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IMPRESSUM

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Abstract

Top-down computable general equilibrium (CGE) models are used extensively for analysis of energy and climate policies. Energy-intensive industries are usually represented in top-down economic models as abstract economic production functions, of the constant-elasticity-of-substitution (CES) functional form. This study explores methods for improving the realism of energy-intensive industries in top-down economic models. We replace the CES production function with a set of specific technologies and provide a comparison between the traditional production function approach in CGE models and an approach with separate technologies for making iron and steel. In particular, we investigate the response of the iron and steel sector to a set of CO_2 price scenarios. Our technology-based, integrated approach permits a choice between several technologies for producing iron and steel and allows for shifts in technology characteristics over time towards best practice, innovative technologies. In addition, the general equilibrium framework allows us to analyze interactions between production sectors, for example between electricity generation and iron and steel production, investigate simultaneous economy-wide reactions and capture the main driving forces of greenhouse gas emissions reductions under a climate policy. We conclude that technology specific effects are crucial for the economic assessment of climate policies, in particular the effects relating to process shifts and fuel input structure.

Keywords: Industrial technologies, energy use, iron and steel production, technological change, general equilibrium modeling

JEL classification: C6, D5, L6, Q4, Q5

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1 Introduction

Industrial technologies, their energy consumption and change over time, are important for analysis of energy and climate policies. Bottom-up models simulate the operation of specific energy technologies based on cost and performance characteristics in a partial equilibrium framework. They contain detail on current and future technological options but lack interaction with the rest of the economy. Top-down models, including computable general equilibrium (CGE) models, use a broader economic framework. However, in order to include behavioral and other non-technical factors such as policy instruments, they usually compromise on the level of technology detail, which may be relevant for an appropriate assessment of energy or climate policies (Jaffe et al. 2003, Edmonds et al. 2000).

The focus of this paper is the representation of industrial energy technologies in a computable general equilibrium framework. CGE models are used extensively for analysis of energy and climate policy and offer several advantages. They emphasize the interaction between energy and non-energy markets and simulate combined, economy-wide, responses to price changes induced by such policies. Energy-intensive industries are usually represented in general equilibrium models as abstract economic production functions of the constant-elasticity-of-substitution (CES) functional form. This paper demonstrates an alternative approach based on cost and performance data for specific iron and steel technologies within a CGE model of Germany. For a more realistic representation of an energy-intensive industry, we replace the CES cost function with a set of fixed-coefficient cost functions describing specific technologies. The technology-specific cost functions are based on engineering cost and performance characteristics.

This paper directly addresses the following questions: What difference does it make in a CGE model whether the iron and steel sector is represented by an aggregate production function or by distinct steel-producing technologies? How might a climate policy affect the iron and steel sector in the context of overall economic activity?

The primary strength of our technology-based approach is that it maintains the richness of engineering characteristics of key technologies, yet allows for a full general equilibrium analysis of energy or climate policies. We work at an intermediate level of technology detail, between the traditional aggregate production functions of top-down models and the extensive technology detail used in bottom-up models. We permit a choice between several technologies for producing steel and allow for shifts in technology characteristics over time towards best practice, innovative technologies. Shifts in energy consumption, in response to changes in energy or CO_2 prices, are consistent with shifts between technologies. The general equilibrium framework allows us to analyze interactions between production sectors, for example between electricity generation and iron and steel production, investigate simultaneous economy-wide reactions and capture the main driving forces of greenhouse gas emissions reductions under a climate policy.

We select the iron and steel sector because it is one of the most energy-intensive sectors in the majority of industrialized countries, and is responsible for a large share of greenhouse gas emissions. The industry is subject to climate and energy policies to improve energy efficiency, induce innovation, and reduce greenhouse gas emissions, which may put the international competitiveness of the industry at stake (Ameling and Aichinger 2001, Rynikiewicz 2005). Currently, two main technology alternatives exist in this sector: the oxygen or integrated technology where iron ore is smelted by burning fossil fuels; and the electric arc furnace which melts scrap steel using electricity. While the integrated technology is mainly based on coke, coal, and iron ore as feedstocks, the electric arc furnace is highly electricity intensive and mainly based on scrap input. New and innovative technologies are expected to play a major role in the near future (de Beer et al. 1998).

Other researchers have addressed the inconsistency of top-down economic analysis with bottom-up engineering approaches to industrial energy use. Böhringer (1998) demonstrates a hybrid approach within a CGE model where electricity generation is represented by bottom-up activity analysis and other sectors represented by CES functional forms. Lutz et al. (2005) simulate technology choice in German steel production within an econometric multi-sector model. Ruth and Amato (2002) provide a similar study for the United States. Hidalgo et al. (2005) use a global partial-equilibrium model of iron and steel to simulate the evolution of the iron and steel industry under a series of emissions trading scenarios. However, these iron and steel studies do not provide a direct application to a computable general equilibrium model.

The paper is organized as follows. We describe our methodology in Section 2, including data requirements, two approaches for simulating iron and steel within a general equilibrium framework, and assumptions about technical change over time. Section 3 provides background on the iron and steel industry in Germany. It highlights important features with respect to past and future technologies, energy consumption, carbon dioxide emissions, and costs. In Section 4, we compare the results of the two approaches, provide detailed results for production and energy use for iron and steel technologies and place these results in the context of overall economic development. Section 5 concludes the paper.

2 Methods

In this study we use the Second Generation Model (SGM; Edmonds et al. 2004), an economy-wide computable general equilibrium model, to demonstrate two approaches for modeling steel production in Germany.[1] The usual approach, typical for CGE models, is to simulate iron and steel production using a CES functional form that does not differentiate among specific technologies to produce iron and steel. Our new approach replaces the CES cost function for iron and steel with a logit nest of fixed-coefficient cost functions: each fixed-coefficient cost function represents a specific technology for producing steel with technical coefficients constructed from engineering data. The logit nesting approach has been demonstrated for electricity generation in SGM in Sands (2004) and Schumacher and Sands (2006). This is the first application of the logit nesting approach to iron and steel in SGM.

We are interested in how the two approaches compare, especially in response to changes in fuel prices or CO_2 prices. We construct several illustrative climate policy scenarios to demonstrate the price response of both approaches. The technology approach is data intensive and requires reconciliation of data across economic input-output tables, energy balances, and engineering data by technology. However, once a benchmark data set is constructed for the technology approach, it can also be used for the CES approach.

2.1 Benchmark data

A benchmark table for the model base year is constructed using a 1995 economic input-output table for Germany (Statistisches Bundesamt, 1995), a 1995 energy balance table for Germany (AGEB, 1999), and cost data for iron and steel technologies (see Section 3.2). We have some

[1] We use a transitional version of SGM, which includes some features beyond those documented in Fawcett and Sands (2005), and Sands and Fawcett (2005). The major changes are: (1) consumer demand is based on the Linear Expenditure System; (2) sector-level investment is determined by the zero-profit conditions that price received equals levelized cost; and (3) the lifetime of capital stocks can be set to any desired multiple of five years.

flexibility on how we define production sectors in a CGE model; we maintain detail in production sectors of interest and collapse detail elsewhere. Here we are interested in the behavior of iron and steel technologies, and we use all of the sector detail available for iron and steel from the 1995 input-output table.

Data are organized into a benchmark use table as shown in Figure 1. A use table is essentially an expanded input-output table that allows for more production processes than commodities. The intermediate flows section of the table has the same number of rows as distinct products, but in the cases of electricity and steel, several technologies are available for production. The following technologies are available for making steel: basic oxygen furnace (BOF), electric arc furnace (EAF), and a direct reduction process (DRP). Advanced versions of the basic oxygen furnace (BOFA) and the electric arc furnace (EAFA) become available some time after the base year, with a start date determined by the model user.

We distinguish between “crude steel” and “shaped steel” in the benchmark data set, even though the 1995 input-output table for Germany has these activities combined into one sector. We are able to make this distinction using engineering data for the various steel making processes. The processes are quite different up to the point of crude steel (molten steel), but similar afterwards. All output from the crude steel sector becomes an input to the steel shaping sector. All other sectors consume steel as shaped steel. These relationships are shown as shaded areas in Figure 1.

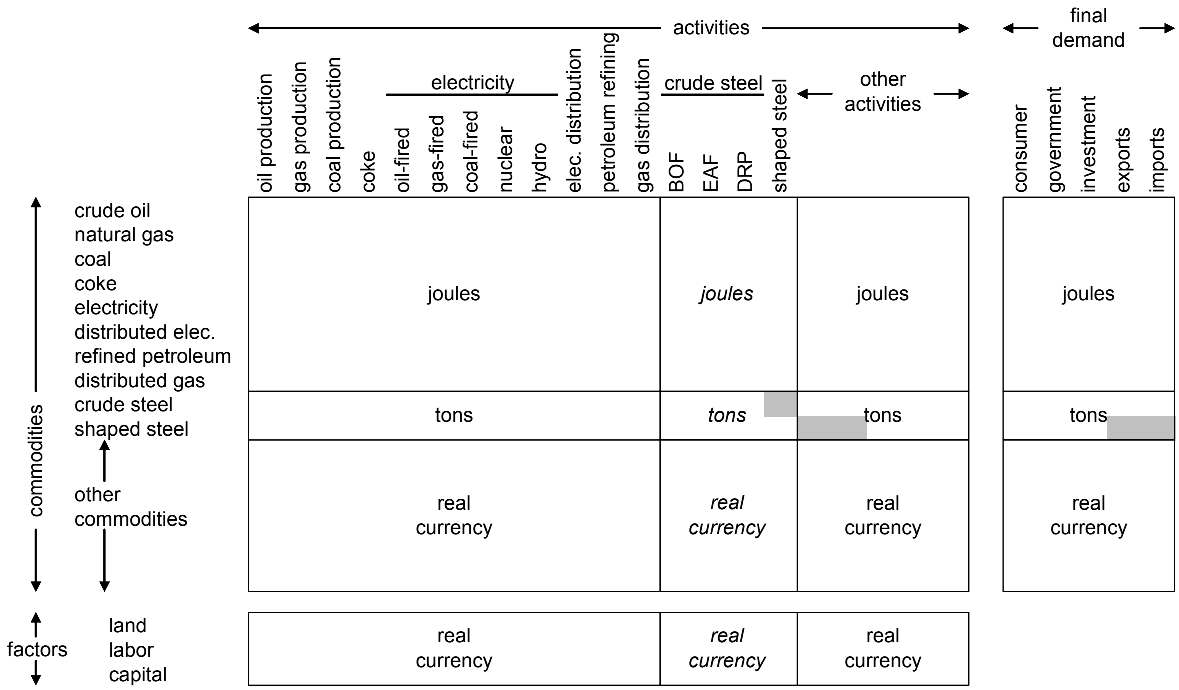

Figure 1 Organization of benchmark use table for Germany in 1995. Each row is a distinct commodity and each column represents production activities. Three distinct activities (technologies) are available for crude steel production: basic oxygen furnace (BOF), electric arc furnace (EAF), and direct reduction process (DRP).

This data set can be used for either the technology approach or the aggregate production function approach: the only difference is that the columns under "crude steel" are combined to form a single aggregate technology for making steel in the aggregate production function approach. Further background on methods used to construct a benchmark data set is found in Sands and Fawcett (2005).

2.2 Technology-based approach

In the technology based logit approach each steel technology is first modeled as a fixed-coefficient production function. Then these production functions are combined in a logit nest. This approach has proven useful for the electricity generation sector (Schumacher and Sands, 2006). We construct an engineering cost description for each steel technology; cost descriptions for technologies that operate in the model base year are embedded in the benchmark data set. The logit nesting structure for the steel technologies in this study is provided in Figure 2.

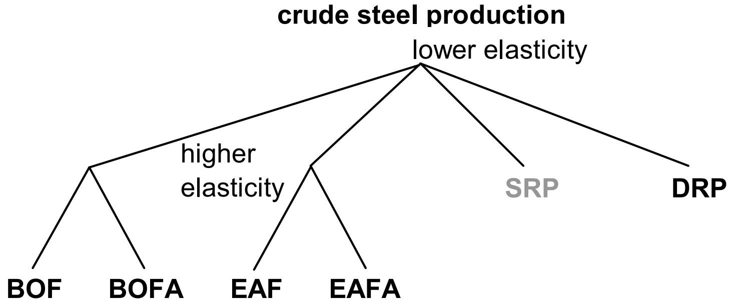

Figure 2 Nesting structure of steel technologies. Each leaf of the nesting structure is a fixed-coefficient technology: basic oxygen furnace (BOF), advanced BOF (BOFA), electric arc furnace (EAF), advanced EAF (EAFA), and direct reduction process (DRP). The model has space for another advanced technology, smelt reduction process (SRP), but it is not presently populated with data.

The unit cost function for a fixed-coefficient technology *j* can be written as

$$C_j = \frac{1}{\alpha_{0j}} \sum_{i=1}^{n} \frac{p_i}{\alpha_{ij}} \tag{1}$$

where C_j is the unit cost or levelized cost per ton of crude steel. Levelized cost is a function of prices and technical coefficients α_{0j}, α_{ij}, i=1,…,N. N is the number of inputs to production. If the input is capital, the corresponding price is the annualized cost of capital, covering interest plus depreciation. The share of output provided by each technology is determined by Equation (2),

$$s_j = \frac{b_j C_j^{\lambda}}{\sum_k b_k C_k^{\lambda}} \tag{2}$$

where C_i is the levelized cost per ton of crude steel, b_j is a calibration parameter to match base-year generation, and λ determines the rate that one technology can substitute for another.[2] This formulation prevents knife-edge switching from one technology to another. The lambda parameter is actually an elasticity and can be expressed as

$$\lambda = \frac{\partial\left(\frac{s_i}{s_j}\right)}{\partial\left(\frac{C_i}{C_j}\right)} \frac{\left(\frac{C_i}{C_j}\right)}{\left(\frac{s_i}{s_j}\right)} \tag{3}$$

A cost function for crude steel production using a logit nest can be written as

$$g(\mathbf{p}) = \sum_j s_j C_j \tag{4}$$

where the s_j are the logit shares from Equation (2) and the C_j are fixed-coefficient unit cost functions in Equation (1). The key parameter that determines the price response of iron and steel is λ . Technologies with lower unit costs provide a larger share of output. Technical change occurs mainly through changing shares of technologies, and not through changes in technical coefficients within production functions.

2.3 Aggregate production function approach

The usual approach in CGE modeling is to represent each production sector as a single production function, usually of the CES functional form and sometimes nested. The key parameter that determines response to a change in prices is the elasticity of substitution. The CES cost function is written as:

$$g(\mathbf{p}) = \frac{1}{\alpha_0}\left[\sum_{i=1}^{N}\left(\frac{p_i}{\alpha_i}\right)^r\right]^{1/r} \tag{5}$$

[2] The lambda parameter is set to -1.5 in the top nest of Figure 2, and to -15 in the lower nests of Figure 2.

Where unit cost is a function of prices and technical coefficients α_0, α_i, i=1,…,N. N is the number of inputs to production.[3] The elasticity of substitution is

$$\sigma = 1 - r \tag{6}$$

The physical input-output coefficients are functions of prices and technical coefficients

$$\mathrm{a}_{ij}(\mathbf{p}) = \alpha_{0j}^{\sigma-1}\alpha_{ij}^{\sigma-1}\left[\frac{p_j}{p_i}\right]^{\sigma} \tag{7}$$

With this approach, we do not distinguish among the separate steel technologies, but combine the columns under "crude steel" in Figure 1 to form an aggregate technology. Technical coefficients are calibrated in order to match benchmark data for each activity at base year prices. Equation (7) clearly shows the relationship between input-output coefficients, relative prices, and the substitution elasticity.

Exogenous technical change is introduced by specifying a time path for the alpha coefficients in Equations (5) and (7). As the alpha coefficients increase, less of an input is needed to produce the same quantity of output and unit costs decline. We apply technical change independently to specific inputs, especially to labor and the energy carriers.

2.4 CGE framework

The benchmark data set described by Figure 1 provides base-year calibration data for a computable general equilibrium model for Germany, that we call SGM-Germany. The base year is 1995 and the model runs to 2050 in five-year time steps. SGM-Germany is a dynamic-recursive model of a small open economy.

[3] Note that Equation (5) collapses to Equation (1) when r = 1.

Capital stocks are divided into five-year vintages and old capital cannot move between production sectors. Old capital is of the fixed-coefficient functional form and is retired at the end of its lifetime, anywhere from 20 to 40 years. We have assigned capital stocks in the iron and steel sector a lifetime of 25 years. Because of the time required for turnover of capital stocks, any change in relative prices, whether due to an exogenous change in oil prices or to a carbon policy, takes time to be fully reflected in model output.

Prices of oil, gas, and coal are given exogenously: the model can import as much of these fuels as desired at the given world price. However, a balance of payments constraint requires that any increase in imports of fuels be offset by exports of other goods.

SGM-Germany contains 20 produced commodities. Besides the commodities shown in Figure 1, the model includes the following production sectors: agriculture, food processing, wood products, chemical products, non-metallic minerals, other metals, other industry, rail and land transport, other transport, and a large services category. All production sectors except electricity generation and crude steel production are represented by CES production functions.

The advantages of modeling technology-based iron and steel production within a CGE framework are that interactions between the iron and steel sector and other sectors, especially electricity generation, are handled automatically and a combined response to changes in relative prices can be analyzed. In the presence of a carbon policy, an integrated technology-based CGE approach allows for sectoral output adjustments in response to higher production costs, for process shifts from one technology to another not only at a single point of time but over time as new investment enters the capital stock and induces long term changes in production capacities. Moreover, the approach allows the carbon intensity of electricity and iron and steel to change at the same time. Handling both sectors within a common framework avoids double counting of emissions reductions.

2.5 Technical change

An important difference between the two approaches is the treatment of technical change over time. Both approaches assume exogenous technical change, but the CES approach allows an annual percentage rate reduction in the quantity of inputs per unit of crude steel while the logit technology approach relies on substitution of one technology for another over time.

In the CES approach, we have assumed the following annual rates of technical change in the iron and steel sector for the following inputs: coal and coke, 0.5% per year; refined petroleum, 0.5% per year; electricity, 0.2% per year; natural gas, 0.5% per year; labor, 1.5% per year; other inputs to production, 0.1% per year. These rates of change begin in the model base year and continue at the same rate throughout the model time horizon and they allow production with fewer inputs per unit of steel produced.

In the technology-based approach, BOF and EAF are the only steel production technologies that operate in the model base year of 1995. However, advanced versions of these technologies (BOFA and EAFA), with lower energy requirements, are assumed available in 2015. Because the use less energy, steel can be produced at lower cost and the advanced technologies replace the older technologies over time. A direct reduction process (DRP) also becomes available in 2015 and gains a share of the market in the base case.

3 Iron and steel technologies

We use iron and steel production in Germany as an example to demonstrate a methodology for embedding technology data into a general equilibrium economic framework. This section provides background on the main types of steel production processes and the data required to represent them in an economic model. We begin with a general description of alternative steel production routes and how they relate to the benchmark data set for SGM-Germany. An economic analysis of these technologies requires data on all inputs to production, including energy, capital, labor, and materials. At the end of this section, we summarize all input costs and energy requirements for each of the steel production technologies.

3.1 Production routes

Figure 3 shows the main production routes of steel production including the two currently in use: (1) the integrated route of producing crude steel in a two-step process based mainly on iron ore, and (2) the electric arc furnace route based on scrap steel. Future, innovative technologies for energy-efficient iron and steel making, such as direct reduction and smelt reduction of iron ore, are investigated in the literature (de Beer et al. 1998, Luiten 2001, Nil 2003, Knop 2000) but still surrounded by high uncertainties with respect to their energy requirements, production costs and time they will become commercially available.

In the integrated route, iron ore is first reduced to pig iron with coke or injected coal in a blast furnace (BF). In a second step, pig iron is fed into the basic oxygen furnace (BOF) or open hearth furnace (OHF) and converted into crude steel. The BOF route is the predominant one, while the open hearth furnace route is an obsolete and more energy-intensive process (Phylipsen, et al. 1998). Along with pig iron, scrap can be added in the second step. For process physics reasons, the basic oxygen furnace is limited in the amount of scrap it can take, up to 15-25% per ton of metal only.

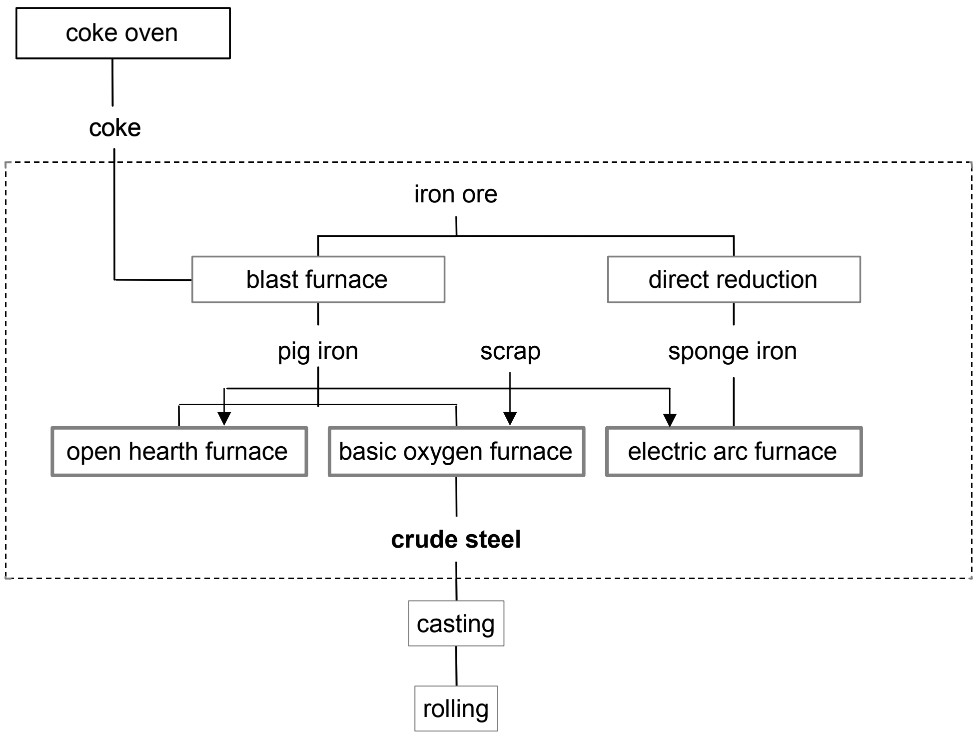

Figure 3 Iron and steel production routes; dotted rectangle indicates system boundary

Another possibility for steel production is the electric arc furnace (EAF) route, which melts recycled steel (scrap) into liquid steel. The quality of EAF steel may in some cases be lower because of contaminants in the scrap. Alternatively, crude iron from a direct reduction process (DRP) can serve as a substitute for scrap and as a source of iron for steel production in an EAF. Producing steel from direct reduced iron has the advantage that the steel quality is improved compared to merely scrap-based EAF production. Direct reduced iron is used as an input if scrap is scarce, low quality, or expensive (Schumacher and Sathaye 1998).

Fossil fuels (coke and coal) are the main energy inputs to the integrated route (BF/BOF); the EAF route uses mainly electricity; and the DRP/EAF route consumes both electricity and natural gas. The DRP/EAF route is more energy intensive than the scrap-only EAF route but less energy intensive than the BF/BOF route. Because smelt reduction avoids coke making, it is expected to reduce energy requirements up to 35% compared to the conventional BF/BOF route. Moreover, production costs are expected to be lower than in the conventional route (de Beer 1998). Various studies in the literature assess the potential for energy efficiency improvement and CO_2 emissions reduction in the iron and steel industry for existing and future technologies (WEC 1995; Phylipsen, 1998; Kim, 2002, Rynikiewicz, 2005). They agree that substantial energy efficiency improvement possibilities exist but depending on their assessment of current energy consumption, the potential for efficiency improvements differs.

Because of resource availability and quality of steel products, production of crude steel in Germany is mainly through the conventional integrated blast furnace/basic oxygen (BF/BOF) route (70%) and to a lower extent through the electric arc furnace (EAF) route (30%) (see Figure 4, WV Stahl and VDEH 2005, Aichinger et al. 2001). As can be seen in Figure 4, the open hearth furnace technology (OHF) played a small role in Germany in the early years after reunification (1990-94) as a relic of outdated East German technology. Since it provides an inefficient production process, plants using this technology were taken out of service soon after reunification.

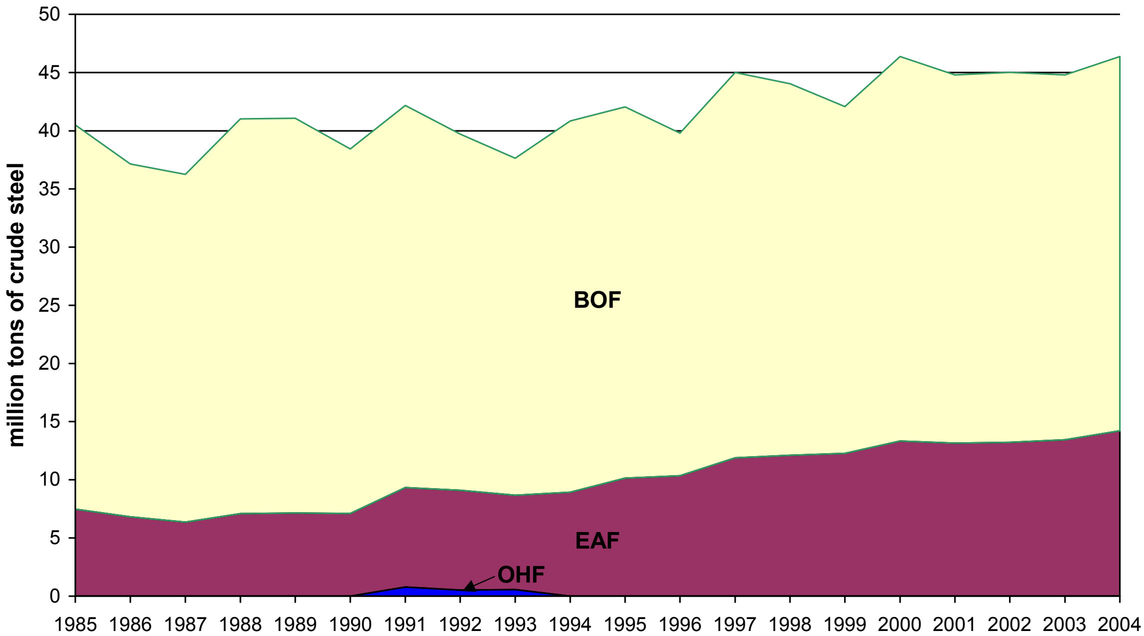

Figure 4 Crude steel production by process type, Germany 1985-2004

To produce finished steel, crude steel must be cast, rolled and shaped. Technologies for casting and rolling and further processing of crude steel can be considered to be the same for different crude steel production routes (Aichinger et al. 2001). The structure of the benchmark data set for SGM-Germany (Figure 1) reflects the fact that there are many ways to make crude steel, but further processing of steel is relatively independent of the crude steel technology. This can be seen in Figure 1, where the benchmark data includes separate rows for crude steel and shaped steel, indicating that these are separate commodities in the model with separate market prices. The columns in Figure 1 indicate that there are three distinct activities for making crude steel but only one for shaped steel. All of the output from the crude steel sector is an input to the shaped steel sector. Shaped steel is then sold to all of the other production activities that require steel as an input.

3.2 Cost structure

Detailed information on production costs and performance of German iron and steel making is shown in Table 1. Five iron and steel technologies are represented: basic oxygen furnace, advanced basic oxygen furnace, electric arc furnace, advanced electric arc furnace, and a direct reduction process. The direct reduction process assumes that an equal share of scrap and direct reduced iron is fed into an electric arc furnace.

For each technology, Table 1 provides the cost and energy information needed to populate the benchmark data set for SGM-Germany. Energy inputs by fuel type are presented as both quantities and values. In line with the source data, the values in Table 1 are presented in US$. Cost data other than energy for all technologies are based on Knop (2000). Energy use and costs in BOF, advanced EAF (EAFA) and DRP technologies are based on the same source. Advanced BOF (BOFA) is based on the assumption of a 10% energy efficiency improvement, while current EAF energy use is based on data provided by the German steel association (WV Stahl and VDEH 2005). Total production costs are the sum of energy, raw material, labor and capital costs. Energy costs by technology depend on fuel prices and the fuel mix. Raw material costs include non-energy related costs for iron ore, pig iron, sinter, scrap and other materials to produce crude steel. The energy contained in each of these material inputs (and its related costs) is separately accounted for as energy inputs to crude steel production. Investment costs are discounted over a 10 year lifetime at a rate of 8% (Knop 2000). Production costs differ slightly when converted to euros using Germany-specific fuel, electricity, scrap and iron ore prices.

CO_2 emissions are calculated as direct emissions from fossil fuel use and indirect emissions from electricity input based on a typical coal fired power plant in Germany with emissions of 0.7 kg CO2/kWh. Emissions from coke production are not accounted for; however, emissions that result from the use of coke, i.e. the carbon contained in coke, are accounted for.

Table 1 Cost structure of iron and steel technologies

	Units	BOF	BOFA	EAF	EAFA	DRP
Electricity	kWh	223	201	512	350	385
	US$/tcs	5.13	4.87	11.78	8.05	8.85
Fossil fuels						
Coal	GJ	4.54	4.08	0.08	-	-
	US$/tcs	10.55	10.23	0.18		
Coke	GJ	9.88	8.89	0.01	-	-
	US$/tcs	38.02	36.88	0.04		
Nat. Gas	GJ	-	-	0.34	-	5.51
	US$/tcs			1.29		21.17
Capital	US$/tcs	38.75	38.75	11.92	11.92	23.12
Labor	US$/tcs	16.82	16.82	3.89	3.89	5.79
Materials	US$/tcs	86.59	86.59	149.09	149.09	125.10
Energy Credits	US$/tcs	-9.67	-9.67			
SUM	**US$/tcs**	**186.19**	**184.48**	**178.19**	**173.96**	**184.03**
Emissions						
direct from fossil fuels	kg CO_2/tcs	966	937	25	0	273
indirect from electricity	kg CO_2/tcs	156	148	359	245	269

Note: Assumed electricity price 0.023 cent/kWh, natural gas 3.84 US$/GJ, coal 2.32 US$/GJ, coke 2.32 US$/GJ, plant lifetime 10 years, interest rate 8%. Source for BOF, EAFA and DRP: Knop (2000), DRP assumes 50% scrap input, 50% direct reduced iron into an electric arc furnace. EAF: WV Stahl and VDEH (2005). Emissions: indirect emission from electricity based on typical coal fired power plant in Germany 0.7 kg CO_2/kWh. tcs – tons of crude steel.

4 Analysis and results

To demonstrate the operation of iron and steel production, several carbon policy scenarios are considered. The scenarios are intended to provide insights to the European Union CO_2 emissions trading system, but not to replicate all its features. The CO_2 prices are applied to the electric power sector, oil refining, coke production, and energy-intensive industries (i.e. those covered by the EU emissions trading scheme). Each policy scenario is simulated as a constant CO_2 charge instead of a price resulting from a cap and trade system in the European Union. Revenues from the CO_2 price are returned as a lump sum to a representative consumer. Our policy analysis consists of four constant-price scenarios at 10, 20, 30 and 50€ per ton of CO_2 starting in 2005. For the latter two scenarios, the CO_2 price is introduced in 2005 at 20€ per ton of CO_2 and increased to 30 and 50€ respectively by 2010. In addition, we conduct a scenario with a stepwise CO_2 price increase 10€ in 2005, 20€ in 2010, and so on up to 50€ in 2025.

Each policy scenario is run for the CES representation of iron and steel and for the logit-based technology approach. The results of both these approaches are shown in the following sections. We start out with detailed results from the technology-based approach (Section 4.1), then move on to a comparison of the CES and the technology-based approach (Section 4.2) and to economic and emissions results for the whole economy (Section 4.3). The general equilibrium framework allows analyzing the interaction of the steel sector with other production sectors and the combined response to changes in relative costs and prices.

4.1 Technology analysis

Our methodology allows us to take a closer look at the structure of iron and steel production and its development over time. We first present a base case for iron and steel production in Germany through 2050 that includes a mix of technologies. Then we discuss the response of the various iron and steel technologies to a range of CO_2 prices. The technology response depends directly on the way that levelized cost changes as a function of the CO_2 price.

Production of crude steel in Germany in a base case, i.e. without any carbon policy, is shown in Figure 5. New and advanced technologies come in after 2010 and capture a share of output in the base case as capital stocks retire and investment in new and less expensive technologies picks up. The mix of technologies after 2010 is the same as in the logit nest in Figure 2. Most of the conventional EAF technology is replaced by the advanced version (EAFA) by 2050. Similarly, investment in advanced BOF replaces old capital stocks of BOF and takes up an increasing share of output over time. At the same time, it competes with the new natural gas based direct reduction process (DRP). The DRP technology partly replaces existing BOF steel production and accounts for most of the increase in iron and steel production. It is constrained by increasing natural gas prices and scrap availability. Scarcity of high and medium quality scrap may lead to higher and increasing scrap prices in the future. This would then affect the share DRP and EAF technologies hold in the future. In our analysis, scrap prices are assumed to remain at their 2004 level.

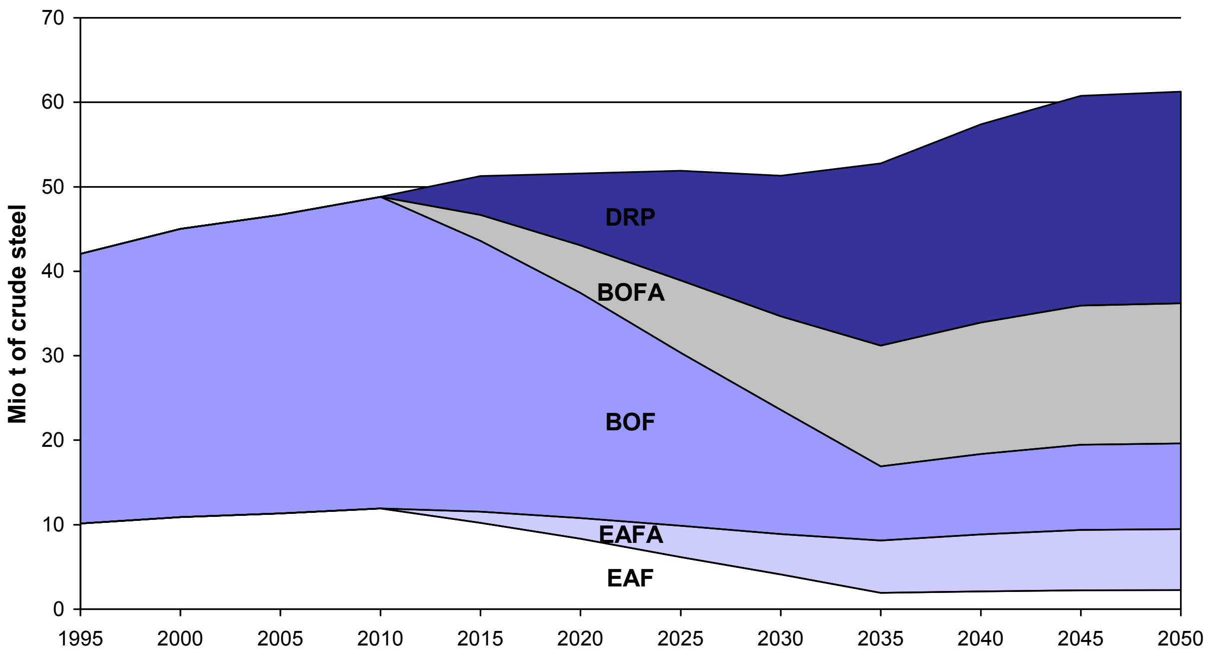

Figure 5 Production of crude steel through 2050 in a base case for Germany. Steel production occurs with basic oxygen furnace (BOF) and electric arc furncace (EAF) technologies before 2010. Advanced technologies are introduced after 2010, including advanced versions of BOF and EAF, and a direct reduction process (DRP).

A scenario with a stepwise increase in CO_2 prices was constructed so that we could plot the levelized cost of each iron and steel technology as a function of the CO_2 price. The technologies vary in their carbon intensity and therefore vary in the rate that levelized cost changes with respect to a CO_2 price. Figure 6 depicts the development of levelized costs for five technologies (BOF, BOFA, EAF, EAFA, DRP) over time and with a stepwise increase of the CO_2 price.

Besides scrap prices, levelized costs of crude steel production increase over time for two main reasons: because of rising fuel prices (coke, coal, natural gas) and because of carbon policies. Technologies that use more carbon intensive fuels, such as coke and coal, experience a higher increase in levelized costs of production than technologies that use less carbon intensive fuels. The incline of BOF technologies is steepest reflecting the higher carbon intensity. Levelized costs of the DRP technology are initially higher but break even with conventional and advanced BOF technology at a fairly low CO_2 price. Their deployment is more restricted by the time they become available than by cost competitiveness. Because of relatively high electricity prices in Germany, the conventional EAF technology is slightly more expensive than the other technologies in the beginning, but is less sensitive to increases in CO_2 price and soon becomes economically viable. The gap between levelized costs of BOF and other technologies widens as time moves on and higher CO_2 prices are introduced.

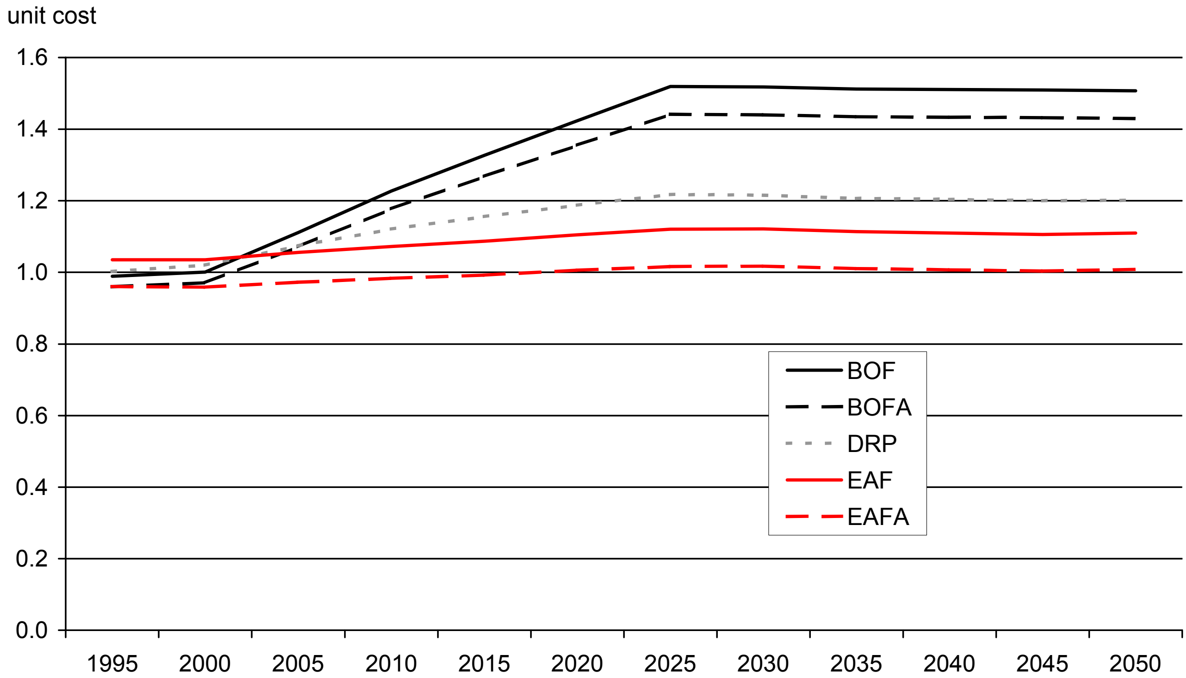

Figure 6 Development of levelized costs for five technologies (BOF, BOFA, EAF, EAFA, DRP) over time and with a stepwise increase of the CO_2 price (2005=10€/t CO_2, 2010=20€/t CO_2, 2015=30€t CO_2, 2020=40€/t CO_2, 2025=50€/t CO_2). Levelized costs are indexed to the average cost of crude steel production in the base year (cost index equals 1 in 1995).

The effect on the structure and development of iron and steel production by technology can be seen in Figure 7. In 2020, some of the old capital stock will have been replaced by investment into advanced technologies. Production from BOFA, EAFA and DRP takes up an increasing share in total iron and steel production. With a higher CO_2 price, steel output declines for the coke intensive BOF technology, but increases slightly for the more electricity intensive EAF and EAFA technologies. Emissions from electricity are accounted for in the electricity sector, where the CO_2 price is applied and added onto the price of electricity according to the carbon intensity of the electricity generation mix. Thus, the EAF and EAFA technologies face higher electricity prices. The increase in electricity prices for EAF steel, however, is not as pronounced as the increase in coke and coal prices for carbon intensive

BF/BOF steel. By 2030, as the capital stock turns over, more and more advanced technologies come into production. With a higher CO_2 price, the shifts we noticed in 2020 are more distinct in 2030. The effect of the CO_2 price on DRP production is very small. With a mixed input of natural gas and electricity the effect is similar to EAF steel production.

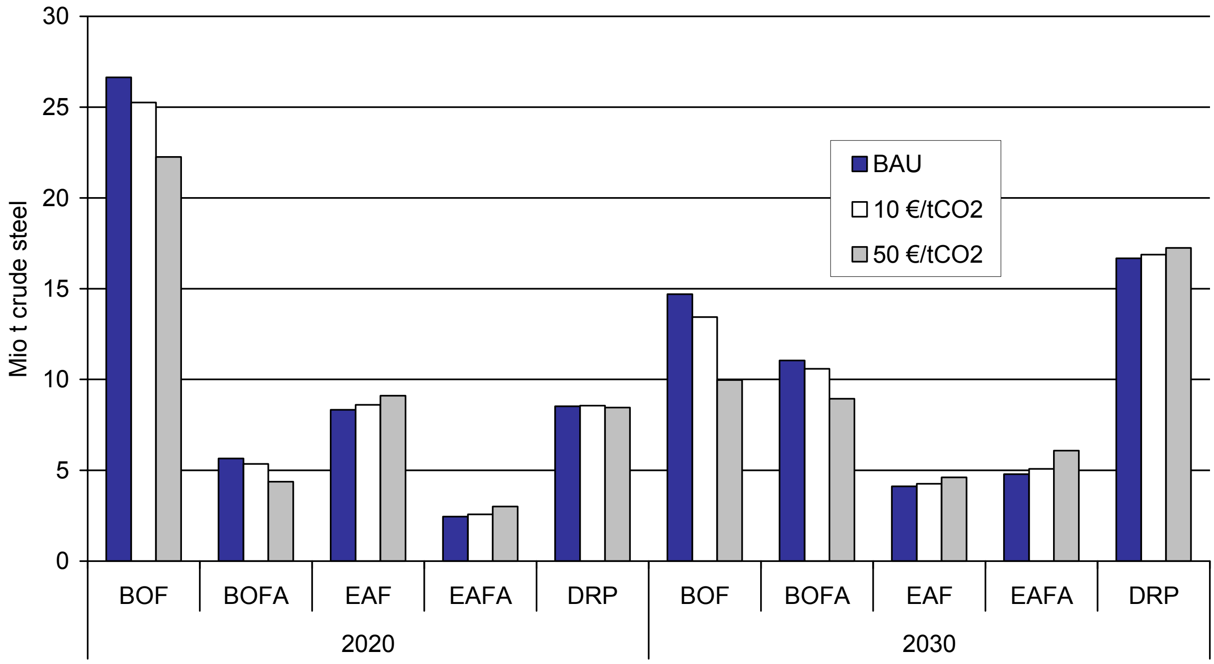

Figure 7 Simulated production of crude steel in 2020 and 2030 at three CO_2 prices: zero €/t CO_2 or business as usual (BAU), 10€/t CO_2, and 50€/t CO_2.

4.2 Conventional CES versus technology-based approach

This section compares results for the technology-based approach (LOGIT) and the traditional CES cost function approach. The same carbon policies are applied to both approaches, and the policies result in similar effects on production levels of iron and steel. Production increases over time, but to a lower extent at higher CO_2 prices. Because the CES approach does not distinguish between different technologies, we cannot compare the technology mix to produce iron and steel. Instead, we take a closer look at the energy inputs to iron and steel production, which reflects the underlying technologies and their distinct energy input structure. Energy input to iron and steel develops differently for the two approaches, over time and in response to a CO_2 price. Figure 8 shows specific energy input, in gigajoules per ton of crude steel, into iron and steel production in the base year and in year 2010. While in the base year, both approaches show the same specific energy consumption, the picture has changed by the year 2010. Specific energy consumption is lower in the traditional approach and decreases with higher CO_2 prices. The differences in specific energy consumption are due to the assumptions on technological change in the two approaches. As explained in Section 2.5, exogenous assumptions on energy efficiency improvement are taken in the traditional approach. They imply an annual decrease in energy consumption with respect to each individual fuel in a continuous way. Assumptions on technological change do not relate to specific technological characteristics. On the contrary, the approach with specific technologies uses assumptions about current and future technologies that are explicitly based on engineering data and allows for substitution of one technology for another over time. New technologies come into the model after the year 2010. No efficiency improvement is applied to the existing capital stock. Therefore, the reduction in energy input to iron and steel production in the base case is nil in the technology case (LOGIT) compared to the base year. Specific energy input in the technology-based case decreases with a higher CO_2 price. This is due to a shift in production technologies based on a change in levelized costs of production. Coal intensive iron and steel production becomes relatively more expensive with a higher CO_2 price than natural gas or electricity based iron and steel production. However, the price response in 2010 is limited by the rate that existing capital stocks retire.

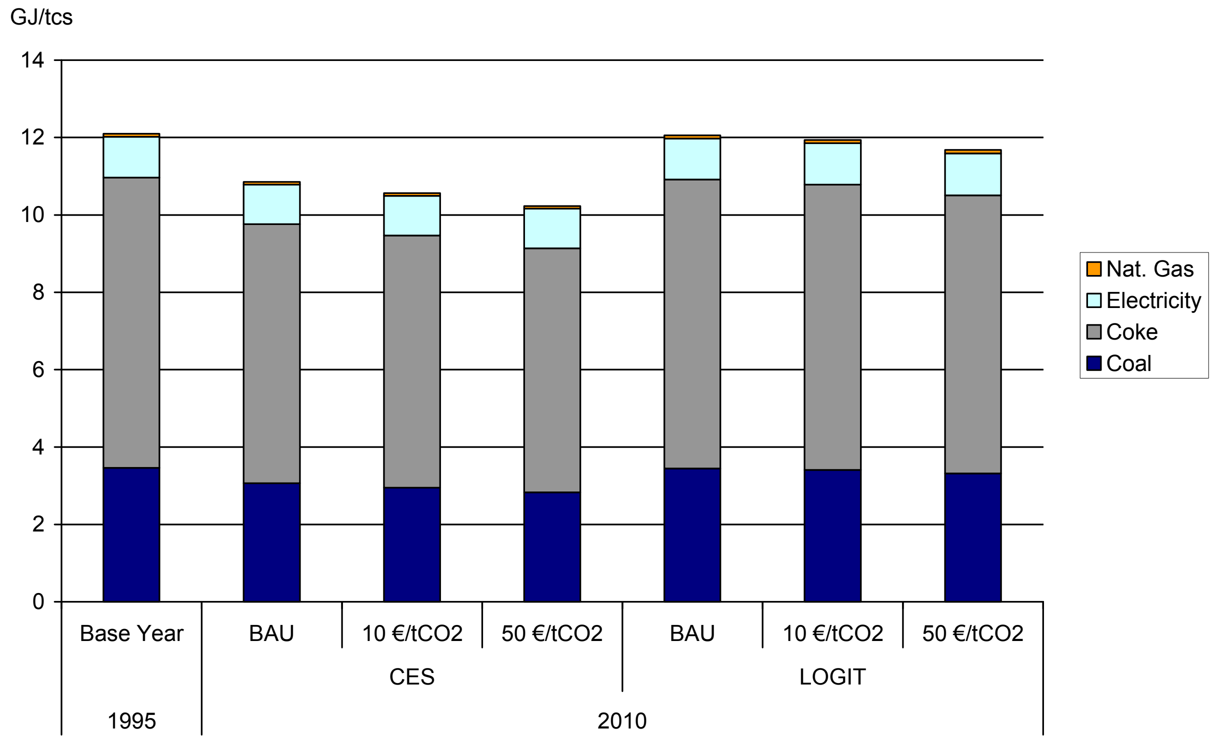

Figure 8 Specific fuel input to iron and steel production, base year and 2010. Units are gigajoules (GJ) per ton of crude steel.

After 2010, new and more advanced technologies become available in the technology-based approach. They change the structure of iron and steel production depending on their relative production costs according to the logit function described in Section 2.2. Figure 9 shows specific energy input to iron and steel production in the year 2030 for the traditional approach (CES) and for the technology-based approach (LOGIT). Specific energy consumption decreases over time and with higher CO_2 prices for both the CES and the LOGIT approach. The response to higher CO_2 prices is more pronounced in the traditional approach; this depends directly on the assumed elasticity of substitution ($\sigma = 0.3$). We can vary this response simply by changing the substitution elasticity. The CES approach is essentially locked into the same pattern of fuel inputs over time and in response to a carbon price. For this reason, almost no natural gas is used in the CES approach. In the technology-based approach, however, a higher CO_2 price induces production technologies to shift away from coal and coke based technologies (BOF) towards natural gas based technologies (DRP). Thus, the average carbon intensity per unit of crude steel declines. There are some similarities in the carbon price response of the two approaches: coke use dominates iron and steel production; yet, coal and coke consumption per unit of crude steel declines substantially; and electricity consumption remains relatively constant.

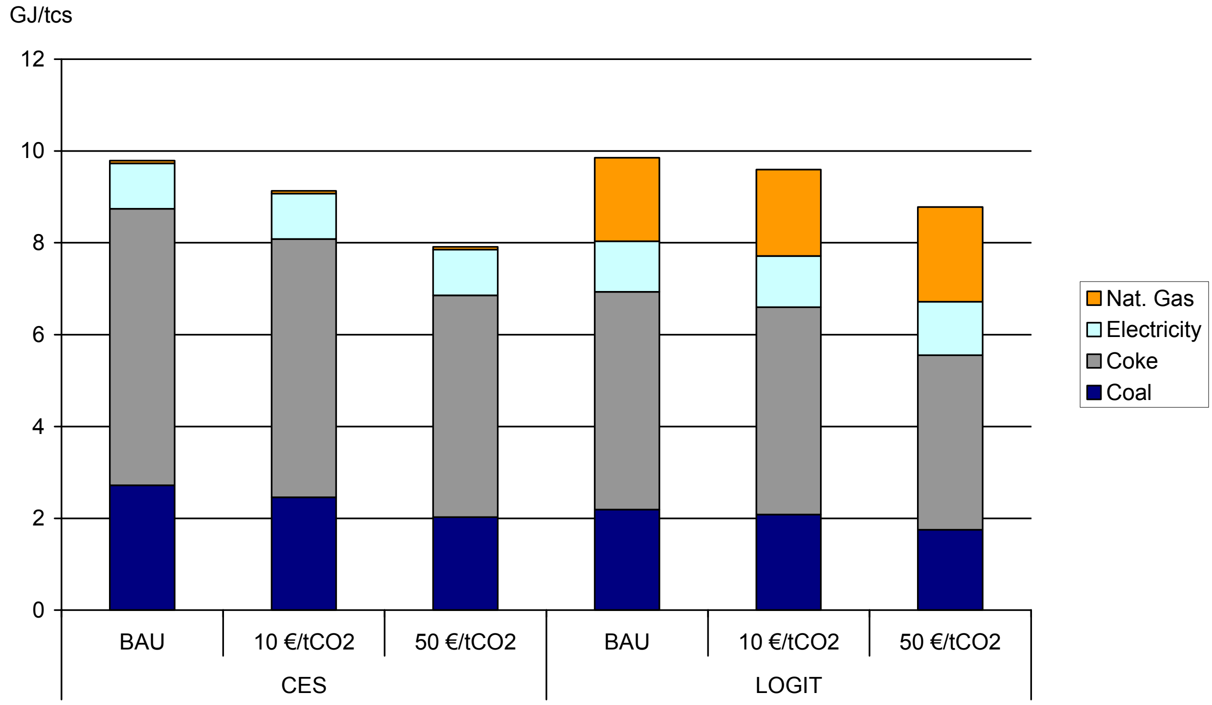

Figure 9 Specific fuel input to iron and steel production, year 2030. Units are gigajoules (GJ) per ton of crude steel.

To summarize, we see a development in the traditional CES approach that is solely based on base year fuel input structure and the assumptions about fuel specific technological change over time. Depending on the rate of technological change, energy intensity decreases more or less rapidly. No fuel switching other than that allowed by the input substitution elasticity can occur. If the substitution elasticity is relatively low, the base year structure dominates future development of energy use. The technology-based approach provides a greater flexibility with respect to structural change in steel production and its inputs. It allows for new technologies with different input characteristics to compete with existing technologies. Thus, it decouples base year structure from future development as seen in Figure 9. Specifically, this flexibility arises from the possibility to account for 1) engineering based technology information on input and cost structure, 2) discrete and different technologies with their specific characteristics at various points in time, 3) improvements of technology characteristics according to engineering knowledge and projections.

4.3 Economic and emissions results

One clear advantage of a CGE framework is the comprehensive coverage of CO_2 emissions on a national basis. In this study, CO_2 emissions are calculated at the point of emission, which is usually the point that fossil fuels are combusted. This presents an accounting difficulty for electricity because there are no emissions at the point the energy is consumed. This is important for the iron and steel sector as a significant amount of electricity is consumed but there are no direct CO_2 emissions where the electricity is used. A purchaser of electricity pays the average price across all generating options, so the appropriate amount of emissions to be charged is the average amount of CO_2 per kWh. However, the generating mix is changing over time and the average amount of CO_2 per kWh is also changing. Emissions calculations at the national level in a CGE model consider all of these interactions, but it would take some extra effort to reassign emissions from the electricity-generating sector to the various users of electricity.

Results presented so far in this paper were obtained by operating a CGE model for Germany at various CO_2 prices. However, the CO_2 prices were applied only to sectors covered by the EU CO_2 emissions trading program. As a point of comparison, we also ran the same CO_2 price scenarios, but with the entire economy exposed to a CO_2 price. As expected, national emissions reductions are greater with CO_2 prices applied to the entire economy. Figure 10 provides a time series of emissions projections from SGM-Germany for the following emissions scenarios: baseline (no CO_2 price); partial coverage at 20 euros per t CO_2; partial coverage at 50 euros per t CO_2; full coverage at 20 euros per t CO_2; full coverage at 50 euros per t CO_2. These scenarios are placed in context of various historical measures of CO_2 emissions in Germany and some future projections by others (Markewitz and Ziesing (M&Z 2004), Prognos/EWI 1999, U.S. Energy Information Administration 2002, E3M Lab 2003 and Esso 2001).

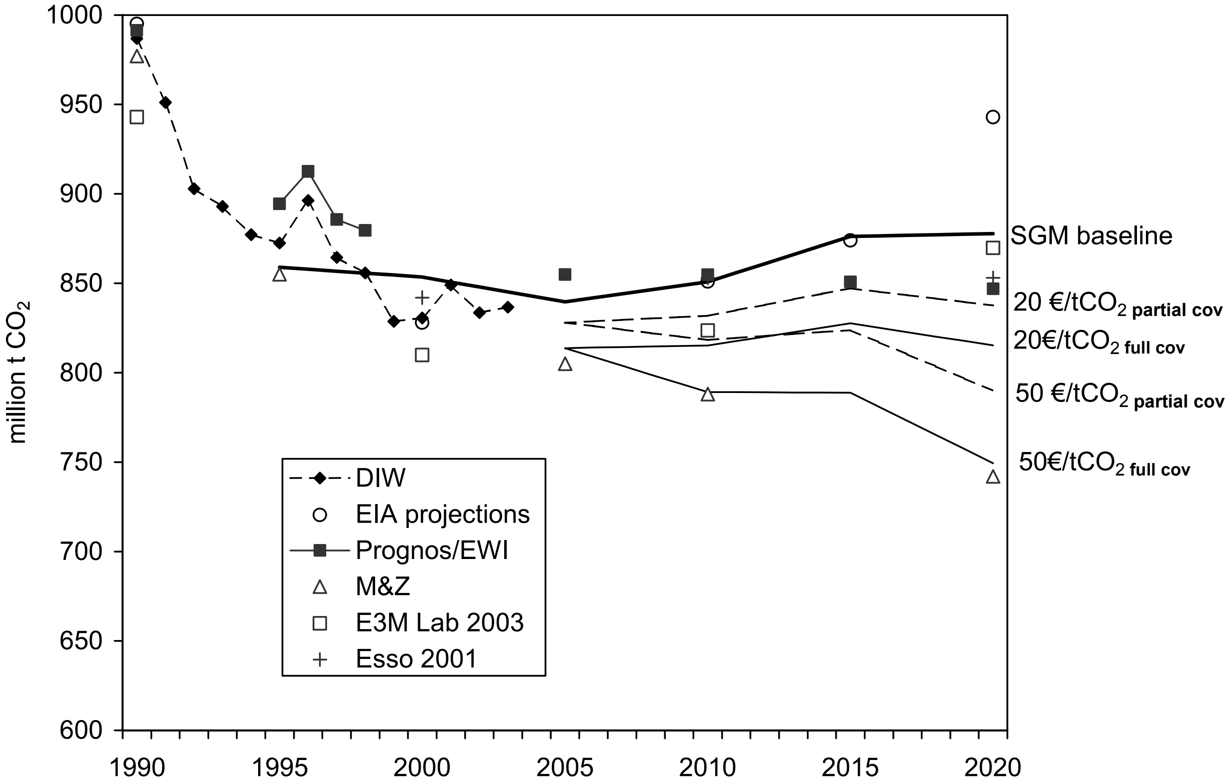

Figure 10 CO_2 emissions Germany: historical and future projections from various sources.

Figure 11 provides a breakdown of emissions reductions into broad groups of energy-consuming sectors at a CO_2 price of 50 euros per t CO_2. CO_2 emissions from electricity generation are nearly the same between the partial- and full-coverage scenarios. In either scenario, emissions reductions increase over time due to the time it takes for existing capital stocks to turn over. Some of the reductions in emissions from electricity generation, especially in later years, are due to carbon dioxide capture and storage. Further background on the role of CO_2 capture and storage in SGM can be found in Schumacher and Sands (2006).

Manufacturing industries include energy-intensive and non-energy-intensive sectors. Thus, a difference in emissions reductions can be seen when a CO_2 price is only applied to the energy-intensive parts of manufacturing. Energy transformation sectors are included in the partial-coverage case, while services, transport and agriculture do not face a CO_2 price and thus do not contribute directly to emissions reductions.

The household sector provides an interesting comparison between full and partial coverage. Even though households are not included in the partial-coverage case, there is still a reduction in emissions because the petroleum refining sector is covered and its price is higher in the partial-coverage case than in the base case.

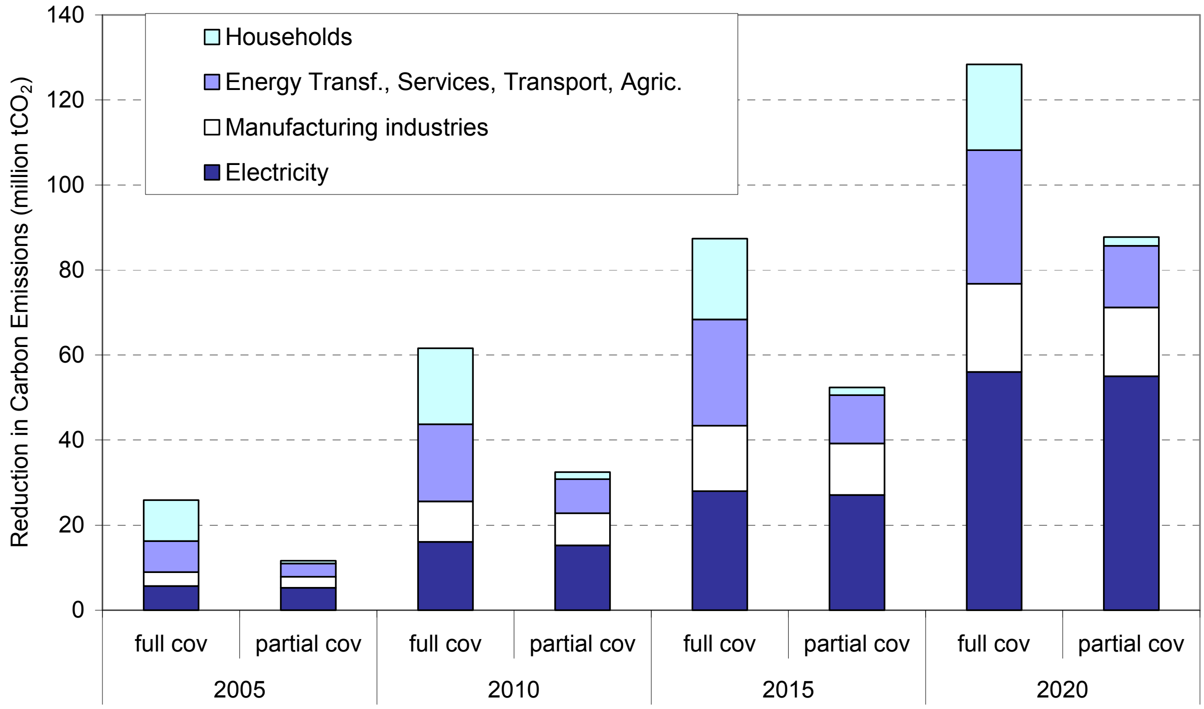

Figure 11 Decomposition of emissions reductions at 50€/t CO_2 across households and major types of industries.

A CGE framework also allows us to simulate the change in output by production sector in response to changing prices, especially CO_2 prices. Figure 12 shows the change in gross output for groups of production sectors at 50 euros per t CO_2, relative to the base case. There is an overall loss in output, but it is most pronounced for energy-intensive sectors directly exposed to the CO_2 price, as the price of those products increases more than the prices of other products. The overall loss in GDP in 2050 for the partial coverage case is 0.57%, very close to the loss in gross output from the large services sector.

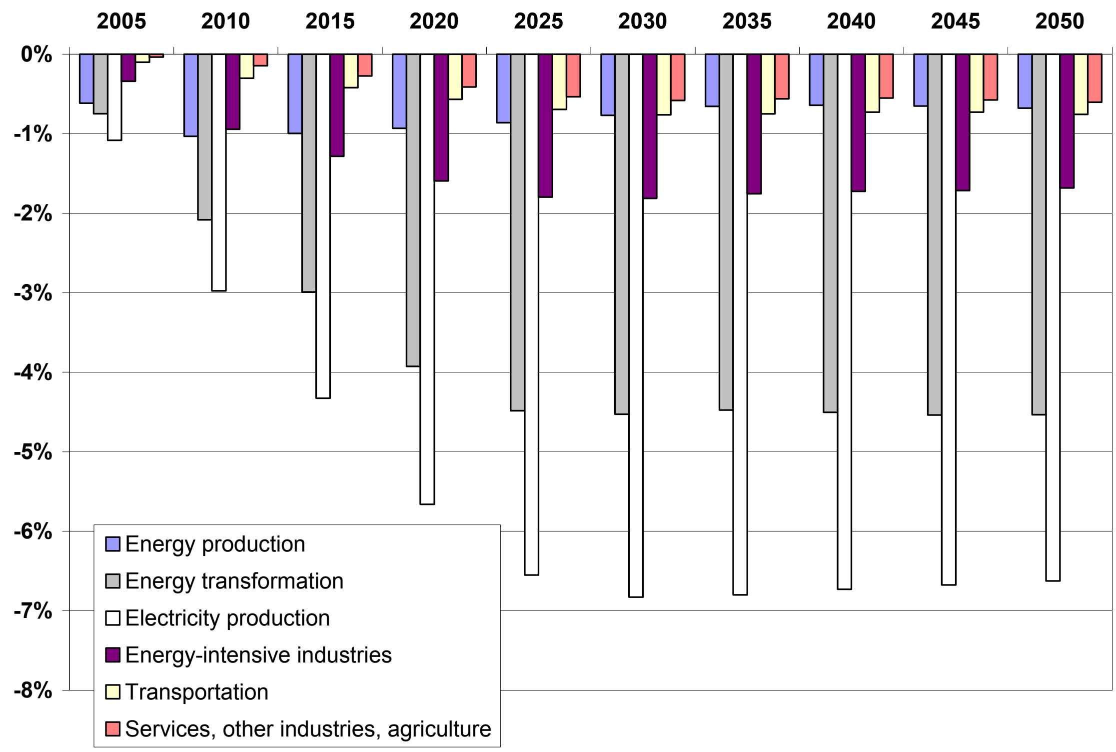

Figure 12 Change in sectoral gross output at 50€ per ton CO_2 for major sectors of the economy (partial coverage) relative to base case.

5 Conclusions

Computable general equilibrium models have become the standard tool for analysis of economy-wide impacts of policy intervention (such as greenhouse gas abatement policies) on resource allocation and the associated implications for incomes of economic agents (Grubb et al. 1993). They provide a consistent framework for studying price-dependent interactions between the energy system and the rest of the economy. For example, demand for energy-intensive goods will fall under a carbon policy because these goods become relatively more expensive. In some energy-intensive industries, especially electricity generation and steel production, response to an energy or climate policy occurs mainly through shifts between alternative production processes. This suggests that CGE models would benefit from including a representation of specific technologies. Advantages of a technology-based approach include: shifts in energy consumption are consistent with shifts between technologies, and the least-cost technology bounds the analysis.

This study explores a technology-based method for improving the realism of energy-intensive industries in a top-down economic model used for analysis of climate policy. Traditionally in top-down models, production sectors are represented by a CES cost function and limited input substitution possibilities. Industrial processes and technological change in these processes are generally not used to parameterize the CES cost function. The new integrated approach replaces the CES cost function with a set of specific processes: each represents a specific technology with technical coefficients constructed from engineering data. We apply this new approach to the iron and steel sector in Germany and account for five different production processes.

The paper compares two ways of representing iron and steel production in a CGE model for Germany: the standard CES cost function approach, and shifts between distinct production processes. The study is designed to provide insights on the response of the iron and steel sector to a policy induced price change, including changes in technological choice, in output, in the fuel mix and carbon emissions. Furthermore, the integrated, technology-based, approach permits an analysis of interaction with other sectors, in particular the electricity sector and its efficiency, and their combined response to policy induced price changes.

Our technology-based analysis reveals that CO_2 reductions in the iron and steel sector take place primarily due to process shifts towards less carbon-intensive production routes and due to output adjustments. These occur as a reaction to higher production costs under a climate policy. We conclude that prices and availability of fuels, as well as the efficiency and the fuel mix of electricity production are important factors for iron and steel production under a climate policy and need, indeed, to be modeled simultaneously. It is important to model electricity and steel production together in a consistent framework because CO_2 emissions from an electric arc furnace, for example, depend on the mix of electricity generation processes, which itself will change with a climate policy. We also see that shifts in technology are not singular events but continue over time as new investment decisions are taken. Thus, policies induce long-term shifts in production capacities, technological change and carbon abatement.

One of the tradeoffs of using a technology approach within a CGE model is the time required to construct a benchmark data set. It requires collection of engineering cost and performance data, which can be drawn from the same sources as for bottom-up analysis, and also a reconfiguration of the input-output structure to accommodate the most important production pathways.

This type of analysis can be extended to other energy-intensive industries and to other countries. Ultimately, we would like to compare results between countries, especially between developed and developing countries. A technology-based approach may help address questions about relative costs of producing steel between countries and how that might change when one country faces carbon constraints but another does not. Further model development could also include endogenous adjustment of technological characteristics, such as through learning-by-doing or R&D investment.

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