Energy-Capital-Labor Substitution and the Economic Effects of CO_2 Abatement: Evidence for Germany

Claudia Kemfert
kemfert@feem.it

Heinz Welsch
welsch@.uni-oldenburg.de

University of Oldenburg
Department of Economics
26111 Oldenburg
Germany

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Abstract

Although the economic effects of CO2 abatement depend substantially on the degree to which capital and labor can substitute for energy, the issue of energy-capital-labor substitution is surrounded by considerable uncertainty. In this paper we use econometrically estimated, sectorally differentiated elasticities of substitution for Germany to shed some light on this issue. The elasticity estimates are used within a dynamic multi-sector CGE model to assess the economic effects of CO2 emission limits for Germany. In particular, we consider the implementation of emission limits by means of a carbon tax, assuming two alternative ways of tax revenue recycling, i.e. lump-sum transfer to private households vs. labor cost reduction. The results are compared with results based on 'standard' substitution elasticities from the literature. Since the estimated elasticities are on average higher and closer to unity than the 'standard' elasticities, we get lower tax rates and tax revenues, and a more stable revenue/GDP ratio. In the case of using the tax revenue to reduce labor costs, the smaller revenue translates into a less favorable (but still positive) effect on employment and GDP. If the revenue is transferred to private households, the sensitivity of GDP with respect to the elasticities is rather negligible, whereas its various components are affected somewhat stronger.

Key words: Substitution elasticities, CO2 tax, General Equilibrium model
JEL Classification: C5, D5, Q2

1 Introduction

The economic effects of CO2 abatement depend substantially on the degree to which capital and labor can substitute for energy. In particular, the elasticities of substitution between energy, capital and labor affect the following issues: (i) How high will be the carbon tax rate required to attain a given CO2 reduction target ? (ii) How stable will the revenue from such a tax be in relation to GDP ? (iii) Will the tax revenue be sufficient to boost employment if used to reduce labor costs ? (iv) How strong will be the macro-sectoral effects of CO2 abatement?

Compared to its importance, the issue of energy-capital-labor substitution is still surrounded by considerable uncertainty. In empirical energy-economy modeling this uncertainty involves two dimensions. First, when using multi-tier 'nested' production functions there is disagreement in the literature as to the appropriate way of 'nesting' energy, capital, and labor. Second, the numerical values of the substitution elasticities are controversial.

With respect to the nesting structure, Manne and Richels (1992) treat capital and labor as a composite input which trades off against energy, whereas Burniaux et al. (1992) argue that energy utilization requires appropriate equipment, implying that energy and capital are quasi-complements, trading off against labor. The usual practice in model building is to select the nesting structure *ad hoc*, and to pick the substitution elasticities from the literature, frequently without any sectoral differentiation.

In this paper we use econometrically estimated, sectorally differentiated elasticities of substitution for Germany to shed some light on the issue of energy-capital-labor substitution and its implications for CO2 abatement. We first use estimates based on alternative nesting structures to select the most appropriate structure. Then we incorporate the estimated elasticities in a dynamic multi-sector CGE model to assess the economic effects of CO2 emission limits implemented by means of a carbon tax. In particular, we address the above-mentioned issues (i) - (iv), assuming two alternative ways of tax revenue recycling, i.e. lump-sum transfer to private households vs. labor cost reduction. The results are compared with results based on 'standard' substitution elasticities from the literature that are uniform across sectors. Since the estimated elasticities are on average higher and closer to unity than the ‘standard’ elasticities, we get lower tax rates and tax revenues, and a more stable revenue/GDP ratio. In the case of using the tax revenue to reduce labor costs, the smaller revenue translates into a less favorable (but still positive) effect on employment and GDP. If the revenue is transferred to private households, the sensitivity of GDP with respect to the elasticities is rather negligible, whereas its various components are affected somewhat stronger. The effect of CO2 abatement on the sectoral outputs responds more to the variation of substitution elasticities than the macroeconomic effects. Overall we find that higher substitution elasticities do not necessarily imply that the economic effects of a given degree of CO2 abatement become more favorable.

The next section addresses the estimation of elasticities of substitution between energy, capital, and labor for Germany and the implications for the nesting structure. Section 3 provides a brief description of the CGE model used and the assumptions made, with an emphasis on the mechanisms by which the substitution elasticities influence the model results. Section 4 discusses the non-abatement baselines and the carbon tax rates and tax revenues implied by a given abatement target, whereas section 5 addresses the macro-sectoral results. Section 6 concludes.

2 Substitution Elasticities

2.1 Previous Literature

Currently, most energy-economy models of the CGE variety use nested CES production functions to describe the production technology. Mostly, these production functions include the input factors energy, capital and labor. The elasticities of substitution among these input factors are usually given exogenously.

Within such a framework, two questions arise. The first question is, which nesting structure should be used. In the literature, there is considerable variety on this issue. For instance, the GREEN model (Burniaux et al. 1992) uses a composite of energy and capital, trading off against labor, whereas the Global 2100 model (Manne and Richels 1992) uses a composite of capital and labor, trading off against energy. The choice of a particular nesting structure is usually settled by a priori reasoning. In this paper, by contrast, econometric evidence for the German industry is use to shed some light on this issue.

The second question concerns the numerical values of the elasticities of substitution. The usual approach here is to refer to literature research on previous estimations (or ‘guestimations’). In fact, there exist plenty of previous estimations of elasticities of substitution among energy, capital and labor. Unfortunately, these estimates are frequently not compatible with the simulation models in which they are used, in terms of both country and industry coverage and functional form. In addition, available estimates cover a wide range and are sometimes implausible. For instance, some previous estimations have produced negative substitution elasticities for capital and energy, see Prywes (1986), Berndt and Wood (1975), Hudson and Jorgenson (1974) and Magnus (1979). On the other hand, some estimated elasticities between these factors are higher than one or even two, see Chang (1994) and Hazilla and Kopp (1986).

To get an answer to both of these questions, three differently nested CES production functions are estimated for the entire German industry and for selected industrial sectors.

2.2 Data

To estimate the substitution elasticities in the German industry, two different data sets are considered: (1) aggregate time series data for the entire German industry for the period 1970 to 1988, (2) disaggregated time series data for the period 1970 to 1988 for seven industrial sectors: chemical industry, stone and earth, non-ferrous metal, vehicles, food, and paper. The data are taken from the German statistical office: Output is taken to be gross value added and capital is given by the gross stock of fixed assets, both at 1991 prices. Labor input is measured by the persons employed in the industrial sector and energy input by final energy consumption (in coal equivalents) of the industrial sector.

2.3 Estimated Equations

Three versions of a nested CES production function are estimated, using the econometric computer program SHAZAM (White et al. 1993):

(1) A two-level CES function with an energy/capital composite and labor, including a neutral technical progress factor m_1:

$$Y_1 = e^{m_1 t} A \left[a_1 (b_1 K^{-a_1} + (1-b_1) E^{-a_1})^{\frac{b_1}{a_1}} + (1-a_1) L^{-b_1} \right]^{-\frac{1}{b_1}}$$

(2) A two-level CES function with a capital/labor composite and energy, including a neutral technical progress factor m_2:

$$Y_2 = e^{m_2 t} A \left[a_2 (b_2 K^{-a_2} + (1-b_2) L^{-a_2})^{\frac{b_2}{a_2}} + (1-a_2) E^{-b_2} \right]^{-\frac{1}{b_2}}$$

(3) A two-level CES function with an energy/labor composite and capital, including a neutral technical progress factor m_3:

$$Y_3 = e^{m_3 t} A \left[a_3 (b_3 E^{-a_3} + (1-b_3) L^{-a_3})^{\frac{b_3}{a_3}} + (1-a_3) K^{-b_3} \right]^{-\frac{1}{b_3}}$$

2.4 Estimation Results

2.4.1 Estimation for the entire German industry

The estimation for the period 1970 to 1988 for the German industry[1] as a whole yields the results shown in Table 1.

Table 1: Estimation Results for Entire Industry

[1] For a complete overview see (Kemfert 1997)

		Coefficient	Standard Error	t-Ratio
(K/E)/L	α_1	0.1535	0.0337	4.554
	β_1	0.7271	0.7206	1.009
	m_1	0.0249	0.0014	17.28
(K/L)/E	α_2	0.2608	0.0889	2.9342
	β_2	0.4325	0.1252	3.4553
	m_2	0.0171	0.0022	7.854
(E/L)/K	α_3	4.9615	0.6256	7.9305
	β_3	0.1117	0.0533	2.0964
	m_3	0.0196	0.0052	3.7692

Judging from the t-ratios, all coefficients except possibly β_1 are significant.

Table 2 shows the R^2 and the Durbin-Watson statistics for the various approaches. According to R^2 , the degree of explanation is highest in the first approach. The DW values show no indication of positive or negative first order autocorrelation of the residuals. Overall, approach (1) is our preferred model for the entire German industry.

Table 2: Durbin-Watson (d) and R^2 Values

	R^2	DW - Statistic (d)
1st approach: (K/E)/L	0.6769	1.11552
2nd approach: (K/L)/E	0.6205	1.01739
3rd approach: (E/L)/K	0.6680	1.33250

The substitution elasticities can be recovered from the estimated coefficients as follows: $s_{a_i} = \frac{1}{1+a_i}$ or $s_{b_{ii}} = \frac{1}{1+b_i}$. They are shown in Table 3.

Table 3 : Substitution Elasticities for Entire Industry

	$\sigma_{\alpha 1}$	$\sigma_{\beta 1}$
1st approach: (K/E)/L	0.871 [K / E]	0.579 [(K,E) / L]
2nd approach: (K/L)/E	0.793 [K / L]	0.698 [(K,L) / E]
3rd approach: (E/L)/K	0.167 [E / L]	0.899 [(E,L) / K]

The estimated coefficients all imply positive substitution elasticities. Thus, energy, capital and labor are substitutes in the production function of the German industry.

2.4.2 Estimation for industrial sectors

To estimate the substitution elasticities of the three versions of the nested CES production function, time series data from 1970 to 1988 for the individual sectors are used.

Table 4 shows the coefficients of determination for the three versions of the production function.

Table 4: Sectoral R^2 Measures

	KE / L	KL / E	EL / K
Chemical industry	0.9894	0.9850	0.5127
Stone and Earth	0.8809	0.9990	0.8909
Non-Ferrous	0.8997	0.9999	0.8854
Iron	0.8653	0.9998	0.9596
Vehicle	0.9897	0.9998	0.9994
Paper	0.9996	0.9753	0.9989
Food	0.7969	0.8999	0.7929

All R^2 values are substantially higher than their counterparts for the entire industry. The ranking of the various models differs from sector to sector.

The problem of serial autocorrelation can be neglected in all approaches because all Durbin-Watson values are not in the critical area.

The implied elasticities of substitution are shown in Table 5.

Table 5: Sectoral Substitution Elasticities

	K / E	KE / L	K / L	KL / E	E / L	EL / K
Chemical	0.49	0.85	0.55	0.96	0.68	0.95
Stone & Earth	0.98	0.94	0.54	0.91	0.90	0.94
Non- Ferrous	0.23	0.91	0.20	0.77	0.97	0.32
Iron	0.17	0.92	0.55	0.98	0.88	0.71
Transport	0.31	0.87	0.17	0.88	0.52	0.83
Paper	0.91	0.62	0.52	0.96	0.20	0.89
Food	0.75	0.76	0.58	0.64	0.07	0.90
Estimation for whole Industry	0.871	0.579	0.793	0.698	0.167	0.899

Compared to the results for the entire industry we see that the sectors ‘stone and earth’ and ‘paper’ show a higher elasticity of substitution between capital and energy than estimated for the whole industry. The sector non-ferrous metal has very low substitution elasticities between capital and the other input factors. In all sectors the substitution elasticities (KE / L) and (KL / E) are higher than the corresponding elasticities for the whole industry. The substitution elasticities between capital and labor are lower and those between energy and labor are higher than for the entire industry. All other substitution elasticities differ more or less from the aggregated substitution elasticity.

Overall, it can be concluded that a nested CES production function with a composite of capital and energy seems most appropriate for the entire industry, whereas the evidence is mixed on the sectoral level. All substitution elasticities are in the range between zero and one, which means that the inputs are imperfect substitutes. Sectorally disaggregated estimations exhibit intersectoral differences of substitution elasticities.

3 Model and Assumptions

3.1 General Description

The simulation model used in this paper is LEAN-TCM, a general equilibrium model of Germany and the rest of the European Union.[2] The simulation exercises described below focus on the sub-model for Germany. The model has the following sectors: hard coal, lignite, petroleum, gas, electricity, agriculture, intermediate products, equipment goods, consumption goods, construction, transportation, private services, and public services. The model is recursively dynamic, with a time horizon to 2020.

As is common for computable general equilibrium models, foreign trade modelling follows the approach of Armington (1969), wherein goods of the same kind but different place of origin are treated as incomplete substitutes. The incomplete substitutability of goods of different origin is captured by CES aggregator functions. The model has a flexible exchange rate which reacts to changes in the current account. More specifically, the price of foreign exchange remains constant whenever the current account is in equilibrium, whereas it increases/decreases if there is a deficit/surplus.

Capital is assumed to be internationally mobile. Thus, there is a uniform real interest rate which is determined implicitly by the equality of income generated and income spent.

[2] Except for some key relationships that are particularly relevant in the current paper, we give only a brief, non-technical description of the model. A formal and more detailled representation can be found in Welsch and Hoster 1995.

Technically speaking, this means that the interest rate serves as the closure variable of the model. Investment is allocated across sectors and regions according to a sector-specific investment calculus that is based on the uniform interest rate.

As concerns primary inputs, labor is assumed to be immobile across borders and completely mobile across sectors. Aggregate labor supply within each country is described by a dynamic wage equation, according to which the current wage equals the wage of the previous period times the increase in labor productivity and the price level (see, e.g., Conrad and Wang 1993), modified by the ratio of actual employment to 'normal' employment (Phillips curve). Employment is the sum of labor demand across sectors.

Considering the final demand categories, we first note that the consumption expenditures of the representative household are a fraction of available income, which is composed of wages and profits plus, if applicable, the revenue from carbon taxation. The savings ratio is assumed to depend on the interest rate, with a constant elasticity.[3] Total consumption expenditures are allocated to consumption of the different goods utilizing the Linear Expenditure System.

Nominal macroeconomic investment is the sum of the sectors' investment in value terms. The price of investment goods is sector specific, since each sector's capital good is characterized by its specific composition in terms of sectors of origin. Investment demand for a sector's goods is the sum of sectoral investment requirements, weighted by the (constant) coefficients of the capital composition matrix.

Factor demand is derived from a five-stage nested production function for each sector, which allows for a flexible treatment of substitution possibilities. Figure 1 displays the production hierarchy. At the top level, output is linked to an aggregate of energy, capital and labor (EKL) and to the various intermediate inputs via constant input-output coefficients. The EKL aggregate is further broken down into labor and an energy-capital aggregate, which is in agreement with the results of the preceeding section. Next, energy-capital is separated into capital and energy. Energy, in turn, is an aggregate of fossil energy and electricity. Finally, fossil energy is a composite of hard coal, brown

[3] This encompasses the frequently-considered special case of a constant savings ratio.

coal, petroleum and gas. Typically, the elasticity of substitution among fossil fuels is larger than that between fossil fuels and electricity. The latter, in turn, is larger than that between energy and capital.[4]

Factor demand is derived from profit maximization subject to the production structure just outlined. At the top level of the production process inputs are linked to output via fixed coefficients. At the subsequent levels there are CES demand functions similar to those used in the foreign trade model. The sectoral capital stock in operation in any period is the capital stock considered optimal in the previous period. Thus, capital is a quasi-fixed factor. Energy, being a variable factor, adjusts to the predetermined capital stock.

The supply side is represented by the price model. The exogenous driving forces of the price model are the export prices of the rest of the world, expressed in the ROW currency, and the carbon tax. Together with the wage rate and the interest rate they determine the product prices via price aggregator functions dual to the quantity aggregators (production functions) discussed above.

3.2 Some Key Relationships

This sub-section elaborates on some model relationships which are of key importance for the influence of altered elasticities of substitution. In particular, we focus on the effect of a higher elasticity of substitution between energy/capital and labor, because the estimates in section 2 suggest that this elasticity is higher than usually assumed (see section 3.3).[5] The presentation is slightly simplified in comparison with the full model structure. Especially, the sectoral differentiation is disregarded.

Let X denote the output produced from energy/capital EK and labor L according to the following production function:

$$(1) \qquad X = \left[d_{EK} \left(a_{EK} EK \right)^{\frac{s-1}{s}} + d_L \left(a_L L \right)^{\frac{s-1}{s}} \right]^{\frac{s}{s-1}},$$

[4] For an overview of estimates see again Burniaux et al. (1992).

[5] Similar considerations apply to the substitution elasticity between energy and capital, but this seems to be less important for interpreting the simulation results discussed below.

where σ is the elasticity of substitution between EK and L, d_{EK} and d_L are the distribution parameters, and a_{EK} and a_L the efficiency factors. The associated demand function for EK is

$$(2) \qquad EK = d_{EK}^{\sigma} \left(\frac{p_X}{p_{EK}} \right)^{\sigma} a_{EK}^{\sigma - 1} X .$$

Thus, the elasticity of substitution translates straightforwardly into the price elasticity of demand. Observe that with $\sigma < 1$ a higher efficiency factor a_{EK} reduces demand.

We will now consider how the evolution of the efficiency factor together with the prices p_X and p_{EK} influence the factor intensity EK/X. To see this, it is useful to rewrite equ. (2) in terms of growth rates g(.). This gives

$$(3) \qquad g(EK/X) = \sigma\, g(p_X) - (\sigma\, g(p_{EK}) + (1 - \sigma)\, g(a_{EK})\,).$$

This equation shows that EK/X declines if $g(p_{EK})$ and $g(a_{EK})$ are sufficiently large, relative to $g(p_X)$. Furthermore it shows that an increase in σ reduces the rate of decline of EK/X, provided that $g(p_{EK}) < g(a_{EK})$. When considering the numerical assumptions in section 3.3 it will be seen that the latter is in fact the case. Therefore, a higher elasticity of substitution between EK and L implies a slower decline of EK/X, hence a higher EK/X at all points in time (given the initial value).

Complementary to the slower decline of EK/X we have a slower *increase* of the labor intensity L/X or, equivalently, a faster increase of the labor productivity X/L. Since the rate of growth of the labor productivity is the main determinant of the growth of the wage rate, we can conclude that under the conditions specified above ($g(p_{EK}) < g(a_{EK})$, $g(p_X)$ sufficiently small) an increase in σ implies a higher growth and, hence, level of the wage rate (given the initial value).

These conclusions hold *ceteris paribus*, i.e., without consideration of CO_2 abatement. If, conversely, we do consider CO_2 abatement policies, it is clear that a policy-driven reduction of EK has less impact on labor productivity if σ and, hence, the EK/X ratio in the non-abatement baseline is higher. Thus, under a higher elasticity CO_2 abatement will imply a smaller reduction of wages.

These considerations will turn out to be important when considering the effects of CO2 abatement under alternative elasticity assumptions.

Assumptions and Scenarios

The ‘standard’ assumptions on substitution elasticities are as follows:

energy/capital vs. labor	0.6,
energy vs. machinery	0.3,
energy vs. structures	0.9,
electricity vs. fuels	0.6,
fuel vs. fuel	0.8.

These ‘standard’ assumptions are mostly near the center of the range of estimates to be found in the literature (see Burniaux et al. 1992 for an overview). They are uniform across sectors. The elasticities of substitution between energy and ‘capital’ required in the model are sector-specific averages of the energy/machinery and the energy/structures elasticities. Thus, the overall energy-capital elasticity becomes larger as the share of structures in the overall capital stock becomes larger.

As an alternative to the ‘standard’ elasticities we have used the estimates described in section 2, for those sectors for which they are available. These elasticities are:

	energy/capital vs. labor	energy vs. machinery
intermediate products	0.85	0.49
equipment goods	0.90	0.20
consumption goods	0.70	0.80
transportation	0.87	0.31

Note that these elasticities are mostly higher than the ‘standard’ assumptions.

As discussed in the preceding sub-section, the choice of substitution elasticities influences the non-abatement baseline. In addition, the baseline is determined by assumptions on factor productivities and the development of the exogenous variables. The productivity factor for energy is assumed to grow at 2 percent annually and the productivity factor for labor and capital at 1.5 percent. The exogenous driving forces of the model are the import volumes and the export prices of the rest of the world. The former are assumed to grow at 2 percent, while the (real) export prices are assumed to be constant, except for the energy carriers. For the latter, an annual price increase of 1.4 percent and 2 percent is assumed for petroleum and gas, respectively, while the world market price for coal is assumed to be approximately constant.[6] Thus, average energy prices grow less than energy efficiency.

These assumptions imply a baseline GDP growth of about 2 percent and an annual growth in CO_2 emissions by 0.9 percent in West Germany under 'standard' elasticity assumptions.

The CO2 abatement target is specified as involving a stabilization of emissions in 2005 through 2020 at their level in 1990. For 2000-2005 a linear adjustment of emissions towards this target value is postulated. The abatement target is implemented by means of a carbon tax whose level is determined implicitly from the emission limit. The revenue from the tax can be used in two ways: REDIST refers to a lump-sum redistribtion of the tax to private households. EMPLOY means that the revenue is used to subsidize wages, i.e., the 'purchase price' of labor is smaller than the wage rate by the amount 'tax revenue/employment'.[7]

4 CO2 Emissions and Carbon Tax

In order to understand the influence of higher elasticities, it should be recalled that they change not only the effects of abatement, but, in the first place, the non-abatement emission baseline. This effect arises because world energy prices are assumed to grow at a lower rate than the autonomous energy efficiency factor. Under these circumstances, a higher elasticity of substitution between energy-capital and labor implies a higher energy intensity (see section 3.2). As a result, the baseline emission level will be higher under higher substitution elasticities.

[6] These assumptions are compatible with the energy price projections in IEA 1994.
[7] This variant works in a similar way as a reduction in payroll taxes.

Table 6 shows the baseline carbon emissions under alternative elasticity assumptions, along with GDP and the emission intensity (CO2/GDP). It can be seen that the difference in emissions is quite pronounced.[8] Because of the higher energy input in the high-elasticity case, GDP is also somewhat higher.

Table 6: Non-Abatement Baseline under Alternative Elasticity Assumptions

Standard Elasticities	Emissions (million tons CO2)	GDP (billion ECU)	Emissions/GDP (tons/1000 ECU)
2000	835.89	1139.57	0.73
2005	878.83	1263.31	0.70
2010	920.92	1397.69	0.66
2015	963.63	1543.48	0.62
2020	999.78	1701.69	0.59
Higher Elasticities	**Emissions (million tons CO2)**	**GDP (billion ECU)**	**Emissions/GDP (tons/1000 ECU)**
2000	914.02	1148.82	0.80
2005	960.15	1275.07	0.75
2010	1004.80	1410.45	0.71
2015	1050.33	1556.11	0.67
2020	1087.19	1713.17	0.63

The fact that the non-abatement baselines develop differently under alternative sets of elasticities has important implications for the macroeconomic effects of abatement, as will be seen in the next section. In the first place, however, it raises the problem of how to define ‘equivalent’ abatement targets under alternative sets of elasticities. Obviously, requiring the *same target emission level* under both sets of elasticities would imply a much *higher degree of abatement* in the high-elasticity case than in the low elasticity case, which would bias our estimates of the required tax rate as well as the economic effects of abatement.[9] Thus, our preferred definition of an equivalent abatement target is in terms of *equal absolute abatement*. In other words, we compute how much abatement is required in the low-elasticity case to attain the emission level of 1990; then we subtract

[8] That the deviation is rather strong already in 2000 arises because the base year for model calibration is as early as 1985.

this abatement level from the high-elasticity emission baseline to obtain high-elasticity target emissions. Alternatively, we experiment with *equal percentage abatement* targets (which are more ambitious in absolute terms than the equal absolute abatement targets).

Overall, the following abatement scenarios are considered.

A-R: Stabilization of emissions at 1990 level under standard elasticities, REDIST.
B-R: Equal absolute abatement under higher elasticities, REDIST
C-R: Equal percentage abatement under higher elasticities, REDIST.
A-E:Stabilization of emissions at 1990 level under standard elasticities, EMPLOY.
B-E: Equal absolute abatement under higher elasticities, EMPLOY.
C-E: Equal percentage abatement under higher elasticities, EMPLOY.

The tax rates, tax revenues and revenue shares in GDP which are associated with these abatement scenarios are shown in Table 7. Consider first the cases in which the revenue is rebated to private households (REDIST). It can be seen that in the high elasticity case significantly lower tax rates are required than under standard elasticities, for equal absolute abatement (B-R). Even under the equal percentage abatement target the tax rate is lower in the high elasticity case (C-R). If the tax revenues is used to reduce labor costs (EMPLOY), we also find that higher elasticities imply lower tax rates (even in the case C-E in which the abatement requirement is stricter in absolute terms than in A-E and B-E). This is what one would expect: Higher elasticities of substitution mean higher price elasticities, which implies that a given abatement target requires a smaller tax-induced price increase.

If we compare the EMPLOY cases with the corresponding REDIST cases we find that the tax rates are higher in the former than in the latter. The reason for this is that under EMPLOY we have a higher level of economic activity than under REDIST (see section 5).

The tax revenues in the various cases are an immediate consequence of the corresponding tax rates: Higher elasticities imply lower revenues and lower revenue/GDP ratios, and EMPLOY implies higher revenues and revenue/GDP ratios than REDIST.

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[9] From a strictly ecological point of view it is the target emission level rather than the target abatement

Table 7: Tax Rates and Tax Revenues

Scenario A-R	Tax Rate (ECU/ton CO2)	Revenue (billion ECU)	Revenue/GDP (percent)
2000	3.25	2.64	0.19
2005	21.88	16.17	1.31
2010	30.03	22.20	1.64
2015	39.40	29.12	1.97
2020	48.24	35.66	2.20

Scenario B-R	Tax Rate (ECU/ton CO2)	Revenue (billion ECU)	Revenue/GDP (percent)
2000	2.56	2.28	0.20
2005	15.01	12.36	0.98
2010	20.84	17.16	1.26
2015	27.49	22.64	1.52
2020	33.53	27.67	1.69

Scenario C-R	Tax Rate (ECU/ton CO2)	Revenue (billion ECU)	Revenue/GDP (percent)
2000	2.81	2.50	0.22
2005	17.78	14.36	1.15
2010	24.51	19.77	1.45
2015	31.75	25.58	1.72
2020	38.79	31.18	1.91

Scenario A-E	Tax Rate (ECU/ton CO2)	Revenue (billion ECU)	Revenue/GDP (percent)
2000	3.52	2.86	0.25
2005	24.88	18.39	1.46
2010	34.46	25.47	1.84
2015	45.65	33.74	2.22
2020	56.27	41.59	2.49

level that counts. Some further remarks on this issue are made in the concluding section.

Scenario B-E	Tax Rate (ECU/ton CO2)	Revenue (billion ECU)	Revenue/GDP (percent)
2000	2.80	2.29	0.21
2005	16.95	13.96	1.10
2010	23.64	19.47	1.40
2015	31.39	25.84	1.69
2020	38.38	31.61	1.89

Scenario C-E	Tax Rate (ECU/ton CO2)	Revenue (billion ECU)	Revenue/GDP (percent)
2000	3.07	2.73	0.24
2005	20.01	16.22	1.27
2010	28.01	22.59	1.62
2015	36.07	29.06	1.90
2020	44.33	35.63	2.12

A question that has received much attention in the public finance literature on an ‘ecological tax reform’ concerns the stability of the revenue/GDP ratio (see Pethig 1997). In this regard we find that in all six scenarios the revenue share in GDP increases over time. However, in line with theoretical expectations, the increase is less pronounced under the higher (and closer-to-unity) elasticities.

5 Macro-Sectoral Effects

We consider the macro-sectoral effects separately for the two types of recycling of the tax revenue .

Consider first the lump-sum transfer of revenues to private households (REDIST). The results are compiled in Table 8. The sectoral results refer to sectoral output. Considering the scenario A-R, i.e., the standard elasticity case, we find that (at least in the long term) all macroeconomic aggregates and most of the sectoral outputs decline. The long term decrease in GDP is about one percent. Among the components of GDP, consumption and investment exhibit a stronger long-term decline, whereas exports decrease substantially less. The latter result has to be viewed in conjunction with the strong reduction of imports, which occurs because German imports contain a substantial fraction (more than 20 percent) of fossil fuels. As a result of the strong decline in imports, the exchange rate (price of foreign currency) drops. This explains why exports decrease less than domestic demand. Employment decreases less than GDP because energy is partly substituted by labor. Sectoral outputs decline by varying degrees, depending on their energy intensity.[10] Only the equipment-good industry shows a small increase, which is mainly due to the initial increase in investment.

Table 8:Macro-Sectoral Effects in REDIST Case, Percentage Difference from Baseline

Scenario A-R	2000	2005	2010	2015	2020
CO2 Emissions	-2,83	-15,89	-19,74	-23,29	-26,07
GDP	0,35	-0,08	-0,25	-0,64	-1,03
Consumption	0,28	-0,47	-0,87	-1,35	-1,78
Investment	5,26	3,88	0,53	-0,99	-2,06
Export	-0,87	-1,26	-0,40	-0,43	-0,49
Import	0,96	-0,83	-2,16	-2,69	-2,93
Employment	0,63	-0,15	-0,02	-0,12	-0,12
Hard coal	0,00	0,00	0,00	0,00	0,00
Lignite	-8,91	-36,77	-41,81	-45,68	-48,43
Petroleum	-0,71	-6,04	-8,13	-10,30	-11,60
Gas	-0,73	-6,24	-9,17	-12,30	-14,96
Electricity	-1,38	-6,05	-7,82	-10,13	-12,28
Agriculture	-0,24	-0,87	-1,03	-1,63	-2,26
Intermed. Products	-0,60	-2,37	-2,30	-3,13	-3,89
Equipment Goods	0,71	0,20	0,40	0,20	0,09
Consumption Goods	-0,09	-0,52	-0,26	-0,55	-0,83
Construction	2,74	1,36	-0,41	-1,46	-2,18

[10] Hard coal mining is not affected by C02 abatement because the output of this industry is regulated and therefore determined exogenously.

Transportation	0,13	-0,55	-0,62	-0,98	-1,28
Private Services	0,34	-0,30	-0,64	-1,12	-1,58
Public Services	-0,26	-0,73	-0,91	-0,99	-1,08

Scenario B-R	2000	2005	2010	2015	2020
CO2 Emissions	-2,59	-14,23	-18,04	-21,60	-24,25
GDP	0,34	-0,07	-0,29	-0,66	-1,02
Consumption	0,28	-0,40	-0,81	-1,27	-1,66
Investment	4,97	2,56	-0,35	-1,58	-2,42
Export	-0,89	-1,06	-0,43	-0,53	-0,63
Import	0,92	-0,99	-2,12	-2,57	-2,73
Employment	0,58	-0,12	-0,05	-0,12	-0,10
Hard coal	0,00	0,00	0,00	0,00	0,00
Lignite	-7,47	-32,86	-38,56	-42,95	-45,90
Petroleum	-0,64	-5,37	-7,31	-9,29	-10,41
Gas	-0,66	-5,13	-7,78	-10,65	-13,00
Electricity	-1,27	-5,76	-7,55	-9,72	-11,60
Agriculture	-0,22	-0,79	-1,14	-1,82	-2,49
Intermed. Products	-0,67	-2,22	-2,36	-3,23	-4,00
Equipment Goods	0,65	0,12	0,21	0,07	0,04
Consumption Goods	-0,15	-0,57	-0,48	-0,85	-1,20
Construction	2,52	0,59	-0,99	-1,88	-2,46
Transportation	0,15	-0,47	-0,62	-0,98	-1,29
Private Services	0,32	-0,34	-0,75	-1,25	-1,70
Public Services	-0,23	-0,57	-0,68	-0,74	-0,80

Scenario C-R	2000	2005	2010	2015	2020
CO2 Emissions	-2,83	-15,89	-19,74	-23,29	-26,07
GDP	0,37	-0,20	-0,36	-0,77	-1,14
Consumption	0,31	-0,57	-0,96	-1,46	-1,87
Investment	5,46	1,60	-0,61	-1,80	-2,11
Export	-0,98	-1,12	-0,43	-0,55	-0,74
Import	1,01	-1,38	-2,43	-2,85	-2,87
Employment	0,63	-0,32	-0,04	-0,08	-0,01
Hard coal	0,00	0,00	0,00	0,00	0,00
Lignite	-8,13	-35,12	-40,47	-44,64	-47,59
Petroleum	-0,71	-6,34	-8,42	-10,47	-11,68
Gas	-0,73	-6,08	-9,01	-12,05	-14,62
Electricity	-1,39	-7,05	-9,15	-11,38	-13,40
Agriculture	-0,24	-0,92	-1,32	-2,10	-2,87
Intermed. Products	-0,73	-2,63	-2,72	-3,66	-4,57
Equipment Goods	0,71	-0,15	0,26	0,14	0,18
Consumption Goods	-0,16	-0,70	-0,53	-0,94	-1,35
Construction	2,77	-0,01	-1,24	-2,12	-2,47
Transportation	0,16	-0,64	-0,72	-1,11	-1,43
Private Services	0,36	-0,51	-0,88	-1,43	-1,90
Public Services	-0,26	-0,51	-0,77	-0,85	-0,93

Turning to scenario B-R, i.e. the case of equal absolute abatement under higher elasticities, we see that the effect on GDP is practically the same as in the A-R case. However, the GDP components are now affected differently. Especially, investment is reduced more whereas consumption is reduced less than in the previous case. This is surprising because, as discussed in the preceding section, the tax revenue, to be rebated to private households, is now lower. Thus, the smaller reduction of consumption can only be explained by referring to a component of available household income other than the tax rebate. In fact, a more detailed inspection of the results (not shown in the table) reveals that the wage rate and, hence, the wage income is about 4 to 5 percent higher in the B-R case than in the A-R case. This is in line with the reasoning developed in section 3.2 that a given amount of CO2 reduction reduces labor productivity less if the baseline CO2 intensity is higher. What remains surprising, then, is that this effect dominates the effect of the smaller tax revenue, leading to a smaller reduction of overall household income in B-R than in A-R, and to a smaller decline in consumption.

In contrast to consumption, investment and the sectoral outputs are now more strongly reduced than in the A-R case. This is nothing more than an implication of the mechanism just sketched: The wage reduction is now smaller than in the A-R case, and this effect dominates the effect of the lower tax rate, leading to production costs being higher in the B-R case than in the A-R case.[11]

These considerations suggest that the effects of higher substitution elasticities are rather involved.

Turning to scenario C-R, we find that most of the effects are now reinforced relative to scenario B-R. This is no surprise because the absolute amount of CO2 abatement is now higher.

We next consider the effects of CO2 abatement when the tax revenue is used to reduce the wage rate facing the employers (relative to consumer wages). The results are given in Table 9.

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[11] This reasoning is confirmed by the numerical results on production costs (including taxes), not shown explicitly.

In scenario A-E (standard elasticities) this leads to an increase in GDP, consumption, investment, exports and, especially, employment. Imports decrease, as previously, because of the high share of fossil fuels in German imports. The sectoral outputs increase, except for the energy sectors and the energy-intensive basic-materials industry.

In scenario B-E, i.e. equal absolute abatement under higher elasticities, all the increases are lower than in scenario A-E. This holds especially for employment and GDP. The reason for the smaller increase in economic activity levels is simply that in the high elasticity case a smaller tax revenue is available for labor cost reduction.[12]

Table 9: Macro-Sectoral Effects in EMPLOY Case, Percentage Difference from Baseline

Scenario A-E	**2000**	**2005**	**2010**	**2015**	**2020**
CO2 Emissions	-2,83	-15,89	-19,74	-23,29	-26,07
GDP	0,64	1,97	2,39	2,61	2,70
Consumption	0,49	1,12	1,25	1,32	1,34
Investment	5,83	6,19	2,97	1,91	1,20
Export	-0,70	-0,17	0,95	1,25	1,43
Import	1,06	-0,21	-1,40	-1,78	-1,91
Employment	1,12	3,26	4,15	4,85	5,39
Hard coal	0,00	0,00	0,00	0,00	0,00
Lignite	-9,10	-37,20	-42,21	-45,95	-48,63
Petroleum	-0,63	-5,68	-7,71	-9,87	-11,13
Gas	-0,66	-5,68	-8,76	-11,90	-14,61
Electricity	-1,32	-5,28	-6,78	-8,94	-11,04
Agriculture	-0,11	0,18	0,53	0,50	0,37
Intermed. Products	-0,34	-0,58	-0,02	-0,31	-0,66
Equipment Goods	1,16	2,87	3,63	4,16	4,58
Consumption Goods	0,17	1,24	2,05	2,41	2,63
Construction	3,16	3,49	2,11	1,59	1,28
Transportation	0,37	1,10	1,53	1,71	1,81
Private Services	0,58	1,44	1,63	1,71	1,69
Public Services	-0,02	2,01	2,77	3,48	3,93

[12] The *percentage* reduction of *imports* is now smaller, because the percentage reduction of CO2 is smaller under higher baseline emissions.

Scenario B-E	2000	2005	2010	2015	2020
CO2 Emissions	-2,59	-14,23	-18,04	-21,60	-24,25
GDP	0,59	1,51	1,79	1,92	1,93
Consumption	0,47	0,85	0,90	0,90	0,86
Investment	5,60	4,82	2,15	1,35	0,77
Export	-0,78	-0,35	0,51	0,68	0,78
Import	1,04	-0,38	-1,39	-1,72	-1,80
Employment	0,99	2,36	3,02	3,55	3,94
Hard coal	0,00	0,00	0,00	0,00	0,00
Lignite	-7,71	-33,37	-39,03	-43,35	-46,23
Petroleum	-0,56	-4,98	-6,84	-8,78	-9,86
Gas	-0,60	-4,76	-7,32	-10,16	-12,54
Electricity	-1,20	-5,07	-6,62	-8,67	-10,50
Agriculture	-0,10	0,01	0,10	-0,10	-0,35
Intermed. Products	-0,44	-0,93	-0,69	-1,16	-1,62
Equipment Goods	1,03	2,10	2,70	3,17	3,58
Consumption Goods	0,07	0,75	1,29	1,42	1,46
Construction	2,94	2,47	1,28	0,83	0,55
Transportation	0,36	0,82	1,07	1,14	1,15
Private Services	0,54	1,02	1,07	1,05	0,96
Public Services	-0,04	1,48	2,09	2,62	2,95

Scenario C-E	2000	2005	2010	2015	2020
CO2 Emissions	-2,83	-15,89	-19,74	-23,29	-26,07
GDP	0,65	1,73	2,06	2,17	2,22
Consumption	0,52	0,97	1,04	1,03	1,02
Investment	6,15	5,58	2,90	1,92	1,94
Export	-0,85	-0,44	0,56	0,76	0,80
Import	1,15	-0,39	-1,46	-1,81	-1,76
Employment	1,09	2,72	3,53	4,06	4,57
Hard coal	0,00	0,00	0,00	0,00	0,00
Lignite	-8,37	-35,92	-41,21	-45,19	-48,05
Petroleum	-0,62	-5,80	-7,80	-9,85	-11,04
Gas	-0,65	-5,63	-8,45	-11,47	-14,09
Electricity	-1,31	-5,78	-7,43	-9,58	-11,59
Agriculture	-0,11	0,00	0,12	-0,10	-0,40
Intermed. Products	-0,48	-1,12	-0,79	-1,29	-1,85
Equipment Goods	1,13	2,39	3,17	3,67	4,22
Consumption Goods	0,08	0,85	1,50	1,62	1,66
Construction	3,23	2,84	1,71	1,15	1,14
Transportation	0,40	0,93	1,25	1,31	1,34
Private Services	0,59	1,17	1,25	1,20	1,13
Public Services	-0,04	1,75	2,35	2,92	3,26

In scenario C-E, which entails a stronger absolute reduction of CO2 than B-E, the favorable effects are even reinforced, because a higher tax revenue is now available for labor cost reduction. Of course the energy sectors decline more than in the B-E case. The same is true for the energy intensive basic-materials industry, because here the cost increase due to the higher carcon tax dominates the tax-financed labor cost reduction.

6 Conclusions

In this paper we have used econometrically estimated elasticities of substitution between energy, capital, and labor to assess the general equilibrium effects of CO2 abatement in Germany. Emphasis was placed on comparing these effects with results obtained under ‘standard’ elasticity assumptions picked from the literature.

Because the estimated elasticities are on average higher than the ‘standard’ assumptions they imply lower carbon tax rates and tax revenues associated with a given target amount of CO2 reduction. Also, being closer to unity than the ‘standard’ assumptions, the estimated elasticities imply a revenue/GDP ratio that is more stable over time.

The influence of the higher elasticities on the macro-sectoral effects of CO2 abatement is found to depend substantially on the way in which the tax revenue is recycled into the economy. If the revenue is used to reduce labor costs, the lower revenue implied by higher elasticities translates into less expansionary impulses. If the revenue is rebated to private households, the impact of higher elasticities on the macro-sectoral effects of abatement is ambiguous. It depends considerably on the non-abatement baseline. Under plausible assumptions on world energy prices and autonomous energy efficiency improvements, higher substitution elasticities imply higher baseline emissions. Therefore, reducing emissions (i.e., fossil energy input) by a fixed amount reduces labor productivity substantially less under high elasticities than under low ones. Thus, wages remain higher in the high elasticity case, whereas the transfer income from the carbon tax is lower. In our simulations, the former effect dominates the latter, implying a smaller decrease of consumption under high elasticities than under low ones. On the other hand, investment and exports show a stronger decrease under high elasticities because prices are higher in this case.

It should be noted that in these considerations the economic effects of CO2 abatement are measured against non-abatement baselines that are differentiated according to the elasticity assumptions made. In contrast to this approach, one could argue that higher elasticities are always economically favorable, because a *given fixed amount of abatement* leads to a higher economic activity level if applied to a higher rather than a lower baseline. Against such reasoning it may be objected, however, that applying a given fixed amount of target abatement equally to high and low baseline emissions is not ecologically sensible. From a strictly ecological point of view, target emissions rather than target abatement levels should be kept fixed in comparing the economic effects of abatement under alternative elasticity assumptions. Had we used this normalization, the effects of abatement under higher elasticities would have been less favorable than described in this paper.

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Figure 1. Production Hierarchy