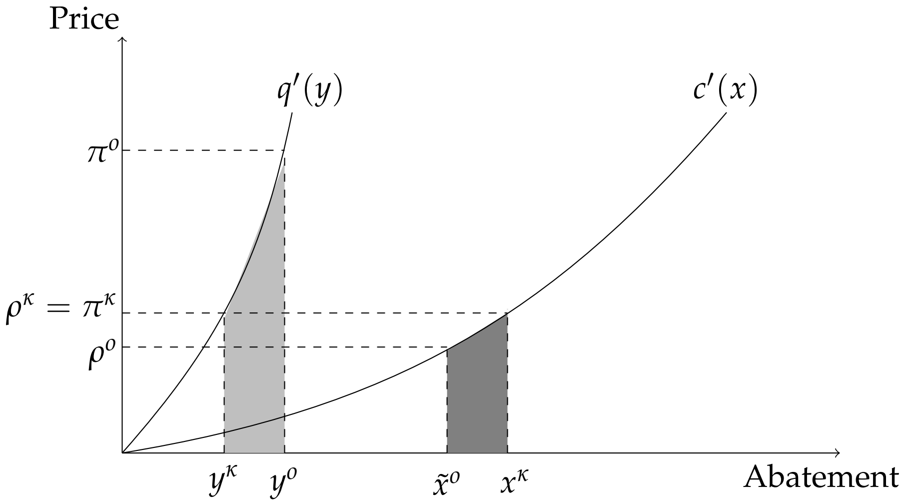
To simplify notation, we define the emission target as an abatement target denoted by z. That is, if e is the overall national emission target and e^B is some business-as-usual emission level, the abatement target is $z := e^B - e$.

Obviously, the optimum is characterized by the first order conditions that marginal abatement costs equalize across both sectors. Under the national policy option *cost optimization*, in the following denoted by the superscript κ, the optimal abatement quantities x^κ and y^κ solve (4.1) for the case that the national benchmark abatement target $z^o = \tilde{x}^o + y^o$ is attained, i.e. $x^\kappa, y^\kappa = \arg\min\left(c(x) + q(y)\right)$ for $z = z^o$. This results in lower total abatement costs $C(x^\kappa, y^\kappa) = C^\kappa$ compared to the benchmark level C^o. The policy option is also depicted in Figure 4.3 below. The dark gray shaded area are the additional costs in the ETS sector and the light gray shaded area are the reduced costs in the non-ETS sector, respectively. The difference is the lowest at the cost-efficient, optimal national price floor

$$\rho^{\kappa} = c'(x^{\kappa}) = q'(y^{\kappa}). \tag{4.2}$$

Thus, since $x^{\kappa} + y^{\kappa} = z^{o}$, this policy option is environmentally not effective but improves national as well as overall cost efficiency of the carbon market.

Figure 4.3: Cost efficiency of climate policy under national *cost optimization*



Assuming simple linear MACCs of the form $c'(x) = ax$ and $q'(y) = by$ with slope parameters a and b, it is possible to derive a closed form solution x^*, y^* of the optimal national price floor level that can also be easily interpreted. It is obvious from (4.1) and (4.2) that in the optimum $x^*/y^* = b/a$ and $x^* + y^* = z$. Rearranging the former and plugging into the latter leads to optimal quantities

$$x^* = \frac{b}{a+b} z$$

and

$$y^* = \frac{a}{a+b} z$$

for any national target $z > 0$. Thus, the optimal total abatement costs can be formulated as a function of the abatement target only, namely

$$C^*(z) = \frac{a}{2}\left(\frac{b}{a+b}z\right)^2 + \frac{b}{2}\left(\frac{a}{a+b}z\right)^2 = \frac{1}{2}\frac{z^2}{(a+b)^2}\left(ab^2 + ba^2\right) = \frac{1}{2}z^2\frac{ab}{a+b}.$$

(4.3)

That is, the total abatement costs are proportional to the square of the abatement target. For instance, if the abatement target doubles, the costs quadruple.

In the benchmark situation, it holds that $\rho^o = a\tilde{x}^o$, $\pi^o = by^o$ and $z^o = \tilde{x}^o + y^o = \rho^o/a + \pi^o/b$. Thus, the optimal national price floor under *cost optimization* is given by

$$\rho^\kappa = ax^\kappa = \frac{ab}{a+b}z^o = \frac{b}{a+b}\rho^o + \frac{a}{a+b}\pi^o. \tag{4.4}$$

It is a weighted average of the old benchmark prices in the country of interest, where the benchmark ETS and non-ETS price is weighted by the marginal cost parameter of the non-ETS and ETS sector, respectively.

4.3.3 *Environmental optimization*

Instead of optimizing national cost efficiency, policymakers might want to introduce a carbon price floor that optimizes national environmental effectiveness. That is, the country shifts its abatement effort between the ETS and non-ETS sector such that the national benchmark costs are attained at a higher abatement target. The national optimization problem is now given by

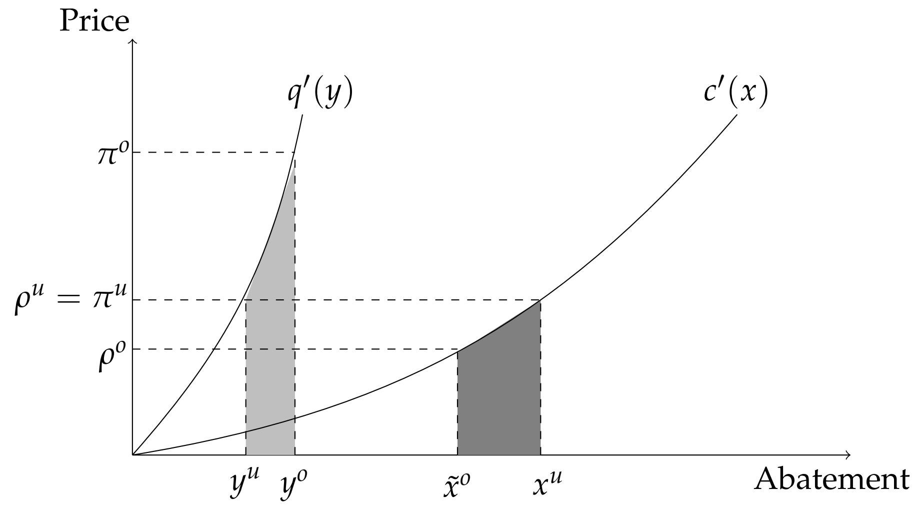
$$\begin{aligned} &\max_{x,y} \; x + y \\ \text{s.t.} \quad & c(x) + q(y) = C. \end{aligned} \tag{4.5}$$

Thus, under the national policy option *environmental optimization*, in the following denoted by the superscript u, the optimal abatement quantities x^u and y^u solve (4.5) for the case that the national benchmark abatement costs C^o are attained, i.e. $x^u, y^u = \arg\max(x+y)$ for $C = C^o$. This results in a higher abatement target z^u compared to the benchmark level z^o.

The policy option is also depicted in Figure 4.4 below. The additional costs in the ETS sector (the dark gray shaded area) equals the reduced costs in the non-ETS sector (the light gray shaded area). The overall abatement quantity increases from $\tilde{x}^o + y^o = z^o$ to $x^u + y^u = z^u$. Therefore, compared to the previous policy option, the optimal national price floor is higher, i.e. $\rho^u > \rho^\kappa$. The difference between the new and old target quantity i.e. environmental effectiveness is the highest at the optimal national price floor

$$\rho^u = c'(x^u) = q'(y^u). \tag{4.6}$$

Figure 4.4: Effectiveness of climate policy under national *environmental optimization*



Assuming simple linear MACCs as before, it is possible to derive a closed form solution of the optimal price floor which is again a weighted average of the old benchmark prices. Given (4.3) and

$$C^o = \frac{1}{2}\tilde{x}^{o2} + \frac{1}{2}y^{o2} = \frac{1}{2}\left(\frac{\rho^{o2}}{a} + \frac{\pi^{o2}}{b}\right),$$

solving $C^*(z^u) \stackrel{!}{=} C^o$ for z^u leads to

$$z^u = \sqrt{\frac{(a+b)\left(\rho^{o2}/a + \pi^{o2}/b\right)}{ab}}.$$

Thus, the optimal national price floor level under *environmental optimization* is given by

$$\rho^u = ax^u = \frac{ab}{a+b}z^u = \sqrt{\frac{ab}{a+b}\left(\frac{\rho^{o2}}{a} + \frac{\pi^{o2}}{b}\right)}. \tag{4.7}$$

4.4 EMPIRICAL ANALYSIS

We now extend our stylized one-country, two-sector model and conduct a numerical partial equilibrium analysis of the EU carbon market. The question is whether it is cost-efficient and effective if a certain EU country introduces a national price floor in the ETS sector. In order to do so, we need estimates of the MACCs for each of the 28 EU countries as well as Norway, Liechtenstein and Iceland, who also participate in the EU ETS. To this end, we follow Ellerman and Decaux (1998), Klepper and Peterson (2006) and Böhringer et al. (2008), among others, and obtain a sequence of carbon price and abatement quantity combinations from a computable general equilibrium (CGE) model solution for the year 2020. A brief description of the CGE model and its calibration to the actual EU emission reduction targets for 2020 is presented in the next section. After approximating the MACCs by least squares, we are able to evaluate the policy options from Section 4.3 empirically.

4.4.1 *Generation of marginal abatement cost curves*

In order to approximate the MACCs in the ETS and non-ETS sectors for each country that participates in the EU ETS, we generate a sequence of carbon price and emission level combinations from the Dynamic Applied Regional Trade (DART) model. DART is a multi-region, multi-sector recursive dynamic computable general equilibrium (CGE) model of the world economy including 21 EU regions (see Table 4.1 below).[2] The EU regions include all major EU countries as well as two aggregations of countries, namely the Baltic States and the Rest of the EU[3]. The economy in each region is modeled as a competitive economy with flexible prices and market clearing. All regions are connected through bilateral trade flows. The model is calibrated to the GTAP8 database, which includes production, trade as well as CO_2 emissions data for the base year 2007 (The Global Trade Analysis Project, 2012). The major exogenous drivers of the dynamic structure are the GDP projections, the savings rate, the depreciation rate, and the rate of change of the population. For each year and region, the representative agent's labor productivity is adjusted such that the

2 For a detailed description of the DART model see Weitzel et al. (2012) and Weitzel (2010).

3 The Rest of the EU includes Croatia, Romania, Bulgaria, Slovenia, Malta, Cyprus, Luxemburg, Liechtenstein and Iceland. Besides the 21 EU regions, the rest of world is aggregated to nine regions: North America, Latin America, India, China, Former Soviet Union, Pacific Asia, Middle East and Northern Africa, Subsaharan Africa and Rest of Annex B countries.

exogenous GDP path (OECD, 2014) is reached. The model horizon here is the year 2020.

The GTAP data for sectoral CO_2 emissions of fossil fuels resulting from final demand and intermediate input demand is linked to the consumption and production structure of DART. In a CGE model, the marginal abatement cost is defined as the shadow cost that is produced by a quantity constraint on CO_2 emissions for a given region and a given time. It is equal to the tax that would have to be levied on the emissions to achieve the targeted level or the price of an emission allowance in the case of emissions trading (Klepper and Peterson, 2006). This price is plotted against a corresponding abatement quantity, which is the difference in emissions levels between an unconstrained business-as-usual reference scenario and a constrained policy scenario. Here, for the EU regions, the policy scenario is characterized by emission constraints for the ETS and non-ETS sectors according to the EU's ETS cap and Effort Sharing Decision, respectively. For the rest of world regions, we assume that countries fulfill their emission targets stated in the 'Copenhagen Agreement' from 2012.

In general, there are two possibilities to generate individual MACCs. First, to generate the MACC of a particular country by varying its emission constraints while the rest of world does nothing regarding the abatement of emissions. Second, to generate the MACC of a particular country while the rest of world also undertakes abatement policies. Here, we follow the second approach and vary the constraints for each of the 21 EU regions in 2020 simultaneously while the rest of world emissions are constrained according to the Copenhagen pledges. Therefore, the national MACCs are not independent from one another since the marginal abatement cost in one country is affected by emission constraints in other countries via e.g. world energy prices as discussed in Klepper and Peterson (2006) and Morris et al. (2012). That is, when also policies in other countries are considered, energy prices fall which leads to higher emissions in the country of interest (absent its own policy). Therefore, it becomes more expensive to reach the same emission target and the MACC is shifted upwards in order to represent other countries' undertaken policies. Thus, by simultaneously varying the quantity constraints across countries and sectors as well as considering the constraints in the rest of world regions, the resulting MACCs are likely to have an intercept with the y-axis. As a result, the business-as-usual reference assumed here does not correspond to a reference scenario in which an abatement quantity of zero results in no marginal cost as it is assumed in the stylized model of Section 4.3.

Therefore, we assume non-linear MACCs of the form

$$\rho = c_i'(x_i) = \alpha_i x_i^3 + \beta_i x_i^2 + \gamma_i x_i + \delta_i \tag{4.8}$$

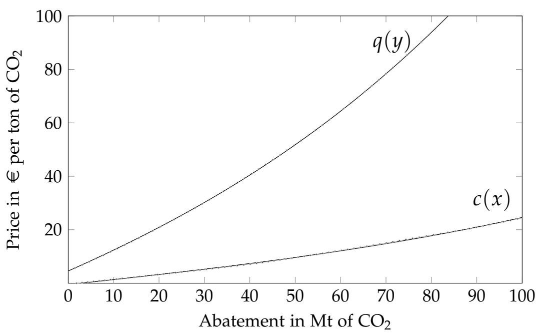
and

$$\pi_i = q_i'(y_i) = \zeta_i y_i^3 + \eta_i y_i^2 + \theta_i y_i + \mu_i \tag{4.9}$$

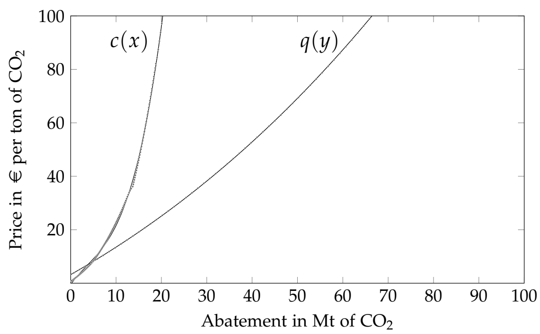
for $i = 1, \ldots, 21$ EU regions. Since the underlying GTAP data is in million US dollars, we convert the CO_2 prices with an exchange rate given by the GDP forecast in million Euro for the EU in 2020 from the European Commission (2018b) divided by the GDP in million US dollars of the DART model in 2020. The resulting exchange rate is 1\$=0.79 €. Inserting the sequence of abatement quantities $\tilde{x}_i$ and y_i in Mt and respective prices ρ and π_i in € per ton into (4.8) and (4.9), we fit the MACCs by least-squares to obtain estimates for the parameters $\hat{\alpha}_i$ to $\hat{\mu}_i$.

The fit of the OLS regression for selected EU regions is shown in Figure 4.5 below, where the dotted curves are absolute abatement levels obtained from the CGE model and the solid curves are the respective OLS fits. As assumed in Section 4.3, it is generally cheaper to abate emissions in the ETS than in the non-ETS sector. In this respect, France is an exception mainly because of its high share of nuclear power generation within the ETS sector.

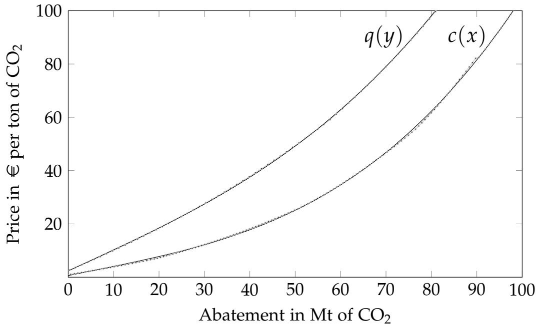
Figure 4.5: OLS fit of non-linear marginal abatement cost curves for the ETS and non-ETS sector in selected EU countries



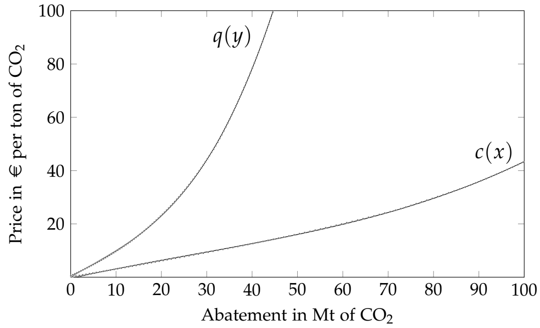
(a) Germany



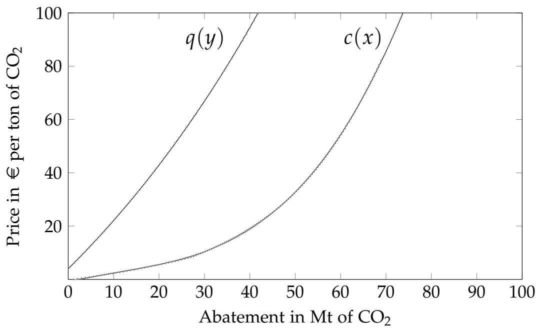
(b) France



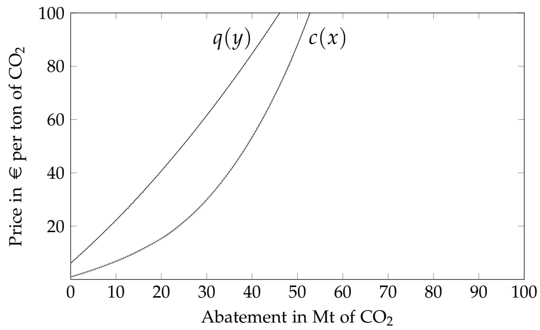
(c) UK



(d) Poland



(e) Spain



(f) Italy

Moreover, marginal abatement costs also differ across the different ETS and non-ETS sectors. Figure 4.7, Appendix A.1 shows selected MACCs of different sectors in Germany, France and the UK. In order to account for sector size, the x-axis shows the percentage abatement relative to the business-as-usual emissions in 2020. For all three countries, the electricity sector shows the cheapest abatement possibilities within the ETS sectors. The refined oil production sector shows the most expensive abatement possibilities within the ETS sectors in Germany and the UK. In France, abatement is the most expensive in the chemical sector. Within the non-ETS sectors, the coal mining sector shows the cheapest abatement possibilities in Germany and the UK. In France, it is the cheapest to abate emissions in the natural gas extraction sector. For all three countries, it is the most expensive to abate emissions in the mobility sector.

4.4.2 *Analysis of the EU carbon market*

We begin by calculating the EU ETS and non-ETS abatement targets for the year 2020 as follows. Table 4.1 summarizes the EU carbon market data based on the GTAP emissions in the DART model. The first column shows the baseline emissions in the year 2007. By running the DART model without any emission constraints until the year 2020, we obtain the business-as-usual emissions (second column). The major difference between the second (2008-2012) and third (2013-2020) phase of the EU ETS is the change from grandfathered national emission caps to an EU-wide cap. Therefore, in order to obtain the emission target of the ETS sector in the year 2020, we apply the country-specific allocation factors according to the National Allocation Plans for the second phase (European Commission, 2007), whereas for 2013-2020 we apply a yearly relative reduction of 1.74% p.a. for each EU region as envisaged by phase 3 of the EU ETS in order to obtain the EU-wide cap. Regarding the non-ETS sector, national emission targets are given by the Effort Sharing Decision (European Commission, 2009), which implies a reduction of 1.95% p.a. from 2013 to 2020 for each EU member country. The business-as-usual emissions less the emission targets then lead to abatement targets for the year 2020. The last column shows the resulting EU-wide emission reductions for the ETS and non-ETS sector in 2020 with 27% and 13% lower emission levels compared to 2007, respectively.

Table 4.1: EU emissions data and resulting abatement target for the year 2020

	Emissions in 2007 (Mt CO_2)		Business-as-usual emissions in 2020 (Mt CO_2)		Emission target in 2020 (Mt CO_2)		Abatement target in 2020 (Mt CO_2)		Reduction factor: 2020 to 2007 emissions	
EU region	ETS	non-ETS	ETS	non-ETS	ETS	non-ETS	ETS	non-ETS	ETS	non-ETS
Austria	20	44	12	48		39		9		
Baltic States	21	22	16	23		19		4		
Belgium	34	72	52	78		63		15		
Czech Rep.	76	34	84	43		30		13		
Denmark	25	47	17	51		41		10		
Finland	36	26	25	27		23		4		
France	91	299	59	303		261		42		
Germany	390	357	371	366		311		55		
Greece	56	155	66	186		135		51	↑	↑
Hungary	23	28	14	29		25		4		
Ireland	18	34	9	34	Joint target	29	Joint target	5	0.73	0.87
Italy	189	250	156	230		218		12		
Netherlands	67	104	61	118		91		27	↓	↓
Norway	7	60	5	59		52		7		
Poland	188	103	243	121		90		31		
Portugal	26	35	20	34		30		4		
Rest of EU	113	96	144	111		84		27		
Slovakia	15	14	21	18		12		6		
Spain	161	189	141	194		165		29		
Sweden	12	36	10	38		31		7		
UK	232	314	238	326		274		52		
Total	1801	2322	1764	2437	1318	2023	446	414	0.73	0.87

Note: In order to obatin the emission targets of the ETS sector in the year 2020, we apply the country specific allocation factors according to the National Allocation Plans for the second phase of the EU ETS (2008-2012), whereas from 2013 to 2020 we apply a reduction of 1.74% p.a. for each EU region as envisaged by phase 3 of the EU ETS. Regarding the non-ETS sectors, national emission targets are given by the Effort Sharing Decision (European Commission, 2009), implying a reduction of 1.95% p.a. from 2013 to 2020 for each EU member country.

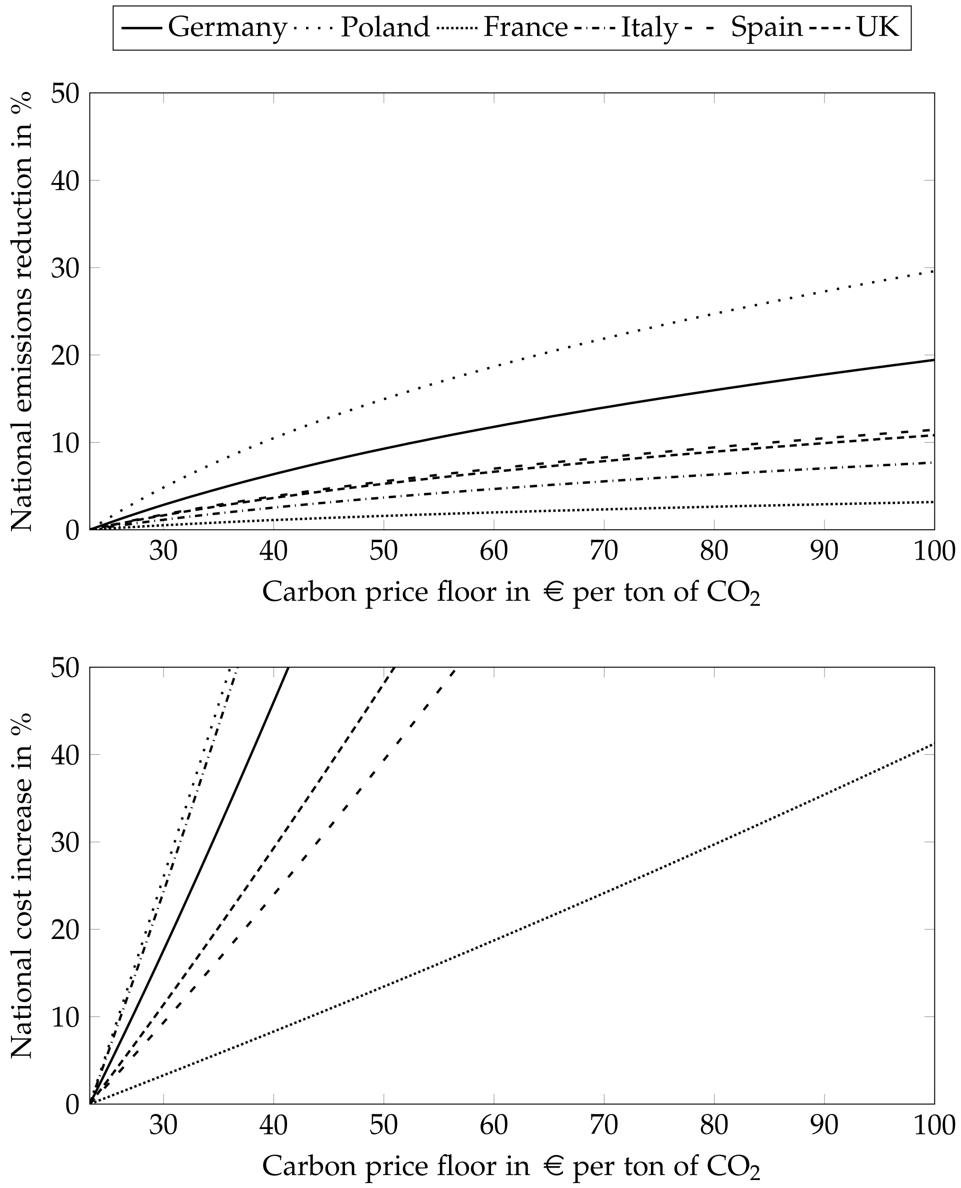
Given the estimates of parameters and the abatement targets from Table 4.1, we are now able to solve the partial equilibrium model for the benchmark situation with a fixed joint target for the ETS sector and individual national targets for the non-ETS sector. That is, we minimize abatement costs in the ETS sector across all countries subject to the joint EU ETS target denoted by Z, whereas the individual targets for the non-ETS sector are assumed to be met by national carbon taxes, i.e.

$$\begin{aligned} q_i(y_i) + \min_{x_i} \sum_i c_i(x_i) \\ \text{s.t.} \quad \sum_i x_i = Z. \end{aligned} \tag{4.10}$$

The resulting benchmark EUA price ρ^0 in the year 2020 is around 23 € per ton. The price is well in line with predictions of other energy-economy models for the year 2020 (cf. Knopf et al., 2013, p.22), though significantly higher than the actual EUA price of around 5 € per ton in recent years (2013-2018). For the discussion of possible reasons for the deviation between the actual price and predictions of energy-economy models, we refer to Edenhofer et al. (2014, p.14f.). National non-ETS benchmark prices π_i^0 range from 25 € per ton in Italy up to 105 € per ton in the Netherlands (see second column of Table 4.2). The total abatement costs of the partitioned EU carbon market in the second best solution (4.10) are 17bn € in the year 2020, of which 4.5bn € and 12.5bn € are abatement costs in the ETS and non-ETS sector, respectively. In the first best solution, in which all countries and sectors are included in the ETS, the efficient price is 37 € per ton. The total abatement costs in the first best solution are 13.6bn € and thus 25% lower than in the second best solution. This is within the range of results in e.g. Böhringer et al. (2008).

We now turn to the policy options from Section 4.3 and introduce a national carbon price floor in each of the 21 EU regions, but only in one country at a time. Figure 4.6 shows that the *climate levy* is a highly costly policy option with rather limited environmental effects. The top figure shows the national emissions reduction for the six largest EU emitters. We find that Poland and Germany show the highest potential to reduce national emissions. However, this policy option comes at significant costs for the country introducing the price floor as shown in the bottom graph of Figure 4.6. For instance, a price floor of 30 € per ton in Germany's ETS sector leads to an emissions reduction of only 2.9% (17 Mt) in 2020, but to a cost increase of 18% (447mn €).

Figure 4.6: National emissions reduction and cost increase of the *climate levy*



In contrast, in our two alternative policy options we suggest that policy-makers follow an optimization behavior. The results for the policy option *cost optimization* are shown in Table 4.2. The first two columns show the benchmark prices of the ETS and non-ETS sector in the second best solution. The optimal national price floor levels ρ^{κ} are shown in the third column. They range from 24 € per ton in Italy to 79 € per ton in Sweden. National cost reductions of the optimal price floors can be significant and savings are as high as 15-30% in almost half of the countries. In only one third of the countries the savings are less than 10%. Besides the country aggregation 'Rest of the EU', we find that Finland, Slovakia, and Belgium show the highest potential to reduce national abatement costs. By introducing a price floor of 38.3 €, 40.9 € and 52.9 € per ton, these countries are able to reduce costs by 32.5% (95mn €), 24% (61mn €), and 23.5% (162mn €), respectively. The policy leads to a significant shift in abatement costs between the ETS and non-ETS sector. In almost half of the countries, the costs in the ETS sector double, triple or even quadruple while the costs in the non-ETS sector only halve in most of the countries. From an EU-wide perspective, Germany shows the highest potential to reduce inefficiencies of the overall EU carbon market since it is the largest emitter. A national price floor of around 32 € per ton in Germany would lead to an EU-wide cost reduction of around 2.2% (370mn €) in 2020.

Table 4.2: Policy simulation results under national *cost optimization*

	ETS benchmark price in € per ton of CO_2 (ρ^0)	Non-ETS benchmark price in € per ton of CO_2 (π_i^0)	Optimal national carbon price floor in € per ton of CO_2 (ρ^κ)	National cost reduction in %	National cost change in ETS sector in %	National cost change in non-ETS sector in %	EU-wide cost reduction in %
Austria	23.3	81.1	58.0	17.6	328.4	-43.5	0.41
Baltic states	23.3	52.8	34.4	11.4	33.5	-52.2	0.10
Belgium	23.3	86.2	52.9	23.5	253.7	-57.3	0.95
Czech Rep.	23.3	86.3	33.0	22.2	41.5	-77.0	1.02
Denmark	23.3	98.8	68.2	20.9	275.0	-47.3	0.67
Finland	23.3	97.9	38.3	32.5	104.9	-82.4	0.56
France	23.3	56.6	49.2	6.8	145.6	-21.6	0.51
Germany	23.3	57.2	32.4	14.6	54.9	-63.0	2.17
Greece	23.3	49.7	39.9	7.7	75.3	-29.8	0.63
Hungary	23.3	42.0	33.0	6.1	94.9	-32.6	0.04
Ireland	23.3	47.4	40.5	6.1	43.3	-23.9	0.05
Italy	23.3	25.0	24.1	0.1	16.4	-7.2	0.00
Netherlands	23.3	104.5	75.9	19.4	407.4	-41.7	1.59
Norway	23.3	59.2	55.0	4.1	79.1	-12.2	0.05
Poland	23.3	45.6	27.3	6.5	22.2	-51.4	0.50
Portugal	23.3	54.8	37.4	12.4	75.1	-51.1	0.12
Rest of EU	23.3	90.6	38.7	29.0	105.1	-76.3	2.59
Slovakia	23.3	85.5	40.9	24.0	135.2	-65.3	0.36
Spain	23.3	65.2	40.6	17.0	69.3	-57.1	1.30
Sweden	23.3	104.2	78.5	19.0	278.3	-39.6	0.40
UK	23.3	52.0	36.1	10.9	92.0	-45.5	1.15

Note: The table shows national results for the case that only one of the respective EU regions introduces a national carbon price floor in 2020.

The results for the policy option *environmental optimization* are shown in Table 4.3. The first two columns show the benchmark abatement quantities in the ETS and non-ETS sector in the second best solution. The optimal national price floor levels ρ^u are again shown in the third column. Similarly to the previous policy, they range from 24 € per ton in Italy to 90 € per ton in Sweden. Compared to the cost reductions of the previous policy, the national emissions reduction of the optimal price floors are less significant and savings are only as high as 1-6%. We find that the Czech Republic, Finland and Slovakia show the highest potential to reduce national emissions without any additional costs. By introducing a price floor of 41 €, 50 € and 50 € per ton, these countries are able to reduce emissions by 5.8% (4.7 Mt), 5.5% (2.2 Mt), and 5.1% (1.3 Mt), respectively. In one third of the EU regions the emissions reduction is only around 1% or less. Therefore, the shift of emissions between the sectors is less significant than the shift of abatement costs in the previous policy. In more than one third of the countries, the emissions savings in the ETS sector are as high as 20-30% while the emissions in the non-ETS sector only increase by around 5-10%. From an EU-wide perspective, again Germany shows the highest potential to reduce inefficiencies of the overall EU carbon market. A national price floor of around 36 € per ton in Germany would lead to an EU-wide emissions reduction of around 0.3% (10.8 Mt).

Table 4.3: Policy simulation results under national *environmental optimization*

	ETS bench-mark abate-ment in Mt of CO_2 ($\bar{x}_i^0$)	Non-ETS bench-mark emissions in Mt of CO_2 (y_i^0)	Optimal national carbon price floor in € per ton of CO_2 (ρ^u)	National emissions reduction in %	National emissions change in ETS sector in %	National emissions change in non-ETS sector in %	EU-wide emissions reduction in %
Austria	2.6	9.5	65.3	2.3	-27.0	3.9	0.03
Baltic states	6.8	3.8	37.5	1.7	-14.9	5.1	0.01
Belgium	8.9	14.9	62.3	2.7	-14.9	5.6	0.08
Czech Rep.	32.7	13.0	40.9	5.8	-18.5	16.0	0.14
Denmark	5.5	10.4	79.6	3.0	-29.0	4.2	0.05
Finland	9.0	4.4	50.2	5.5	-25.5	8.9	0.06
France	10.5	42.4	51.3	0.6	-10.5	1.3	0.05
Germany	96.5	54.4	36.0	1.8	-10.8	6.0	0.32
Greece	22.0	50.9	42.1	1.4	-19.0	4.3	0.08
Hungary	2.8	4.2	34.3	0.6	-7.1	2.5	0.01
Ireland	2.2	5.0	42.1	0.5	-9.9	1.7	0.01
Italy	26.0	11.6	24.1	0.0	-0.4	0.2	0.00
Netherlands	8.0	26.9	87.2	2.3	-13.0	3.9	0.10
Norway	0.8	6.8	56.4	0.3	-9.9	0.5	0.00
Poland	68.0	30.6	28.6	1.2	-6.0	8.2	0.09
Portugal	5.9	4.0	41.0	1.2	-11.1	3.4	0.02
Rest of EU	37.4	27.5	49.5	5.3	-18.9	12.2	0.30
Slovakia	6.8	5.8	50.2	5.1	-20.7	12.3	0.04
Spain	43.8	29.3	46.3	1.9	-13.3	4.8	0.15
Sweden	1.8	6.7	89.8	2.0	-19.9	2.6	0.02
UK	47.8	52.2	39.0	1.1	-8.4	4.0	0.16

Note: The table shows national results for the case that only one of the respective EU regions introduces a national carbon price floor in 2020.

4.4.3 *Discussion*

Our policy simulations for the EU carbon market show that there are possibilities for effective and cost-efficient additional national climate policy efforts. The introduction of a *climate levy* is in principle already possible, especially since the establishment of the MSR that allows for retiring allowances. However, instead of imposing the levy only on certain power stations as intended by the German proposal from 2015, we suggest to introduce a true national carbon price floor for all emitters in the ETS. Nevertheless, our empirical results show that such a policy option, in which allowances are only retired but not shifted between sectors, is very expensive and has only limited effects on national emissions reduction.

Compared to the *climate levy*, our two alternative policy options, in which emission targets are fully or partially shifted from the ETS to non-ETS sectors, are not yet possible in practice since the non-ETS targets are fixed in the EU Effort Sharing Decision (European Commission, 2009). However, we argue that such an option is advisable. In fact, the more recent plan of the German government to buy additional EUAs from other member states in order to compensate for missing its non-ETS target goes in a similar direction (Tutt, 2018). Moreover, since our two policies do not interfere with all EU targets but only increase the options for more ambitious countries, it may be easier to agree on compared to other reforms. Further, if it would be possible for a country to reduce national costs or emissions according to our suggestions, other countries might follow which could create a momentum for introducing an EU-wide price floor in the ETS sector as suggested by e.g. Edenhofer and Schmidt (2018).

In order to put our simulation results into context, we compare our estimates of the optimal national price floor levels from Section 4.4.2 with price floors that have been discussed in certain EU countries, even though they do not include any retirement of allowances and shifting of targets. Thus, they do not imply any emissions reduction and further increase EU-wide inefficiencies as shown by Böhringer et al. (2008) and Heindl et al. (2014). A price floor as for instance announced in France (The Guardian, 2016) will simply increase national and EU-wide costs without being effective because the additional abatement is offset by EU ETS sectors outside France not facing the price floor.

We find that the announced French price floor of 30 € per ton would lead to additional cost of 43mn € in the year 2020, which corresponds to an increase of national and EU-wide abatement costs by 3.3% and 0.25%, respectively. According to our policy simulations, France shows generally little potential to reduce national abatement costs or emissions. The optimal price floor levels of 49 € per ton under *cost optimization* and 51 € per ton under *environmental optimization* lead to national cost and emission reductions of 6.8% (87mn €) and 0.6% (1.7 Mt) in 2020, respectively.

In addition to introducing a national price floor, France tried to convince Germany of jointly establishing a price floor in the ETS sector in order to create a momentum for other European countries (De Beaupuy and Amiel, 2016). Similar to the cost effects of the *climate levy*, such a simple price floor of 30 € per ton in Germany would lead to additional cost of 447mn € in 2020. However, in contrast to the *climate levy*, the price floor has no effect on the EU-wide emission level. The additional cost of 447mn € correspond to a national and EU-wide cost increase of around 18% and 2.6%, respectively. Nevertheless, if allowing for shifting emission targets, the idea is promising since Germany shows the highest potential for reducing EU-wide inefficiencies of the carbon market. Besides, a price floor of 30 € per ton comes close to our estimates of the optimal level.

Finally, we may compare our results with the UK price floor of 25 € per ton, which was introduced in 2013 when the actual EUA price was only around 5 € per ton. Thus, at that time, the UK price floor corresponded to a tax of around 20 € per ton on top of the EUA price. In our simulations for the year 2020, the benchmark EUA price is 23 € per ton and thus much higher than the actual price of 5 € per ton between 2013 and 2018. Therefore, as a rough approximation, we estimate the additional cost of the UK price floor by the introduction of a price floor of 43 € per ton in our setting. We find that the additional cost amount to 593mn € in 2020, which corresponds to a national and EU-wide cost increase of 33% and 3.5%, respectively. Yet again, the UK price floor does not reduce the EU-wide emission level. Regarding our two alternative policy options, we estimate optimal price floor levels for the UK of 36 € per ton under *cost optimization* and 39 € per ton under *environmental optimization*. These would lead to a national cost reduction of 11% (195mn €) and emissions reduction of 1.1% (5.2 Mt).

All in all, we find that both our policy options are very promising from a national perspective. However, under *cost optimization* policymakers have to be aware that the price floor leads to a significant shift of costs between ETS and non-ETS sectors. Under *environmental optimization*, the potential for national emissions reduction at basically no extra cost is rather limited. According to our analysis, the German *climate levy* proposal would have been a highly costly policy option while its cost efficiency results can hardly be determined since both costs and benefits change.

In any case, our empirical results have to be taken with care since our policy options are very stylized. In practice, it would be very hard to monitor how much emissions may be shifted from the ETS to non-ETS sector or retired due to the price floor. Policymakers would need to have reliable estimates of abatement costs for specific sectors or firms. Further, there exist huge sectoral differences in abatement costs within the ETS and non-ETS sectors (recall Figure 4.7, Appendix A.1). Therefore, potential cost or emission reductions very much depend on whether coal-fired power plants in the electricity sector or rubber production plants in the chemical sector face the price floor. Policymakers might increase emission targets in ETS sectors that face high marginal abatement costs but relax targets in non-ETS sectors that face low marginal abatement costs which may even result in efficiency losses. That is, our assumption that it is usually more expensive to abate emissions in non-ETS sectors ignores the large innovation potential with regard to abatement technologies in sectors such as transport and housing.

Yet, a pragmatic approach may be to implement a price floor in the order of 30 € per ton, which roughly is a lower bound in our estimates, in order to use the revenue to buy EUAs and retire them. Then, abatement efforts in the non-ETS sectors can be reduced by the same amount (*cost optimization*) or a smaller amount (*environmental optimization*). In most countries where there is strong evidence that more abatement should take place within the ETS and less outside, these policies are likely to decrease overall costs or to achieve additional emissions reduction at basically no extra costs.

4.5 CONCLUSION

In this paper, we explored the potential scope and optimal design of national climate policy in the current EU policy framework. The question is whether certain carbon pricing policies in the national EU ETS sectors, although interfering with the EU ETS, can reduce emissions (and thus be effective) and abatement costs (and thus be cost-efficient). While additional national climate policy efforts analyzed in previous papers are always found to be inefficient, we find that this does not need to be the case if policies are designed in such a way that they allow for retiring emission allowances as well as shifting emission targets from the ETS to non-ETS sectors.

Therefore, we discuss three carbon pricing policy options. First, a carbon price floor that simply allows for retiring emission allowances as stipulated by the Germany *climate levy* proposal from 2015. Secondly, a carbon price floor in which national policymakers follow a *cost optimization* behavior by fully shifting additional reduction targets from the ETS to non-ETS sectors as well as retiring emission allowances. Thirdly, a carbon price floor in which national policymakers follow an *environmental optimization* behavior by partially shifting additional reduction targets from the ETS to non-ETS sectors as well as retiring emission allowances. The latter two options allow for either achieving the same emission target as before at lower abatement costs or achieving a higher emission target at the same abatement costs as before.

In a simple theoretical framework with one country and two sectors, we argue that introducing a *climate levy* in the national ETS sector is likely to be a highly costly policy option while its cost efficiency results are very unclear. Therefore, we rather suggest to follow an optimization behavior when introducing a carbon price floor. We show that this is possible by shifting emission targets between sectors in order to hedge against the differences in marginal abatement costs across sectors. In this regard, we derive the optimality conditions for the carbon price floor level under *cost* and *environmental optimization* behavior, respectively. Moreover, we are able to derive a closed form solution for the optimal price floor level for both these policy options. According to that, the optimal price floor level is a weighted average of the old carbon prices in the ETS and non-ETS sector before the introduction of the policy.

In order to determine the empirical relevance for the EU, we conduct a numerical partial equilibrium analysis of the EU carbon market in 2020. The current inefficiency in the already second best benchmark situation with two carbon markets, one with emissions trading and one without, leads to additional costs of around 3.4bn €. Thus, total abatement costs are 25% higher compared to a market with all sectors included in the EU ETS.

We find that the *climate levy* is a highly costly policy option with rather limited environmental effects. For instance, the introduction of a price floor of 30 € per ton in Germany's ETS sector leads to an emissions reduction of only 2.9% (17 Mt) in 2020, but to a cost increase of 18% (447mn €). In contrast, our two alternative policy suggestions are very promising from a national perspective without interfering with the EU ETS. Under *cost optimization*, the optimal price floor levels range from 24 € per ton in Italy to 79 € per ton in Sweden. The resulting national cost reductions can be significant and savings are as high as 15-30% in almost half of the EU countries. For instance, the introduction of a price floor of 32 € per ton in Germany would lead to cost savings of 370mn € in 2020, corresponding to a national and EU-wide cost decrease of 14.6% and 2.2%, respectively. Under *environmental optimization*, the optimal price floor levels are very similar to the previous policy, but slightly higher because a lower emission target is reached. Compared to the cost savings under *cost optimization*, the national emission reductions of the optimal carbon price floors are less significant and emissions savings are only as high as 1-6%. However, these savings come at basically no extra costs. For instance, the introduction of a price floor of 36 € per ton in Germany would lead to emission savings of around 11 Mt in 2020 without any addition costs, corresponding to a national and EU-wide emissions reduction of 1.8% and 0.3%, respectively.

Despite the stylized nature of the three policies discussed in the course of this paper, we conclude that national climate policy efforts can indeed be effective and cost-efficient in the current EU policy setting. The retirement of emission allowances is in principle already possible since the establishment of the MSR. The shift of abatement efforts from the non-ETS to ETS sectors is not possible within the current framework, but we argue that such an option is very attractive from a national perspective.

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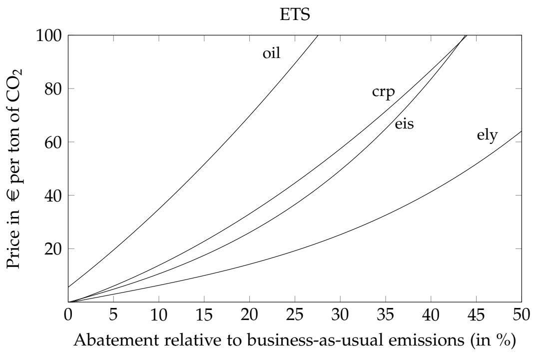
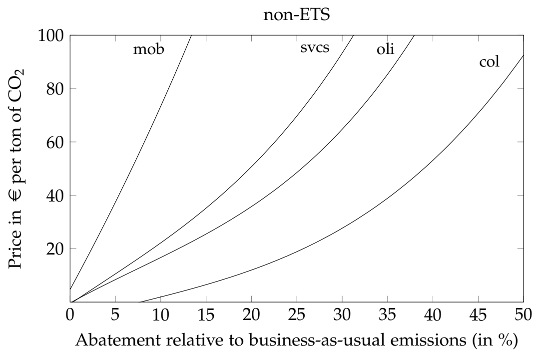
A APPENDIX TO CHAPTER 4

A.1 *Sectoral marginal abatement cost curves*

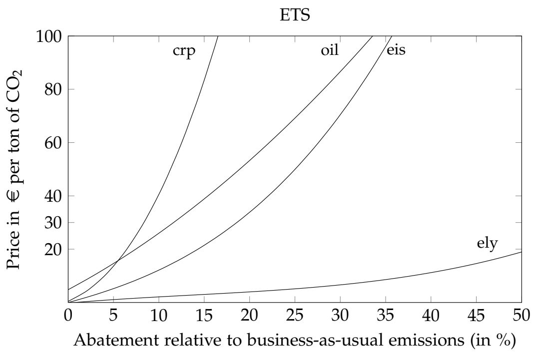
Figure 4.7: OLS fit of non-linear sectoral marginal abatement cost curves in selected ETS and non-ETS sectors of Germany, France and the UK



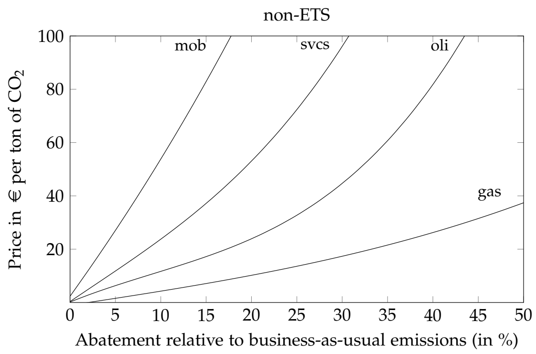
(a) Germany



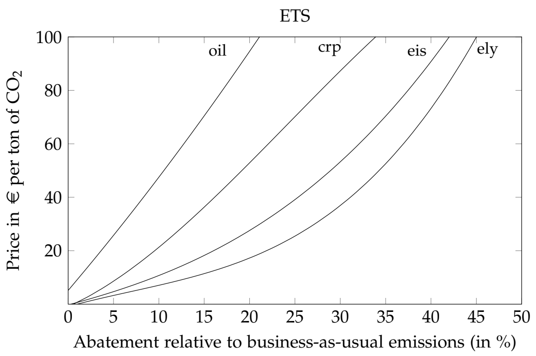
(b) Germany



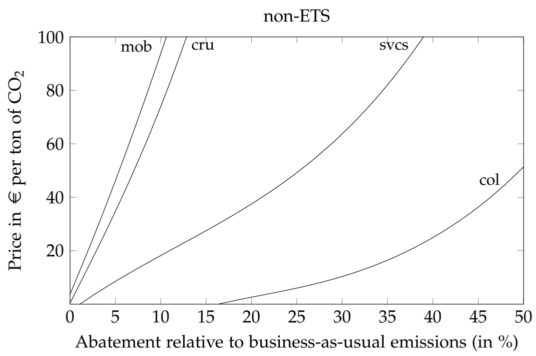
(c) France



(d) France



(e) UK



(f) UK

Note: oil, refined oil products; crp, chemical and rubber products; eis, energy intensive sectors; ely, electricity; mob, mobility; svcs, services; ohi, other heavy industries; oli, other light industries; col, coal; cru, crude oil production.

ERKLÄRUNG ZUM SELBSTSTÄNDIGEN VERFASSEN DER ARBEIT

Ich erkläre hiermit, dass ich meine Doktorarbeit

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selbstständig und ohne fremde Hilfe angefertigt habe und dass ich als Koautor maßgeblich zu den weiteren Fachartikeln beigetragen habe. Alle von anderen Autoren wörtlich übernommenen Stellen, wie auch die sich an die Gedanken anderer Autoren eng anlehnenden Ausführungen der aufgeführten Beiträge wurden besonders gekennzeichnet und die Quellen nach den mir angegebenen Richtlinien zitiert.

Kiel, den 29. März 2019 Johannes Burmeister