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A General-Equilibrium Analysis of European Carbon/Energy Taxation

Model Structure and Macroeconomic Results*

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1. Introduction

In 1992 the German Parliament established the Enquete Commission "Protection of the Earth's Atmosphere", which shortly afterwards launched an extensive study program. One major objective of the study program was to provide an assessment of the economic effects of various forms of carbon and/or energy taxation.

The starting point for the formulation of tax scenarios was the combined carbon/energy tax suggested by the Commission of the European Communities. Initially, the tax was meant to be introduced in 1993 in all Member States. However the proposal failed to be implemented, as yet. Therefore the Enquete Commission specified the following two tax variants to be analyzed:

(a) a European carbon/energy tax along the lines of the initial proposal, but with introduction date 1996 (EC tax);

(b) an energy tax with features similar to those of the European tax, but on a national basis (national energy tax).

The most important difference between the two variants is that the latter one is designed to be introduced unilaterally in Germany. This entails that the national tax should be based on final energy consumption, not on primary energy, because otherwise the tax could be avoided by importing final energy. Another difference is that the suggested national tax is to be based exclusively on the heat content of energy,

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rather than on a combination of heat content and carbon content. This is apparently motivated by the desire to protect carbon-intensive domestic energy carriers.

Both tax designs raise a variety of interesting issues. A question that is common in analyzing environmental taxes is how the way in which taxes are recycled into the economy affects their environmental and economic impacts. A second question, which deserves attention especially with respect to the national tax, concerns international competitiveness. Other issues are the effect of world energy prices and domestic energy policies on the working of carbon or energy taxes.

The current paper focuses on the first two items, tax recycling and international feedback effects, with an emphasis on comparing the two tax designs described. In addressing these questions it utilizes LEAN-TCM, a two-region general equilibrium model of the European Community, which was especially developed for this purpose. The two-region structure is the minimum geographical disaggregation that permits to compare the European and the national tax. The number of sectors within each region is relatively small, allowing future extensions of the model to a larger number of regions.

There is a variety of models from which we borrowed one feature or another. One group of models is national general equilibrium models. Examples are *Jorgenson* and *Wilcoxen* (1990) for the U.S., *Bergman* (1991) for Sweden, *Stephan* et al. (1992) for Switzerland, *Conrad* and *Wang* (1993) for West-Germany. Another major group is integrated multi-region world models such as *Burniaux* et al. (1992), *Manne* and *Richels* (1992), *Mc Kibbin* and *Wilcoxen* (1992).

For the European Community there exists the HERMES system of models (CEC 1993). The problem with HERMES is that it is a collection of quite inhomogeneous national econometric models which it proved difficult to link. In contrast to that, our aim in developing LEAN was to create a tool that is able to address the issue of European carbon/energy taxation within a uniform and integrated modeling framework.

With respect to Germany there are by now several applications of general equilibrium techniques to environmental questions. *Wirl* and *Hoffman* (1991) extend and apply input-output techniques to quantify the impact of existing environmental policy targets in Germany. Taxes on air pollutants are analyzed in *Conrad* and *Schröder* (1991a), while the control of CO_2 emissions is addressed in *Conrad* and *Schröder* (1991b) and *Conrad* and *Wang* (1993). The difference between the latter two papers lies mainly in the treatment of technical progress and of possible market power in the energy industries. In comparison to those papers, the main distinguishing feature of the current paper is the European wide context of German carbon/energy taxation[1].

The paper is organized as follows. The next section provides a description of the model in economic terms. Section 3 describes the simulations performed and discusses the results obtained. Section 4 concludes the paper. A more technical presentation of the model is relegated to several appendices.

2. The Model

2.1 Overall Structure

LEAN (**L**ow **E**mission **A**ssessment e**N**gine) is a multi-country general equilibrium system to assess the macro-sectoral effects of various carbon dioxide reduction options in the European Community. The currently used version TCM4 is a **t**wo-**c**ountry **m**odel comprising West Germany (GER) and the rest of the European Union, except Greece and Luxembourg (EC9)[2]. The model is written in GAMS, Release 2.25 (*Brooke* et al. 1992). The solution algorithm used is CONOPT (*Drud* 1992).

LEAN-TCM4 is a recursively-dynamic two-country, 14-sector model whose time horizon extends until 2020. The recursively dynamic structure, obtained by assuming myopic expectations, permits to solve the model for a sequence of temporary equilibria.

For labor and energy we assume disembodied factor-augmenting technical progress. For capital, technical progress is of an embodied type, such that the average efficiency of each sector's aggregate capital stock can only be increased by introducing new, more modern equipment (*Solow* 1962).

Aggregate labor supply is described by a dynamic wage equation which explains wage formation by the dynamics of labor productivity (see, e.g., *Conrad* and *Wang* 1993) in conjunction with a Phillips curve mechanism.

Foreign trade is modeled by means of a world trade pool, rather than by modeling bilateral trade relations (see Figure 1)[3]. In the foreign trade model, the rest of the world (ROW) is represented by exogenous import volumes and export prices (in terms of the rest of the world's currency).

1 A selection of further approaches is surveyed in *Welsch* 1993.

2 Greece and Luxembourg were not included due to poor data.

3 This is motivated by our intention to disaggregate *EC*9 in future model versions.

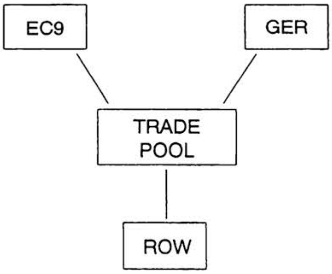

Figure 1: Multi-country-model

Both the European Community (EC) and the rest of the world are treated as exchange rate unions vis a vis each other. Thus, two currencies may be said to exist in the model. They are linked by a flexible exchange rate, which is assumed to react to changes in the EC's balance of current account vis a vis ROW.

All aggregator functions in the model (quantity and price aggregators) are of the Leontief or CES type. A nested production structure allows the substitution elasticities to differ among sub-aggregates. Consumer demand is modeled by means of the Linear Expenditure System.

The model has been benchmarked against input-output tables for 1985, which were aggregated to 14 sectors. Among them are the energy sectors hard coal, brown coal, petroleum, gas, and electricity, each being identified with a homogeneous product.

2.2 Market Clearance and Macro Closure

For each good there are several classes of markets: A world market and two domestic goods markets. Also, there are two domestic labor markets and one international capital market.

In the world market the world trade volume is determined as being the sum across GER, EC9, and ROW of import demands[4]. Since German and EC9 imports are endogenous, a considerable fraction of the world trade volume, to be allocated to exports from GER, EC9 and ROW, is endogenous.

In the domestic goods markets total supply equals the sum of intermediate demands, consumption demand, government demand, investment demand, and export demand. For the energy sectors, intermediate

[4] For a formal statement of the model see Appendix A.

demand for their own product is split into energy throughput and energy consumption, because only energy consumption leads to emissions of CO_2[5].

Labor is assumed to be immobile across borders. Employment in each country is determined as being the sum of labor demand across sectors.

In contrast to the demand side, which is captured by ordinary demand functions, supply is modeled in an inverse fashion, via supply prices. Because, in any model solution, the demand functions are evaluated at those supply prices, the overall quantities demanded are equilibrium quantities[6].

The capital market is treated differently. Capital market equilibrium requires that the value of macroeconomic net investment equals private savings less the budget deficit less the balance of current account. This condition is a way of stating the equality of income generated and income used. The way in which a model *achieves* this accounting identity is usually referred to as the macro closure. In the current model we use the interest rate as the closure variable. More specifically, we assume free capital mobility, such that there is a uniform interest rate. Then the *consolidated* flow of funds constraint of EC vis a vis ROW determines the interest rate.

As the numeraire we choose the consumer price level in EC9.

2.3 Foreign Trade and Final Demand

As is common in computable general equilibrium models, foreign trade modeling follows the approach of *Armington* (1969), according to which imported and domestically produced goods of the same kind are treated as incomplete substitutes. Thus the aggregate amount of each good is divided among imports and domestic production. For exports, there is a similar, but nested, structure: First, the world trade volume of each good is allocated to exports from ROW and exports from EC. The latter is then subdivided among German exports and EC9 exports.

The incomplete substitutability between goods of different origin is captured by CES aggregator functions. Accordingly, the demand for imports and domestic production as well as the two levels of export demand are determined by CES demand functions[7].

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5 Energy throughput comprises, e.g., the use of hard coal as "raw material" for the production of coke.

6 This is a convenient and frequently-employed method of computing equilibria (see, e.g., *Conrad* 1993).

7 CES demand functions (and price functions) are compiled, in general terms, in Appendix B.

Turning to consumption, we assume that the consumption expenditures of the representative household are a fraction of available labor and capital income. The savings ratio is assumed to depend on the interest rate, with a constant elasticity[8]. Total consumption expenditures are then allocated to consumption of the different goods, utilizing the Linear Expenditure System.

Government expenditure in nominal terms is determined as a constant fraction of nominal GDP in the previous period, and real government expenditure is obtained from this by division by the price of the sector non-market services[9].

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. A sector's real investment is the difference between the capital stock considered optimal for the next period and that part of the current capital stock that will still be in operation in the next period. Finally, investment demand for a sector's goods is the sum of sectoral investment requirements, weighted by the (constant) coefficients of the capital composition matrix.

2.4 Factor Demand

Factor demand is derived from a five-stage nested production function for each sector, which allows for a flexible treatment of substitution possibilities. Figure 2 displays the production hierarchy.

At the top level, output is linked to an aggregate of energy, capital and labor (EKL) and to the various non-energy intermediate inputs via constant input-output coefficients. Note that energy in the EKL aggregate is to be understood in the narrow sense, i.e., it comprises only the "energetic" use of energy carriers. The "non-energetic" use is separated out and treated as an intermediate input. Non-energetic use is considered for the energy sectors only, where it is taken to be a constant fraction of output.

The EKL aggregate is further broken down into labor and an energy-capital aggregate. This choice of disaggregation reflects our interpretation of capital as a collection of facilities for using energy. While the

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

[9] In the Input-Output table the column "government expenditure" is non-empty only in the row "non-market services".

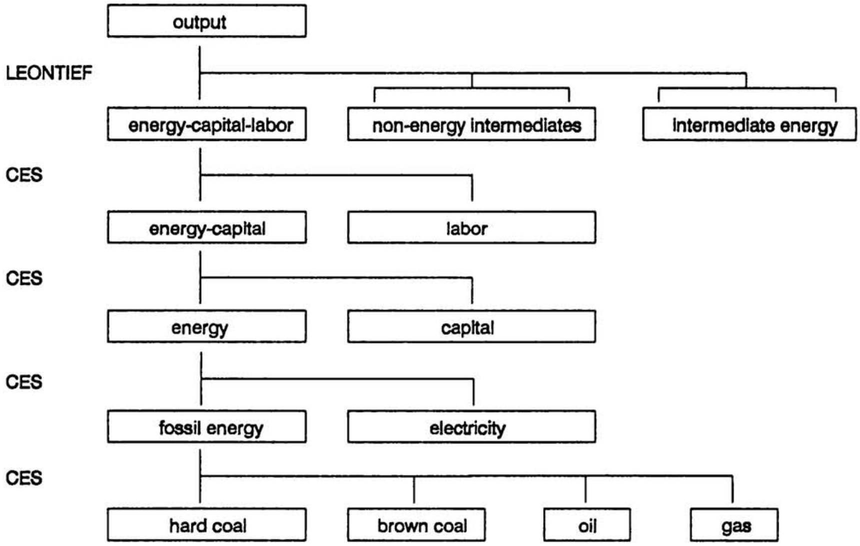

Figure 2: Production Hierarchy

substitution possibilities *within* the energy-capital aggregate are small, they are larger *between* energy-capital and labor[10].

Next, energy-capital is separated into capital and energy. Energy, in turn, is an aggregate of fossil energy and electricity. Finally, fossil energy is composed of the four different fossil fuels distinguished in the model.

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[11].

Factor demand is derived from profit maximization subject to the production structure just outlined. At the top level of the production process inputs are related to output via fixed coefficients. At the subsequent levels there are CES demand functions similar to those used in the foreign trade model (for the precise form, see Appendix B). The sectoral capital stock (in effective units) in operation in any period is the capital stock considered optimal in the previous period[12]. Thus, capital is a

10 For an extensive discussion in conceptual and empirical terms see *Burniaux* et al. (1992).

11 For an overview of estimates see again *Burniaux* et al. (1992).

12 Our theory of capital formation in the presence of embodied technical progress is outlined in Appendix C.

quasi-fixed factor. Energy, being a variable factor, adjusts to the predetermined capital stock.

2.5 Prices and Taxes

Prices represent the supply side of the 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 and energy taxes. The model provides the possibility to tax the various production sectors and the households at different rates.

Due to the assumption of perfect intersectoral mobility of labor there is a uniform wage rate in each region. The current wage equals the wage of the previous period times the increase in labor productivity and in the price level, modified by the ratio between actual employment and "normal" employment. This may be taken to be a dynamic version of the Phillips curve. This wage equation is equivalent to a labor supply function according to which labor in excess of its normal level is attracted whenever wages increase by more than the growth rate of productivity.

As mentioned in subsection 2.2, the uniform interest rate is determined by the requirement of capital market equilibrium.

For the exchange rate of the EC vis a vis ROW we specify a dependence on the consolidated balance of current account of the EC. More specifically, we assume that the exchange rate remains constant whenever the current account balance is in equilibrium. A negative balance represents excess demand for foreign exchange and brings about an increase in the exchange rate, while a positive balance works in the opposite direction.

The prices and taxes discussed so far are the "fundamentals" of the price model. All other prices are derivatives thereof. These derivatives are obtained from price aggregator functions dual to the quantity aggregators (production functions) discussed above. These price aggregator functions may be interpreted as marginal cost functions, or inverted supply functions. The assumption of constant returns to scale, implicit in the CES specification of the production functions, implies constant marginal costs, which are at the same time average costs. Hence there are no quantities among the arguments of the price functions[13]. Only for the price of the energy-capital aggregate there is a dependence on the level of the aggregate and on the capital stock. This is due to capital being a fixed factor (in the short term), which implies that marginal and average costs differ and neither of them is constant.

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13 The functional form is stated in Appendix B.

Of special interest is the world market price of the different goods. The world market price is an aggregate of the export prices of EC and ROW and is expressed in terms of EC currency. Thus it depends on the exchange rate. It is identical to the import price of the EC countries.

Also of interest is the price of electricity and the price of the fossil fuels. The purchase price of these energy carriers equals their generation price plus the carbon and energy tax. Note that these energy prices may differ by user, due to possibly differing tax rates. Also observe that only energy *consumption* is subject to taxation, not the use of energy carriers for non-energy purposes.

3. The Simulations

3.1 Assumptions and Scenarios

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 2.5%/a while the export prices (relative to the numeraire) are assumed to be constant, except for the energy carriers. For the latter, the Enquete Commission suggested a (real) annual price increase of 0.1, 1.3 and 2.0% for hard coal, oil and gas, respectively. Also, exogenous quantities for German hard coal mining have been specified by the Commission. They are 45 million tons by 2005 and 25 million tons by 2020, with a linear adjustment in the intermediate periods.

These assumptions are valid for all simulations. Another group of assumptions concerns the baseline simulation only. First, GDP is assumed to grow at 2.0 percent in both regions. These growth rates are based on suggestions by the Enquete Commission. The growth rates for CO_2 have been adapted from EC projections (CEC 1992). They are 0.6 percent in Germany and 1.0 percent in the rest of the EC[14].

We turn now to the tax scenarios. They are all derived from a basic tax path, which starts at 3 USD per barrel of oil (bbl). The starting date is assumed to be 1996. Up to 2005 there is an annual increase by 1 USD,

[14] If the model is to reproduce these predetermined baseline growth rates, the rates of labor-augmenting and energy-augmenting technical progress have to be fixed at about 1.5 percent and 2.0 percent, respectively, in both regions. Of course, fixing the rates of progress in this way entails an interdependence problem: four "target" growth rates are to be hit by means of four "instruments". Our strategy was to keep the deviations between the progress rates of *GER* and *EC*9 to a minimum. Then it turned out that there is a strong connection between *GDP* and labor-augmenting technical progress on the one hand and between CO_2 and energy-augmenting technical progress on the other, whereas cross-connections are less important. For capital-augmenting technical progress we assume a rate of 2.0 percent, in line with *Berndt* et al. (1993). These progress rates are kept fixed in all simulations.

and in 2006 - 2020 the increase is 0.5 USD per year. These tax rates are in nominal terms. For modeling purposes they are converted to real terms using a deflator of 3% per year.

This basic tax path has been adapted by the Enquete Commission from the initial proposal by the Commission of the European Communities. One specific feature of this proposal is the way in which the basic tax level is to be translated into tax rates for the different energy carriers. The EC proposal is specified as a combined carbon/energy tax, meaning that of the amount of x USD/bbl, $x/2$ is linked to the energy content and $x/2$ to the carbon content. This implies that initially every fuel is taxed at 0.21 ECU per GJ energy content and 2.81 ECU per ton of CO_2[15]. Electricity is treated differently. Here, predetermined energy conversion efficiencies (heat rates) in combination with the carbon content of the fuels were used to translate the basic tax rates into fuel-specific rates per unit of electricity produced[16]. Clearly, non-fossil electricity is faced with the lowest rate because only the energy component is relevant here.

In contrast to the EC-wide carbon energy tax, the national energy tax relates the basic tax rate exclusively to the energy content. This gives an initial energy tax of 0.42 ECU/GJ (which is, of course, twice the energy tax component of the combined tax). For energy-intensive industries tax exemptions are provided. In terms of the broader classification in the model this translates into reduced rates for the sectors basic materials and chemistry and consumption goods[17].

In addition to the tax design, there is a second dimension to the scenario definition: tax recycling. The central case, labeled REDIST, refers to a lump-sum redistribution of the tax to private households[18]. By contrast, GOVEXP means that the tax revenue is used entirely to increase government expenditures. Finally, CONSOL is the case in which the revenue is used to consolidate the government budget, leading to an increase in the supply of capital available for private investment.

We will now describe the effects of the two types of tax, differentiated by the mode of tax recycling.

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15 The relevant USD/ECU rate has been fixed in the proposal.

16 The rates are as follows: 4.6 ECU/MWh (hard coal), 5.5 ECU/MWh (brown coal), 4.1 ECU/MWh (oil), 3.5 ECU/MWh (gas), 2.1 ECU/MWh (non-fossil fuels).

17 For basic materials and chemistry the tax rate is only about 10 percent of the normal rate; for consumption goods it is about 90 percent.

18 A frequently discussed mode of tax recycling is the reduction of the value-added tax. This cannot be modelled because the data contains no value-added tax.

3.2 Simulation Results

Figure 3 shows the effect of the two taxes on carbon dioxide emissions. Considering the EC tax we see that its effect in Germany is somewhat stronger than in EC9. In 2020 the tax leads to a decrease in German emissions by 9 - 10 percent relative to the baseline, whereas the decrease in EC9 is 7 - 8 percent. Comparing modes of tax recycling, the effect is somewhat less in the CONSOL and REDIST case than in the GOVEXP case. The reasons for this will become clear below.

Turning to the national tax, the first observation to be made is that its effect is significantly less than in the case of the EC tax: the decrease in German emissions by 2020 is only 5 - 6 percent. This result is only partly due to the reduced rates for energy intensive industries. Additionally, there is an economic explanation which will become clear below, when considering the economic effects. Before turning to that, however, it should be observed that, associated with the unilateral introduction of the tax in Germany, there is a small so-called carbon leakage effect: emissions increase in EC9, in accordance with common reasoning on unilateral emission reduction measures (see, e.g., *Hoel* 1991). However, the extent of the effect is very small[19].

Overall, it can be said that both taxes are far from stabilizing (or even reducing) European CO_2 emissions[20]. What can be achieved by the tax is that the projected baseline increase is reduced by half in Germany and by one quarter in the rest of EC.

We turn now to the macroeconomic effects of the two taxes. Figure 4 displays the effect on GDP. The first thing to observe is that the impact is rather small. In the case of the EC tax, the GDP decrease by 2020 is about 0.4 percent in Germany and 0.3 percent in EC9. It may appear surprising that the impact is not larger. Yet, the result is quite plausible because it implies an elasticity of GDP with respect to CO_2 emissions of 0.04 - 0.05. Considering the typical share of energy costs in GDP, this corresponds to a reasonable estimate of the macroeconomic production elasticity of energy. Additionally, the GDP impact can be considered in relation to the tax-induced energy-price increase. The average energy price rises by about 11 percent in 2020, hence the energy price elasticity of German GDP is about −0.04. This is surprisingly well in line with the GDP impact of the 1973/74 and 1979/81 oil price hikes, which imply an estimated price elasticity of German GDP

19 Similar results in a more aggregated, worldwide context are desdribed in *Oliveira-Martins* et al. 1992.

20 A stabilization at 1990 levels is the declared objective of EC policy on climate change.

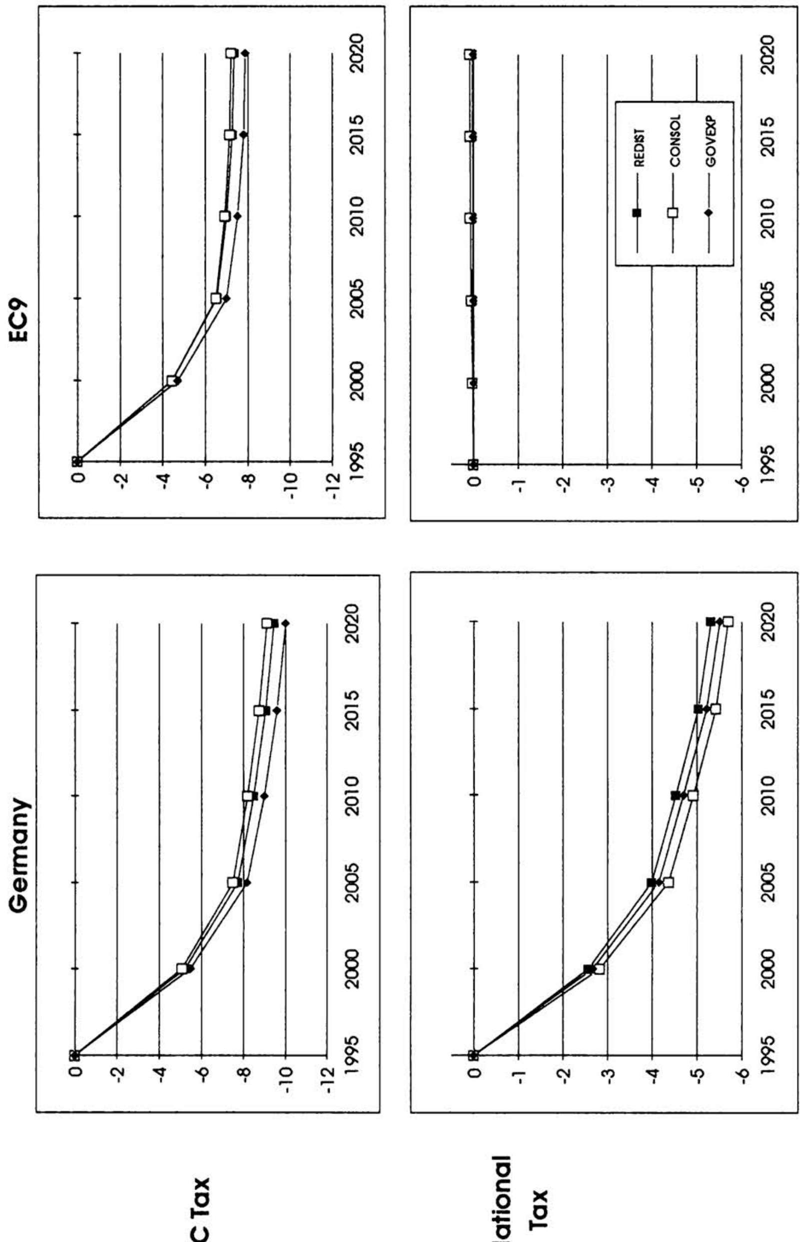

Figure 3: Carbon Dioxide Emissions (% difference from base)

of about -0.03[21]. Thus, although the price hikes and a smoothly increasing carbon/energy tax are quite different things, this back-of-the-envelope consideration shows that the computed GDP impact is of a rather reasonable order of magnitude[22].

Considering the tax recycling scenarios, there is a marked difference in the results. For both taxes and both countries there is a clear ranking of alternatives: CONSOL is always the best option and GOVEXP is always the worst one in terms of growth effects, whereas REDIST takes an intermediate position[23]. This observation can directly be linked to the behavior of the interest rate. After the initial 3 - 5 years, the interest rate is lower in all tax scenarios than in the base run. This is due to the weak substitutability between energy and capital and the corresponding tax-induced decrease in capital demand. Yet, there is a marked difference between the tax recycling modes: While the change in the interest rate is almost zero in the GOVEXP case (-0.5 percent, or -0.02 percentage points), it is quite a bit higher under CONSOL (-4.5 percent, or almost -0.2 percentage points); the REDIST case takes an intermediate position. This difference is, of course, due to the larger supply of capital available to the private sector under CONSOL, as compared to REDIST and GOVEXP. The difference in the interest rate directly translates into differing rates of capital formation, and explains why (neglecting the short run) CONSOL leads to the smallest loss in GDP, while GOVEXP leads to the largest[24].

The fact that GDP is higher under CONSOL than under its alternatives explains why, in the case of the EC tax, emissions are slightly

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21 In 1973/74 the average oil import price in Germany increased by 170 percent while the growth rate of GDP decreased by 4.6 percent. This implies an elasticity of -0.027. Similarly the 130 percent rise of the oil import price in 1979/81 was followed by a reduction in the growth rate by 3.9 percent, implying an elasticity of -0.03 (data taken from SVR 1993, Statistical Appendix).

22 A common feature of all simulations is that in the first few years there ia s GDP *increase* in comparison to the baseline. This is due to the way in which the formation of expectations is modelled. As stated in Appendix C, firms are assumed to compute the expected *activity level* by means of a moving average of the latest two growth rates. With respect to *prices* firms are assumed to expect current prices to be valid in the next period as well. Both assumptions introduce some inertia into the model dynamics (which has the technical advantage of avoiding potential stability problems).

23 Only in the first five years GOVEXP shows an advantage in the case of the EC tax.

24 It may be noted in passing that these results were obtained under the assumption of an 0.8 elasticity of the savings ratio with respect to the interest rate (see Appendix D). Had we assumed a constant savings ratio, as in many models, the difference in the interest rate impact as well as in the impact on capital formation and on GDP would have been even larger. A flexible savings ratio provides an additional outlet for a capital supply impulse which otherwise would have been accomodated entirely by the interest rate.

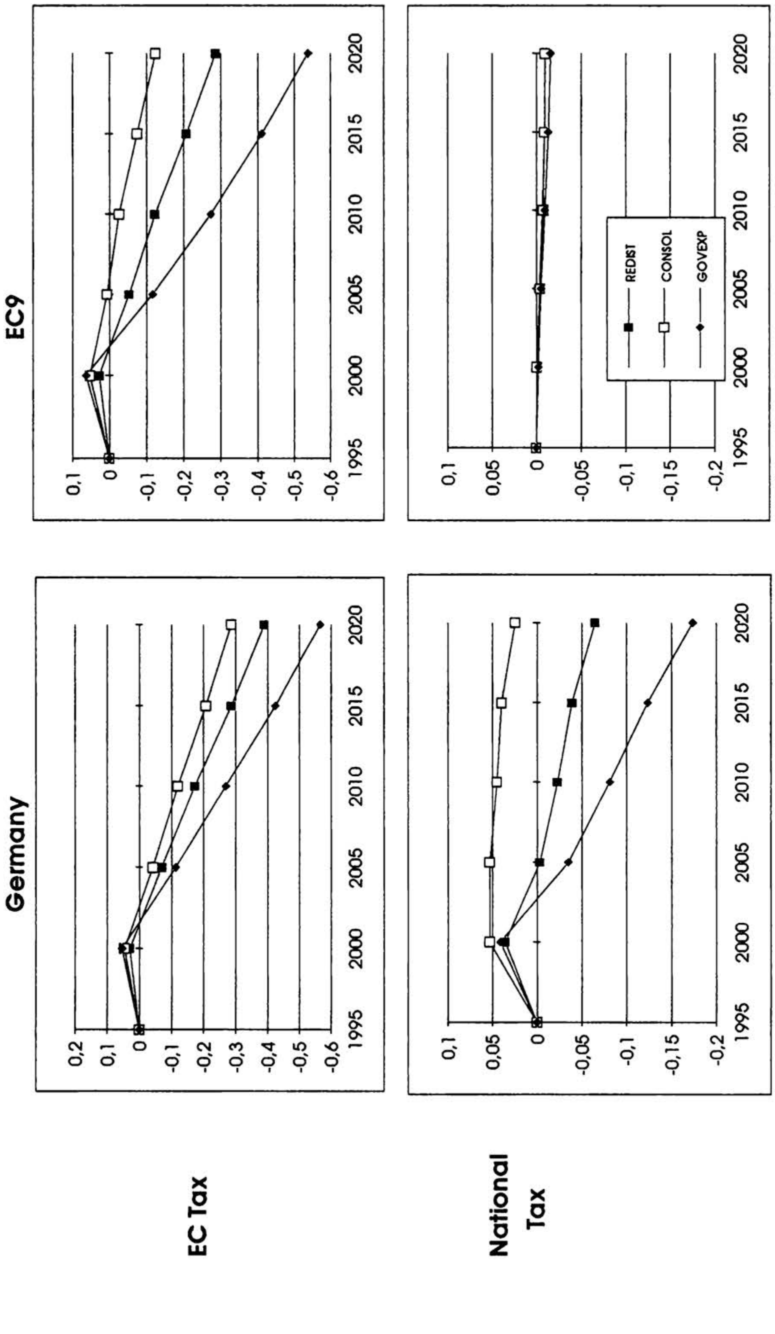

Figure 4: Gross Domestic Product (% difference from base)

higher under CONSOL than under its alternatives. However, the difference in terms of GDP is much more pronounced than the difference in terms of emissions. In other words, CONSOL clearly is the most efficient strategy, in the sense that the elasticity of GDP with respect to emissions is smaller than in alternative recycling modes. This dominance is even more pronounced when we consider the national tax. In this case, CONSOL has the most favorable effect in terms of both GDP *and* emissions.

With respect to the national tax we find that the decrease in GDP is much less than under the EC tax. Under CONSOL there is even a small *increase* in GDP. This can only partly be explained by the reduced tax rate for energy-intensive sectors. A more important reason can be understood when we compare the effect of the two taxes in EC9. Clearly, while the effect of the EC tax is small, the effect of the German tax is even negligible. Given that a large fraction of German exports depends on EC9 demand, this largely explains why the effect of the national tax on both German emissions and GDP is smaller than the effect of the EC tax[25]. This means: for the tax level considered, the difference between the two taxes in terms of their effect on foreign-trade *prices* is less important than their difference in terms of their effect on the *level* of foreign demand. This becomes even more visible when we consider foreign trade in more detail.

Consider Figure 5, which displays the macroeconomic effects of CO_2 reduction in 2005 and 2020. The results shown refer to the REDIST case only. As concerns the EC tax we find that investment shows the strongest reaction to the tax, due to the small substitution elasticity between energy and capital. Accordingly, the capital stock is more strongly affected than employment. In fact, employment hardly reacts at all. This holds for both Germany and EC9. Similarly, in both countries consumption is slightly positively affected by the tax because revenue recycling increases available income and the savings ratio falls slightly, due to the depressed interest rate.

Turning to foreign trade, we see that imports decrease more than exports, where the difference is somewhat more pronounced in Germany. The reason for this outcome is, of course, that imports are much more energy-intensive than exports. As a result, the balance of current account (not shown) improves.

In the case of the national tax it is useful to consider Germany and EC9 simultaneously. It is evident that in EC9 there is almost no reaction

[25] Similar observations have been made with the HERMES system of models (*Standaert* 1992).

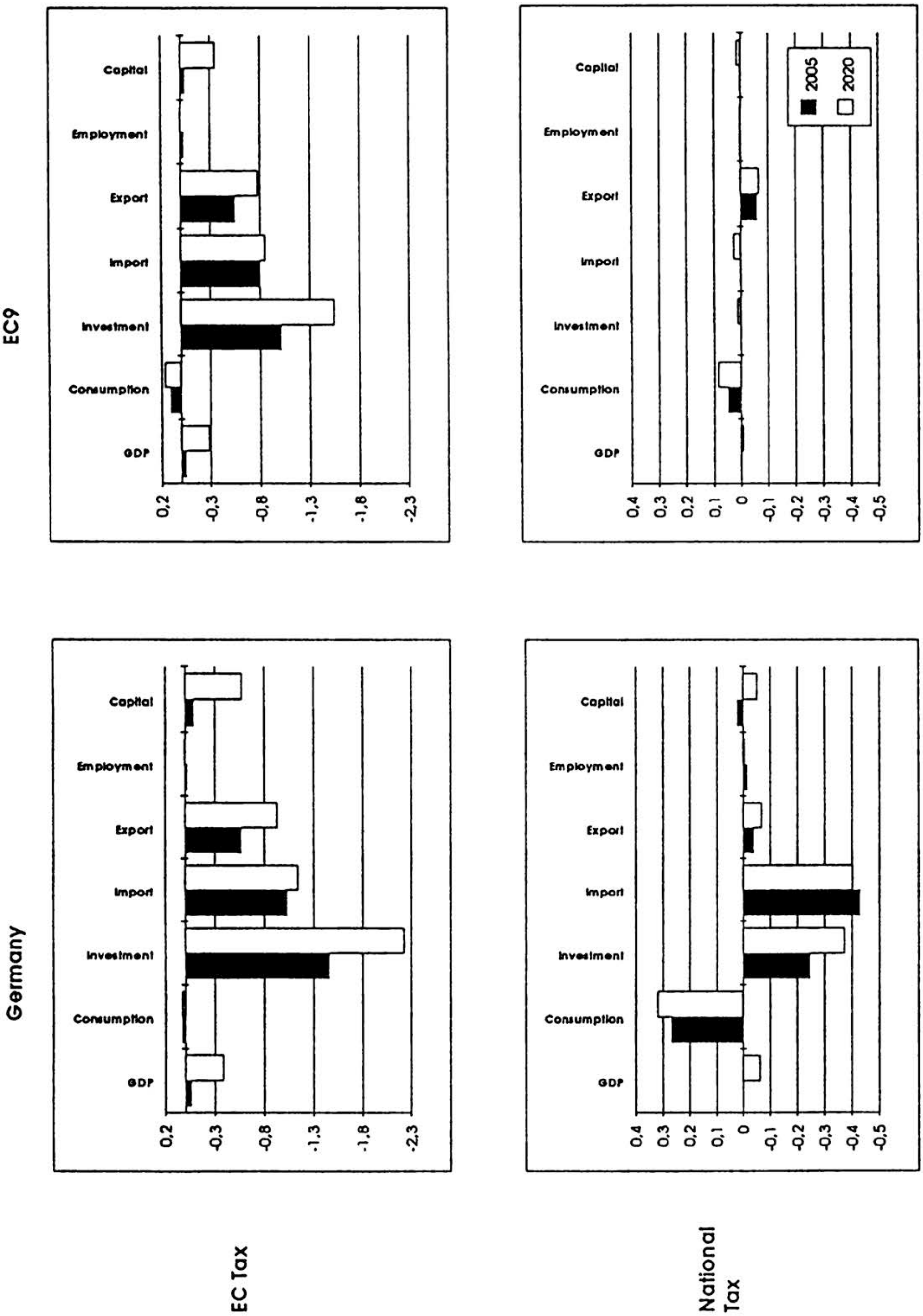

Figure 5: Macroeconomic Effects of Carbon Dioxide Reduction: Redistribution case (% difference from base)

to the tax. Of special interest are the imports of EC9. They are more or less unaffected by the German tax, in contrast to the EC tax case. This explains why German exports decrease less under the national tax than under the EC tax. As a consequence, the overall activity level in Germany is less affected by the national tax than by the EC-wide tax, as mentioned above.

4. Conclusions and Caveats

The paper has provided a quantitative analysis of an EC-wide carbon/energy tax and a national energy tax in Germany. Emphasis was placed on the issue of tax recycling and on international feedback effects. We would highlight the following results:

(a) Both taxes likely bring about an improvement rather than a deterioration in the balance of current account, due to the decrease in energy imports.

(b) Given the tax level considered, the national tax leads to a smaller decrease in both emissions and GDP than the EC-wide tax. This is mainly due to the strong dependence of the German activity level on that of the rest of the EC.

(c) The macroeconomic effects of both European carbon/energy taxation and national energy taxation are systematically influenced by the way in which the tax revenue is recycled into the economy. Consolidation of the government budget clearly outperforms the redistribution of the tax revenue as well as increasing government expenditures.

Of course we must emphasize that our results are preliminary. Major caveats refer to the following:

(a) Are the results robust with respect to changes in the substitution elasticities?

(b) How would the relatively favorable performance of the national tax be affected if higher tax rates were considered?

(c) Would the superiority of the budget consolidation scenario be preserved if the elasticity of the savings ratio with respect to the interest rate were higher (above unity)?

(d) To what extent do the results depend on the exchange rate elasticity and the wage rate elasticity?

These and related questions provide areas for future work.

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Appendix A: Formal Statement of the Model

This Appendix provides a technical statement of the model. An explanation in economic terms is given in section 2 of the paper. Demand functions and price functions are indicated simply by $f(.)$. The precise functional form follows from the functional specification of the aggregator functions and is discussed in Appendix B. Country indices are omitted unless necessary. Notation is introduced in order of appearance.

Market clearance and macro closure

World trade market

Notation: EX_i^W: world trade volume of good i; IM_i^{GER}; IM_i^{EC9}; IM_i^{ROW}: import demand of Germany, rest of EC, rest of world.

(1) $$EX_i^W = IM_i^{GER} + IM_i^{EC9} + IM_i^{ROW} \qquad \text{where } IM_i^{ROW} = \text{exog.}$$

Domestic goods markets

Notation: X_i: total supply; XX_{ij}: intermediate demand; XC_i: consumption demand; XG_i: government demand; XEX_i: export demand; S: set of sectors.

(2) $$X_i = \sum_{j \in S} XX_{ij} + XC_i + XG_i + XI_i + XEX_i$$

Labor markets

Notation: LAB: employment; L_j: sectoral labor demand.

$$LAB = \sum_{j \in S} L_j \tag{3}$$

Capital market and macro closure

Notation: IN: investment; $DEPN$: depreciation; YVN: available income; GN: government expenditure; TN total tax revenue; EXN: exports; IMN: imports; s: savings ratio, z: real interest rate. Symbols containing "N" refer to nominal variables.

$$IN - DEPN = s \cdot YVN - (GN - TN) - (EXN - IMN) \tag{4}$$

$$z^{EC9} = z^{GER} \text{ (arbitrage)} \tag{5}$$

Price Normalization

Notation: PC: consumer price index.

$$PC^{EC9} \equiv 1 \text{ (numeraire)} \tag{6}$$

Foreign Trade and Final Demand

Imports

Notation: PIM_i: import price; IM_i: import volume; PX_i: price of total supply; Q_i: domestic output; PQ_i: price of domestic output.

$$IMN = \sum_i PIM_i \cdot IM_i \tag{7}$$

$$IM_i = f(X_i, PX_i, PIM_i) \tag{8}$$

$$Q_i = f(X_i, PX_i, PQ_i) \tag{9}$$

Exports

Notation: PEX_i^W; PEX_i^{EC}; PEX_i^{GER}; PEX_i^{EC9}: export price of world, EC, GER, rest of EC.

$$EXN = \sum_i PX_i \cdot XEX_i \tag{10}$$

$$XEX_i^{EC} = f(EX_i^W, PEX_i^W, PEX_i^{EC}) \tag{11}$$

(12) $$XEX_i^{GER} = f(XEX_i^{EC}, PEX_i^{EC}, PEX_i^{GER})$$

(13) $$XEX_i^{EC9} = f(XEX_i^{EC}, PEX_i^{EC}, PEX_i^{EC9})$$

Consumption

Notation: CN: consumption expenditures; $WAGE$: labor income; NOS: net operating surplus; a, b, γ_i: parameters.

(14) $$CN = (1 - s) \cdot YVN = (1 - s) \cdot (WAGE + NOS)$$

(15) $$s = a \cdot z^b$$

(16) $$XC_i = \overline{XC}_i + \gamma_i \frac{CN - \sum_j \cdot PX_j \cdot \overline{XC}_j}{PX_i}$$

Government Expenditure

Notation: YN: nominal GDP; PX_{NMSV}: price of non-market services; s_{GY}: parameter.

(17) $$GN = s_{GY} \cdot YN_{-1}$$

(18) $$XG = GN / PX_{NMSV}$$

Investment

Notation: I_j: sectoral investment; PI_j: sectoral purchase price of capital; K_j: capital stock at beginning of period; K_j^*: capital stock planned for next period; δ_j: depreciation rate; κ_{ij}: coefficient of capital composition matrix.

(19) $$IN = \sum_{j \in S} PI_j \cdot I_j$$

(20) $$I_j = K_j^* - (1 - \delta_j) K_j$$

(21) $$XI_i = \sum_{j \in S} \kappa_{ij} \cdot I_j$$

Factor Demand

Notation: EKL_j: energy-capital-labor aggregate; L_j: labor; $PEKL_j$: price of energy-capital-labor aggregate; PL: wage rate; EK_j: energy-capital aggregate; PEK: price of energy-capital aggregate; K_j: capital stock; E_j: energy aggregate; $XXEC_{ELj}$: electricity input; PE_j: price of energy aggregate; PEL_j: price of electricity; $XXEC_{Fj}$: fossil fuel aggregate; PF_j: price of fossil fuel aggregate; $XXEC_{F1j}, \dots XXEC_{F4j}$: individual fossil fuel inputs; $PF1, \dots PF4$: price of individual fossil fuel inputs. Tildas refer to variables in "effective units". Planned capital stock is derived in Appendix C.

(22) $$XX_{ij} = f(Q_j)$$

(23) $$EKL_j = f(Q_j)$$

(24) $$\tilde{L}_j = f(EKL_j, PEKL_j, \widetilde{PL})$$

(25) $$EK_j = f(EKL_j, PEKL_j, PEK_j)$$

(26) $$\tilde{K}_j = \tilde{K}^*_{j,-1}$$

(27) $$\tilde{E}_j = f(EK_j, \tilde{K}_j)$$

(28) $$XXEC_{ELj} = f(E_j, PE_j, PEL_j)$$

(29) $$XXEC_{Fj} = f(E_j, PE_j, PF_j)$$

(30a) $$XXEC_{F1j} = f(XXEC_{Fj}, PF_j, PF1_j)$$

(30d) $$XXEC_{F4j} = f(XXEC_{Fj}, PF_j, PF4_j)$$

Prices and Taxes

Prices of primary inputs

Notation: Π: rate of nominal productivity growth.

(31) $$PL = \Pi \cdot PL_{-1} \cdot \left(\frac{LAB}{\overline{LAB}}\right)^{\alpha} \quad \left(\Leftrightarrow LAB = \overline{LAB} \cdot \left(\frac{PL}{\Pi \cdot PL_{-1}}\right)^{1/\alpha}\right)$$

(32) $z \leftarrow$ capital market equilibrium

Price of foreign exchange

Notation: ER: exchange rate EC vs. ROW.

(33) $$ER = ER_{-1} \cdot \left(\frac{\sum_r IMN_r}{\sum_r EXN_r}\right)^{\beta}, \ r \in \{GER, EC9\}$$

Price aggregates

Notation: TC_{ji}: carbon tax rate $(ECU/t\,CO_2)$; TE_{ji}: energy tax rate (ECU/TOE); c_j: specific carbon content of energy; e_j: specific energy content of energy good; $coef_{ij}$: share of non-energetic use of energy good i in sector j.

(34) $$PEX_i^W = f\left(PEX_i^{ROW} \cdot ER, PEX_i^{EC}\right) \equiv PIM_i$$

(35) $$PEX_i^{EC} = f\left(PX_i^{GER}, PX_i^{EC9}\right)$$

(36) $$PX_i = f\left(PQ_i, PIM_i\right)$$

(37) $$PQ_i = f\left(PX_i, PEKL_i\right)$$

(38) $$PEKL_i = f\left(PL, PEK_i\right)$$

(39) $$PEK_i = f\left(EK_i, K_i, PE_i\right)$$

(40) $$PE_i = \left(PEL_i, PF_i\right)$$

(41) $$PF_i = f\left(PF1_i, \ldots, PF4_i\right)$$

(42) $$\left.\begin{array}{l} PEL_i \\ PF1_i \\ \vdots \\ PF4_i \end{array}\right\} = PX_j + (1 - coef_{ji}) \cdot \left[c_j\, e_j\, TC_{ji} + e_j\, TE_{ji}\right],$$

Appendix B: Functional Forms

The quantity aggregator functions in the foreign trade model are specified as CES functions. The production functions are of a nested Leontief/CES form.

Maximizing profit or utility on the basis of these quantity aggregators yields demand functions which, in turn, can be used to compute cost functions[26]. Our special interest lies in average cost functions, which we interpret as inverse supply functions. To emphasize the duality between quantities and prices, average cost functions will be referred to as price aggregators.

Consider the CES quantity aggregator function (production function)

$$X = \left[\sum_{i=1}^{n} d_i \left(g_i X_i\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{43}$$

where X_i = input of good i in quantity units,

$g_i X_i$ = input of good i in effective units,

σ = elasticity of substitution,

d_i = distribution parameter.

If $g_i \geq 1$ increases in time, this is referred to as factor-augmenting technical progress. If, conversely, $g_i = 1$; the technology is stationary.

If all inputs are variable, the demand functions corresponding to (43) are

$$X_i = d_i^{\sigma} \left(\frac{PX}{PX_i}\right)^{\sigma} g_i^{\sigma-1} X, \tag{44}$$

and the price aggregator is of the form

$$PX = \left[\sum_{i} d_i^{\sigma} \left(\frac{PX_i}{g_i}\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}} \tag{45}$$

These formulas are valid for the foreign trade model and the production model, except for the top level and the *EK* level.

At the top level, demand is obtained from fixed input-output coefficients, and the price aggregator is the weighted average of input prices.

At the *EK* level, there are only two inputs to the quantity aggregator (43), one of which (capital) is fixed. The demand for the other factor (energy) is then obtained by rearranging the eq. (43). The profit-maximizing supply price has the form

[26] Frequently, cost functions are taken as the basic description of technology. Demand functions are then obtained utilizing Shephard's lemma. Our exposition arbitrarily starts from production functions as the basic concept.

(46)
$$PEK = \frac{\widetilde{PE} \cdot \tilde{E}}{EK - d_K EK^{\frac{1}{\sigma}} K^{\frac{\sigma-1}{\sigma}}},$$

where the variables indicated by a tilda are in effective units.

To see this, consider the profit-maximization problem at the EK level:

(47)
$$\max_{\tilde{E}} \; PEK \cdot EK - \widetilde{PE} \cdot \tilde{E} - uc \cdot \tilde{K}$$

in which $\tilde{K}$ is predetermined. This gives the first-order condition

(48)
$$\frac{\partial EK}{\partial \tilde{E}} = \frac{P\tilde{E}}{PEK}.$$

Because the EK aggregator function is linear homogenous, we have

(49)
$$EK = \frac{\partial EK}{\partial \tilde{E}} \tilde{E} + \frac{\partial EK}{\partial \tilde{K}} \tilde{K}$$

Inserting (48) into (49) and solving for PEK gives:

(50)
$$PEK = \frac{\widetilde{PE} \cdot \tilde{E}}{EK - \frac{\partial EK}{\partial \tilde{K}} \tilde{K}}.$$

Finally, from observing the functional form of the EK aggregator we have

(51)
$$\frac{\partial EK}{\partial \tilde{K}} = d_K \left(\frac{EK}{\tilde{K}} \right)^{1/\sigma},$$

which together with (50) gives (46).

Appendix C: Capital Formation

Our theory of capital formation differs from the usual approach by taking account of embodied technical progress. The theory is meant to apply to each sector separately, but sector indices are omitted.

The usual stock-flow accounting relationship for capital is:

(52)
$$K_t = (1 - \delta) K_{t-1} + I_{t-1}$$

Observe that investment becomes effective with a one-period delay.

Because there is capital-augmenting technical progress, it is useful to introduce the concept of capital efficiency. Our key assumption on capital efficiency is that the efficiency of the existing capital stock (a_t) is a weighted average of the efficiency of last period's capital stock (a_{t-1}) and the efficiency of the latest vintage now in operation (b_{t-1}):

$$a_t = \frac{(1-\delta)K_{t-1}}{K_t} a_{t-1} + \frac{I_{t-1}}{K_t} b_{t-1} \tag{53}$$

The efficiency of the latest vintage is assumed to grow at an exogenous rate.

This equation can be rearranged to give the stock-flow accounting relationship for capital in efficiency units:

$$\begin{aligned} a_t K_t &= (1-\delta) a_{t-1} K_{t-1} + b_{t-1} I_{t-1} \\ \tilde{K}_t &= (1-\delta)\tilde{K}_{t-1} + \tilde{I}_{t-1} \end{aligned} \tag{54}$$

By turning to continuous time, the equation of motion of the capital stock in efficiency units is obtained:

$$\dot{\tilde{K}}_t \approx \tilde{K}_t - \tilde{K}_{t-1} = \tilde{I}_{t-1} - \delta \tilde{K}_{t-1} \tag{55}$$

Using the variable cost function[27]

$$VC = VC(\underset{+}{EK}, \underset{-}{\tilde{K}}, \underset{+}{\widetilde{PE}}) \tag{56}$$

the intertemporal cost minimization problem can now be stated as:

$$\min_{\tilde{I}} \int_0^\infty e^{-zt}\left[VC(EK, \tilde{K}, \widetilde{PE}) + \widetilde{PI} \cdot \tilde{I}\right] dt \quad s.t. \dot{\tilde{K}} = \tilde{I} - \delta \tilde{K}, \tag{57}$$
$$\text{where } \widetilde{PI} = PI/b$$

With static price expectations the optimal investment program is then characterized by the condition that the marginal decrease in variable costs brought about by expanding the capital stock (in efficiency units) should just match the user costs incurred (uc):

$$-VC_{\tilde{K}} = \tilde{u}c \overset{CES}{\Leftrightarrow} \tilde{K}^* = \left[\left(\frac{\tilde{u}c\, d_E\, 1/\rho}{\widetilde{PE}\, d_K}\right)\frac{\rho}{1-\rho} + d_K\right]^{-1/\rho} EK^e \tag{58}$$

$$\text{where } \tilde{u}c = (z + \delta + w_b) \cdot \widetilde{PI}$$

[27] The variable cost function gives the minimum costs to be spent on variable factors, conditional on variable factor prices and the quantities of output and of the fixed factor.

Note that, in contrast to the usual case, the user cost expression includes the growth rate of the efficiency of new capital (w_b). This indicates opportunity costs in terms of technical progress foregone by investing "now", rather than "later".

In the case of CES production functions and in the absence of adjustment costs, this first-order condition can be readily solved for the optimal capital stock in efficiency units. Because capital formation always takes place one period in advance, expectations as to the activity level need to be formed. We assume that the expected activity level governing capital formation (EK^e) is obtained by extrapolating past growth rates, i.e. there are myopic expectations with respect to growth rates.

Appendix D: Parameter Assumptions

The following table shows our current assumptions on elasticities.

$\sigma(ROW, EC) = 0.1 - 0.8$

$\sigma(GER, EC9) = 0.1 - 2.0 \qquad (\geq \sigma(ROW, EC))$

$\sigma(Q, IM) = 0.1 - 2.0$

$\sigma(EK, L) = 0.6$

$\sigma(E, K) = 0.3$

$\sigma(EL, F) = 0.6$

$\sigma(F_i, F_j) = 0.8$

$\varepsilon(s, z) = 0.8$

$\varepsilon(ER, BCA) = 0.3$

$\varepsilon(PL, LAB) = 1.5$

σ refers to the substitution elasticities employed. They are mostly near the center of the range of estimates to be found in the literature[28]. For foreign trade, elasticities are differentiated by type of good. The differentiation has been guided especially by considerations of transport costs, the availability of transmission networks (if applicable) and institutional restrictions. Of course the existence of domestic sources of the good is also essential for substitution elasticities. An example for non-existing domestic sources is natural gas. Also, there is no world market for natural gas due to high costs of shipment for liquified natural gas. Thus, the natural gas market is a continental one, with a low substitution elasti-

28 For an overview see *Burniaux* et al. (1992).

city. For brown coal, world trade does not pay and, hence, does not exist. For obvious reasons there is no world trade in electricity, and trade within Europe is (as yet) severely restricted by regulatory arrangements. It is also evident that non-market services are poor international substitutes.

In all cases in which international trade, be it on the world scale or the European scale, is non-existent or strongly restricted we fix the corresponding substitution elasticity at 0.1. Otherwise, the default value for the world trade elasticity ($\sigma(ROW, EC)$) is 0.8 and the one for trade within the EC ($\sigma(GER, EC9)$) is 2.0.

For production we assume uniform elasticities across sectors[29]. The values for energy-capital versus labor and for energy versus capital are those employed by *Burniaux* et al. (1992). Within the EK aggregate we follow the idea that substitution elasticities become smaller as aggregates become broader. Probably most remarkable is the low value for energy-capital substitutability. However, the figure employed is in line with other studies as well, e.g., *Manne* and *Richels* (1992). In fact, a range of 0.3 to 0.4 may be regarded as a "consensus outcome" of the long-lasting substitutability-complementarity controversy.

The elasticities denoted by ε refer to the reaction functions for the savings ratio, the exchange rate and the wage rate. They have been chosen quite informally, with a view to long-term stability. For instance, if there is capital-augmenting technical progress a strictly positive elasticity of the savings ratio with respect to the interest rate turns out to be necessary in order to keep the interest rate in a reasonable range. Similarly, a reasonable long-term behavior of the balance of current account (BCA) requires sufficient flexibility of the exchange rate. Finally, it is plausible to assume that the elasticity of the wage rate with respect to employment is above unity (otherwise, more labor could be mobilized at no incremental cost).

Zusammenfassung

In diesem Artikel werden eine EU-weite CO_2-Energiesteuer und eine nationale Energiesteuer für Deutschland quantitativ untersucht. Im Vordergrund steht die Frage der Steueraufkommensverwendung sowie der internationale Kontext. Als Analyseinstrument dient ein rekursiv-dynamisches Allgemeines Gleichgewichtsmodell der EU, in welchem (West-)Deutschland und die Übrige EU interdependent modelliert sind. Der Modellansatz berücksichtigt sowohl faktorgebundenen als auch faktorungebundenen technischen Fortschritt. Weitere Modellmerkmale sind die endogene Bestimmung des Realzinses sowie des Wechselkurses der EU

[29] This is an obvious candidate for future improvement.

gegenüber der Übrigen Welt. Simulationsexperimente zeigen, daß die makroökonomischen Auswirkungen von CO_2-/Energiesteuern systematisch mit der Art der Steueraufkommensverwendung variieren. Ferner zeigt sich, daß eine im nationalen Alleingang eingeführte Steuer weniger ungünstig wirkt als vielfach befürchtet.

Abstract

The paper provides a quantitative assessment of an EC-wide carbon/energy tax and a national energy tax in Germany. Emphasis is placed on the issue of tax recycling and on international feedback effects. The analysis utilizes a recursively-dynamic two-region general equilibrium model of the European Community. The model takes account of both embodied and disembodied technical progress. Other features include the endogenous treatment of the interest rate and the flexible exchange rate of the EC vis a vis the rest of the world. Our results indicate that the macroeconomic effects of both taxes are systematically influenced by the way in which taxes are recycled into the economy. Also, we find that a purely national tax may be noteably less unfavorable than frequently expected.

JEL classification: D5, Q2, Q4