Environmental Taxation and Structural Change in an Open Economy

A CGE Analysis with Imperfect Competition and Free Entry

Christoph Böhringer, Heinz Welsch and Andreas Löschel

Non-technical summary

To combat global warming several European countries have introduced carbon taxes. The latter imply a shift in comparative advantage, depending on the level of the carbon tax and the degree to which various industries differ in terms of emission intensity. There has been extensive empirical work on the economic adjustment induced by environmental taxes in open economies under the assumptions of constant unit costs and perfect competition. What has been largely ignored, however, is that these shifts in comparative advantage may be significantly reinforced under imperfect competition where changes in market structure affect both production costs as well as markup rates. Under conditions of imperfect competition with free entry and exit, the number and size of firms and, hence, their ability to exploit economies of scale depend on the elasticity of market demand. If market demand is composed of domestic demand and export demand, each characterized by a different demand elasticity, the elasticity of total market demand will depend on the shares of domestic sales and sales abroad. To the extent that environmental taxes lead to a shift in comparative advantage, these shares will change, and so will firm size and unit costs, i.e. economies of scale.

This paper uses a multi-sector computable general equilibrium model for Germany to examine the impacts of a unilateral national carbon tax under both perfect and imperfect competition on goods markets. Under imperfect competition, we find that economies of scale decline in industries which lose comparative advantage, whereas economies of scale increase in industries whose comparative advantage improves. The key to these results is the empirical evidence that the elasticity of demand is typically higher for sales abroad than for sales in domestic markets. As a consequence of induced changes in the economies of scale, the degree of structural change is larger under imperfect competition than under perfect competition. At the macroeconomic level, the costs of environmental regulation under imperfect competition turn out to be higher than under perfect competition for the German economy, because on the whole the changes in economies of scale across imperfectly competitive sectors are negative.

Environmental Taxation and Structural Change in an Open Economy

A CGE Analysis with Improper Competition and Free Entry[*]

Christoph Böhringer[a], Heinz Welsch[b] and Andreas Löschel[c]

Abstract

The economic effects of environmental taxes depend on the market structure. Under imperfect competition with free entry and exit, environmental taxes have an impact on economies of scale by changing the number and size of firms. Whether economies of scale rise or fall in a particular industry depends on induced changes in the price elasticity of demand. Because export demand is more price elastic than domestic demand, the overall price elasticity rises (falls) as the industry gains (loses) in comparative advantage. We use a computable general equilibrium model for Germany to examine the effects of a unilaterally introduced carbon tax under both perfect and imperfect competition. Our key finding is that induced structural change in favor of the less energy intensive, more labor intensive industries is more pronounced under imperfect competition than under perfect competition. At the macroeconomic level, the total costs of environmental regulation under imperfect competition can be higher or lower than those under perfect competition depending on whether aggregate gains or losses in economies of scale across imperfectly competitive sectors prevail.

JEL classification: D43, D58, L13, Q25

Keywords: environmental taxation, imperfect competition, structural change

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1. Introduction

For decades, the theory of environmental policy has recommended environmental taxes, or likewise tradable emission permits, on the grounds that they provide a cost-effective means of environmental regulation. In view of the need to combat global warming and the relative ease of designing an appropriate tax scheme for CO_2 as the most important greenhouse gas, environmental taxes have recently become popular in the political arena, too. Several European countries have introduced environmentally motivated taxes on energy, but most of these tax initiatives deviate from the basic principles of environmental taxation in various regards. In addition to not being based on the carbon content of different energy carriers, tax schemes typically involve reduced tax rates or tax exemptions for industries that are energy intensive and/or export-oriented. The motivation for this type of unequal treatment is the intention of protecting these industries against a loss in 'international competitiveness' (see e.g. Böhringer and Rutherford 1997).

From a theoretical perspective, it is evident that a tax strictly in proportion to emissions implies a shift in comparative advantage, depending on the degree to which several industries differ in terms of emission intensity. What has been largely ignored, however, is that these shifts in comparative advantage may be significantly reinforced under imperfect competition where changes in market structure affect both production costs as well as markup rates. Under conditions of imperfect competition with free entry and exit, the number and size of firms and, hence, their ability to exploit economies of scale depend on the elasticity of market demand. If market demand is composed of domestic demand and export demand, each characterized by a different demand elasticity, the elasticity of total market demand will depend on the shares of domestic sales and sales abroad. To the extent that environmental taxes lead to a shift in comparative advantage, these shares will change, and so will firm size and unit costs, i.e. economies of scale.

This paper uses a multi-sector computable general equilibrium model for Germany to examine the impacts of a unilateral national carbon tax under both perfect and imperfect competition on goods markets. Under imperfect competition, we find that economies of scale decline in industries which lose comparative advantage, whereas economies of scale increase in industries whose comparative advantage improves. The key to these results is the empirical evidence that the elasticity of demand is typically higher for sales abroad than for sales in domestic markets (Burniaux et al. 1992).[1]

As a consequence of induced changes in the economies of scale, the degree of structural change is larger under imperfect competition than under perfect competition. At the macroeconomic level, the costs of environmental regulation under imperfect competition turn out to be higher than under perfect competition for the German economy, because on the whole the changes in economies of scale across imperfectly competitive sectors are negative.

Given that any assessment of the structural effects of environmental taxes in open economies is crucially affected by market structure and the induced changes thereof, it is surprising that the literature seems to have largely ignored the impact of environmental taxes on market structure. Whereas general equilibrium models with scale economies and endogenous market structure are standard tools in the analysis of trade policy (see, e.g., Harris 1984, Norman, Branson and Winters 1990, Capros, Karadeloglou and Mentzas 1991, Willenbockel 1994), environmental economics has mostly addressed market structure in a partial-equilibrium framework (see, e.g., the contributions in Carraro, Katsoulacos and Xepapadeas 1996), which, by definition, does not allow the analysis of structural change. An early environmentally-oriented computable general equilibrium model with imperfect competition on good markets is presented by Conrad and Wang (1993), but in this model, as in the partial equilibrium models, firm numbers and scale economies are fixed.

The paper is organized as follows. Section 2 provides a non-technical overview of our analytical framework. Section 3 presents the simulation results and their economic interpretation. Section 4 summarizes and concludes.

2. The Model

2.1 General Framework

This section presents the main characteristics of our comparative static multi-sector computable general equilibrium (CGE) model for the German economy, which is designed to assess the medium-run effects of carbon/environmental taxes on trade and industrial structure

[1] Unlike the elasticity on the export market, the elasticity on the domestic market is derived from production and consumption elasticities which are typically less than one. See, e.g., Burniaux et al. (1992).

(see Appendix 1 for an algebraic model formulation). The analysis covers 13 sectors and 3 primary factors as described in Table 1. The sectoral aggregation captures key dimensions in the analysis of greenhouse gas abatement, such as differences in carbon intensities and the degree of substitutability across energy goods and carbon-intensive non-energy goods. The energy goods identified in the model are hard coal (HCO), lignite (SCO), crude and refined oil (OIL), natural and manufactured gases (GAS) and electricity and steam (ELE). The non-energy sectors include important carbon-intensive and energy-intensive industries that are potentially most affected by carbon abatement policies, such as basic materials and chemical products (MMC), investment goods (EQP) and transport (TRN). The rest of the economy is divided into agricultural production (AGR), consumption goods (CSG), construction (CST), private services (SER) and public services (PUB). Primary factors include labor (LAB), capital (CAP) and fossil-fuel resources (RES). Labor and capital are treated as perfectly mobile across sectors whereas fossil-fuel resources are sector-specific. Factor markets are treated as perfectly competitive.

Table 1: Sectors and primary factors in the general equilibrium model for Germany

Commodities		Primary factors	
AGR	Agricultural goods	CAP	Capital
MMC	Basic materials / chemical products	LAB	Labor
EQP	Investment goods	RES	Sector-specific resource
CSG	Consumption goods		
CST	Construction		
TRN	Transport		
SER	Private services		
PUB	Public services		
HCO	Hard coal	FOS	Fossil fuels
SCO	Lignite	FOS	Fossil fuels
OIL	Crude oil and refined oil products	FOS	Fossil fuels
GAS	Natural and manufactured gases	FOS	Fossil fuels
ELE	Electricity and steam		

Production

Nested constant elasticity of substitution (CES) cost functions are employed to specify the substitution possibilities in domestic production between capital, labor, energy and material (non-energy) intermediate inputs.

Figure 1 illustrates the nesting structure employed for production sectors other than fossil fuels and electricity. Output is produced with fixed-coefficient (Leontief) inputs of intermediate non-energy goods and an aggregate of energy and a value added composite. The value-added composite consists of a CES aggregation of capital and labor. The energy aggregate is, in turn, produced with a CES function of electricity and a composite of primary energy inputs. The primary energy composite is then defined as a CES function of a CES aggregate of hard coal and lignite and a CES aggregate of refined oil and natural gas. In the production of electricity, the primary energy composite is defined as a CES function of oil and an aggregate of coal and gas. The coal-gas composite is a CES function of gas and a CES aggregate of hard coal and lignite. In the production of fossil fuels, labor, capital and fossil fuel inputs are aggregated in fixed proportions at the lower nest. At the top level, this aggregate trades off with the sector-specific fossil fuel resource at a constant elasticity of substitution. The latter is calibrated in consistency with exogenously given price elasticities of fossil fuel supplies.

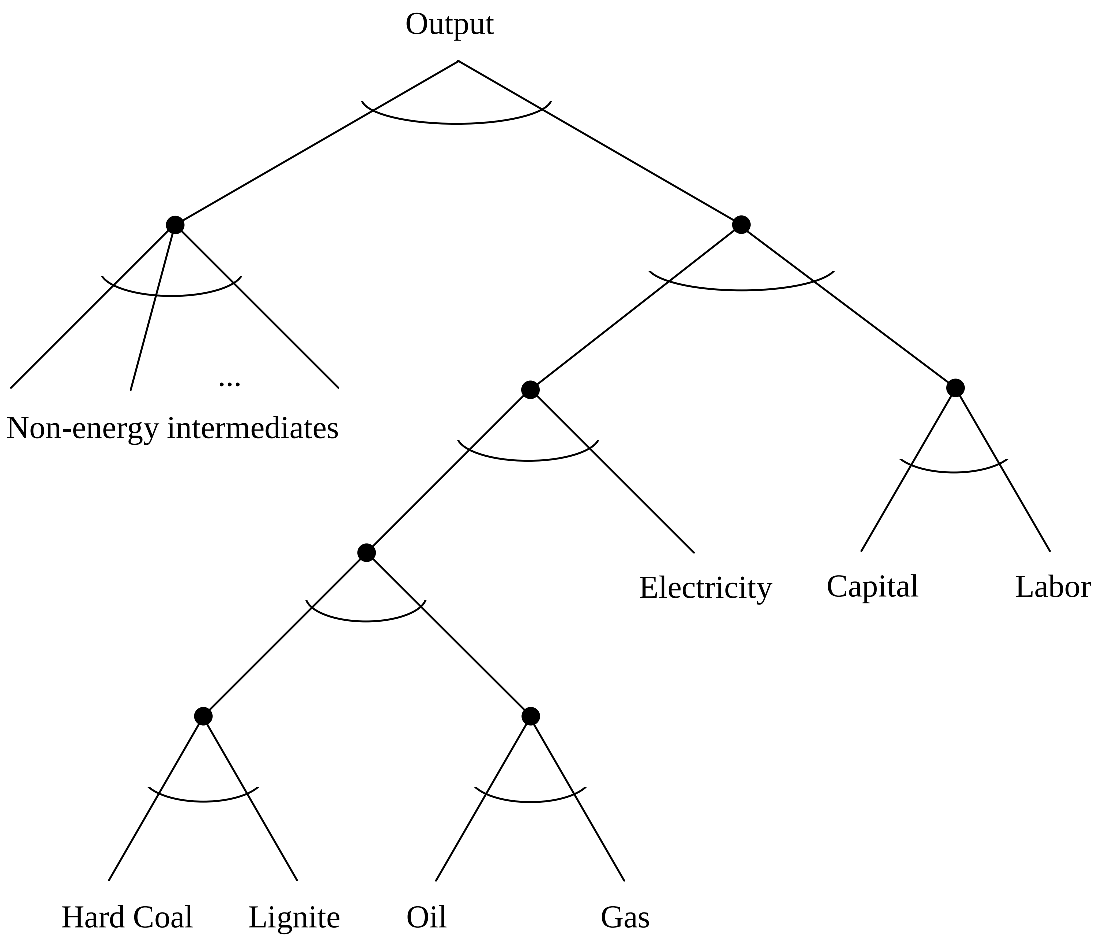

Figure 1: Structure of production

The model allows for perfect as well as imperfect competition on good markets. Imperfect competition due to fixed costs is modeled as a Cournot oligopoly with free market entry/exit, i.e. each domestic industry consists of identical firms, whose number is determined by the zero profit condition in conjunction with fixed costs and free market entry/exit (see section 2.2 and Appendix 2).

Private demand, government and investment demand

Private demand for goods and services is derived from utility maximization of a representative household subject to a budget constraint. Total income of the representative household consists of factor income and transfers. Utility is derived from real consumption and savings. The top level of the utility function is specified as a Cobb-Douglas function resulting in a constant savings rate. Real consumption of the representative agent is a CES composite of an energy aggregate and a Cobb-Douglas non-energy composite. The energy composite is defined as a CES function of electricity and the primary energy composite. The primary energy composite is given as a CES function of hard coal, lignite and a CES aggregate of oil and gas. The structure of final demand is given in Figure 2.

Government and investment demand is fixed exogenously. The public good consists of intermediate inputs in fixed proportions, the investment good is a Cobb-Douglas aggregate of intermediate inputs.

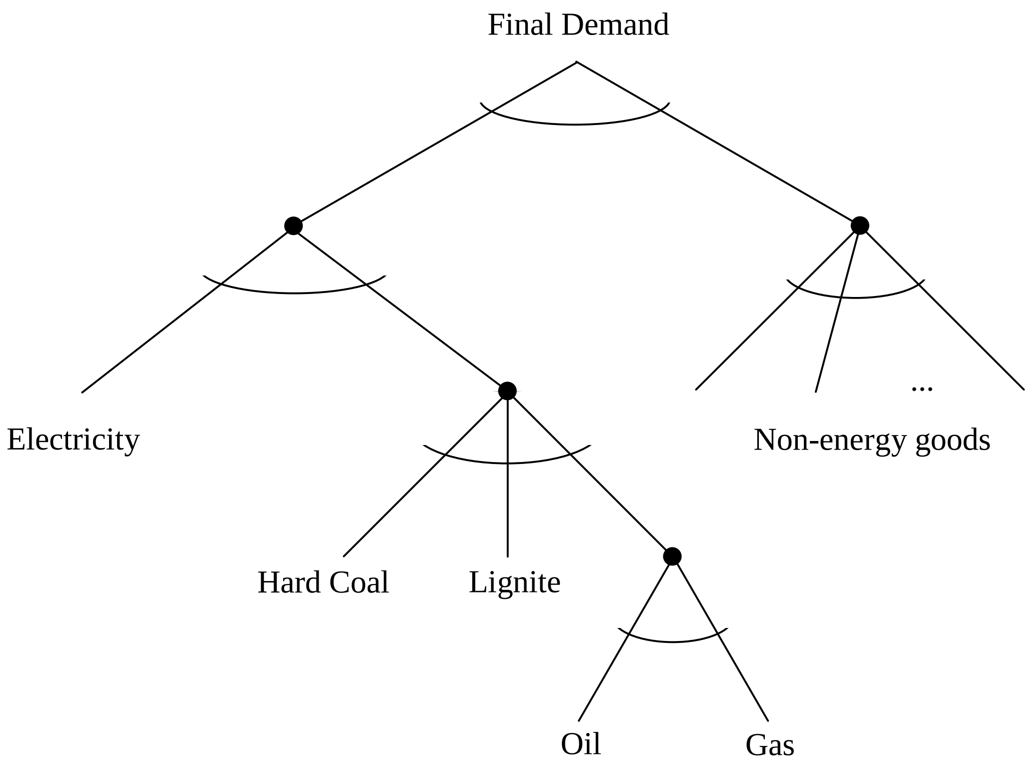

Figure 2: Nesting structure for final demand

International trade

All goods are traded internationally. According to Armington (1969), foreign trade modeling involves international product differentiation in the sense that imported and domestically produced goods of the same kind are treated as incomplete substitutes. For each product variety (Armington aggregate) the substitution possibility between the domestically produced good and the world import good is described by a CES function. The world import goods, in turn, are given as a CES aggregate of exports from Germany and exports from the rest of the world (ROW). The ROW closure requires that the value of imports to ROW are equal to the value of exports from ROW after including a constant benchmark trade surplus (deficit). Exports from ROW are determined by an export supply function. An endogenous exchange rate assures that demand equals supply for ROW exports.

2.2 Market Structure

Starting with the seminal work by Krugman (1979), theoretical and empirical work in the field of international trade has increasingly adopted scale economies and imperfect competition as a standard framework(for an overview see Helpman and Krugman 1985). By contrast, international aspects of environmental policy have mostly been examined under the more traditional assumptions of constant unit costs and perfect competition (see, e.g., Felder and Rutherford 1993, Pezzey 1992, Oliveira-Martins, Burniaux and Martin 1992, Manne and Oliveira-Martins 1994, Welsch 1996, Harrison and Rutherford 1999, Bernstein et al. 1999, Conrad and Schmidt 1998, Böhringer 2000).

Within the general framework described in section 2.1, each sector can deliberately be modeled as being perfectly or imperfectly competitive. Imperfect competition, if present, is due to fixed costs, not to regulation of entry. In the presence of fixed costs; the number of firms is determined by the usual zero-profit condition.

There are several ways in which imperfect competition can be specified. In the case of monopolistic competition (Krugman 1979), there are several incompletely substitutable varieties of each good, and each firm in a particular industry supplies exactly one variety. Since the elasticity of substitution is the same for all pairs of varieties, there is no differentiation between domestic and foreign suppliers.

In contrast to this assumption, we choose a set-up in which varieties from the same country of origin are closer substitutes for each other than are varieties from different countries. This is in the spirit of Armington (1969), who introduced the theory of demand for goods distinguished by place of production. More specifically, we assume that all domestic varieties are perfect substitutes for each other, as are all foreign varieties, but that domestic and foreign varieties are incomplete substitutes. This specification avoids the difficulty of selecting intra-country elasticities of substitution; the inter-country (Armington) elasticities are available from econometric estimation or literature search (see Appendix 3).

In the presence of fixed costs, the chosen set-up implies that domestic suppliers form a Cournot oligopoly. The market demand facing these suppliers reflects the fact that domestic varieties compete with incompletely substitutable varieties from abroad. As usual in Cournot oligopoly, prices are a markup over marginal costs, where the markup rate reflects the number of firms and the elasticity of market demand (see Appendix 2).

With respect to the demand elasticity, it should be observed that market demand is the sum of several demand categories: intermediate demand from the various production sectors, consumption demand, investment demand, and export demand. The price elasticity of market demand is the weighted average of the elasticities of the individual demand categories, each weighted with the corresponding value share. As environmental taxes affect these shares, the elasticity of market demand is also affected, as are the markup rates. If the elasticity of market demand rises, the markup drops and firms are driven out of the market. As a consequence, economies of scale become effective, and both unit costs and prices fall. The reverse happens if the value shares change in such a way that the overall demand elasticity gets reduced (see Figure 3).

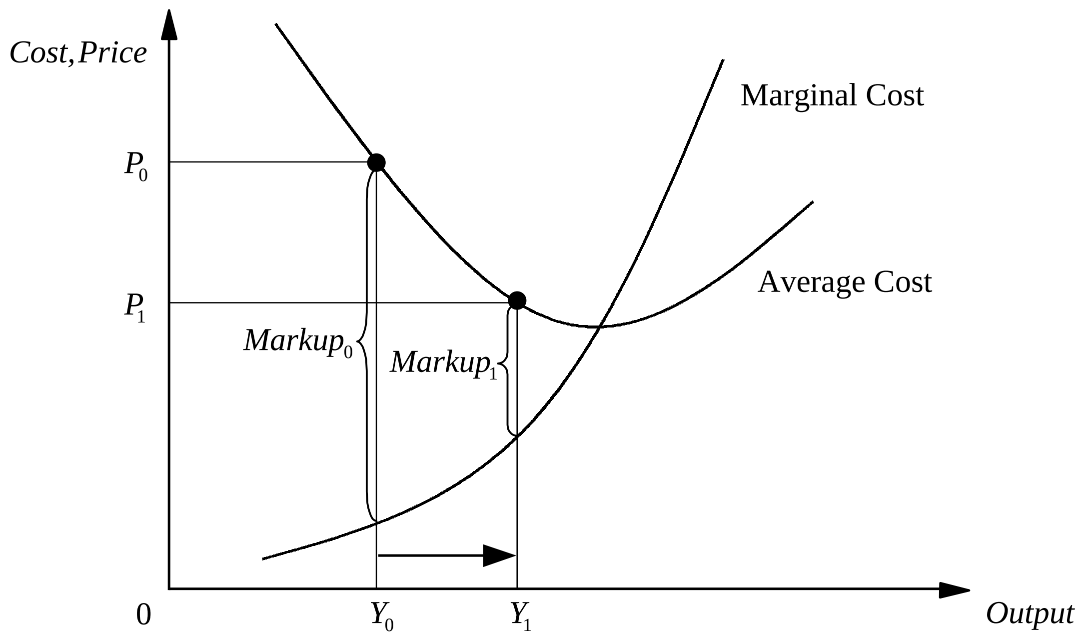

Figure 3: Cost curves under imperfect competition due to fixed costs

2.3 Data and Parameterization

Benchmark data are used to calibrate parameters of the functional forms from a given set of quantities, prices and elasticities. Data from two different sources are combined to yield a consistent benchmark data set for 1995:

- EUROSTAT Input-Output-Table for Germany with 25 sectors (Beutel 1999, EUROSTAT 1999).
- IEA energy balances and energy prices/taxes (IEA 1999). IEA provides statistics on physical energy flows and energy prices for industrial and household demands.

The information from IEA energy balances and energy prices is used to split up the aggregate energy sector, as given in EUROSTAT's input-output table for Germany, into the 5 energy sectors described above. Our choice of elasticities is mostly based on reviews of the relevant literature (see, e.g. Burniaux et al. 1992). The Armington elasticities between domestic output and imports have been estimated on time series data from the 'NEW CRONOS' databank of EUROSTAT (for details, see Böhringer et al. 2000).

Estimates of markup rates in various industries can be found in Capros et al. (1997). These estimates suggest that, in terms of our sectoral classification, imperfect competition can be taken to prevail in the sectors 'basic materials and chemicals' (MMC) and 'investment goods' (EQP). The markup rates determine the share of fixed costs in total costs. Fixed costs are treated as part of capital costs. Appendix 3 provides a summary of key elasticities and the markup rates employed for our simulations.

3. Simulation Results

Our simulations refer to a uniform tax on carbon dioxide that is unilaterally introduced in Germany to achieve the country's declared target of reducing its carbon emissions until 2005 by 25 percent as compared to 1990 emission levels (Bundesregierung 2000). Since BaU (Business as Usual) emissions in 2005 are projected to be 14 percent below 1990 levels (see European Commission 1999), this target implies an effective abatement requirement of 11 percent below BaU. The revenue from the carbon tax is redistributed to private households in a lump-sum fashion. Simulations have been performed under several assumptions concerning market structure. We contrast a scenario in which we assume perfect competition on all markets (scenario PC) with a scenario where the sectors MMC and EQP are imperfectly competitive (scenario IC). The effects arising in the latter scenario are decomposed into the contributions of each of the two imperfectly competitive sectors (scenarios IC_MMC and IC_EQP).

3.1 Macroeconomic Effects

Table 2 shows the required rate of the carbon tax and the induced percentage changes in macroeconomic indicators as compared to the benchmark level. In the case of all markets being perfectly competitive (column PC) the tax rate is around 36 ECU per ton of CO_2. The reduced utilization of fossil fuels leads to a reduction of welfare (measured as Hicksian equivalent variation HEV in income) by less than 0.1 percent and of GDP by one fourth percent. Wages and rental rates are almost 1.7 percent below BaU, indicating that reduced energy input implies a considerable drop in factor productivity at the given employment level.

Table 2: Carbon tax and macroeconomic effects (percentage change)

	PC	IC_MMC	IC_EQP	IC
Welfare (HEV)	-0.06	-0.13	-0.03	-0.09
GDP	-0.24	-0.30	-0.20	-0.26
Consumption	-0.41	-0.47	-0.39	-0.44
Investment	0.98	0.88	1.03	0.95
Wage rate	-1.69	-1.80	-1.60	-1.69
Rental rate	-1.66	-1.60	-1.72	-1.67
Exchange rate	-0.90	-0.83	-0.92	-0.85
Carbon tax*	35.64	35.20	35.66	35.20

* in ECU_{95} per ton of CO_2

The total costs of carbon abatement under imperfect competition can be higher or lower than those under perfect competition depending on whether aggregate gains or losses in economies of scale across imperfectly competitive sectors prevail. Under imperfect competition (IC), environmental taxes have implications for the number and size of firms and, hence, for their ability to exploit economies of scale. For reasons explained below, carbon taxes reduce economies of scale in the MMC sector and hence exacerbate the "competitive" costs of carbon abatement. The reverse is true for imperfect competition in the EQP sector.

On the whole - with imperfect competition in both sectors - the macroeconomic effects of carbon taxes for the German economy are slightly more unfavorable compared to the competitive case because the negative effect in the MMC sector dominates the positive effect in the EQP sector.

3.2 Sectoral Effects under Perfect Competition

Even though the macroeconomic effects of carbon taxation under imperfect competition do not differ much from those under perfect competition, the effects on the sectoral level show a substantial difference across the market structures. Consider first the perfect competition case. As displayed in Table 3, the suppliers of fossil fuels and the electricity industry are facing a substantial decline in output. Other negatively affected sectors are agriculture, basic materials and transport, all of them rather energy intensive. On the other hand, consumption goods, construction, and private and public services experience a small increase; the investment goods industry has a rather significant expansion of output.

The sectoral effects are determined by the various industries' factor intensities (see Appendix 3). Especially, sectors with a high energy/labor ratio (EQP, CST, SER, PUB) are losers of structural change, whereas those with a low energy/labor ratio (AGR, FOS, ELE, MMC, TRN) benefit from the change in the ratio of wages to energy costs. These relationships are consistent with standard factor endowment models in which emissions represent the factor input "environment": The imposition of an environmental tax on emissions increases the price of the factor "environment". Consequently, less of this factor will be used. The production of the "dirty" goods, which use the environment intensively, will therefore decrease, and that of the environmentally friendly, i.e., capital/labor intensive good will increase. Previous simulation studies in perfect competition settings have typically been in line with this logic and produced results very similar to ours: Basic industries of outward oriented economies experience losses, whereas other manufacturing sectors tend to gain.[2]

On the international level, these changes in the cost structure translate into changes in comparative advantage. As shown in Table 4, any increase (or decrease) in output goes along with an increase (decrease) in exports. Note that the changes in exports are more pronounced than the corresponding changes in output. For instance, exports of investment goods rise by 3 percent, whereas total output increases not more than 1.4 percent. Exports of basic materials

[2] For a review of the standard (perfect competition) factor endowment approach to environmental taxes, production and trade as well as of simulation results obtained in this framework see Klepper (1998).

and chemicals, conversely, drop by almost 10 percent, whereas output drops by only about 3.6 percent. The reason for these results is that the price elasticity of export demand is larger than the price elasticity of the various categories of domestic demand.

Table 3: Change in output (percentage change)

	PC	IC_MMC	IC_EQP	IC
AGR	-0.56	-0.49	-0.61	-0.56
FOS	-14.17	-14.14	-14.18	-14.15
ELE	-6.89	-7.05	-6.88	-7.05
MMC	-3.64	-5.19	-3.77	-5.45
EQP	1.36	1.60	1.69	2.06
CSG	0.13	0.22	0.07	0.14
CST	0.35	0.31	0.35	0.31
TRN	-4.19	-4.03	-4.35	-4.23
SER	0.08	0.03	0.11	0.06
PUB	0.03	0.02	0.03	0.01

Table 4: Change in exports (percentage change)

	PC	IC_MMC	IC_EQP	IC
AGR	-4.47	-4.02	-4.68	-4.31
FOS	-29.21	-28.93	-29.28	-29.01
ELE	-46.40	-45.56	-46.53	-45.70
MMC	-9.69	-13.69	-10.15	-14.54
EQP	3.01	3.78	3.71	4.78
CSG	0.42	1.10	0.02	0.59
CST	2.18	3.25	1.58	2.49
TRN	-14.68	-13.11	-15.46	-14.04
SER	6.62	7.73	6.27	7.27
PUB	6.99	8.92	5.89	7.58

3.3 Sectoral Effects under Imperfect Competition

With respect to the structure of trade, environmental taxes lead to a change in comparative advantage. This is true irrespective of the market structure. Under imperfect competition, however, the change in comparative advantage has implications for market structure: With free entry and exit, the number of firms in a particular industry is inversely related to the price elasticity of market demand. A gain in an industry's comparative advantage leads to a shift in sales from the domestic markets to the export markets. Given that the price elasticity of export demand is larger than the price elasticity of domestic demand, this implies a rising overall price elasticity, with an increase in scale economies. The reverse happens if an industry faces a loss in comparative advantage.

These effects are illustrated in Table 5 and Table 6. If imperfect competition is restricted to the basic materials/chemicals industry (IC_MMC), the overall demand elasticity of this sector reduces by more than 6.5 percent, and economies of scale (defined as output per firm) drop by almost 7 percent. In the case of the investment goods industry being imperfectly competitive (IC_EQP), both its demand elasticity and scale economies rise by about 1.3 percent. In our core scenario, in which both of these industries are imperfectly competitive, scale economies drop by almost 7.3 percent in the basic materials/chemicals industry, while rising by 1.7 percent in the investment goods sector.

Table 5: Change in demand elasticities (percentage change)

	PC	IC_MMC	IC_EQP	IC
MMC	-	-6.55	-	-7.05
EQP	-	-	1.35	1.82

Table 6: Change in economies of scale (percentage change)

	PC	IC_MMC	IC_EQP	IC
MMC	-	-6.83	-	-7.27
EQP	-	-	1.26	1.72

The induced changes in economies of scale imply that structural change is more pronounced under imperfect competition than under perfect competition. As shown in Table 3, the drop of basic materials/chemicals output is 50 percent larger if the basic materials/chemicals and investment goods industries are imperfectly competitive than it is in the perfect competitive case. Conversely, the increase of investment goods output is substantially enhanced if these two industries are characterized by imperfect competition.

The effects at the sectoral level explain the macroeconomic outcome described above (see section 3.1): Rising scale economies in the investment goods industry would imply that the losses in welfare and GDP decline, relative to the perfect competition case, whereas decreasing scale economies in the basic materials/chemicals industry enhance these losses (see Table 2, columns IC_EQP and IC_MMC). If both sectors are imperfectly competitive (column IC), the induced efficiency losses in basic materials/chemicals dominate the efficiency gains in investment goods, and the welfare loss is larger than it is in the perfect competitive case.

4. Conclusions

In this paper we analyzed how the economic effects of environmental taxes depend on the underlying market structure. Under imperfect competition with free entry and exit, environmental taxes have an impact on economies of scale by changing the number and size of firms. Whether economies of scale rise or fall in a particular industry depends on induced changes in the price elasticity of demand. Because export demand is more price elastic than domestic demand, the overall price elasticity rises (falls) as the industry gains (loses) in comparative advantage.

We used a computable general equilibrium model for Germany to contrast the effects of a unilaterally introduced carbon tax under perfect vis-a-vis imperfect competition. Irrespective of the market structure, environmental taxes lead to a change in comparative advantage - industries with a high energy/labor ratio lose and industries with a low energy/labor ratio gain.

Under imperfect competition, these changes have direct consequences on the economies of scale in imperfectly competitive sectors. In the case examined, the investment goods industry (EQP) gains a comparative advantage and, hence, in economies of scale whereas the reverse applies to the basic material/chemicals industry (MMC). Therefore, the structural change induced by carbon taxes is more pronounced under imperfect competition as compared to perfect competition.

At the macroeconomic level, the total costs of carbon abatement under imperfect competition can be either higher or lower than those under perfect competition, depending on whether aggregate gains or losses in economies of scale across imperfectly competitive sectors prevail. In our simulations for Germany, the loss in economies of scale within MMC dominates the gains within EQP; on the whole the total costs of carbon abatement turn out slightly higher than under perfect competition.

The impact of imperfect competition on the structural change induced by environmental taxes has so far been little explored. Given that imperfect competition prevails in various goods markets, our findings suggest that the structural impacts of environmental taxes may be larger than previously assumed.

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Appendix

Appendix 1: Algebraic Model Summary

This appendix provides an algebraic summary of the equilibrium conditions for the generic comparative-static model with perfectly competitive markets (see Appendix 2 for the extension with respect to the specification of imperfectly competitive good markets). Two classes of conditions characterize the competitive equilibrium: zero profit conditions and market clearance conditions. The former class determines activity levels and the latter determines price levels. In our algebraic exposition, the notation Π_i^z is used to denote the profit function of sector *i* where *z* is the name assigned to the associated production activity. Differentiating the profit function with respect to input and output prices provides compensated demand and supply coefficients (Shephard's lemma) that appear subsequently in the market clearance conditions. Table A1 explains the notations for variables and parameters. Key elasticities are summarized in Table A2. Estimated Armington elasticities are given in Table A3. Table A4 gives sectoral benchmark capital and energy intensities. Sectoral markup rates are summarized in Table A5. For the sake of transparency, we do not write down the explicit functional forms but instead use the acronyms CET (constant elasticity of transformation), CES (constant elasticity of substitution), CD (Cobb-Douglas) and LT (Leontief) to indicate the class of functional form in place.

Zero Profit Conditions

Aggregate output:

(A.1) $$\Pi_i^Y = P_i - LT\left[PA_{n,n\in N}, CES\left(PE_i, CES\left(PL, PK\right)\right)\right] = 0 \qquad \forall i \in V$$

$$\Pi_i^Y = P_i - CES\left[PR_i, LT\left(PL, PK, PA_j\right)\right] = 0 \qquad \forall i \in F$$

Energy aggregation:

(A.2) $$\Pi_i^E = PE_i \text{ - } CES\left[PA_{ELE}, CES\left(CES\left(PA_{HCO}, PA_{SCO}\right), CES\left(PA_{GAS}, PA_{OIL}\right)\right)\right] = 0 \qquad \forall i \in I \setminus ELE$$

$$\Pi_i^E = PE_i \text{ - } CES\left[PA_{ELE}, CES\left(PA_{OIL}, CES\left(PA_{GAS}, CES\left(PA_{HCO}, PA_{SCO}\right)\right)\right)\right] = 0 \qquad i = ELE$$

Armington aggregation:

(A.3) $\Pi_i^A = PA_i - CES\left(P_i, PM_i\right) - P^{CO2} a_i^{CO2} = 0$

World import good production:

(A.4) $\Pi_i^M = PM_i - CES\left(PA_i, PFX\right) = 0$

Utility production:

(A.5) $\Pi^U = PU - CD\left(PC, PINV\right) = 0$

Investment:

(A.6) $\Pi^{INV} = PINV - LT\left(PA_{i,i\in I}\right) = 0$

Final demand:

(A.7) $\Pi^C = PC - CES\left[CES\left(PA_{n,n\in N}\right), CES\left(PA_{ELE}, CES\left(PA_{HCO}, PA_{SCO}, CES\left(PA_{OIL}, PA_{GAS}\right)\right)\right)\right] = 0$

Market Clearance Conditions

Labor:

(A.8) $\overline{L} = \sum_i Y_i \frac{\partial \Pi_i^Y}{\partial PL}$

Capital:

(A.9) $\overline{K} = \sum_i Y_i \frac{\partial \Pi_i^Y}{\partial PK}$

Natural resources:

(A.10) $\overline{Q}_f = Y_f \frac{\partial \Pi_f^Y}{\partial PR_f}$

Domestic output:

(A.11) $Y_i = A_i \frac{\partial \Pi_i^A}{\partial P_i}$

Energy aggregate:

(A.12) $E_i = Y_i \dfrac{\partial \Pi_i^Y}{\partial PE_i}$

World import good:

(A.13) $M_i = A_i \dfrac{\partial \Pi_i^A}{\partial PM_i} + M_i^{ROW}$

Armington aggregate:

(A.14) $A_i = \sum_j Y_j \dfrac{\partial \Pi_j^Y}{\partial PA_i} + C \dfrac{\partial \Pi^C}{\partial PA_i} + INV \dfrac{\partial \Pi^{INV}}{\partial PA_i} + M_i \dfrac{\partial \Pi_i^M}{\partial PA_i}$

Private demand:

(A.15) $C = U \dfrac{\partial \Pi^U}{\partial PC}$

Investment:

(A.16) $INV = U \dfrac{\partial \Pi^U}{\partial PINV}$

Carbon emissions:

(A.17) $\overline{CO2} = \sum_i A_i \cdot a_i^{CO2}$

ROW closure:

(A.18) $\sum_i PM_i \cdot \underbrace{\theta_i \cdot \frac{INC^{ROW}}{PFX}}_{M_i^{ROW}} = \underbrace{\sum_i PFX \cdot \left(\frac{PM_i}{PFX} \right)^{\sigma_M} + \overline{B}}_{INC^{ROW}}$

Foreign closure (PFX):

(A.19) $\sum_i \dfrac{\partial \Pi_i^M}{\partial PFX} \cdot M_i = \sum_i \left(\dfrac{PM_i}{PFX} \right)^{\sigma_M}$

Table A1: Sets, activity and price variables, endowments

Sets:	
I, i, j	Sectors and goods (13 commodities)
E, e	Energy goods (HCO, SCO, OIL, GAS and ELE)
N, n	Non energy goods
F, f	Fossil fuels (HCO, SCO, GAS)
V, v	Non fossil fuels
Activity variables:	
Y_i	Aggregate production
E_i	Aggregate energy input
A_i	Armington aggregate
M_i	World import aggregate
M_i^{ROW}	ROW import demand
U	Household utility
INV	Aggregate investment
C	Private consumption
Price variables:	
P_i	Output price
PE_i	Price of aggregate energy
PA_i	Price of Armington aggregate
PM_i	Price of world import aggregate
PFX	ROW export and import price
PU	Utility price index
PC	Price of aggregate household consumption
$PINV$	Price of investment demand
PL	Wage rate
PK	Price of capital services
PQ_f	Rent from natural resource
P^{CO2}	Price of carbon permit
Endowments:	
$\overline{L}$	Aggregate labor endowment
$\overline{K}$	Aggregate capital endowment
$\overline{Q}_f$	Endowment of natural resource f
$\overline{B}$	Balance of payment surplus
$\overline{CO2}$	Endowment with carbon emission rights
Other parameters:	
a_i^{CO2}	Carbon coefficient
θ_i	Expenditure share of world import good i
σ_M	ROW export supply elasticity

Appendix 2: Specification of Imperfect Competition

Each imperfect competitive sector j is modeled as a homogenous Cournot-Oligopoly. The output price (P_j) is then given as markup on marginal cost (MC_j):

$$\text{(A.20)}\quad P_j = \frac{MC_j}{1 - \frac{1}{N_j \cdot \eta_j}},$$

where η_j is the price elasticity of market demand and N_j the number of firms in the sector. Because of free market entry, the zero profit condition holds, i. e. the number of firms changes in such a way that output price equals average cost.

The elasticity of market demand is consisting of the substitution elasticities and value shares of the different market stages. If several goods $Z_1, ..., Z_N$ form an aggregate Z, the price elasticity of good $n \in (1,...,N)$ is:

$$\text{(A.21)}\quad \eta_n = \sigma \cdot (1 - \theta_n)$$

where σ is the elasticity of substitution between the different goods and θ_n is the value share of good n, given that the level of the aggregate Z is seen as exogenous. If Z *is* in contrast a sub-aggregate in an aggregation hierarchy, one has to consider the price elasticity of Z, which depends in the same manner on the substitution elasticities and value shares of higher stages. This logic continues until a stage is reached that is no longer price dependent from the view of the agents.

In our market hierarchy, there are two of these stages. Domestic output Y_i of the good i competes with imports M_i of the world import good. Both form the Armington aggregate A_i, whereby the Armington substitution elasticity is denoted as σ_A and the value share of the domestic output as $s_{Y,A}$. A portion s_D of the Armington good goes to the domestic market with the price elasticity η_D, whereas a portion s_M is sold on the export market (forming the world import good M_i) with a price elasticity of η_M. The price elasticity on the export market depends on the substitution elasticity between exports from Germany and ROW exports in the production of the world import good σ_M and the value share of the German Armington good exports in the world import composite $s_{EX,M}$. The level of the world import aggregate is seen as exogenous by German firms. The demand elasticity for Y_i with regard to the price P_i is then given as:

(A.22) $\eta_{Y,P} = \sigma_A \cdot (1 - s_{Y,A}) + s_D \cdot \eta_D + s_M \cdot \sigma_M \cdot (s_{Y,A} \cdot (1 - s_{EX,M}))$

Important is the last term of equation A.22, which is related to the competition on the world market. Since the elasticity of substitution on the world market σ_M is higher than the substitution elasticity on the domestic market σ_A, an increased (decreased) share of exports in total output results in a higher (lower) price elasticity of the good and a lower (higher) markup on marginal cost. Increasing export orientation thus reduces market power.

Appendix 3: Summary of Key Elasticities and Markup Rates

Table A2: Selected substitution elasticities

Production	
Capital-labor-energy vs. intermediates	0
Capital-labor vs. energy	0.6
Capital vs. labor	0.8
Electricity vs. primary energy inputs	0.3
Hard coal and lignite vs. gas and oil	0.5
Hard coal vs. lignite	2
Gas vs. oil	2
Hard coal, lignite and gas vs. oil in electricity production	0.5
Hard coal and lignite vs. gas in electricity production	2
Hard coal vs. lignite in electricity production	3
Consumption	
Energy goods vs. non-energy goods	0.5
Electricity vs. primary energy inputs	0.5
Hard coal and lignite vs. oil and gas	0.2
Oil vs. gas	0.3
Non-energy goods vs. non-energy goods	1
Trade	
Armington goods and ROW exports in world import good	16

Table A3: Estimated Armington elasticities for Germany (1979-1991)*

Sector		Armington Elasticity	t-Value
MMC	Basic materials / chemical products	2.039	6.908
EQP	Investment goods	2.325	3.669

* Armington elasticities for all other sectors are set equal to 2.

Table A4: Sectoral benchmark capital and energy intensities

	Labor intensity	Energy intensity	Energy/labor ratio
HCO	0.38	0.26	0.67
SCO	0.06	0.44	7.54
OIL	0.07	0.59	8.03
GAS	0.13	0.13	0.97
ELE	0.16	0.26	1.69
AGR	0.14	0.07	0.49
MMC	0.20	0.08	0.42
EQP	0.28	0.02	0.06
TRN	0.48	0.07	0.15
CSG	0.21	0.03	0.13
CST	0.36	0.02	0.07
SER	0.21	0.01	0.05
PUB	0.57	0.01	0.02

Table A5: Sectoral markup rates*

	Markup rate
MMC	5.2
EQP	7.1

* based on Capros et al. (1997)