AN INNOVATIVE CGE APPROACH FOR THE INCLUSION OF INDUSTRIAL TECHNOLOGIES IN ENERGY-ECONOMY MODELS

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Abstract

Computable general equilibrium (CGE) models are used extensively for analysis of climate policies. Industries are usually represented as abstract economic production functions, commonly of the constant-elasticity-of-substitution (CES) form. This study explores methods for improving the realism of energy-intensive industries in such models. We replace a CES production function with a set of specific technologies and provide a comparison between the traditional production function approach and an approach with separate technologies. 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

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., 2001).

Energy-intensive industries are commonly represented in general equilibrium models as abstract economic production functions of the constant-elasticity-of-substitution (CES) or translog 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 a 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.

The focus of this paper is the representation of industrial energy technologies in a computable general equilibrium framework and we directly address 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?

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. Employing a general equilibrium framework allows for sectoral output adjustments in response to higher production costs, which may be induced by climate policies. It allows us to analyze interactions between production sectors, for example between electricity generation and iron and steel production, and to investigate a combined response to changes in relative prices. The carbon intensity of electricity and iron and steel can change simultaneously. Handling both sectors within a common framework avoids double counting of emissions reductions. The CGE approach helps determine where in the economy and energy system reductions in greenhouse gas emissions are more likely to occur.

However, the aggregate production functions typically used in CGE models are only abstract representations of energy-intensive industries, each of which contains a complex set of production routes. The aggregate production functions are consistent with base-year energy consumption across technologies within an industry because they are calibrated to base-year economic and energy data. However, it may not be possible to demonstrate that simulated changes in energy consumption, in response to changes in prices or other economic drivers, are consistent with shifts among technologies. This is particularly important for analysis of climate policy where energy prices can be driven far outside their historical range.

Other researchers have addressed the inconsistency of top-down economic analysis with bottom-up engineering approaches to industrial energy use. Böhringer (1998) and Böhringer and Löschel (2006) demonstrate a hybrid approach within a CGE model where electricity generation is represented by bottom-up activity analysis and other sectors are represented by CES functional forms. Another hybrid approach is demonstrated in the CIMS model, which iterates between energy demand, energy supply, and macroeconomic modules (Bataille et al., 2006; Jaccard et al., 2003). Pant (2002) and Pant and Fisher (2004) adopt a technology bundle approach for two production sectors to incorporate technology detail in a dynamic multisector CGE model. Li et al. (2003, 2000) use a similar approach for known electricity technologies in the case of Taiwan. Recent efforts devoted to coupling detailed energy models, such as MARKAL, with CGE frameworks include those by Schäfer and Jacoby (2006, 2005) for transport technologies and by Proost and van Regemorter (2000) for energy services in the Belgium economy.

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 feedstocks, the electric arc furnace is highly electricity intensive and based mainly on scrap input. New and innovative technologies are expected to play a major role in the near future (Daniels, 2002; de Beer et al., 1998).

A few studies focus directly on iron and steel production. 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. Similarly, Gielen and Moriguchi (2002a and 2002b) apply a partial foresight model (STEAP) of the European Union and Japan to analyze the effect of CO_2 taxes on the iron and steel industry, including trade and leakage effects of unilateral tax settings. Mathiesen and Moestad (2004) use a global static partial equilibrium model (SIM) to investigate the effect of a CO_2 tax in industrialized countries on global steel-related emissions and potential relocation of steel production. However, none of these iron and steel studies provide a direct application to a computable general equilibrium model.

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. This is important for both baseline and policy scenarios. Allowing for shifts in discrete technologies provides flexibility for future technology development to be decoupled from the base year structure. Further, improvements in technology characteristics can be based directly on engineering knowledge and projections.

Although the technology-based approach is a step forward in representing industrial technologies in CGE models, several weaknesses remain. First, even though the level of detail is much greater than typically found in a CGE model, it is less than in some bottom-up linear programming models. We must make judgments as to the amount of detail to maintain and where to draw a system boundary around the processes we model. In our analysis of iron and steel production, this affects the number of production technologies and the variety of products. For example, we focus on crude steel production technologies, but do not attempt to distinguish downstream processing technologies and types of final steel products. In principle, however, CGE models are well suited to handle further disaggregation of technologies and products, given sufficient data. Second, it remains difficult to find empirical support for the behavioral parameters that determine that rate of shift between technologies as their relative costs change. It is also difficult to parameterize future advanced technologies. Other CGE and linear programming modelers must also determine important behavioral and technical change parameters. This challenge is inherent to all technology modeling and remains a challenge in our technology-based approach. These parameters deserve further, and Germany-specific, empirical justification. Third, even though we have added technology detail to the CGE framework, we still must characterize each steel production route with a single equipment lifetime. This means we have little capability to represent retrofit options and possibilities for lifetime extension. Fourth, this study covers only one of the energy-intensive industries (iron and steel) besides electricity production. An analysis of the effects of climate policy in Germany would deserve technological detail for additional sectors, at least the set of major energy-intensive industries.

Both the aggregate production function approach and the technology-based approach allow for exogenous improvements in energy efficiency within the steel production sector. The ultimate impact of these energy efficiency improvements depends a great deal on substitution elasticities in production processes that use steel. The aggregate production function approach assumes a constant elasticity of substitution among all input factors and exogenous technical change (efficiency) for each input. The technology-based approach assumes fixed input coefficients for each of the technologies; technical change occurs through shifts from one technology to another. These assumptions have implications for the ability of the model to respond to changes of specific prices or factor efficiencies induced, for example, by price or non-price based climate policies (UK Energy Research Centre 2006, Saunders 2000a). We have not explored more general functional forms, such as translog, generalized Leontief or nested CES production functions, or endogenous forms of technical change.

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 from the aggregate production function and technology-based approaches, provide detailed results for production and energy consumption for iron and steel technologies, and place these results in the context of overall economic development. Section 5 concludes the paper.

2. Methods

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] A common approach 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. We refer to this approach as the aggregate production function approach or aggregate CES approach. Our technology-based 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 technology-based approach (or logit nesting approach) has been demonstrated for electricity generation in SGM in Sands (2004) and Schumacher and Sands (2006). This study represents the first application of the logit nesting approach to iron and steel in SGM. Another example of the logit mechanism is in the CIMS model, which uses the same functional form (Jaccard et al., 2003) to determine market share of technologies in new investment.

We are interested in how the aggregate CES and technology-based 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-based 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-based approach, it can also be used for the aggregate 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 flexibility in how we define production sectors in a CGE model: we maintain

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[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 condition that price received equals levelized cost; and (3) the lifetime of capital stocks can be set to any desired multiple of five years.

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.

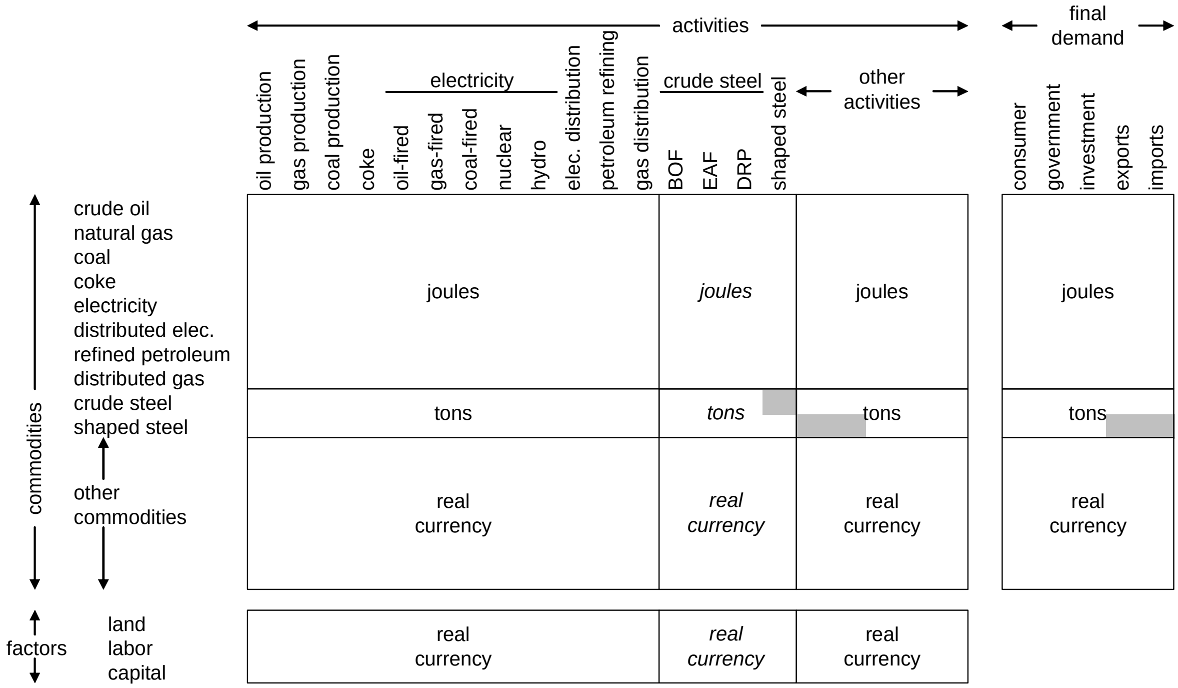

Figure 1 Organization of benchmark use table for Germany in 1995. Each row is a distinct commodity and each column represents production activities. Three distinct activities (technologies) are available for crude steel production: basic oxygen furnace (BOF), electric arc furnace (EAF), and a direct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

This data set can be used for either the technology-based approach or the aggregate CES 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 for SGM 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 (Leontief) production function. Then these production functions are combined in a logit nest. This approach has proven useful for the electricity generation sector in SGM-Germany (Schumacher and Sands, 2006).[2] We construct an engineering cost description for each steel technology (see Section 3.2); 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.

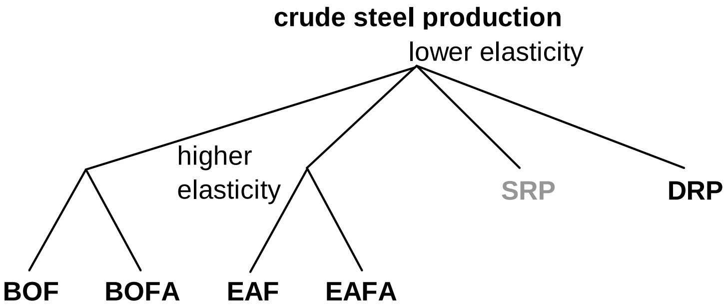

Figure 2 Nesting structure of steel technologies. Each leaf of the nesting structure is a fixed-coefficient technology: basic oxygen furnace (BOF), advanced BOF (BOFA), electric arc furnace (EAF), advanced EAF (EAFA), and a direct reduction process (DRP). The model has space for another advanced technology, 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. During each model time step, new investment is allocated across steel technologies as a function of levelized cost. The share of output provided by each technology is determined by Equation (2),

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

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[2] This approach could be generalized to a logit nest of CES technologies or a logit nest of nested CES technologies. Representing each technology as a Leontief production function is somewhat restrictive, as it does not allow input substitution possibilities within the technology that may exist in reality (Saunders, 2000b).

where C_j is the levelized cost per ton of crude steel, b_j is a calibration parameter to match base-year production, and λ determines the rate that one technology can substitute for another.[3] This formulation prevents knife-edge switching from one technology to another. The lambda parameter is actually an elasticity and can be expressed as

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

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.

The technology-based approach presented here is in some ways similar to efforts by researchers who incorporate engineering-process representations of energy supply into general equilibrium models. The main difference is in the functional form used to distinguish technologies. McFarland et al. (2004), for example, use engineering information for a number of electricity technologies to parameterize a nested CES production function in a way that accounts for limits in thermodynamic efficiency and represents market penetration of technologies as their competitiveness changes. Pant (2002), Pant and Fisher (2004), and Li et al. (2003) use a generalized form of CES, the CRESH function (constant ratio of elasticities of substitution, homothetic) to aggregate a set of Leontief technologies. An important difference between a logit nest, as applied in our analysis, and a CES aggregate of Leontief technologies is that a logit nest preserves quantity balance while a CES function does not. In other words, the total quantity of steel production in a logit nest is always equal to the sum of steel production from the nested technologies.

Our approach differs from efforts by others to couple detailed engineering-process models, such as MARKAL, with multi-sector computable general equilibrium (CGE) frameworks (Schäfer and Jacoby, 2006 and 2005, Proost and van Regemorter, 2000). By loosely coupling the two model types, they aim to establish consistency of parameters that determine substitution possibilities. Providing consistency remains a challenge, as the models are based on different data sets (value terms and physical flows) and have different analytical structures.

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[3] 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.

2.3. Aggregate production function approach

CGE models for analysis of climate policy generally use production functions that are well behaved over a wide range of relative prices, especially energy prices. A climate policy could drive energy prices, especially the price paid for coal, far outside the range of historical experience. The usual approach in CGE modeling is to represent each production sector as a single production or cost function. The CES functional form, or nested variations, is used more frequently than any other functional form. This form has the important property of being globally regular so that input demands can be calculated for any set of prices. It is possible to use more flexible functional forms, such as the translog, in a CGE model. However, they are more difficult to handle because they have additional parameters that require empirical support. Shoven and Whalley (1992) and Perroni and Rutherford (1995) provide further discussion on the choice of functional form in CGE models.

The key parameter in the CES function that determines response to a change in prices is the elasticity of substitution. The CES cost function is written as:

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

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.[4] 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.[5] Equation (7) clearly shows the relationship between input-output coefficients, relative prices, and the substitution elasticity.

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

[5] CGE models are generally calibrated to a benchmark social accounting matrix for a single year. This year may not be representative (it could be during a recession). Therefore, it would make sense to allow the benchmark data set to be constructed using time-series data, but this is rarely done. However, a lot of progress has been made over the past decade to integrate energy balances into the benchmark social accounting matrix (e.g., Sands and Fawcett 2005). This provides much greater realism, in terms of energy quantities and greenhouse gas emissions, than is possible without direct use of energy balances.

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. The labor productivity parameter primarily determines the rate of economic growth. Similarly, the energy productivity parameters affect the future path of energy consumption and greenhouse gas emissions.

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.

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.[6] 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 (FEES, 2006): 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. The balance of payments constraint is imposed by setting an exogenous capital flow during each model time step. In this study, the exogenous capital flow is set equal to its base-year level throughout the model time horizon. Therefore, the balance of payments constraint does not change over time and has little impact on overall production or consumption.

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.

2.5. Technical change

An important difference between the technology-based approach and the aggregate production function approach is the treatment of technical change over time. Both approaches assume exogenous technical change: the aggregate production function approach allows an annual percentage rate reduction in the quantity of inputs per unit of crude steel, while the technology-based approach relies on substitution of one technology for another over time.

In the aggregate CES approach, we 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 (Sands and Fawcett, 2005). These

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[6] This refers to the average lifetime of capital stock in the iron and steel sector. Investment in retrofits of existing furnace technologies (vintages) can lead to much longer individual lifetimes (Worrell and Biermans, 2005).

rates of change begin in the model base year and continue at the same rate throughout the model time horizon.

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 at a later point in time (see section 3.2 for exact specification). Because they 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 at a specified point in time 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. We account for several distinct production routes with their inherent engineering characteristics. A mix of generic technologies, which do not reflect as much technological detail as is common in bottom-up engineering analysis, represents each production route. An economic analysis of these technologies requires data on all inputs to production, including energy, capital, labor, and materials.

3.1. Background on production routes

Iron and steel production is among the most energy-intensive industries in the majority of industrialized countries and is responsible for a large share of greenhouse gas emissions. Germany is a major steel producing country. With 46 million metric tons[7] of crude steel produced annually, Germany is the largest producer in the European Union and ranks sixth worldwide, following China, Japan, the US, Russia and South Korea (data for 2005, IISI, 2006). Crude steel production in Germany in 2001 was responsible for approximately 52 million tons of CO_2 emissions and thus about one-third of industrial CO_2 emissions or 6% of economy-wide German CO_2 emissions (Buttermann and Hillebrand, 2001).

Two distinct iron and steel producing routes are currently in use in Germany: (1) the integrated route of producing crude steel in a two-step blast furnace/basic oxygen process based mainly on iron ore and coke, and (2) the electric arc furnace route based on scrap steel and electricity. They differ mainly with respect to fuel and raw material input, production technology and scale, and variety 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 lesser extent through the electric arc furnace (EAF) route (30%) (see Figure 3, WV Stahl and VDEH, 2005; Aichinger et al., 2001). As can be seen in Figure 3, 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 obsolete, energy-intensive and inefficient production process (Phylipsen et al., 1998), plants using this technology were taken out of service soon after reunification.

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[7] In the following, the term tons (t) shall always refer to metric tons.

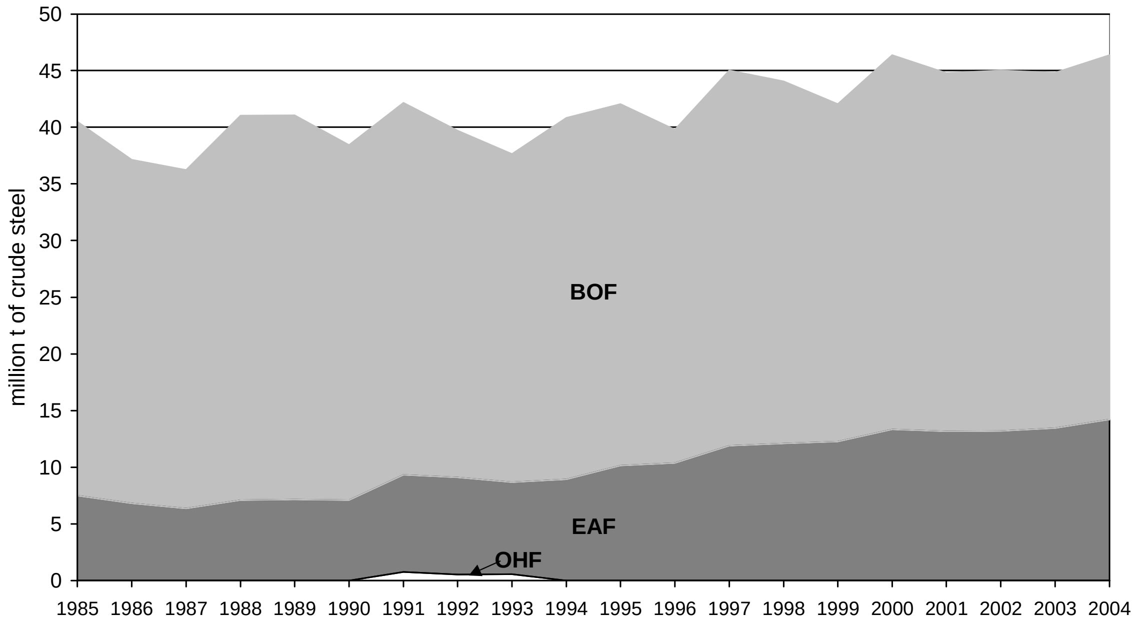

Figure 3 Crude steel production by process type, Germany 1985-2004

Figure 4 shows the main routes of steel production relevant for our analysis of German iron and steel production (adapted from Daniels, 2002; Worrell et al., 1997). The number of processes required to produce crude steel differs for each technology path (production route). The currently used **primary steel route** requires coke, injected coal, and prepared iron ore in the form of sinter or pellets to produce pig iron in a blast furnace. The blast furnace itself is an efficient process but its main inputs, coke and sinter, are very energy-intensive (Daniels, 2002). To reduce energy consumption in the blast furnace, injected coal can partially substitute for coke, but coke is needed as a reduction agent. In a second step, pig iron is fed into the basic oxygen furnace (BOF) and converted into crude steel. The basic oxygen furnace is an exothermal process, i.e. it produces heat. Because of the excess energy, scrap can be added in the basic oxygen furnace as a substitute for pig iron to reduce energy consumption. For process physics reasons, however, the basic oxygen furnace is limited in the amount of scrap it can take, up to 35% (or 45% if pre-heated, Daniels, 2002). The share of scrap input into the basic oxygen furnace in Germany is around 18% (Statistisches Bundesamt, 2006) and thus lower than, for example, in the US with about 28% (USGS, 2006; USGS, 2004). Both blast furnace and basic oxygen furnace yield, to a varying extent, calorific gases as by-products that can be used in subsequent process steps. The primary steel route is therefore highly vertically integrated and optimized over the course of the production chain, e.g. from coke production to final product mix, which implies that it is most efficient at a large scale of production (Daniels, 2002).

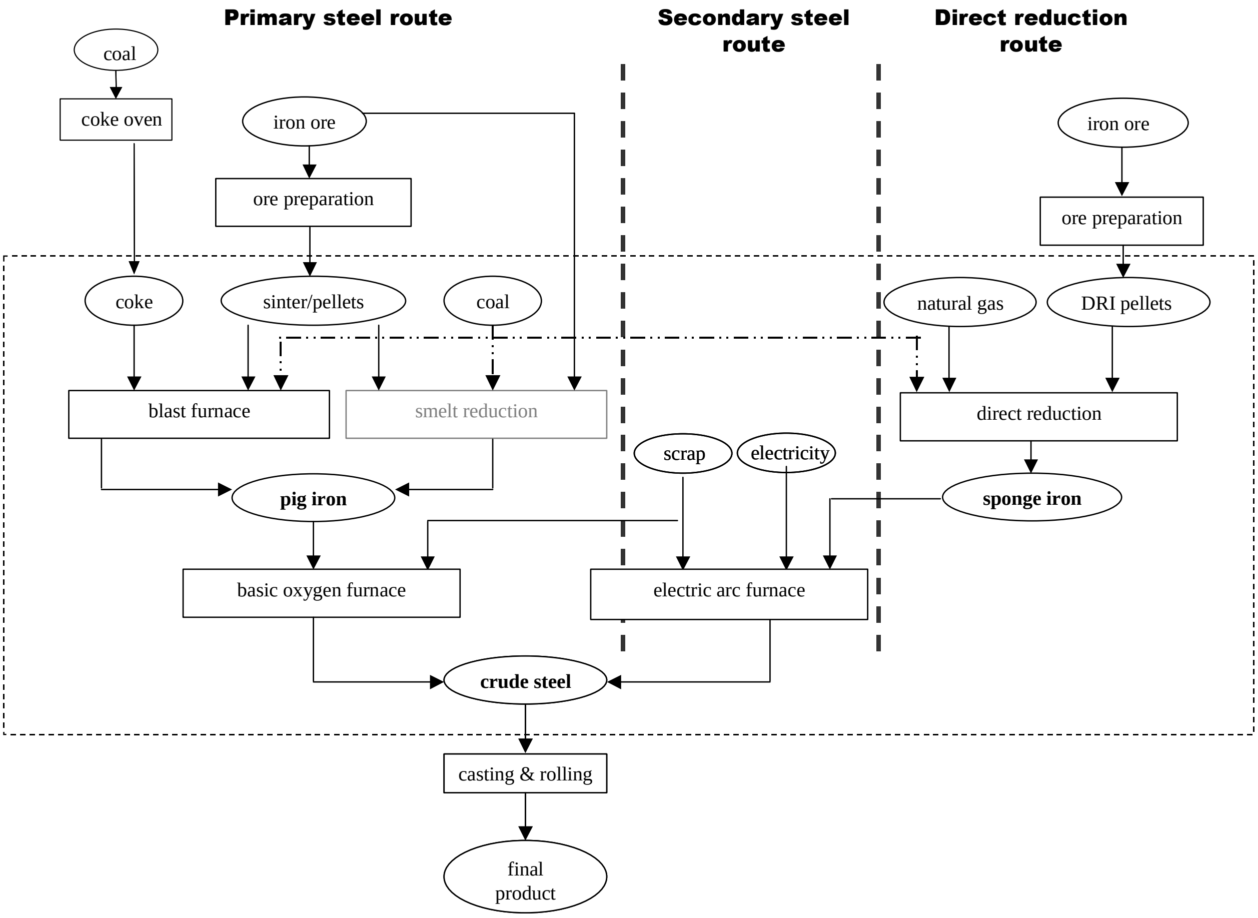

Figure 4 Iron and steel production routes. The dotted rectangle indicates the system boundary for the crude steel production process in SGM-Germany.

Another possibility for steel production is the **secondary steel route,** where recycled steel (scrap) melts into liquid steel in an electric arc furnace (EAF). This route is substantially less energy-intensive than the integrated route. Electricity is the main energy input into the electric arc furnace. The quality of EAF steel is typically not sufficient to produce highest quality products because of contaminants in the scrap (WEC, 1995). The introduction of new downstream processing (casting) technologies, however, allows EAF plants to compete in market segments that were traditionally reserved for integrated mills (Worrell and Biermans, 2005). A major advantage of scrap-based steel making is its lower energy consumption and flexibility. No products from other on-site installations are needed, and it can economically produce steel at substantially smaller scales than the integrated route. Scrap-based electric arc furnaces are often referred to as mini-mills.

Alternatively, sponge 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 electric arc furnace (compare Figure 4). Adding primary iron sources, such as sponge iron, to the input charge in an electric arc furnace reduces the adverse effects of contaminants in the recycled steel (Daniels, 2002). This has the advantage that the steel quality is improved compared to merely scrap-based EAF production. Besides quality improvement, direct reduced iron is also often used as an input if scrap is scarce and expensive (Schumacher and Sathaye, 1998). Scrap prices have been rather volatile in the last decade and may increase with rising world demand and tight supply (Metal Bulletin, various years; Ameling, 2005). The current direct reduction processes are mainly based on natural gas input, although some coal-based technologies also exist or are under development (Daniels, 2002; Knop, 2000; Lüngen and Steffen, 1998; IISI, 1998; de Beer et al., 1998). The combined DRP/EAF route is more energy intensive than the scrap-only EAF route but less energy intensive than the integrated BF/BOF route. For optimal functioning, the DRP/EAF route requires prepared iron ore (DRI pellets). It is therefore more capital intensive and less flexible than mini-mill scrap-based EAF production. Some technologies based on fine ore rather than prepared iron ore exist and are being further explored (Knop, 2000). The DRP/EAF route has the potential to produce steel from any mixture of scrap and primary metals. In particular, it can use more than the maximum of 45% scrap as in the integrated route.

Currently, Germany has the only operating integrated (DRP/EAF) mini-mill in Europe. A direct reduction plant produces sponge iron, which, in equal shares with scrap, is fed into an electric arc furnace to produce steel (Schnabel, 2004). Because this direct reduction plant has a very small share in EAF-based steel production, we do not account for it separately in our analysis but include it in the conventional EAF technology category. In principle, direct reduced iron can also be used as a substitute in a basic oxygen furnace (Buttermann and Hillebrand, 2005; Lüngen and Steffen, 1998; IISI, 1996). In our analysis, we allow direct reduced iron only to be used as an iron input and scrap substitute in the electric arc furnace. Similarly, pig iron is the only iron input into the basic oxygen furnace, complemented by scrap.[8]

Future, innovative technologies for energy-efficient iron and steel making, such as advanced 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 uncertainties with respect to their energy requirements, production costs, and time they will become commercially available. Those innovations focus on substituting away from upfront ore preparation and coke making, as these processes are both capital and energy intensive. Because of data availability, we include an advanced natural gas based direct reduction technology in our analysis (the HYL DR process; Knop, 2000, see next section), but no smelt reduction technology. The latter is therefore shaded in light grey in Figure 4. Smelt reduction avoids coke making in the pig iron production step and therefore reduces energy requirements compared to the conventional blast furnace (IISI, 1998). Smelt reduction (such as the COREX technology) is commercially available but at a rather small-scale and with relatively high capital costs (Fruehan, 2005). More advanced smelt reduction technologies, such as the Cyclone Converter Furnace (CCF) technology, are under research and development but not in commercial use yet (Lüngen et al., 2001). Production costs of these technologies are expected to be lower than in the conventional blast furnace route (de Beer et al., 1998; Daniels, 2002).

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 (Aichinger and Steffen, 2006; Rynikiewicz, 2005; Kim and Worrell, 2002; Worrell et al., 2001; Phylipsen et al., 1998; WEC, 1995). They agree that substantial energy efficiency improvement possibilities exist, but depending on their assessment of current energy consumption, the potential for efficiency improvements varies. Because iron and steel production is a large point source of CO_2 emissions, it is considered well suited for CO_2 capture and storage (CCS). CCS technologies for electricity production are well researched in the literature and can potentially be applied to the iron and steel industry (IPCC, 2005; Daniels, 2002). Currently, we incorporate CCS technologies for the electricity sector and not yet for the iron and steel sector.

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[8] This is in line with production route presentations as in Daniels (2002), Worrell et al. (1997), WEC (1995).

To produce finished steel, crude steel must be cast, rolled, and shaped. Technologies for casting, rolling, and further processing of crude steel can be considered to be the same for different crude steel production routes (Aichinger et al., 2001). Substantial energy savings are possible with new casting technologies (e.g. continuous casting or thin-slab casting), which may also improve the quality and the mix of steel products and, consequently, open up market segments to secondary steel producers (Worrell and Biermans, 2005; Daniels, 2002; Worrell et al., 2001). Currently, we do not distinguish between different technologies for casting, rolling and shaping in our analysis, but draw a system boundary at the level of crude steel production (see Figure 4). Decomposing steel output into different products and into the required casting, rolling and finishing processes adds a substantial level of complexity to the analysis.[9] Daniels (2002) is a good starting point in providing cost and performance data for these processes and technologies.

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 include 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. This implies that, in line with other studies, we assume crude steel to be a homogenous product (Lutz et al., 2005; Hidalgo et al., 2005; Ruth and Amato, 2002). This is a simplifying assumption that neglects quality differences in crude steel.

3.2. Production costs and energy use for iron and steel

Detailed information on production costs and energy use of German iron and steel making is shown in Table 1. These data provide the basis for an engineering cost description of iron and steel technologies in SGM-Germany. 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. The data for the direct reduction process refer to an advanced natural gas based technology (HYL DR) that is not commercially used in Germany yet. It is assumed to be available by 2015 (Knop, 2000).

For the existing blast furnace/basic oxygen furnace route (BOF), it is assumed that sinter, pellets and lump ore are used as inputs at a share 4:2:1 (Knop, 2000). The share of scrap input into existing basic oxygen furnaces is set at 18%. Advanced BOF and EAF (BOFA and EAFA) are assumed to be more efficient in terms of energy use than their currently available counterparts. The efficiency improvement can be achieved either by stock turnover, and thus investment into new and more efficient stock, or by retrofitting existing plants.[10] In SGM-Germany, we do not explicitly distinguish these two options but assume that retrofits, just as investment into new stock, count as additions to the capital stock and are associated with the same costs. Additionally, changing operation modes of existing plants

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[9] In particular, we would need to acquire a good understanding of subsequent use of steel products. The input-output framework in the benchmark data set in SGM-Germany requires allocation of steel products to various users, such as other industry, transport, electricity distribution, food processing, agriculture, export etc., and we would need to assign a share of each product (i.e. output from each process route) to be used by each user.

[10] In line with Worrell and Biermans (2005), retrofit refers to an upgrade of existing capacity by implementing energy-efficient technologies or measures. Worrell and Biermans find in a case study for the US that two-thirds of the achieved energy savings in EAFs between 1990 and 2002 were due to new construction and one-third due to retrofit.

contributes to efficiency improvements, such as changing the composition of feedstock by replacing sinter with pellets or replacing coke with injected coal in the blast furnace, or increasing the share of scrap in the basic oxygen furnace.

Advanced technologies in SGM-Germany are discrete technologies that are assumed to be available for operation in Germany starting after 2010. In principle, most of the technologies are available today with some already being in operation, mostly in developing countries where demand for steel products is soaring (Daniels, 2002; Lüngen et al., 2001). Steel demand in industrialized countries is different both in terms of quality and quantity. Declining or stable demand provides conditions that make large scale capacity expansion via introduction of new technologies unlikely. For the last decade, the number of steel plants in Germany has declined while at the same time capacity utilization has increased from 83% in 1995 to almost 90% in 2004 (WV Stahl and VDEH, 2005). In BF/BOF steel production, the retirement of coke ovens, which are highly capital and fuel intensive, has an important influence on capital turnover and the introduction of new production routes. For Germany and the UK, average coke oven plants are of relatively young age compared to most European countries, and the choice of either rebuilding a coke oven or adopting different production processes will start to come at around 2010 (Daniels, 2002). The characteristics we assume for BOFA, EAFA, and DRP are based on more advanced versions of the currently available technologies as they are expected to evolve (Knop, 2000; Stubbles, 2000). Note that all the technologies reflect engineering characteristics but are stylized in order to be included in a general equilibrium-modeling framework. Each technology should be viewed as a generic technology of its kind.

Table 1 presents energy inputs by fuel type as both quantities and values. In line with the source data, the values are presented in US$. Energy use and costs in BOF, advanced EAF (EAFA) and DRP technologies are based on Knop (2000). 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. Labor and capital costs are based on Knop (2000). Raw material costs include non-energy related costs for iron ore, pig iron, sinter, pellets, scrap and other materials to produce crude steel. They have the highest share in total costs. A price is attached to each material input independent of whether it is produced on-site or bought from a different source. For price information, see Knop (2000). Material costs are driven mainly by scrap prices in the EAF, EAFA, and DRP/EAF production routes. The energy contained in each of the material inputs (and its related costs), such as for pellets or sinter, is separately accounted for as energy inputs to crude steel production. In line with Knop (2000), investment costs are discounted over a 10 year accounting lifetime at a rate of 8% in Table 1.

Capital stock lifetime in SGM-Germany is set to 25 years, which aims to reflect average equipment lifetime of steel technologies. The lifetime used by Knop (2000) is much lower because it is based on a financial depreciation schedule. Similarly, the discount rate (internal rate of return) used by Knop (2000) is higher than the interest rate resulting in SGM-Germany. The data in Table 1 reflect how technologies are described in Knop (2000). We apply our own assumptions to transform the original cost data to a format suitable for a CGE analysis of Germany. Moreover, production costs differ slightly when converted to euros using Germany-specific fuel and electricity prices.[11] CO_2 emissions in Table 1 are calculated

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[11] For example, in 2010 the following fuel prices apply in SGM-Germany: natural gas 4.71 euro/GJ, coal 1.76 euro/GJ, electricity generation 5.03 euro cent/kWh, electricity distribution 10.08 euro cent/kWh.

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 CO_2/kWh.[12]

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 2.3 cent/kWh, natural gas 3.84 US$/GJ, coal 2.32 US$/GJ, coke 3.85 US$/GJ, plant lifetime 10 years, interest rate 8%. Scrap price at 115.38 US$ per ton. 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.[13] Our policy analysis consists of four constant-price scenarios at 10,

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[12] Note that the emissions rates reflect exogenous assumptions here to visualize CO_2 emissions resulting from different technologies to produce crude steel. In SGM-Germany, the carbon factor of electricity production is endogenous according to the generation mix in each time step. Emissions from coke production are not allocated to steel production; however, emissions that result from the use of coke, i.e. the carbon contained in coke, are accounted for.

[13] This version of SGM has a single representative consumer that purchases consumer goods and government services. Lump sum recycling to this consumer has little impact on the relative shares of economic production going to consumer goods and government services. We do not attempt to compare this method of recycling to

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 technology-based approach. The results of both these approaches are presented in the following sections. We start with detailed results from the technology-based approach (Section 4.1), then move on to a comparison of the aggregate CES and technology-based approaches (Section 4.2), and finally to economic and emissions results for the whole economy (Section 4.3).

4.1. Technology-based analysis

The technology-based approach 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. 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 or in retrofits 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 is an electric arc furnace technology that is based on a combination of scrap and sponge iron inputs and produces high quality steel, which directly competes with steel from the BOF route. It therefore partly replaces existing BOF, and to a lesser extent EAF, 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 increased scrap prices in the future. This would then affect the share that DRP and EAF technologies hold in the future. In our analysis, scrap prices are assumed to remain at their 2004 level.[14]

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other fiscal arrangements that might be more likely in practice such as recycling to the government or distributing the majority of emissions rights to current emitters.

[14] We simulate the adoption of technologies with their inherent cost, efficiency and availability characteristics as laid out in Section 3.2. Different assumptions on technology specifications, in particular on the time of deployment, on costs and on quality differences in crude steel, would likely lead to different output shares in the simulation.

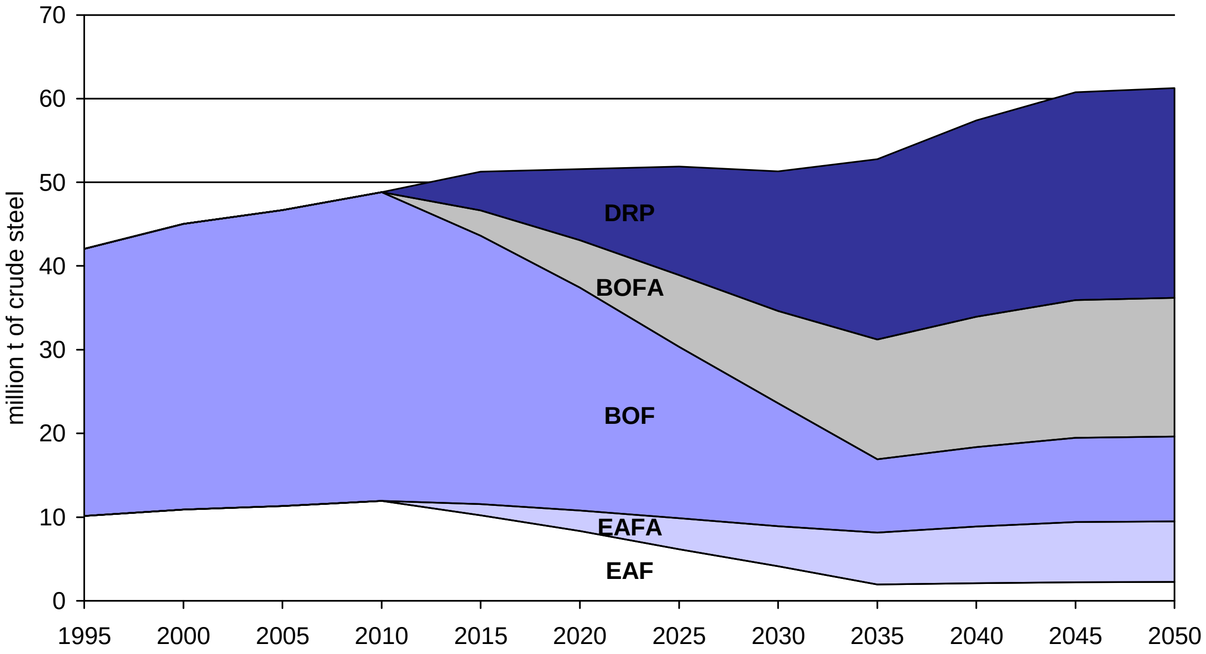

Figure 5 Production of crude steel through 2050 in a base case for Germany. Steel production occurs with basic oxygen furnace (BOF) and electric arc furnace (EAF) technologies before 2010. Advanced technologies are introduced after 2010, including advanced versions of BOF and EAF, and a direct reduction 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. This implies that their deployment is more restricted by the time they become available than by cost competitiveness. As shown in Figure 5, they take up a share of output even in the base case as soon as they become available after 2010. 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 competitive. The gap between levelized costs of BOF and other technologies widens as higher CO_2 prices are introduced.

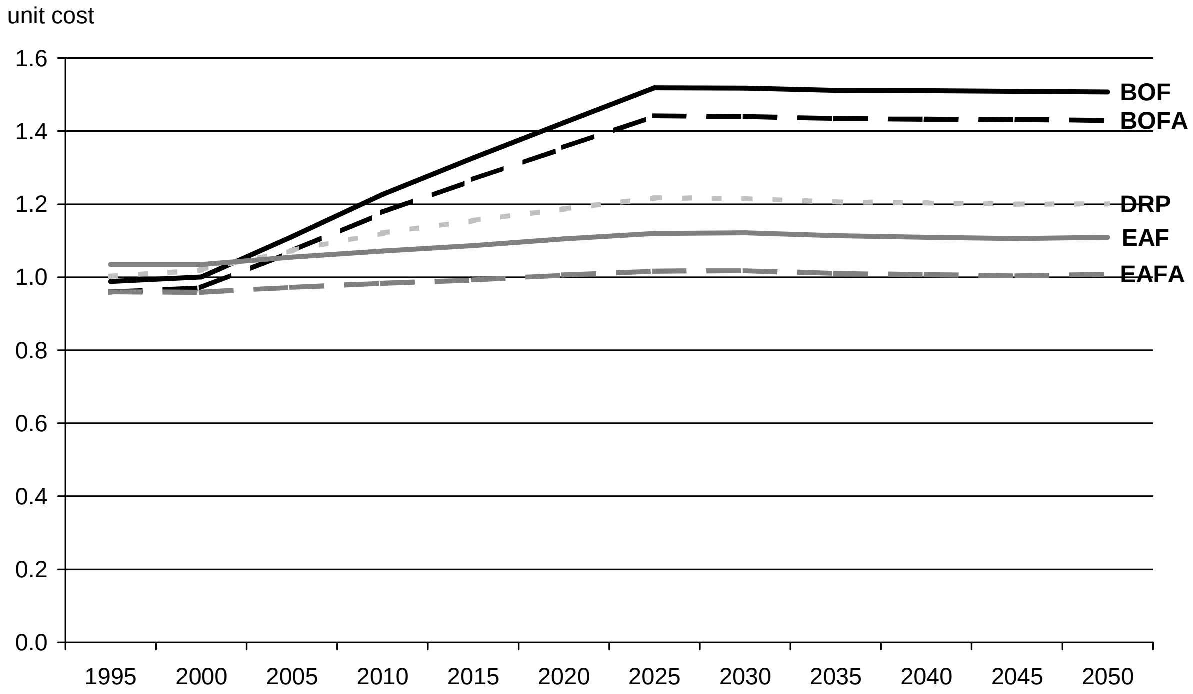

Figure 6 Development of levelized costs for five technologies (BOF, BOFA, EAF, EAFA, DRP) over time and with a stepwise increase of the CO_2 price (2005=10€/t CO_2, 2010=20€/t CO_2, 2015=30€t CO_2, 2020=40€/t CO_2, 2025=50€/t CO_2). Levelized costs are indexed to the average cost of crude steel production 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 costs related to coke and coal use 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.[15]

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[15] The result of a small response to an increase in energy related costs for EAF corresponds with earlier econometric estimations, for example, by Boyd and Karlson (1993), who find that non-price factors, such as technical change and potential costs reductions have a larger influence on the timing of technology adoption than energy prices.

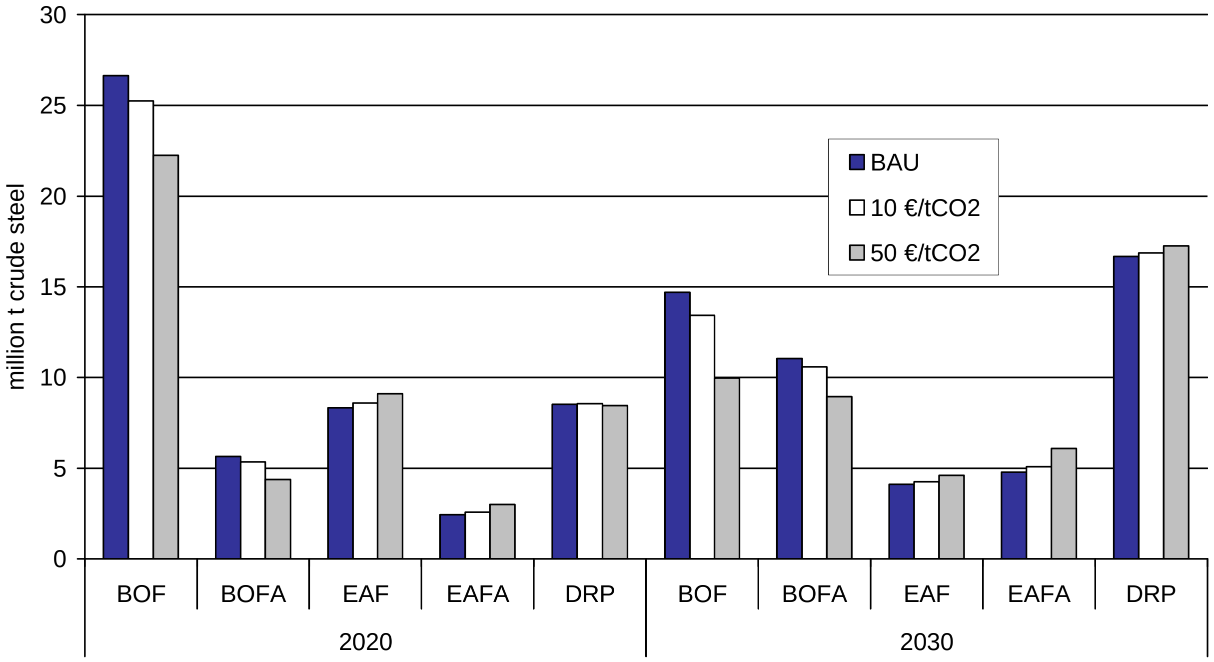

Figure 7 Simulated production of crude steel in 2020 and 2030 at three CO_2 prices: zero €/t CO_2 or business as usual (BAU), 10€/t CO_2, and 50€/t CO_2.

4.1.1. Sensitivity analysis

We conducted a sensitivity analysis for high natural gas and high scrap prices. For illustration, we included three sensitivity cases relative to the base case: i) with respect to increased natural gas prices (assumed to be 30% higher than in base case in 2005, 50% in 2010, 70% in 2015, 90% in 2020 and 100% 2025 and thereafter; all relative to the base case); ii) with respect to increased scrap prices (assumed to more than double to 250 US$/t scrap from 2005 on); and iii) with respect to both increased natural gas and scrap prices (combined effect of i and ii). In all cases no CO_2 price is applied. The sensitivity analysis reveals that the output of DRP is, as expected, quite sensitive to an increase in natural gas and scrap prices. Figure 8 shows the effects on output from DRP as percentage reduction in output compared to the base case. The illustrative specifications of increases in natural gas or scrap prices reveal a substantial decrease in output from DRP steel production for each sensitivity case. Independent of these exact specifications, which are subject to high uncertainties, it can be deducted that a combined increase in natural gas and in scrap prices has an almost cumulative, and thus most deteriorating, effect on output from DRP.

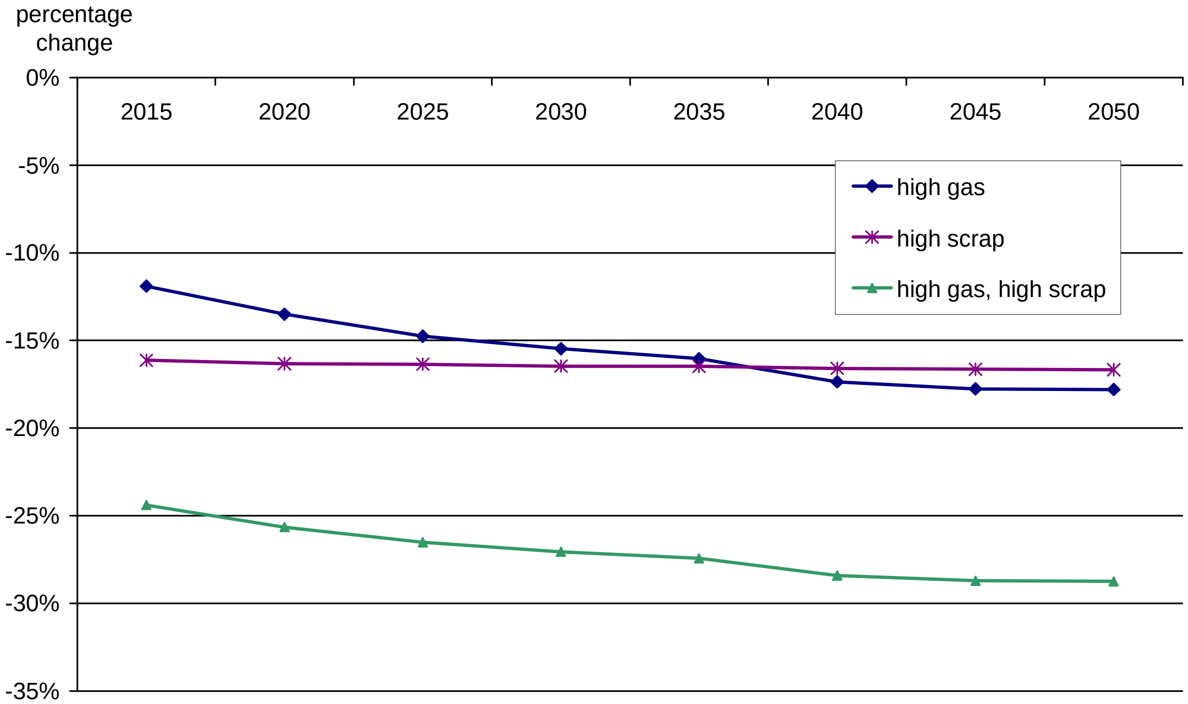

Figure 8 Percentage change in crude steel output from direct reduction process/electric arc furnace production (DRP/EAF) in three sensitivity cases relative to the base case. Sensitivity runs i) with respect to increased natural gas prices (assumed to be 30% higher than in base case in 2005, 50% in 2010, 70% in 2015, 90% in 2020 and 100% 2025 and thereafter; all relative to the base case); ii) with respect to increased scrap prices (assumed to more than double to 250 US$/t scrap from 2005 on); and iii) with respect to both increased natural gas and scrap prices (combined effect of i and ii). In all cases no CO_2 price is applied.

For the EAF technologies (EAF and EAFA, see Figure 9) the picture looks differently. In accordance with their input structure, i.e. mainly scrap based no use of natural gas, they respond highly to changes in the assumptions about scrap prices. A higher scrap prices leads to a reduction in output of EAF steel. On the contrary, an increase in natural gas price, and its related reduction in output from DRP, induces an increase in output from EAF technologies compared to the base case. EAF based steel production partly compensate for the reduction of DRP based steel production. The combined effect of an increase in natural gas and in scrap prices on EAF based crude steel output is somewhat counterbalancing and depends on the exact specifications of price increases.

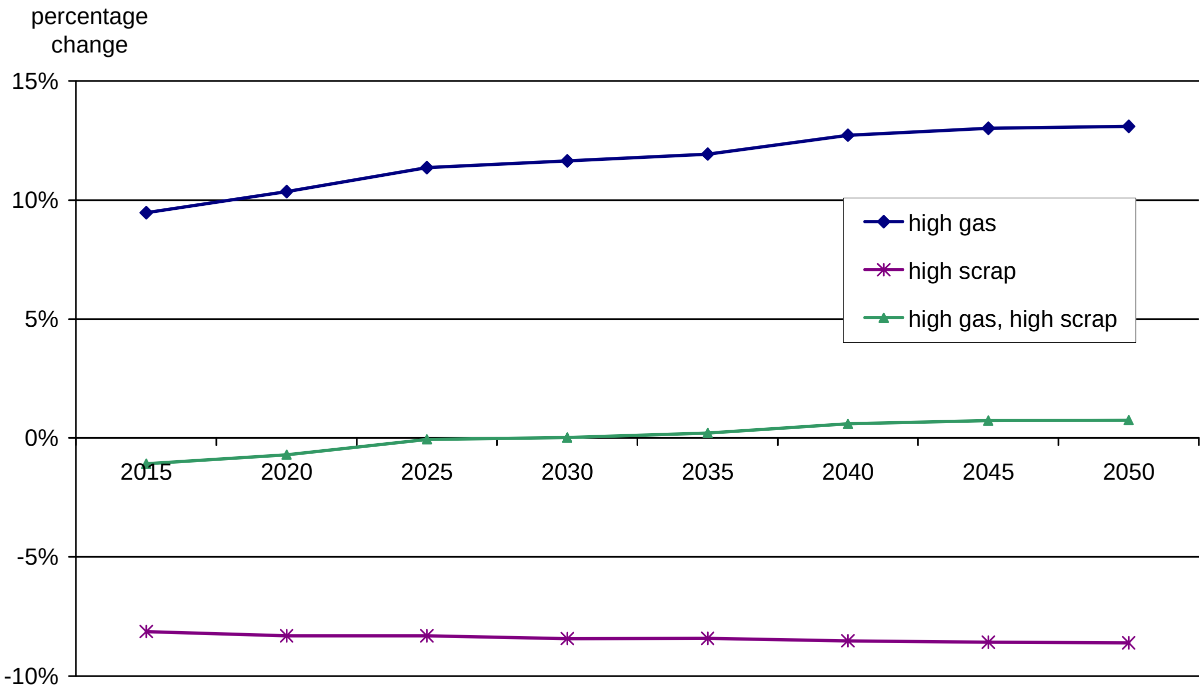

Figure 9 Percentage change in crude steel output from advanced electric arc furnaces (EAFA) in three sensitivity cases relative to the base case. Sensitivity runs as above (Figure 8).

The sensitivity runs also reveal effects on total crude steel output. An increase in natural gas price (ceteris paribus) leads to a reduction in total crude steel output and a higher share of both EAF and BOF based production (current and advanced). A simultaneous increase of both scrap and natural gas prices also leads to a reduction in total crude steel output, partly compensated for by an increase in BOF based production (BOF and BOFA).

4.2. Aggregate CES versus technology-based approach

This section compares results for the technology-based approach (LOGIT) and the aggregate CES 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 lesser 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 10 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 CES 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 aggregate CES 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 (technology-based approach) 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-based 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.

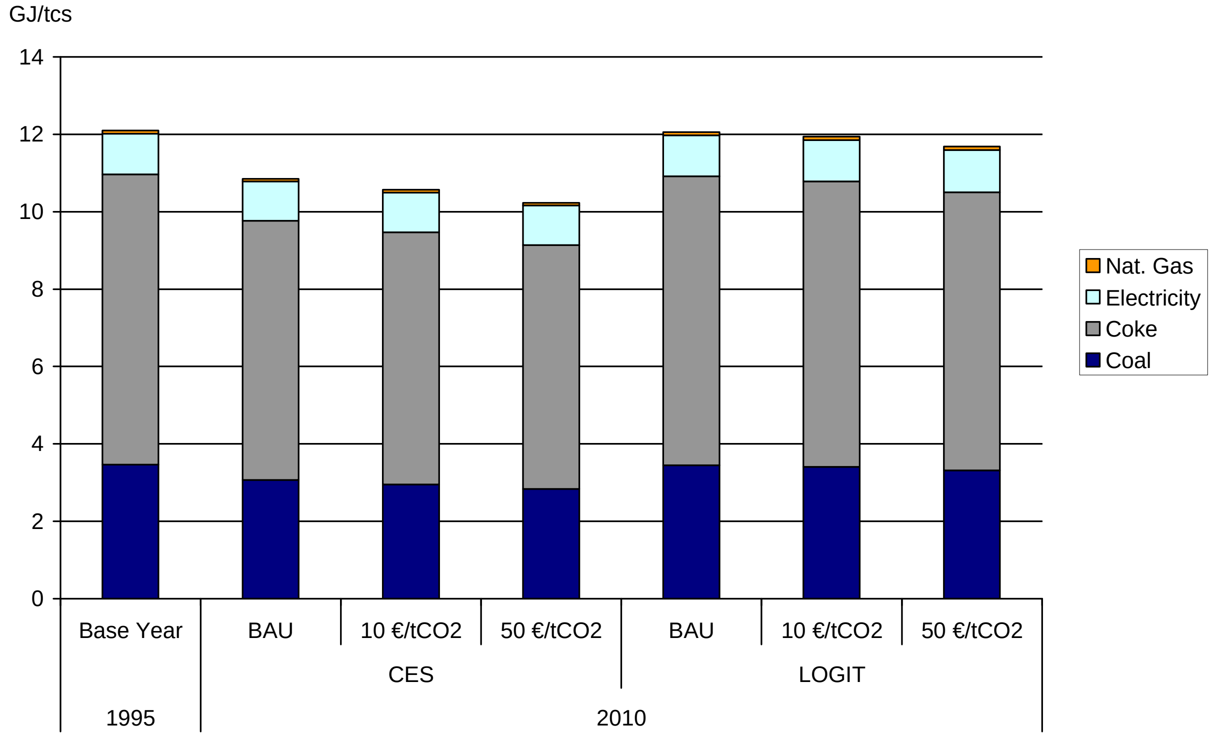

Figure 10 Specific fuel input to iron and steel production, base year and 2010. Units are gigajoules (GJ) per ton of crude steel. LOGIT refers to the technology-based approach, CES to the aggregate CES approach.

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.

Figure 11 shows specific energy input to iron and steel production in the year 2030 for the aggregate production function 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 CES 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 (LOGIT), however, a higher CO_2 price induces production technologies to shift away from coal- and coke-intensive technologies (BOF) towards natural gas-intensive 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. Electricity consumption remains relatively constant in both approaches.

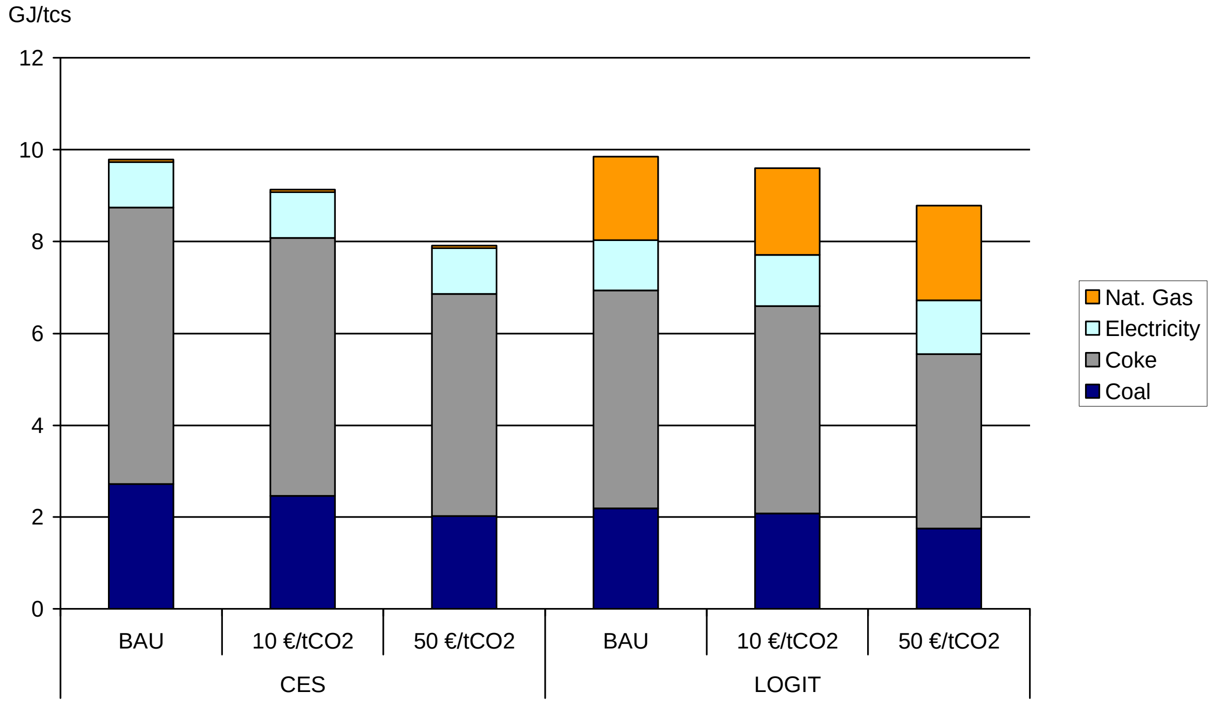

Figure 11 Specific fuel input to iron and steel production, year 2030. Units are gigajoules (GJ) per ton of crude steel. LOGIT refers to the technology-based approach, CES to the aggregate CES approach.

To summarize, we see a development in the CES approach that depends primarily on base year fuel input structure and the assumptions about fuel specific technological change over time. Depending on the assumed 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 (LOGIT) 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 11. 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, and 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. This section presents economy-wide results using a technology-based representation of steel production.

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 12 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 (DIW, 2004; Markewitz and Ziesing (M&Z 2004); Prognos/EWI, 1999; U.S. Energy Information Administration, 2002; E3M Lab, 2003; and Esso, 2001).

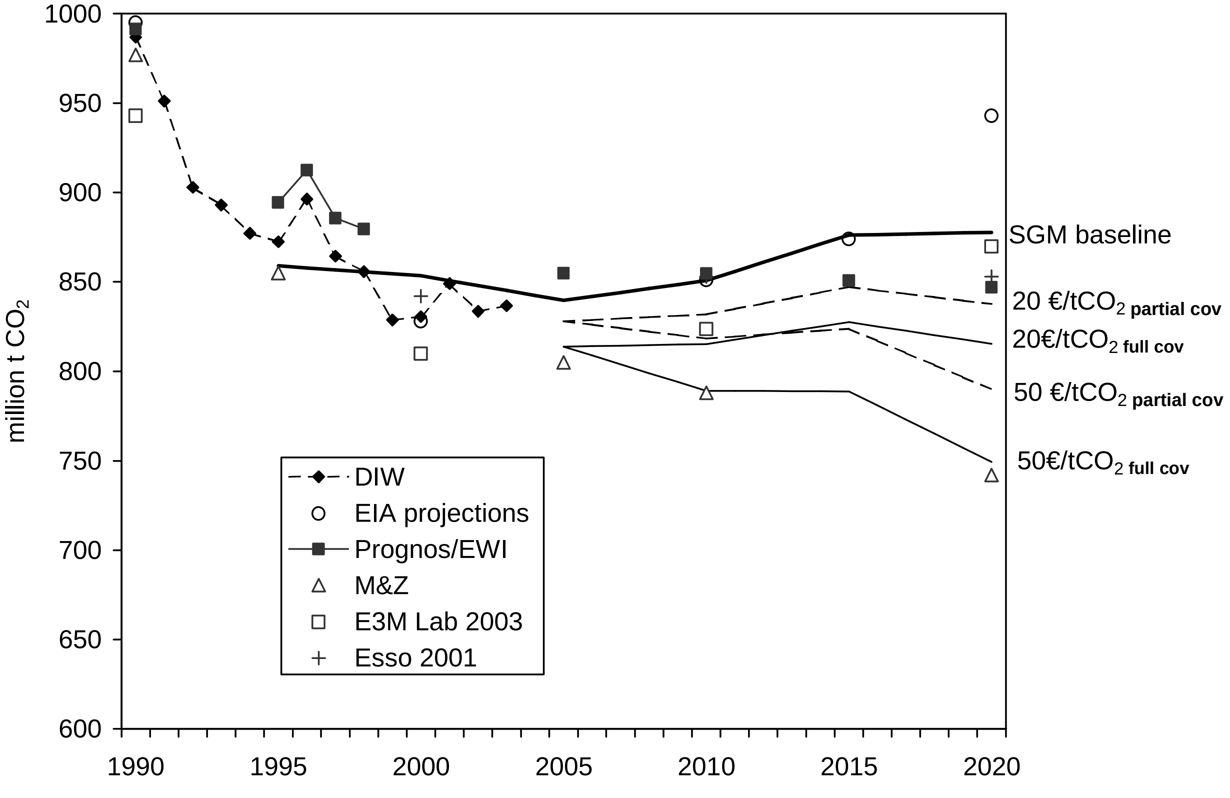

Figure 12 CO_2 emissions in Germany: historical and future projections from various sources.

Figure 13 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.

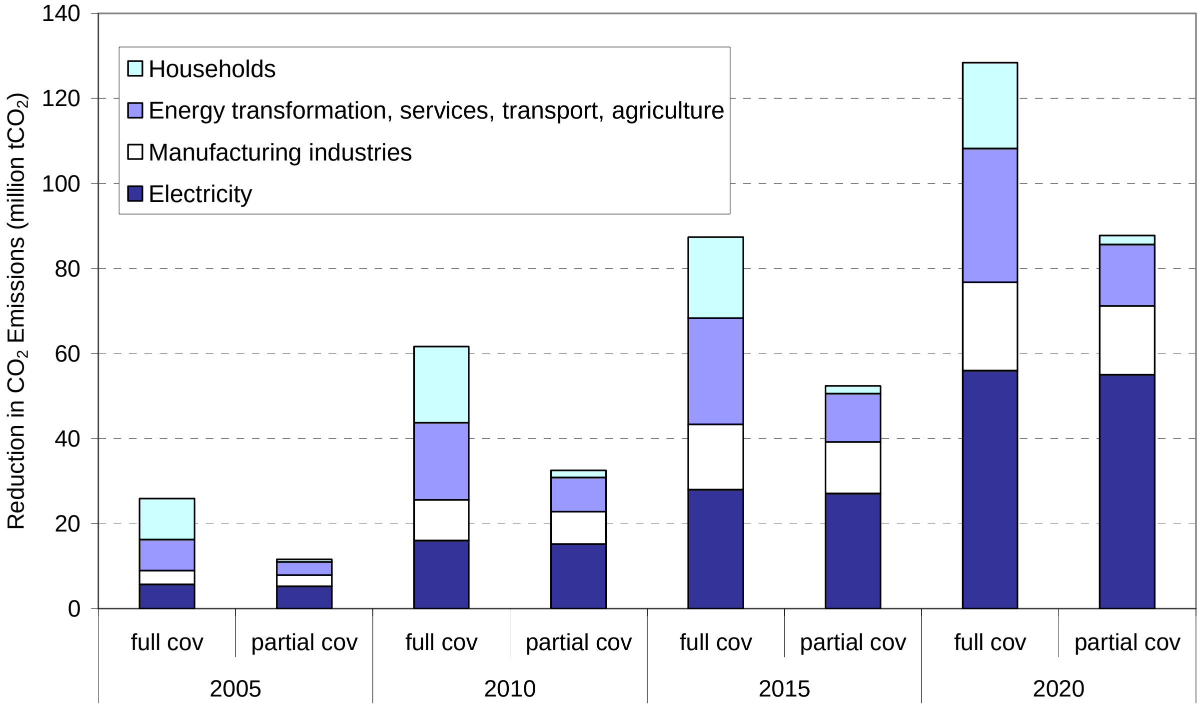

Figure 13 Decomposition of emissions reductions at 50€/t CO_2 across households and major types of industries.

5. Conclusions

Computable general equilibrium models have become a 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 interactions between the energy system and the rest of the economy (Böhringer, 1998). For example, demand for energy-intensive goods will decline 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. Our study demonstrates two important advantages of a technology-based approach: 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 CGE model used for analysis of climate policy. Production sectors are commonly represented in CGE models by a CES cost function. However, industrial processes and technological change in these processes are generally not used to parameterize the CES cost function. Our technology-based 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 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: a typical CES cost function approach, and a technology-based approach that allows 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. Further, 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. 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.

A number of uncertainties affect the future development and selection of steel production routes. First, natural gas and scrap prices are more uncertain than coal prices, and we have conducted a limited sensitivity analysis. Higher natural gas and scrap prices lead to a decrease in the adoption of those technologies that use these factors intensively. Second, the timing of investment decisions depends on capacity utilization in the current capital stock. Implementation of new technologies can be delayed if the current stock of capital is running at less than full capacity. Third, we do not know how long existing plants will continue to operate. Retrofits and life extension could keep plants operating much longer than the 25 years we have assumed, and this limits opportunities for shifts to other production routes. Fourth, future technical change is not easy to predict. But we do have an understanding of the difference between average practice and best practice.

This study demonstrates that it is constructive and feasible to operate CGE models at an intermediate level of technology detail. The extra effort to collect engineering cost and performance data, and to reconfigure a benchmark data set to accommodate these data, can be justified as it improves the realism of policy simulations.

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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