The Determinants of Production-Related Carbon Emissions in West Germany, 1985-1990: Assessing the Role of Technology and Trade

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Abstract

This paper examines the determinants of the substantial decline of West German production-related carbon intensity in the face of falling energy prices. A computable general equilibrium model is used to determine the simulated effects of observed changes of world energy prices and domestic energy policy on the sectoral patterns of carbon emissions, energy consumption, output, value-added and other indicators of structural change. The structural changes not accounted for by energy prices and energy policy are attributed to changing patterns of productivity growth in Germany and the rest of the world (ROW) and changing patterns of ROW demand. Weights on these driving forces are selected by least squares. One key finding is that the contribution of ROW productivity and demand patterns to emission-relevant structural change unaccounted for by energy prices and energy policy is just under 30 percent. The remainder is split almost equally among patterns of domestic autonomous energy efficiency improvement and domestic labor efficiency patterns.

Keywords: carbon emissions, structural change, technology, trade, computable general equilibrium

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1. Introduction

In 1985 - 1990 the production-related carbon-emissions in West Germany (excluding those from the government sector) decreased by 0.2 percent annually whereas the total private supply of goods increased by 4.2 percent. The carbon intensity of private good supply thus decreased by approximately 4.4 percent per year. At the same time, the dollar prices of world energy decreased by 7.3 percent per year (coal), 5.5 percent (oil) and 2.3 percent (gas), see IEA (1995).

This papers examines the determinants of the substantial decline in carbon intensity in the face of falling energy prices. The analysis focuses on *production-related* emissions in the sense that emissions from the government and household sector are not the subject of the paper. In addition, the study is restricted to West Germany because appropriate data on East Germany *before* the unification are not available; the changes in energy use and economic structure in the eastern part of Germany *after* the unification are difficult to analyze in purely economic terms. Focusing on West Germany then implies restriction to the period 1985 - 1990 because separate data for the western part of unified Germany are not supplied by the statistical offices.

Even though the paper disregards emissions from the government and household sector, it captures more than 70 percent of West German emissions in the period considered (and more than 95 percent of non-household emissions). Concentrating on this subset of emissions is useful because it allows to neglect the impact that changes in the average temperature may have had on heating requirements: Energy for heating is important mainly in the household sector (where it amounts to about three quarters of energy consumption); outside the household sector, the share of heating in energy consumption is less than ten percent (VDEW 2000). Therefore, the average temperature of the heating period had only a minor influence on the subset of emissions considered in this paper.[1]

Neglecting temperature changes, there are three broad factors that may have contributed to the decrease in production-related carbon intensity. The first is energy policy, especially the expansion of nuclear power over the period considered. The second comprises technology-based improvements of energy efficiency. The third is structural change in the economy.

With respect to the latter two, there is a well established literature that aims at decomposing changes in aggregate energy intensity into changes in energy intensity at the sectoral level and changes in the sectoral structure of the economy, see e.g. Boyd et al. (1987), Ang (1994), Unander et al. (1999), de Bruyn (2000, chapter 9). The present paper departs from these

[1] Limiting the analysis to a subset of emissions which is fairly independent of temperature changes is important because 1985 was the second coldest year in the period considered whereas 1990 was the warmest, (see www.fh-luebeck.de/an/pt/solar/wstats/temdat.htm).

approaches by not just providing a descriptive decomposition of carbon intensity, but by attempting to identify what *drives* the structural changes that have contributed to the decrease of carbon intensity.

Economic structural change as it has taken place over the period considered has several dimensions (see, e.g., Saeger 1997, Burda and Dluhosch 2000):

(a) *Globalization*: the share of domestic output in total supply decreases.[2]

(b) *Deindustrialization*: the share of industry in domestic output decreases.

(c) *Fragmentation*: the share of intermediate inputs in domestic output increases.[3]

While (a) and (b) tend to reduce the carbon or energy intensity of total supply[4], the impact of (c) is ambiguous, depending on the degree to which intermediate inputs are of domestic origin or imported from abroad.

Several candidates have been proposed as driving forces of these structural changes (see, e.g., Saeger 1997, Berman, Bound and Machin 1998). They can be classified into changes in the structure of world trade and changes in the pattern of productivity improvement at home and abroad. For instance, deindustrialization in advanced economies, such as Germany, has been attributed to growing world demand for services (relative to commodity demand), strong productivity growth in the service sector of advanced economies, and strong productivity growth in the industrial sector of emerging (or developing) economies (Minford, Riley and Nowell 1997).

These potential driving forces of structural change are difficult if not impossible to observe. Regarding trade in services there exists at best rudimentary data, at least for the period considered.[5] As concerns productivity, what would seem to be needed is data on something like "autonomous labor productivity improvement", differentiated at least by the categories "industry" and "services". This is difficult to observe, as is the rate of "autonomous energy efficiency improvement".[6]

Given the unavailability of appropriate data on potentially important explanatory variables, we pursue the following methodological approach.[7]

(0) We provide various decompositions of production-related carbon emissions which reflect structural changes in the use of energy and in the overall economy.

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[2] Total supply is a composite of domestic output and imports. The counterpart to the decreasing share of domestic output in total supply is, of course, the falling share of domestic absorption in total demand.

[3] The statistical phenomenon of fragmentation, as defined above, is the result of a disintegration of production processes along with outsourcing of activities (see Jones and Kierzkowski 1990 and Burda and Dluhosch 2000).

[4] Deindustrialzation reduces not only the carbon and energy intensity of total supply, but also of domestic output; see section 2.

[5] For the 1990s, WTO (2000) indicates that world export of commercial services grew stronger than merchandise export.

[6] These concepts as well as the difficulty of observing them are discussed in section 3.

[7] A similar methodology has been used by Minford, Riley and Nowell (1997) in a different context.

(1) We employ a computable general equilibrium (CGE) model to determine how *observed* changes in energy prices and energy policy have influenced the structural change indicators from step (0).

(2) We use the CGE model to simulate the effect on the indicators from step (0) of arbitrary energy efficiency improvement rates and arbitrary variations of the above mentioned *unobserved* drivers of structural change.

(3) We employ regression analysis to determine the importance of these unobserved drivers in explaining that part of the indicators from step (0) that remain unexplained in step (1).

The paper is organized as follows. Section 2 describes the decomposition of production-related carbon emissions, resulting in the change indicators to be explained. Section 3 provides an outline of the CGE model employed and discusses the model's key exogenous drivers that may serve as explanatory variables for the change indicators. Section 4 considers the simulated contributions of observed energy policy and energy price changes. In section 5 we analyze the simulated partial effects of arbitrary variations in the unobserved exogenous drivers. Section 6 uses regression analysis to determine the weights to be attached to these drivers. Section 7 concludes.

2. Indicators of Change in Energy Use and Economic Structure

Production-related carbon emissions and the associated energy consumption data are available for the 58 sectors of the German input-output table for selected years. Within the period of interest they are available for 1985 and 1990.[8] For the purpose of this paper the original data have been aggregated to eight non-government sectors[9], corresponding to the sectoral classification of the CGE model employed. Data on total supply, output, and value added (Statistisches Bundesamt 1999) has also been aggregated to match these eight sectors.

To provide a first illustration of structural change in energy use, Table 1 displays the carbon intensity and the energy intensity of output in two broad sectoral aggregates, referred to as "industry" and "services".[10]

In 1985 the carbon intensity and the energy intensity, respectively, of industry output was 3.9 and 4.6 times that of service output. In 1990 the corresponding ratios were 3.2 and 4.0. Thus, the "efficiency gap" of industry relative to services became more narrow, with respect to both

[8] I am grateful to Helmut Mayer (German Federal Statistical Office) for supplying unpublished data. These data are a result of the Statistical Office's comprehensive work on establishing a 'Satellite Account on Environment' and conform to the quality standards of official statistics (on sources and methods see Mayer and Stahmer 1989).

[9] The analysis is restricted to the non-government sectors because changes in the government sector are difficult to explain by economic considerations alone.

[10] Note that these labels are suggestive, but depart somewhat from the usual terminology. "Industry" in this paper is meant to include agriculture, but to exclude the energy supply industries. "Services", as a broad concept, includes transportation and excludes non-market services.

carbon and energy. The improvement in carbon efficiency was substantially stronger in industry (25.2 percent) than in services (7.5 percent). The difference in energy efficiency improvement was somewhat less pronounced (18.2 percent in industry vs. 6.6 percent in services). The differences between carbon efficiency improvements and energy efficiency improvements mainly reflect a substitution of electricity for fossil fuels.

Table 1: Carbon and energy intensity of output[a)]

	Industry 1985	Services 1985	Industry 1990	Services 1990
Carbon intensity	93.62	24.00	70.03	22.18
Energy intensity	2175.29	472.24	1780.15	441.29

[a)] Kilotons of CO_2 per billion DM and terajoule per billion DM, respectively; output at 1991 prices.

Despite the narrowing of the industry's relative efficiency gap, the carbon and energy efficiency of output was at least 3 to 4 times higher in services than in industry. Since service output grew faster than industry output in the period considered (4.7 percent per year vs. 3.9 percent per year), it is evident that structural change played a major role in reducing overall carbon and energy intensity.

In a more systematic perspective, the carbon emissions in a particular sector i, C_i , can be decomposed in various ways, to reflect not only the structure of energy use and the sectoral structure of production, but also the share of value added in domestic output and the share of domestic output in total supply. Our decompositions are based on the following identities:

$$(1) \qquad C_i = \frac{C_i}{F_i} \cdot \frac{F_i}{E_i} \cdot \frac{E_i}{Q_i} \cdot \frac{Q_i}{Q} \cdot Q ,$$

$$(2) \qquad C_i = \frac{C_i}{F_i} \cdot \frac{F_i}{E_i} \cdot \frac{E_i}{Q_i} \cdot \frac{Q_i}{X_i} \cdot \frac{X_i}{X} \cdot X ,$$

$$(3) \qquad C_i = \frac{C_i}{F_i} \cdot \frac{F_i}{E_i} \cdot \frac{E_i}{Q_i} \cdot \frac{Q_i}{Y_i} \cdot \frac{Y_i}{Y} \cdot Y ,$$

where C_i = carbon emissions, F_i = emission-relevant energy use[11], E_i = total energy use, Q_i = gross output, Y_i = value added, X_i = total supply.

The first three ratios on the right hand side are the same in each equation. They refer to the structure of energy use in each particular sector. The ratio C_i/F_i basically reflects the composition of fossil energy input in terms of hard coal, soft coal, oil and gas, each having a different carbon content. The ratio F_i/E_i captures the composition of total energy use in terms

[11] Emission-relevant energy use is a subset of total energy use that excludes electricity, district heating, crude oil and lubricants. It corresponds quite closely to fossil energy use, hence the notation "F".

of fossil and non-fossil (carbon-free) energy carriers. E_i/Q_i is the energy intensity of production.

The ratios Q_i/Q, X_i/X, and Y_i/Y in eqs. (1) - (3) give sector i's share in total domestic output, total supply, and value added, respectively. The ratio Q_i/X_i in eq. (2) is an inverse measure of the degree of globalization in sector i (a *high* value of Q_i/X_i indicating a *low* degree of globalization). The ratio Q_i/Y_i in eq. (3) measures fragmentation (a high value indicating a high share of intermediate inputs in sectoral output).

Our decomposition proceeds by computing the average annual percentage changes of the expressions showing up in eqs. (1)-(3). We deliberately avoid any attempt at allocating the residuals that arise when employing rates of change in a discrete-time framework. The residuals are rather small and do not affect our main conclusions.

Table 2 shows the decomposition of carbon emissions according to eq. (1) for eight production sectors and a summary category.[12] It can be seen that carbon emissions (column C_i) decreased in all non-energy sectors except transport and services. Column C_i/F_i reveals a change of the mix of fossil energy carriers in favor of the less carbon intensive fuels (substitution of oil and gas for coal), especially (of course) in the industry sectors. According to column F_i/E_i there was a substitution of carbon-free energy (electricity) for fossil fuels in all sectors except the energy industry. The substitution of electricity for fuels was particularly pronounced in the equipment goods industry. As shown in column E_i/Q_i, the energy intensity of output decreased in all sectors, again with the exception of the energy industry. The equipment goods industry was especially successful in saving energy, whereas the transport sector showed the smallest improvement in energy efficiency. Overall, energy efficiency improvement (energy saving) was by far the most important contributor to the decrease of the carbon intensity of total output, amounting to 3.5 percent p.a. on average. Inter-fuel substitution and electrification were less important (just under 0.7 percent p.a.).

Finally, the column Q_i/Q illustrates the degree of deindustrialization that has taken place: All industry sectors except the equipment goods industry had declining output shares, whereas transportation and services increased their shares. The increasing share of transportation is consistent with the phenomenon of fragmentation, in that the outsourcing of activities leads to higher transport requirements.[13]

[12] Note that the category "services" in table 2 and table 3 is more narrow than the broad category in Table 1 (cf. footnote 5).

[13] One may wonder to what extent the changes portrayed in table 2 are already influenced by German unification. It is true that the unification implied a substantial boost to West German production in 1990. In fact, the growth rate of private output in 1990 was about twice the average rate in 1985-1989. It should be noted, however, that the boost was by far most pronounced in the West German energy industry, whose growth rate in 1990 was 4.7 percent, while there had been an average annual *decrease* by 2.4 percent in 1985-1989. One can therefore conclude that without unification and the ensuing dismantling of East German energy industry (mainly

Table 2: Average annual percentage changes 1985-1990, I

%/a	C_i	C_i/F_i	F_i/E_i	E_i/Q_i	Q_i/Q	Q
Agriculture	-1.77	-0.18	-0.46	-3.09	-1.97	/
Energy	0.22	-0.42	0.17	1.41	-4.86	/
Intermediate goods	-2.29	-0.71	-1.19	-2.87	-1.49	/
Equipment goods	-2.77	-0.72	-2.35	-5.51	1.72	/
Consumption goods	-0.63	-0.72	-0.85	-1.78	-1.24	/
Construction	-0.24	-0.23	-0.07	-3.45	-0.48	/
Transport	4.02	-0.02	-0.19	-1.37	1.52	/
Services	2.21	-0.09	-0.05	-2.23	0.55	/
Total	-0.18	-0.46	-0.23	-3.50	0.00	4.01

In Table 3 the decompositions according to eq. (2) and eq. (3) are displayed; the components common with eq. (1) are not reiterated. The last entry of column Q_i/X_i shows that the share of domestic production in total supply decreased on average by 0.23 percent annually, indicating the degree of globalization over the period considered. This process was especially pronounced in industry, whereas transportation and services were not affected by it. Hence we have another indication of the phenomenon of deindustrialization.

Looking at the last entry of column Q_i/Y_i we find that the ratio of gross output to value added has been increasing on average. This is equivalent to an increase in the ratio of intermediate input to value added, i.e. fragmentation. On the sectoral level, fragmentation can be found in five out of our eight sectors. It has not taken place in agriculture, the intermediate goods sector and the service sector.

Table 3: Average annual percentage changes 1985-1990, II

%/a	Q_i/X_i	X_i/X	X	Q_i/Y_i	Y_i/Y	Y
Agriculture	-0.22	-1.98	/	-0.69	-0.97	/
Energy	-0.31	-4.77	/	0.42	-4.94	/
Intermediate goods	-0.63	-1.10	/	-0.86	-0.32	/
Equipment goods	-0.77	2.25	/	2.31	-0.15	/
Consumption goods	-0.67	-0.81	/	1.66	-2.50	/
Construction	0.00	-0.70	/	1.62	-1.70	/
Transport	0.01	1.29	/	0.88	1.03	/
Services	0.03	0.30	/	-0.52	1.41	/
Total	-0.23	0.00	4.24	0.36	0.00	3.65

for environmental reasons) the decline in West German energy intensity would have been even stronger than presented above. Notwithstanding such considerations, the challenge remains to explain the drop in energy and carbon intensity in 1985-1990 in the face of the energy price decline.

Looking at the sector shares in value added (Y_i/Y) we find an even stronger indication of deindustrialization than was evident in output shares: With respect to the share in value added, the equipment goods industry declined (whereas it increased with respect to output share). We here find a clear dichotomy between the transport and service sectors gaining shares and all other sectors losing.

As illustrated above, the structural change in favor of the less energy intensive service industry may have contributed considerably to the observed decrease in overall carbon and energy intensity. In fact, the literature suggests that even *within* German industry, structural change may have contributed one quarter to the observed change in energy intensity (Unander et al 1999).

Our aim in this paper is not to provide another separation of the overall energy intensity change into aggregate measures of sectoral energy efficiency improvement and changing sectoral structure. Instead, we take the indicators of change in the structure of energy use and in the structure of the economy (globalization, deindustrialization, fragmentation) as representing an intermediate link in a causal chain from more fundamental drivers of structural change to changes in the release of carbon. In this view, the rates of change discussed in this section are taken as the variables to be explained. Overall, there are 70 indicators of change in energy use and economic structure which we seek to explain: The rates of change of the macro indicators C, F, E, Q, X, Y, and the rates of change of the ratios C_i/F_i, F_i/E_i, E_i/Q_i, Q_i/X_i, Q_i/Y_i, Q_i/Q, X_i/X and Y_i/Y.

3. Linking Structural Change Indicators to Driving Forces Utilizing a CGE Model

Evident drivers of change in energy use are improvements in energy technology, changes in world energy prices, and politically determined changes in the energy mix (e.g. expansion of nuclear power). The drivers of deindustrialization, globalization and fragmentation can be classified in a natural way into supply side (technology) and demand side variables. More specifically, the first set of variables comprises changes in the pattern of productivity improvement at home and abroad[14], whereas the second set refers to changes in the structure of world demand.

A key difficulty in any attempt at linking structural change to these potential drivers is that many of the latter are difficult to observe. As regards improvements in energy technology, the concept of "autonomous energy efficiency improvement" represents a purely notional parameter which is difficult to measure directly (see below). Similar measurement problems exist for other forms of productivity improvement, especially if they are to be measured for several sectors and on a world scale. Finally, with respect to the pattern of world demand, there exists only rudimentary data on trade in services, especially for the period considered.

[14] This is broadly consistent with a comparative advantage view of structural change.

For these reasons the methodology used in this paper is an indirect one. We use a CGE model to simulate the effects of observed changes in world energy prices and German energy policy on the indicators (rates of change) discussed in the preceding section. Furthermore, we simulate the (partial) effects of arbitrary changes in the unobserved "drivers" mentioned above. Finally, we use least squares to select the weights on the unobserved drivers that provide the best explanation for structural change not explained by the observable drivers.

The CGE model employed comprises West Germany vs. the exogenous rest of the world. It has 13 sectors, five of which refer to energy carriers: hard coal, soft coal, petroleum, gas and electricity. In this paper, the results relating to the energy sectors are displayed only for the summary category, referred to as energy industry. The other sectors are agriculture, intermediate goods, equipment goods, consumption goods, construction, transport, services, and government.

The model structure is particularly suitable for the current analysis because it incorporates exactly those exogenous inputs which constitute important potential drivers of change in energy use and economic structure in Germany:

- domestic hard coal production and nuclear power generation,
- world market prices of hard coal, mineral oil, and natural gas,
- export prices of the rest of the world's industry and service sectors,
- rest of the world's demand for import of goods and services,
- energy-augmenting technological progress in Germany's industry and service sectors,
- labor-augmenting technological progress in Germany's industry and service sectors.

The evolution of these exogenous inputs impacts on the German economy, as captured by the model, in various ways. The expansion of nuclear power over the period considered leads (*cet. par.*) to a reduction of fossil fuel input, whereas the reduction in world market prices of fossil fuels tends to enhance their utilization. Changes in the rest of the world's industry and service prices affect the structure of comparative advantage in Germany, as do changes in the sectoral pattern of German labor productivity. With respect to the level and structure of German production-related carbon emissions, a relatively strong increase in the rest of the world's industry productivity coupled with a relatively strong increase in the German service sector's labor productivity would produce structural change in favor of the less carbon-intensive German service sector. A high rate of energy-augmenting technological progress in German industry, relative to the service sectors, would explain the observation discussed in section 2 that the carbon and energy intensity declined faster in industry than in services.

The remainder of this section gives a brief, non-technical description of the model and an outline of the following steps of the analysis. A more detailed and technical statement of the model formulation is given in Appendix A.

General Features

As mentioned above, the model has 13 sectors and comprises Germany (GER) vs. the rest of the world (ROW). ROW is captured in terms of exogenous export prices and import quantities for the 13 goods. Other exogenous parameters which determine the dynamics of the model are rates of labor-augmenting technical progress and energy-augmenting technical progress in the various German production sectors. Multiplying these efficiency rates by the quantities of labor or energy input gives input in "effective units".

The output of German hard coal mining is treated as exogenous. Import demand for hard coal is the residual from total demand (at exogenous ROW prices) less administered (and subsidized) domestic supply. The electricity industry is split up into various power generation technologies, one of which is nuclear power. The demand for fossil-fuel based electricity is the residual from total electricity demand and exogenous (administered) nuclear power supply (for details on the electricity sub-model see Welsch and Ochsen 2001).

All aggregator functions (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 time treatment in the model is recursively dynamic, the capital stock being predetermined.[15] This implies intrinsic dynamics which need to be accommodated when using the model to identify the impacts of changes in the exogenous drivers (see below).

Market Clearance and Macro Closure

For each good there are two classes of markets: An international market and a domestic market. In addition, there is one labor markets (labor being mobile across sectors) and one capital market.

In the international market the world trade volume of each good is determined as being the sum across GER and ROW of import demands. In the domestic goods market the total quantity equals the sum of intermediate demands, consumption demand, government demand, investment demand, and export demand. Employment is determined as being the sum of labor demand across sectors.

[15] The capital stocks in the base year reflect, in part, the high energy prices up to the year 1985. The model thus integrates the lasting effect of previous induced substitution of capital for energy.

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.

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.

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 (Armington good) is divided among imports and domestic production. For exports, there is a similar structure: The world trade volume of each good is allocated to exports from ROW and German 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 demand for German exports are determined by CES demand functions.

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. 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.

Nominal macroeconomic investment is the sum of the various 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 survive until 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.

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.

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 coefficients. 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 (for empirical evidence backing this kind of disaggregation see Kemfert and Welsch 2000).

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.

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. 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.

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.

Due to the assumption of perfect intersectoral mobility of labor there is a uniform wage rate. In agreement with the practice of wage formation in Germany (see Carruth and Schnabel 1993), 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. As mentioned above, the interest rate is the closure variable of the model.

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. 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.

Procedure of subsequent analysis

The remainder of the paper seeks to explain the average annual rates of change of C, F, E, Q, X, Y, C_i/F_i, F_i/E_i, E_i/Q_i, Q_i/X_i, Q_i/Y_i, Q_i/Q, X_i/X and Y_i/Y, jointly referred to as structural change indicators. The actual values of these rates of change are collected in a 70-vector *OBS*. The subsequent analysis proceeds in three steps.

Step 1 examines the simulated partial and combined effects of observed changes in domestic energy policy and world energy prices (section 4). The simulated combined effects on the structural change indicators of energy policy and energy price changes are collected in a 70-vector SIM_0 .

Step 2 examines the simulated effects of 1-percent p.a. changes of total factor productivity and import demand in ROW and 1-percent p.a. autonomous energy efficiency improvements and labor efficiency improvements in Germany (section 5). The simulated effects on the structural change indicators of these changes are collected in eight vectors of the dimension 70 x 1, as follows:

SIM_1: effect of 1-percent p.a. rise in ROW industry prices[16],

SIM_2: effect of 1-percent p.a. rise in ROW service prices,

SIM_3: effect of 1-percent p.a. rise in ROW industry demand,

SIM_4 effect of 1-percent p.a. rise in ROW industry demand,

SIM_5: effect of 1-percent p.a. rise in autonomous energy efficiency in German industry,

SIM_6: effect of 1-percent p.a. rise in autonomous energy efficiency in German services,

SIM_7: effect of 1-percent p.a. rise in autonomous labor efficiency in German industry,

SIM_8:effect of 1-percent p.a. rise in autonomous labor efficiency in German services.

Step 3 (section 6) seeks to explain the divergence between the actual structural change vector (*OBS*) and the simulated effects of actual energy policy and energy prices (SIM_0) in terms of the drivers considered in step 2. This is achieved by applying ordinary least squares to the equation

(4) $OBS\text{-}SIM_0 = \Sigma_j\, \beta_j \cdot SIM_j + u$,

where the summation runs from 1 to 8 and u is an error term. The estimates of the coefficients β_j are the annual percentage changes of the drivers from step 2 which provide the best explanation of *OBS*, after SIM_0 is taken into account.[17]

[16] Changes in ROW prices are used to proxy changes in total factor productivity.

Before carrying out this work plan, it may be useful to clarify the notions of energy efficiency improvements and labor efficiency improvements involved in SIM_5 through SIM_8. It is important to note that these simulations relate to (unobservable) parameters of the production function, not to observed energy or labor productivity. A stylized representation of the production function (which omits sector indices) may clarify this:

(5) $Q = const \cdot f(a \cdot E, b \cdot L, K)$,

where E, L, K denote energy, labor and capital and $const$ captures the constant input coefficient which links output Q to the energy-capital-labor composite. The parameters a and b are the efficiency factors of energy and labor. The energy and labor efficiency improvements to be determined in step 3 are the rates of change of a and b, not the rates of change of the observables Q/E and Q/L. Estimates of the former may well differ from observations of the latter. A back-of-the-envelope calculation may illustrate this: In a CES production framework the energy demand function[18] implies the following relationship between the rates of change of energy input, output, the output price (P_Q), the energy price (P_E), and the energy efficiency factor (denoting rates of change by 'hats'):

(6) $\hat{E} = \sigma \cdot (\hat{p}_Q - \hat{p}_E) + (\sigma - 1) \cdot \hat{a} + \hat{Q}.$

From the last row of table 2 we have an observed overall rate of energy efficiency improvement $\hat{Q} - \hat{E} = 3.5$ percent p.a., where $\hat{Q} = 4.0$ percent p.a. and $\hat{E} = 0.5$ percent p.a. Letting $\hat{p}_Q - \hat{p}_E = -5$ percent p.a. capture the decline of energy prices, and fixing σ (the elasticity of substitution between energy and other inputs) at 0.3 implies $\hat{a} = 7.1$ percent. Fixing σ at 0.4 would imply $\hat{a} = 9.2$ percent. This illustrates that observed efficiency rates may be a bad guide to estimating the structural parameters we seek to identify.

4. Effects of National Energy Policy and World Energy Prices

Table 4 shows the simulated effects on the structural change indicators from section 2 of observed changes in German energy policy and world energy prices.[19] The table is restricted to the indicators carbon emissions (C), emission relevant energy use (F), total energy use (E),

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[17] Minford, Riley and Nowell (1997) use a similar combination of simulation and regression analysis (steps 2 and 3) in order to identify the contribution of productivity and other shocks to changes in 21 key macro-sectoral indicators in a two-region world model. The methodology of the present paper departs from that approach by adding step 1.

[18] The generic form of the CES input demand function is stated in eq. (38) of Appendix A.

[19] Note that in order to determine these effects it is necessary to eliminate the intrinsic model dynamics mentioned in section 3. This is achieved as follows: (a) The model is run with all exogenous variables frozen at their base year value. (b) The model is run with the exogenous variable(s) under consideration varied. (c) the vector of indicator variables resulting from simulation (b) is regressed on the corresponding vector from simulation (a). The residual from this regression represents the pure effect of the exogenous variable(s). This

gross output (Q), total supply (X) and value added (Y), added across all non-government sectors. Table B1 in Appendix B supplies similar information for the other indicators.

Table 4: Effects of German energy policy and world energy prices on selected indicators

%/a	C	F	E	Q	X	Y
Observed	-0.18	0.28	0.51	4.01	4.24	3.65
Domestic hard coal	0.00	0.01	-0.17	0.05	0.06	0.05
Nuclear power	-0.58	-0.50	-0.28	-0.01	0.00	0.05
Price of hard coal	1.81	1.62	1.01	0.20	0.24	0.35
Price of oil	0.53	0.58	0.45	-0.02	0.01	0.05
Price of gas	0.03	0.06	0.04	-0.01	-0.01	-0.01
Combined effect	1.73	1.71	1.02	0.18	0.27	0.36
Sum of partial effects	1.79	1.77	1.05	0.21	0.30	0.49

The first row reproduces the observed percentage annual changes discussed in section 2. The second row shows the simulated effect of the administered reduction of German hard coal mining from 96.8 to 82.5 million tons per year. It had almost no effect on carbon emissions and emission-relevant energy use, because in the simulation domestic hard coal was replaced by other fossil fuels, especially imported coal.[20] It did, however, have a negative effect on total energy use, because hard coal mining itself is relatively energy intensive. The effect on total output, total goods supply and value added[21] was slightly positive. Thus, the signs of the impacts are as one would expect them.

In a more detailed perspective (see Table B1), there is a strong simulated increase in the ratio of the energy sector's emission-relevant energy to total energy, due to imported coal (which is cheaper than domestic coal) and other fuels being used more intensively. On the other hand, domestic output of the energy industry decreases in relation to both, its total supply and value added, and the energy industry's share in the *aggregate* output, total supply and value added is also reduced. On balance, these countervailing effects imply a non-existing effect on aggregate emissions.

The third row in table 4 gives the simulated effects of the expansion of nuclear power generation from 115 TWh to 135 TWh. As expected, the effect on emissions and emission-relevant energy use is negative. We can conclude that the expansion of nuclear power reduced the annual rate of change of CO_2 emissions by almost 0.6 percentage points. It also reduced

method of recovering the pure effects of changes in exogenous variables is used throughout all the simulations performed.

[20] It must be noted that this simulation is counterfactual in that it reflects only the partial variation of domestic hard coal. In reality, the use of hard coal in electricity generation was partly replaced by nuclear power. In our simulation framework, the expansion of nuclear power is examined in a separate partial variation.

[21] Note that value added is not exactly GDP because we consider only the non-government sectors.

total energy use.[22] The rate of growth of value added was slightly increased (0.05 percentage points). In a detailed view (Table B1) we find a reduction of the ratio of emission-relevant energy to total energy in all sectors, but especially in the energy industry. The energy intensity of output increases in all sectors, except for the energy industry, where it decreases strongly (nuclear fuels are not classified as energy). The effect on the energy industry dominates that on the non-energy sectors; hence the aggregate energy intensity of output is reduced.

The next three rows give the simulated effects of changes in world energy prices (coal: -7.3 percent per year; oil: -5.5 percent per year; gas: -2.3 percent per year). They each imply an increase in emissions and energy use, and more or less pronounced increases in value added growth (except for the gas price). The fall of the coal price has a particularly strong effect on emissions; it also contributed substantially to the growth of output, total supply and, especially, value added. The effect of the oil price decrease on emissions is smaller; yet it almost offsets the effect of nuclear expansion.

These aggregate effects become more transparent from a more detailed perspective (Table B1). The decline in the hard coal price entails an increase in the share of emission-relevant energy in total energy, especially in the energy sector, and an increasing energy intensity in all sectors. The ratio of output to total supply decreases in the energy sector. The same holds for the decrease of the oil and gas price (imported fuels are substituted for domestic ones). The ratio of energy output to value added in the energy industry rises. As regards the oil price crash, it leads to increasing output shares of transportation and services, whereas the shares of industry decrease.

The row labeled "combined effect" shows the effects of varying the aforementioned drivers simultaneously. The simulated overall effect of national energy policy and the decline of world energy prices is a substantial boost to emissions and emission relevant energy and a somewhat smaller one to total energy use. There is also a sizeable effect on macroeconomic growth, especially value added. Indeed, the simulated growth rate of value added is 0.36 percentage points higher than it would have been otherwise.

Regarding the structural impacts, there is a strong increase in the ratio of emission-relevant energy to total energy and in the energy intensity of output. There is also a decline in the aggregate output-supply ratio (Q/X). Thus, according to these simulations, the development of world energy prices has contributed in a visible manner to globalization of the West German economy. It also contributed to deindustrialization (viz. the output shares in Table B1): The substitution of imported fuels for domestic ones triggered a relative decline of the domestic

[22] Nuclear fuels are not counted as energy.

energy industry. This had negative demand spill-overs to other industry sectors, especially the equipment goods industry (being a supplier of intermediate inputs for the energy industry), whereas construction, transport and services benefited from this development.

If one compares the combined effect to the sum of the various partial effects, one finds that the former is somewhat lower than the latter, which is natural in view of general equilibrium adjustment effects. The deviation is highest with respect to value added; it amounts to more than a quarter of the sum of partial effects.

An important message from this exercise is that the simulated effects of energy policy and energy price changes are broadly consistent with observed patterns of deindustrialization and globalization. However, the observed increase of Q/Y (fragmentation) is not captured by the prediction. Quantitatively, there is a tremendous bias between the observed indicators and the prediction based on energy policy and energy prices.[23] With respect to emissions the bias between predicted and observed change amounts to about 1.9 percentage points. With respect to the macroeconomic indicators it is even stronger.

These deviations are, of course, not surprising, because neither improvements in energy or labor productivity at home nor changing demand and supply patterns abroad have been accounted for in these exercises. Their effect is the subject of the remainder of the paper.

5. Partial Effects of Productivity and Demand Changes

The following exogenous drivers are considered, each differentiated by "industry" (agriculture, intermediate goods, equipment goods, consumption goods, construction) and "services" (transport, other private services):

- growth of total factor productivity in the rest of the world (ROW),
- growth of import demand of ROW,
- energy augmenting technological progress in Germany (so-called autonomous energy efficiency improvement),
- labor augmenting technological progress in Germany.

Each of these eight parameters was set at 1 percent per year. Since production in ROW is not modeled explicitly, factor productivity changes in ROW are captured by changes in output prices, where a price decrease corresponds to a productivity increase[24].

The simulated partial effects on our macro indicators are shown in Table 5. The effects on the other indicators are given in Table B2 in Appendix B. These effects can be interpreted as elasticities.

[23] This statement holds *a fortiori* if the full vector of indicators is considered. In fact, there is a negative correlation between observed and predicted indicators (correlation coefficien: -0.6208).

Table 5: Elasticity of selected indicators with respect to exogenous drivers

	C	F	E	Q	X	Y
ROW industry prices	.202	.201	.135	-.001	-.040	.044
ROW service prices	-.005	-.005	-.003	-.002	-.006	-.009
ROW industry demand	.074	.067	.039	.000	.050	.035
ROW service demand	-.002	-.003	-.001	-.003	-.004	-.020
Energy efficiency in industry	-.347	-.337	-.237	.047	.041	.125
Energy efficiency in service	-.087	-.082	-.060	.041	.032	.035
Labor efficiency in industry	.165	.153	.115	.184	.168	.121
Labor efficiency in service	.127	.118	.090	.169	.155	.055

It should be noted that the two first rows of table 5 (and two first columns of table B2) give the simulated effects of *in*creases in ROW prices. An interesting result in Table 5 is the effect of ROW industry prices on German emissions. It suggests that a 1-percent increase in ROW's industry prices would have increased German production-related carbon emissions by 0.2 percent. Likewise, a corresponding *drop* in ROW industry prices would have *reduced* emissions by 0.2 percent; this is a considerable figure, especially if viewed in comparison with the effect of energy efficiency improvements in German industry. By contrast, a hypothetical 1-percent increase in ROW's service prices would have had a negative (but negligible) effect on German emissions. The reason for both such effects are the induced structural changes to the advantage/disadvantage of German industry (based on comparative advantage), relative to German services (cf. Table B2).

Similar reasoning applies to changes in demand: An increase in ROW demand for industrial goods boosts German emissions, whereas an increase in service demand reduces them.

The effects of domestic productivity improvements on emissions are straightforward: Energy efficiency improvements have a negative effect on emissions, whereas labor efficiency improvements raise emissions. Both of these effects are more pronounced if the productivity improvement takes place in industry than if taking place in services.

The effects of these productivity and demand shocks on emission-relevant energy use and energy use in general are qualitatively the same as those on emissions, but less pronounced.

Regarding domestic output, total supply, and value added, it is straightforward that they all are positively affected by domestic productivity improvements, both of energy and labor. They are also positively affected by rising demand for industry goods. Rising productivity in ROW's industry increases total supply in Germany (because of cheaper imports), but reduces value added (because of increased competition from abroad). The effects of ROW service productivity and service demand on output, total supply and value added are very small.

[24] Aggregate German output is the numeraire in the model, i.e. the aggregate price of German output is fixed.

The impacts of ROW productivity and demand shocks on the sectoral structure are as expected (see Table B2). Especially, an increase in ROW industry productivity entails deindustrialization in Germany, whereas an increase in ROW service productivity would do the opposite.

6. Measuring the Size and Contribution of the Exogenous Drivers

Qualitatively, the effects of the drivers considered are as one would expect them to be. The aim of this section is to measure their size and their contribution to the observed development of the structural change indicators (*OBS*), taking into account the effect of energy prices and energy policy (SIM_0). As explained in section 3, this is achieved by estimating eq. (4).

The estimation results are displayed in Table 6. The coefficients give the estimated annual percentage growth rates of the exogenous drivers.

Table 6: Estimated growth rates of exogenous drivers (t-statistic in parenthesis)

	Regression 1	Regression 2	Regression 3
ROW industry prices	-1.64 (-1.87)	-1.61 (-1.85)	-1.69 (-1.91)
ROW service prices	13.12 (0.35)	/ /	50.95 (3.01)
ROW industry demand	4.01 (1.80)	3.91 (1.78)	4.65 (2.12)
ROW service demand	6.38 (1.13)	8.14 (3.23)	/ /
Energy efficiency in industry	6.97 (7.16)	6.99 (7.23)	6.94 (7.11)
Energy efficiency in service	5.00 (2.70)	5.11 (2.83)	4.97 (2.68)
Labor efficiency in industry	2.98 (3.77)	2.91 (3.85)	3.17 (4.09)
Labor efficiency in service	8.47 (4.93)	8.36 (4.97)	8.28 (4.83)
DW	1.93	1.95	1.87
R^2	.670	.668	.665
R^2 adjusted	.633	.636	.633

Regression 1 comprises the full list of explanatory variables. We find that all signs are as expected and that 6 out of 8 coefficients are statistically significant at the usual confidence levels. The coefficient on ROW service prices is dubious in terms of both its magnitude and t-statistic.[25] All other results appear to be plausible. Especially, we find that service demand has grown stronger than industry demand and that energy efficiency improvements were more pronounced in industry than in the service sector, whereas the opposite holds for labor efficiency improvements.

When we consider Regression 2, in which the regressor "ROW service prices" is omitted, we find that all remaining coefficients are significant at the 95 percent confidence level. Except for the coefficient on ROW service demand, all parameters are quite robust in comparison with Regression 1. The coefficient on ROW service demand is now larger in magnitude and highly significant.

The results for Regression 1 and Regression 2 suggest that it is hard to separate the effect of a change in ROW service prices (productivity) from that of a change in ROW service demand. If we omitt ROW service demand instead of ROW service prices, an extremely unplausible estimate for the ROW service price is obtained (see Regression 3), whereas most other parameters are almost unaffected by this variation.

Overall, we find that the three regressions are in very good agreement with each other, except for the role attributed to ROW service prices and demand. With respect to the latter issue, Regression 2 seems to be the most plausible one, because it highlights the importance of demand growth for the growth of the German service sector, rather than stipulating an extreme divergence between the service sector productivity in Germany and abroad.

In assessing the overall quality of Regression 2, it should be noted that the dependent variable (the 70-vector $OBS\text{-}SIM_0$) exhibits quite a large variance (as it comprises mainly rates of change of ratio variables). The descriptive statistics of the dependent variable are as follows: minimum = -7.086, maximum = 3.970, mean = -0.7376, standard error = 2.1269. In spite of the rather erratic behavior of the dependent variable, the seven explanatory variables which were found significant explain almost 67 percent (R^2) of the variance of the dependent variable.[26]

The main findings based on Regression 2 are as follows.

- ROW industry prices have decreased by 1.6 percent per year, relative to the overall German output price level.
- Commodity demand of ROW has increased by only half the rate of service demand (3.9 vs. 8.1 percent)

[25] In their "North-South" framework, Minford, Riley and Lowell (1997) find the "Southern" service productivity quite insignificant as an explanatory variable of structural changes in the world economy.

[26] The goodness of fit varies substantially across the various components of the vector of dependent variables. For instance, while the fit is relatively poor for total energy input E (-0.51 ($OBS\text{-}SIM_0$) vs. -0.95 (predicted)), it is very good with respect to emission-relevant energy input F (-1.43 vs. -1.42). A similar divergence exists with respect to the accuracy with which sector-specific energy efficiency improvements are captured (for instance, consumption goods (-3.2 vs. -4.9) on the one hand, and agriculture (-4.6 vs. -4.4) on the other. Because the way in which the goodness of fit varies shows no evident pattern, we restrict ourselves to a purely statistical assessment of the quality of the regression, as provided in the main text.

- Energy efficiency in German industry has grown by almost 7 percent, while growing by 5 percent in the service sector.
- Labor productivity in German industry has grown by about 3 percent, while growing by more than 8 percent in the service sector.

In interpreting these results, it should be recalled that the efficiency rates estimated refer to structural parameters of the production technology, which may differ substantially from observed efficiency rates. As illustrated in section 3, the autonomous energy efficiency improvements required to reconcile observed energy efficiency rates with falling energy prices may be in the range of 7 to 9 percent, if changes in the sectoral structure of the economy are disregarded. Therefore, our estimates (5 to 7 percent in the presence of structural change) should not be dismissed as implausible.

The regression results allow an assessment of the relative importance of the various explanatory variables. Table 7 shows their percentage contribution to the overall explanatory power of the regressions. The following can be concluded:

- About 7 percent of the variation in our indicator variables not accounted for by energy policy and energy prices are due to the (relative) decline in ROW industry prices.
- About 18 to 20 percent are due to the pattern of ROW demand growth (based on Regressions 1 and 2).
- About 33 to 34 percent are due to the pattern of domestic energy efficiency improvement.
- About 38 to 39 percent are due to the pattern of domestic labor productivity improvement

If we disregard the energy efficiency issue we find that domestic (labor) productivity patterns (technology) are somewhat more important as drivers of structural change (about 40 percent) than trade-related patterns induced in ROW (about 28 percent).

Table 7: Percentage contribution of explanatory variables

	Regression 1	Regression 2	Regression 3
ROW industry prices	7.1	7.0	7.3
ROW service prices	3.2	/	12.6
ROW industry demand	6.8	6.6	7.8
ROW service demand	10.7	13.8	/
Energy efficiency in industry	23.7	24.0	23.5
Energy efficiency in service	9.9	10.2	9.8
Labor efficiency in industry	14.9	14.7	15.8
Labor efficiency in service	23.7	23.6	23.2

It should be noted that the results discussed in this section are based on the simulated effects of each of the driving forces varied separately. As to the validity of these results, a useful check consists in using the estimated growth rates as a *joint* simulation input and to check the resulting simulated indicator changes for consistency with the corresponding observations. Such an approach allows to examine whether the estimated growth rates may be biased because of neglected interactions.

Table 8 displays the coefficient of correlation between the vector of observed indicator changes and simulated changes arising from the estimated growth rates from Table 6 (and from observed changes in domestic energy policy and world energy prices). For all regressions considered the correlation is not statistically different from one. There is thus no indication that our results are infected by some sort of simultaneity bias. Moreover, comparing the various regressions suggests that Regression 2 yields the best agreement with the vector of observations.

Table 8: Coefficient of correlation between observed and simulated changes (standard error in parenthesis)

Regression 1	Regression 2	Regression 3
0.9320 (0.1055)	0.9342 (0.1052)	0.8911 (0.1095)

7. Conclusions

This paper has examined the determinants of the decline of West German production-related carbon intensity in the second half of the 1980s. The decline is astonishing in view of the substantial drop of world energy prices over that period; it has triggered a substantial amount of research which aims at decomposing changes in aggregate carbon or energy intensity into a measure of energy intensity change at the sectoral level and a measure of change in the sectoral structure of the economy.

The present paper departs from this literature by attempting to identify what *drives* the structural changes that have contributed to the decrease of carbon intensity. The approach pursued is to use a computable general equilibrium model of the West German economy to determine the simulated effects of changes of world energy prices, domestic energy policy, productivity growth in Germany and abroad, and changing patterns of ROW demand. Weights on those driving forces that are unobservable are selected by least squares.

It is found that the expansion of nuclear power over the period considered is just sufficient to offset - in terms of its effect on carbon emissions - the drop of oil and gas prices, but not the additional effect of falling coal prices. Overall, the effects of energy prices and energy policy are qualitatively consistent with observed patterns of globalization and deindustrialization in the West German economy, but inconsistent with the phenomenon of fragmentation that is also present in the data.

The deviation, both qualitatively and quantitatively, between actual changes in energy use and economic structure and changes predicted by energy prices and energy policy are attributed to changing technological patterns in Germany and abroad, and changing patterns of ROW demand. It is found, for instance, that the effect on German production-related carbon emissions of a one-percent increase in industry productivity abroad is more than half of the effect of a one-percent autonomous energy efficiency increase in German industry. Overall, the contribution of ROW productivity and demand patterns to emission-relevant structural change not accounted for by energy prices and energy policy is just under 30 percent. The remainder is split almost equally among patterns of domestic autonomous energy efficiency improvement and domestic labor efficiency patterns.

These findings suggest that a substantial fraction of emission-relevant structural change in West Germany in 1985-1990 is trade-induced. Given that the speed of "globalization" has been increasing over the last decade, it can be expected that the role of trade as a determinant of carbon emissions has become even more important since then. Unfortunately, the structural *breaks* after the unification make it very difficult to examine these issues in a conventional economic framework. However, as more recent data become available that are less infected by these turbulences, it may be worthwhile reconsidering the link between technology, trade and carbon emissions in future research.

References

Ang, B.W. (1994), Decomposition of Industrial Energy Consumption: The Energy Intensity Approach, *Energy Economics* 16, 83-92.

Boyd, G., McDonald, J.F., Ross, M., Hanson, D.A. (1987), Separating the Changing Composition of U.S. Manufacturing Production from Energy Efficiency Improvements, *The Energy Journal* 8, 77-95.

Berman, E., Bound, J., Machin, S. (1998), Implications of Skill-Biased Technological Change: International Evidence, *Quarterly Journal of Economics* CXIII, 1245-1279.

Burda, M., Dluhosch, B. (2000), Fragmentation, Globalization and Labor Markets, *CESifo working paper* 352, University of Munich.

Burniaux, J.-M., Martin, J.P., Nicoletti, G., Oliveira Martins, J. (1992), GREEN - A Multi-Sector, Multi-Region General Equilibrium Model for Quantifying the Costs of Curbing CO2 Emissions: A Technical Manual, *OECD Working Paper* No. 116, Paris: OECD

Carruth, A, Schnabel, C. (1993), The Determination of Contract Wages in West Germany, *Scandinavian Journal of Economics* 95, 297-310.

De Bruyn, S. (2000), *Economic Growth and the Environment*, Dordrecht: Kluwer Academic Publishers.

EUROSTAT (1992), *National Accounts ESVG: Input-Output Tables 1985*, Luxembourg.

IEA (1995), *Energy Prices and Taxes*, Paris: OECD.

Jones, R.W., Kierzkowski, H. (1990), The Role of Services in Production and International Trade: A Theoretical Framework, in: R. W. Jones and A.O. Krueger: *The Political Economy of International Trade: Essays in Honor of Robert E. Baldwin*, CambridgeOxford: Basil Blackwell, 31-48

Kemfert, C., Welsch, H. (2000), Energy-Capital-Labor Substitution and the Economic Effects of CO_2 Abatement: Evidence for Germany, *Journal of Policy Modeling* 22, 641-660.

Mayer, H, Stahmer, C. (1989), *Energy Consumption and Sulphur Dioxide Emissions in the Federal Republic of Germany*, mimeo, Wiesbaden: Federal Statistical Office.

Minford, P., Riley, J., Nowell, E. (1997), Trade, Technology and Labour Markets in the World Economy, 1970-90: A Computable General Equilibrium Analysis, *Journal of Development Studies* 34, 1-34.

Saeger, S. S. (1997), Globalization and Deindustrialization: Myth and Reality in the OECD, *Weltwirtschaftliches Archiv* 133, 549-608.

Statistisches Bundesamt (1999), *Fachserie 18: Volkswirtschaftliche Gesamtrechnungen*, www-zr.statistik-bund.de/zeitreih.

Unander, F., Karbuz, S., Schipper, L., Khrushch, M., Ting, M. (1999), Manufacturing energy use in OECD countries: decomposition of long-term trends, *Energy Policy* 27, 769-778.

VDEW (2000), *Energieverbrauch in Deutschland*, VDEW-Materialie M-35/2000, Frankfurt: Vereinigung deutscher Elektrizitätswerke.

Welsch, H., Ochsen, C. (2001), Dismantling of Nuclear Power in Germany: Sectoral and Macroeconomic Effects, *Energy Policy* 29, 279-289.

WTO (2000), *International Trade Statistics 2000*, Geneva: World Trade Organisation.

Appendix A: Formal Statement of the Model

This Appendix provides a technical statement of the model described in section 3 of the main text. In sections A1-A4, 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 section A5. The country index GER is omitted unless necessary. Notation is introduced in order of appearance.

A1 Market Clearance and Macro Closure

World trade market

Notation: EX_i^W : world trade volume of good i; $\mathrm{IM}_\mathrm{i}^\mathrm{GER}$; $\mathrm{IM}_\mathrm{i}^\mathrm{ROW}$: import demand of Germany or rest of world.

(1) $EX_i^W = IM_i^{GER} + IM_i^{ROW} \text{ where } \quad IM_i^{ROW} = exogenous.$

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 market

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

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

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, Symbols containing „N“ refer to nominal variables.

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

Price normalization

Notation: PC: consumer price index.

(5) $PC \equiv 1 \qquad (numeraire)$

A2 Foreign Trade and Final Demand

Imports

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

(6) $$IMN = \sum_i PIM_i \cdot IM_i$$

(7) $$IM_i = f(X_i, PX_i, PIM_i)$$

(8) $$Q_i = f(X_i, PX_i, PQ_i)$$

Exports

Notation: PEX_i^W; PEX_i : export price of world, GER.

(9) $$EXN = \sum_i PX_i \cdot XEX_i$$

(10) $$XEX_i = f(EX_i^W, PEX_i^W, PEX_i)$$

Consumption

Notation: CN: consumption expenditures; WAGE: labor income; NOS: net operating surplus; z: real interest rate; a,b,γ_i: parameters

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

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

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

Government Expenditure

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

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

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

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}: coefficent of capital composition matrix.

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

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

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

A3 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; $XXEC_{EL,j}$: electricity input; PE_j: price of energy aggregate; PEL_j: price of electricity; $XXEC_{F,j}$: fossil fuel aggregate; PF_j: price of fossil fuel aggregate; $XXEC_{F1,j}$... $XXEC_{F4,j}$: individual fossil fuel inputs; PF1,... PF4: price of individual fossil fuel inputs. Planned capital stock K^* is derived in section A7.

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

(20) $EKL_j = f(Q_j)$

(21) $L_j = f(EKL_j, PEKL_j, PL)$

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

(23) $K_j = K^*_{j,-1}$

(24) $E_j = f(EK_j, K_j)$

(25) $XXEC_{EL,j} = f(E_j, PE_j, PEL_j)$

(26) $XXEC_{F,j} = f(E_j, PE_j, PF_j)$

(27a) $XXEC_{F1,j} = f(XXEC_{F,j}, PF_j, PF1_j)$

$\vdots$

(27d) $XXEC_{F4,j} = f(XXEC_{F,j}, PF_j, PF4_j)$

A4 Prices and Taxes

Prices of primary inputs

Notation: Π: rate of nominal productivity growth.

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

(29) $z \leftarrow$ model closure

Price aggregates

(30) $PEX_i^W = f(PEX_i^{ROW}, PX_i) = PIM_i$

(31) $PX_i = f(PQ_i, PIM_i)$

(32) $PQ_i = f(PX_1, ..., PX_{13}, PEKL_i)$

(33) $PEKL_i = f(PL, PEK_i)$

(34) $PEK_i = f(EK_i, K_i, PE_i)$

(35) $PE_i = f(PEL_i, PF_i)$

(36) $PF_i = f(PF1_i, ..., PF4_i)$

A5 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.

Cost minimization on the basis of these quantity aggregators yields Hicksian demand functions. Prices are obtained from the corresponding price aggregators.

Consider the generic CES quantity aggregator function (production function)

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

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, $g_i \equiv 1$; the technology is stationary.

If all inputs are variable, the demand functions corresponding to (37) are

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

and the price aggregator is of the form

(38) $$PX = \left[\sum_i d_i^{\sigma} \left(\frac{PX_i}{g_i} \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}$$

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 (37), one of which (capital) is fixed. The demand for the other factor (energy) is then obtained by rearranging the eq. (37).

A6 Paramaterization

The model is calibrated against input-output tables (EUROSTAT 1992) for 1985. The key exogenous drivers (i.e., world energy prices, nuclear capacity, renewable energy, domestic hard coal mining) 1985-1990 have been set according to their historical development. The elasticity assumptions used are given in Table A1. The default value for the Armington elasticities of the traditional tradable goods is 3.0. Lower values (typically 0.1 to 0.3) are applied in the case of services (see Burniaux et al.1992 for a review of estimates of Armington elasticities).

Table A1: Elasticity parameters

Armington elasticities:	
export of GER vs. export of ROW	0.1-3.0
domestic products vs. imports	0.1-3.0
Substitution elasticities in production:	
energy/capital vs. labor	0.6
energy vs. capital	0.3-0.7
electricity vs. fuel	0.6
fuel vs. fuel	0.8
Reaction elasticities:	
savings ratio w.r.t. interest rate	0.0
wage rate w.r.t. employment	0.5

Appendix B: Additional Tables

Table B1: Effects of German energy policy and world energy prices

1 = Observed
2 = Domestic Hard Coal
3 = Nuclear Power
4 = Price of Hard Coal
5 = Price of Oil
6 = Pice of Gas
7 = Combined Effect

		1	2	3	4	5	6	7
Ci / Fi	Agriculture	-1.18	0	0	0.029	0.02	-0.007	0.034
	Energy	-0.421	0.006	-0.022	0.013	-0.014	-0.014	-0.024
	Intermediates	-0.713	-0.004	-0.006	0.408	-0.04	-0.058	0.289
	Equipment	-0.715	-0.006	-0.01	0.161	0.166	-0.064	0.231
	Consumption	-0.722	-0.002	-0.007	0.156	0.129	-0.063	0.192
	Construction	-0.23	-0.003	-0.003	0.023	-0.005	-0.006	0.016
	Transport	-0.02	-0.001	-0.001	0.001	0.002	-0.002	0.003
	Services	-0.093	-0.002	-0.005	0.003	0.125	-0.03	0.093
Fi / Ei	Agriculture	-0.46	-0.002	-0.044	-0.083	0.466	0	0.358
	Energy	0.174	0.228	-0.822	1.158	-0.24	0.008	0.372
	Intermediates	-1.181	0	-0.017	0.178	0.053	0.011	0.21
	Equipment	-2.348	0.003	-0.048	0.012	0.361	0.058	0.377
	Consumption	-0.847	0	-0.042	0.01	0.29	0.044	0.307
	Construction	-0.072	0.003	-0.003	-0.011	0.075	0.004	0.058
	Transport	-0.193	-0.002	-0.018	-0.05	0.22	-0.002	0.158
	Services	-0.054	-0.001	-0.06	-0.142	0.618	0.019	0.463
Ei / Qi	Agriculture	-3.09	0.018	0.017	0.057	1.325	0.011	1.493
	Energy	1.41	0.037	-0.524	0.615	-0.034	0.015	0.108
	Intermediates	-2.867	-0.007	0.065	1.901	0.221	0.079	2.111
	Equipment	-5.51	-0.009	0.125	0.616	0.743	0.133	1.576
	Consumption	-1.78	-0.003	0.099	0.561	0.672	0.132	1.41
	Construction	-3.45	-0.017	0.05	0.216	1.49	0.003	1.835
	Transport	-1.367	-0.015	0.056	0.131	1.559	0.001	1.727
	Services	-2.23	-0.052	0.194	0.492	1.962	0.101	2.549
Qi / Xi	Agriculture	-0.22	0.005	-0.014	0.143	0.193	-0.003	0.19
	Energy	-0.31	-0.331	0.068	-0.387	-0.311	-0.02	-0.936
	Intermediates	-0.63	0.022	-0.032	0.028	0.013	0.004	0.045
	Equipment	-0.77	0.024	-0.046	-0.06	-0.042	-0.003	-0.11
	Consumption	-0.67	0.025	-0.04	-0.042	-0.046	-0.005	-0.093
	Construction	0	0	0	-0.001	0	0	-0.001
	Transport	0.01	0.005	-0.006	-0.011	-0.004	-0.001	-0.012
	Services	0.03	0.002	-0.003	-0.006	-0.004	0	-0.009
Qi / Yi	Agriculture	-0.69	-0.059	0.076	0.48	0.421	0.013	0.632
	Energy	0.42	-0.179	0.039	1.311	0.5	0.02	1.351
	Intermediates	-0.86	-0.014	0.072	0.108	0.118	-0.002	0.294
	Equipment	2.31	0	0.019	0.072	0.098	0.002	0.233
	Consumption	1.66	0.018	0.018	0.068	-0.029	-0.01	0.112
	Construction	1.62	-0.012	-0.167	-0.51	0.076	0.028	0.262
	Transport	0.88	0.056	-0.009	0.054	-0.111	-0.016	0.059
	Services	-0.52	0.085	-0.11	-0.248	-0.337	-0.036	-0.448
Qi / Q	Agriculture	-1.97	0.006	-0.027	0.046	0.266	0.002	0.151
	Energy	-4.86	-0.418	0.037	0.023	0.287	0.019	-0.041
	Intermediates	-1.49	0.056	-0.079	-0.041	-0.041	0.011	-0.063
	Equipment	1.72	0.077	-0.072	-0.179	-0.275	-0.022	-0.453
	Consumption	-1.24	0.023	-0.048	-0.16	-0.015	0.002	-0.172
	Construction	-0.48	0.015	0.132	0.31	-0.271	-0.021	0.055
	Transport	1.52	0.007	-0.001	-0.055	0.068	0.004	0.046
	Services	0.55	0.009	0.057	0.123	0.148	0.009	0.339
Xi / X	Agriculture	-1.98	-0.008	-0.023	-0.134	0.036	0.003	-0.131
	Energy	-4.77	-0.097	-0.04	0.375	0.561	0.036	0.805
	Intermediates	-1.1	0.023	-0.058	-0.106	-0.092	0.003	-0.199
	Equipment	2.25	0.043	-0.036	-0.156	-0.27	-0.023	-0.434
	Consumption	-0.81	-0.013	-0.019	-0.154	-0.008	0.003	-0.17
	Construction	-0.7	0.005	0.123	0.275	-0.308	-0.025	-0.036
	Transport	1.29	-0.008	-0.005	-0.081	0.035	0.003	-0.035
	Services	0.3	-0.002	0.049	0.092	0.115	0.006	0.255
Yi / Y	Agriculture	-0.97	0.063	-0.176	-0.589	-0.232	-0.016	-0.661
	Energy	-4.94	-0.241	-0.073	-1.442	-0.289	-0.007	-1.57
	Intermediates	-0.32	0.068	-0.222	-0.302	-0.236	0.007	-0.536
	Equipment	-0.15	0.075	-0.162	-0.405	-0.45	-0.03	-0.864
	Consumption	-2.5	0.003	-0.136	-0.381	-0.063	0.007	-0.462
	Construction	-1.7	0.024	0.229	0.666	-0.425	-0.055	-0.385
	Transport	1.03	-0.051	-0.062	-0.263	0.103	0.015	-0.192
	Services	1.41	-0.079	0.096	0.217	0.408	0.04	0.608

Table B2: Elasiticity of indicators with respect to exogenous drivers

1 = ROW Industry Prices
2 = ROW Service Prices
3 = ROW Industry Demand
4 = ROW Service Demand
5 = Energy Efficiency in Industry
6 = Energy Efficiency in Service
7 = Labor Efficiency in Industry
8 = Labor Efficiency in Service

		1	2	3	4	5	6	7	8
Ci / Fi	Agriculture	0.003	0	0.001	0	-0.003	-0.001	0	0.001
	Energy	0	0	0.003	0.001	-0.009	-0.001	0.004	0.005
	Intermediates	0.004	0	0.004	-0.002	-0.014	-0.005	0.007	0.006
	Equipment	0.006	-0.001	0.004	-0.002	-0.017	-0.008	0.007	0.007
	Consumption	0.003	0	0.004	-0.001	-0.016	-0.004	0.005	0.008
	Construction	0	-0.001	0.001	-0.003	-0.002	-0.003	0.001	0
	Transport	0.001	0	-0.001	0.001	0	-0.001	0	0
	Services	0.004	0	0.003	0	-0.009	-0.002	0.004	0.004
Fi / Ei	Agriculture	0.036	-0.002	0.01	-0.002	-0.004	-0.003	-0.005	0.001
	Energy	0.071	-0.003	0.069	0.011	-0.148	-0.06	0.144	0.07
	Intermediates	0.017	0	0.004	0	0.002	-0.002	-0.003	-0.001
	Equipment	0.048	0.001	0.013	0.001	0.01	-0.002	-0.013	-0.005
	Consumption	0.035	-0.001	0.006	-0.001	0.007	-0.003	-0.015	-0.009
	Construction	0.006	-0.001	0.002	0.003	0.001	0	0.001	0.002
	Transport	0.016	-0.001	0.004	-0.002	-0.004	-0.003	-0.003	-0.001
	Services	0.049	-0.001	0.013	-0.001	0	-0.009	-0.01	-0.002
Ei / Qi	Agriculture	0.263	-0.004	-0.03	-0.027	-0.574	0.014	-0.069	0.063
	Energy	0.06	-0.001	0.041	0.011	-0.064	-0.026	0.055	0.031
	Intermediates	0.136	-0.002	0.015	-0.019	-0.587	0.006	-0.209	-0.017
	Equipment	0.13	-0.002	-0.005	-0.011	-0.505	0.02	-0.312	-0.06
	Consumption	0.113	-0.001	0.003	-0.015	-0.537	0.017	-0.251	-0.029
	Construction	0.178	0	0.033	-0.011	-0.623	0.011	-0.254	-0.029
	Transport	0.116	0	0.017	0.008	0.046	-0.646	0.128	-0.313
	Services	-0.04	-0.012	0.021	-0.042	0.106	-0.37	0.416	-0.199
Qi / Xi	Agriculture	0.08	0.002	-0.1	-0.009	0.009	0	-0.018	-0.053
	Energy	-0.043	0.002	-0.014	0.003	0.037	0.017	-0.025	-0.012
	Intermediates	0.113	0	-0.099	-0.006	0.028	0.014	0.032	0.02
	Equipment	0.11	0.002	-0.083	0.003	-0.019	0.012	0.064	0.018
	Consumption	0.095	0.001	-0.082	-0.002	-0.014	0.013	0.041	0.01
	Construction	0	0	0	0	0	0.001	0.001	0
	Transport	-0.02	0.021	-0.006	-0.001	-0.003	0.006	-0.022	0.028
	Services	-0.005	0.008	-0.002	0.001	-0.001	0.001	-0.009	0.005
Qi / Yi	Agriculture	-0.759	0.01	0.095	0.068	-0.02	-0.022	0.153	-0.233
	Energy	-0.413	-0.02	-0.105	-0.115	-0.145	-0.116	0.201	0.092
	Intermediates	-0.218	0.005	-0.097	0.026	0.021	0.016	0.606	-0.133
	Equipment	-0.05	0.008	-0.036	0.041	0.031	0.013	0.711	-0.085
	Consumption	-0.166	0.008	-0.037	0.034	0.006	0.02	0.567	-0.117
	Construction	0.216	0.018	0.151	0.118	-0.176	0.085	0.641	-0.12
	Transport	-0.006	-0.03	-0.047	-0.23	0.035	0.02	-0.221	0.617
	Services	0.072	0.017	-0.055	0.052	-0.05	0.042	-0.522	0.297
Qi / Q	Agriculture	0.137	0.001	-0.065	-0.008	-0.007	-0.002	-0.069	-0.111
	Energy	0.039	-0.001	0.008	0.002	-0.149	-0.079	-0.109	-0.11
	Intermediates	0.19	-0.002	0.051	-0.025	0.056	0.017	0.031	-0.01
	Equipment	0.017	-0.001	0.038	-0.021	-0.071	0.021	0.128	-0.037
	Consumption	0.097	-0.001	0.002	0	-0.036	0.004	-0.009	-0.055
	Construction	-0.412	-0.013	-0.211	-0.102	0.079	-0.103	0.057	-0.031
	Transport	-0.062	0.03	-0.011	0.205	-0.006	0.019	-0.139	0.078
	Services	-0.044	0.002	0.009	0.02	0.054	0.017	-0.049	0.078
Xi / X	Agriculture	0.096	0.002	-0.014	0.001	-0.01	0.006	-0.034	-0.044
	Energy	0.12	0.001	-0.028	0	-0.18	-0.086	-0.067	-0.086
	Intermediates	0.115	0.002	0.1	-0.019	0.033	0.011	0.016	-0.016
	Equipment	-0.055	0.001	0.07	-0.024	-0.046	0.018	0.081	-0.042
	Consumption	0.04	0.002	0.034	0.002	-0.015	0	-0.034	-0.052
	Construction	-0.375	-0.009	-0.26	-0.101	0.085	-0.095	0.073	-0.017
	Transport	-0.004	0.013	-0.054	0.207	0.003	0.021	-0.099	0.064
	Services	0	-0.002	-0.039	0.02	0.062	0.025	-0.024	0.088
Yi / Y	Agriculture	0.85	-0.002	-0.194	-0.06	-0.064	0.025	-0.158	0.236
	Energy	0.407	0.026	0.077	0.133	-0.081	0.044	-0.247	-0.089
	Intermediates	0.363	0.001	0.113	-0.035	-0.043	0.007	-0.511	0.236
	Equipment	0.022	-0.001	0.038	-0.047	-0.179	0.013	-0.52	0.162
	Consumption	0.218	0	0.005	-0.017	-0.118	-0.01	-0.512	0.176
	Construction	-0.675	-0.024	-0.396	-0.204	0.176	-0.182	-0.521	0.203
	Transport	-0.101	0.067	0.002	0.451	-0.118	0.004	0.145	-0.425
	Services	-0.162	-0.009	0.03	-0.015	0.026	-0.018	0.536	-0.105