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Climate policy and the steel industry: achieving global emission reductions by an incomplete climate agreement

by

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Abstract

The steel industry is one of the largest sources of global CO_2 emissions and hence a candidate for climate policies. A carbon tax on emissions in industrialized countries, however, will cause relocation of steel production to non-industrialized countries, and because of their relatively high emission intensities the effect on total emissions is ambiguous. Using a partial equilibrium model of the steel industry, this paper finds that global emissions from this industry are likely to decline substantially. This is primarily due to factor substitution within the integrated steel mills in the industrialized countries. Such effects are not well accounted for in economy wide models, which typically lump individual industries into aggregates. Furthermore, it is shown that border taxes on steel products are potentially useful instruments for achieving a given reduction in global emissions with less restructuring of domestic steel industry in the industrialized countries.

JEL classification: D58, F14, H32, L61
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1. Introduction

Over the last few years a number of analyses have been conducted in order to evaluate the consequences of various types of climate policy for the world economy and for the environment. Particular attention has been devoted to the effect of incomplete climate agreements, such as the Kyoto Protocol, which impose emission caps only on a subset of the countries that contribute to global warming. An important issue of concern has been that climate policies that are implemented in a limited number of countries may be offset by higher emissions in other regions and thus contribute little, or perhaps even negatively, to global emission reductions.

This paper analyses the implications of an incomplete climate agreement of the Kyoto type for the greenhouse gas emissions in the steel industry. There are several reasons for our interest in this industry. First, the steel industry is a major source of greenhouse gas emissions. Steel production accounts for 7% of world carbon emissions. By adding the emissions related to the mining of iron ore and coal the share may rise to as much as 10% (Ecofys, 2000). In addition, the steel industry accounts for some 20% of world sea borne trade and thereby its emissions (Mæstad *et al.*, 2000a).

Second, there seems to be substantial scope for environmental leakage following the implementation of unilateral climate policies in the steel industry. Paltsev (2000) reports that the steel industry may account for nearly 20% of all carbon leakage in the wake of the Kyoto Protocol. The steel industry is a truly global industry with extensive international trade in finished and semi-finished steel products. Almost 50% of world steel production takes place in countries that do not have obligations to curb their emissions under the Kyoto Protocol. Implementation of carbon taxes or tradable emission permits in the Annex B countries of the Protocol will improve the competitiveness of non-Annex B steel producers and thus increase their levels of production and emissions. If steel production is less carbon efficient in non-Annex B countries than in Annex B countries, as is typically the case, global emissions may even increase. Finally, steel production being relocated to non-Annex B countries may increase the emissions related to transport of steel products from the producing regions to the large steel consuming regions, such as the European Union and the USA.

Third, the steel industry is an interesting case in point because there are several ways of producing steel. Iron making may either take place in the blast furnace process or through direct reduction, and the transformation of iron into steel may occur either in an oxygen blown converter or in an electric arc furnace. Since the various technological options have quite different emission profiles, emissions may be reduced through substitution across technologies. Emissions may in some cases also be reduced by substitution of less polluting inputs for more polluting ones. These substitution possibilities in the steel industry imply that leakage through relocation of production may be counteracted by cleaner production in the remaining production units. But on the other hand; since world market prices of coal and other inputs that are used intensively in the most polluting production processes will decline, the production in non-regulated countries will tend to become more polluting than at the outset. In sum, it is therefore far from obvious whether unilateral climate policies in the steel industry will reduce or increase global emissions of greenhouse gases. Our analysis attempts to shed light on this important issue.

Our approach is based on a numerical partial equilibrium model of the world steel industry. The Steel Industry Model (SIM) encompasses production of steel with three technologies in ten regions, consumption and trade of two steel qualities, and modeling of the markets for iron ore, metallurgical coal, scrap and the transport markets related to the steel industry. The model is designed in order to study medium term effects of implementing carbon taxes or tradable emission permits in the Annex B countries of the Kyoto Protocol. We focus on the effect of such regulations for global emissions through changes in (1) the total amount of steel produced, (2) the allocation of steel production among regions, (3) the market share of different steel producing technologies, (4) the optimal input mix in steel production, and (5) the transport volumes of both inputs to and outputs from the steel industry.

Previous studies of the impact of the Kyoto Protocol on global emissions are mostly simulations with macro-energy models. These are general equilibrium models based on rather aggregated representations of the production and consumption possibilities in the economy. In some models, such as RICE and FUND, all industries are lumped into one activity, and GDP is determined by an aggregate production function. Other models, such as MIT-EPPA, G-Cubed, WorldScan, MS-MRT and GTEM, are multi-sectoral with inter-industry linkages and trade in non-energy goods. But the number of non-energy sectors is typically low, providing little scope for including details at the industrial level. Although several models have iron and steel as a separate sector, little attempt is made to model the potential for substitution across technologies and inputs. Admittedly, the GTEM model distinguishes between two steel producing technologies, but Leontief specification precludes substitution between inputs.[1]

[1] For details about these and other models, see the Special Issue of *The Energy Journal* (1999)

Thus, despite the perceived importance of the steel industry for the amount of leakage in the wake of incomplete climate agreements, little attempt has been made to assess how this sector may respond to climate policies.

There are also some industry level studies of the consequences of carbon regulations, e.g., Manne and Mathiesen (1994) of the world aluminum industry and Miles (1999) of the world coal industry. Such analyses, like ours, allow for considerably greater detail in the description of the relevant industry, while the rest of the economy largely is exogenously stipulated.

In our model, we find that the inclusion of substitution possibilities between different types of steel and between inputs in steel production reduces the predicted rate of leakage in the steel industry from 53% to 26%. This demonstrates that crude and aggregate representations of an industry may conceal mechanisms that are important for the evaluation of the suggested policies.

In public debate it is often claimed that in sectors where leakage problems are prominent, environmental taxes should be reduced relative to other sectors. Theoretical studies have shown that this is not a cost efficient solution. Both from the regulatory country's point of view and from a global point of view it is more efficient to deal with environmental leakage through trade measures rather than through subsidies to domestic firms (Hoel (1996), Mæstad (1998)).

We have simulated the consequences of combining domestic emission taxes with border tax adjustments in the form of import taxes and export subsidies on trade flows between the region that implements climate policies and the region that does not. We find that an "optimal" trade policy could reduce leakage in the steel industry to 10%. Although emissions will increase in the regulated economies, global emissions are reduced by about the same amount as without any border tax adjustments.

The paper is organised as follows. Section 2 summarises some stylised facts about the steel industry. The model is presented in Section 3, and Section 4 reports the results of our simulations. Border tax adjustments are discussed in Section 5. Section 6 concludes.

2. The steel industry

Iron and steel are manufactured from iron ore and scrap in a number of different production processes. A steel making process involves five basic steps (OECD/IEA 2000): (1) treatment of raw materials, (2) iron making, (3) steel making, (4) casting, and (5) rolling and finishing. Iron making (step 2), which is the most energy intensive step, usually takes place in the blast furnace process, with iron ore and coke as the main inputs. Some iron is also produced through a direct reduction process, in which case iron ore and natural gas are the main inputs. The dominating steel production processes (step 3) are the basic oxygen furnace (BOF) and the electric arc furnace (EAF). The open hearth furnace (OHF) has until recently also enjoyed a sizeable market share, but it has now been phased completely out in most countries. Some new processes (e.g., the Corex process) have been introduced in some countries. Due to their small share of the market, these processes will not be discussed explicitly in this study. The shares of various steel making processes vary considerably across regions. Globally, the basic oxygen furnace accounts for nearly 60%, while the electric arc furnace accounts for 34% of total steel production (Table 2.1).

Table 2.1 Steel production by process, 2000

Steel technologies	Share of world production (%)
Basic Oxygen Furnace (BOF)	58
Electric Arc Furnace (EAF)	34
Open Hearth Furnace (OHF)	5
Other technologies	3

Source: IISI (2001)

The BOF process

In the BOF process, pig iron and scrap are converted to steel in an oxygen blown converter. The share of pig iron in the metal input varies between 65 and 90%, with scrap or scrap substitutes accounting for the rest. To substitute scrap for pig iron in the BOF process is one way in which steel producers may adapt to changing climate policies, but the substitution possibilities may be limited by the availability of high quality scrap and by the energy balance of the BOF process.

Steel making in the BOF process typically takes place in a large integrated steel plant that includes all the five process steps outlined above. The main raw materials are iron ore and coal, and the process stages include ore treatment, coke making, and iron making. CO_2 emissions occur at all the process stages, with iron making as the most emission intensive one. Iron making takes place in the blast furnace process, where iron ore is reduced to pig iron with coke as the main reducing agent, and where the resulting iron is melted. Injection of pulverised coal (PCI), oil and natural gas directly into the blast furnace may reduce the coke consumption, but the substitution possibilities are limited because none of these fuels can substitute for coke in providing a strong and permeable support for free flow of gases in the furnace. The blast furnace process involves huge emissions of carbon monoxide (CO). If released into the atmosphere, carbon monoxide eventually forms carbon dioxide. The CO gas produced in the blast furnace is, however, recovered and used as an energy source. Much of the CO_2 emissions from the blast furnace therefore stems from the combustion of CO gas.

The EAF process

In the EAF process, steel is melted via electric arcs between cathode and anode(s). The major raw materials are scrap or scrap substitutes (e.g. directly reduced iron (DRI)), normally accounting for more than 90% of the metal input. Small amounts of pig iron may be used as well. Electricity is the main energy source of the process, and the production of electrical power accounts for a major share of the CO_2 emissions from this steel-making route. The production of electricity causes different levels of CO_2 emissions in various regions due to variations in the production method (coal, gas, hydro, nuclear etc.). These differences are taken into account in the calculation of CO_2 emissions.

In this study, a distinction is made between EAF processes based on scrap and EAF processes based on DRI, because the production of DRI involves significant CO_2 emissions, implying that different EAF processes may entail quite different CO_2 emission profiles. DRI based processes account for 15-20 % of total EAF steel-making. When DRI is used as input, the share of scrap in the metal input is normally between 20 and 50%. The dominating technologies for production of DRI are based on reduction of iron ore by natural gas. Due to the large gas volumes needed, DRI production principally takes place where a cheap supply of gas is available. The use of natural gas in DRI production causes substantially higher CO_2 emissions than in the scrap-based route. This difference is reinforced by the fact that DRI based plants typically are more electricity intensive than scrap based mills.

The steel market

Steel is not a homogenous good. Due to impurities in the scrap, scrap-based routes are not always able to meet the same high quality standards as an ore-based process. Moreover, the capacity of electric arc furnace plants is normally not large enough for them to compete in certain product segments, such as the production of flat products. Hence, it is appropriate to treat BOF steel and EAF steel as differentiated products.

Price data on steel exports from different regions show substantial price variations also within each of these product categories. This may indicate either that the quality of the steel product differs across regions or that there is regional specialisation in different product segments. A natural implication is to treat steel from different regions as imperfect substitutes.

Steel demand is recognised to be relatively irresponsive to changes in steel prices (e.g., Winters, 1995). An increase in steel production costs can therefore to some extent be passed on to steel consumers. However, price increases are constrained by the competition from substitute materials, such as concrete, aluminium, wood, etc. Climate policies will most likely also increase the production costs of some of the major competing materials. Both the production of cement and aluminium, for instance, involves significant CO_2 emissions. Hence, an analysis of only the steel industry, like the present one, runs the risk of overstating the loss of competitiveness for this particular industry.

On the supply side, the steel market is characterised by notorious over-capacity. According to recent estimates, the world steel producing capacity exceeds actual production by some 25% (OECD (2001a, 2002)). Overcapacity is present in most regions, implying that significant shifts in the distribution of steel production across regions are conceivable even within a short to medium time horizon.

Major input markets

The steel industry is a large industry. Therefore, the price of inputs is not necessarily independent of the development in the industry. At least in four important input markets, the prices are affected by the activity level in the steel industry; the markets for iron ore, metallurgical coal and scrap, and the dry bulk transport market. These are all global markets. Iron ore and metallurgical coal are typically traded on long distance routes between continents. Although steel scrap more often is locally supplied, trade volumes are also significant, for instance between Europe and Asian countries.

The steel industry generates substantial amounts of transport work. The main transport routes go by sea. According to estimates in Mæstad *et al.* (2000a), the transport of iron ore, metallurgical coal and steel amounts to almost 4000 billion tonne miles a year. The steel industry thus accounts for about 20% of world seaborne trade and close to 40% of the dry bulk market (see Fearnleys (1996) and Wergeland and Wijnolst (1997)). The activity level in the steel industry therefore has a large potential impact on freight rates.

CO_2 emissions

In an integrated steel mill, on average 2.5 tonne of CO_2 is produced per tonne steel (see Table 2.2). 86% of these emissions stem from the preparation and use of coal. The emission factor varies from around 2.0 in Western Europe and North America to 3.9 in China (see Table 2.3). Most of these differences are explained by variations in coal consumption rates (or energy efficiency). We notice that steel production in some non-Annex B regions is extremely energy demanding.

Table 2.2. Emissions of CO_2 by process from the steel industry, 1995. Million tonnes.

Technologies	Iron and steel production				Rolling and finish.		Total CO_2 emissions	Tonne CO_2 per tonne steel
	Coal	*Power*	*Natural gas*	*Fuel oil*	*Power*	*Fossil fuels*		
Basic Oxygen Furnace	1115	18	12	16	44	87	1292	2.5
Standard EAF	9	59	0	0	17	35	120	0.6
DRI based EAF	2	16	21	0	3	7	50	1.2
Total	1126	94	33	16	64	129	1462	1.9

Source: Mæstad (2000b)

In a standard EAF process, the average emission factor is 0.6 tonne CO_2 per tonne steel, i.e., about one fourth of the emissions in the BOF process and half the emissions in the DRI based EAF process. There are regional differences here as well. The emission factor in a standard EAF process varies from 0.2 in Rest of Western Europe to 0.9 in China. Most of the variation can be explained by varying emission rates in power production. In regions where hydropower is widely used (e.g., Rest of Western Europe and South America) emission rates are typically lower than in regions where coal fired power plants are more common.

Table 2.3. Emissions of CO_2 per tonne crude steel, 1995 (Tonne)

	BOF steel	Standard EAF steel	DRI based EAF steel
EU (excl. Sweden and Finland)	2.1	0.5	1.0
Rest of Western Europe	2.0	0.2	-
Eastern Europe and FSU	2.4	0.8	1.6
North America	2.0	0.6	1.0
South America	2.5	0.3	1.1
Japan	2.5	0.4	-
China	3.9	0.9	-
Rest of Asia	2.4	0.7	1.3
Australia and NZ	2.5	0.7	-
Rest of world	2.8	0.6	1.5

Source: Mæstad (2000b)

The emissions related to the transport of steel and inputs to the steel industry are estimated to 0.14 tonne CO_2 per tonne steel. The transportation related to the steel industry thus emits far less than the production of steel itself.[2]

3. The steel industry model (SIM)

The consequences of climate policies for the steel industry and its emissions of CO_2 are analysed in a partial equilibrium model that captures essential aspects of the steel industry and the related input and transport markets. A technical description of the model is given in the Appendices.

The model structure

A schematic view of the model is presented in Figure 3.1. The key aspects of the model are:

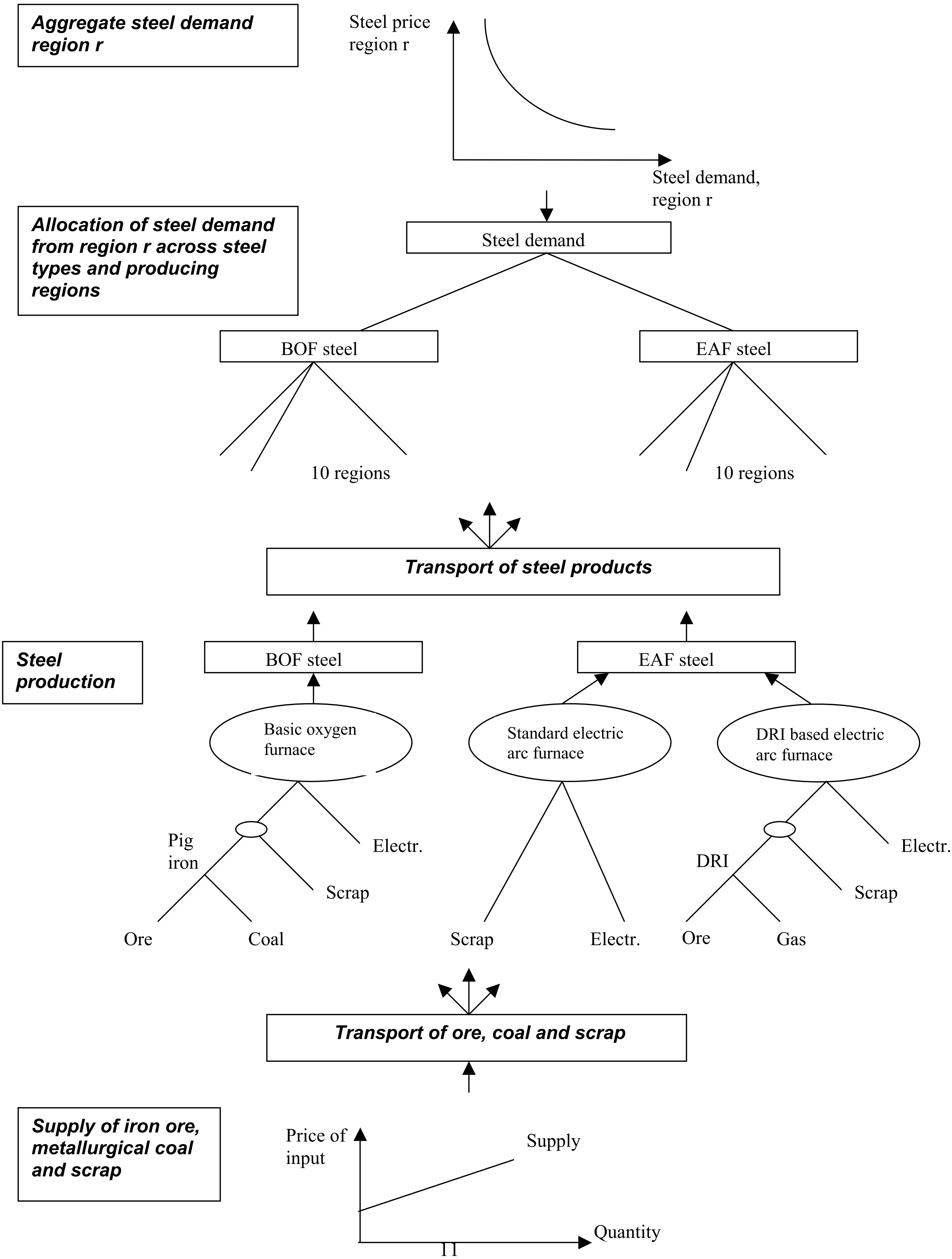
- The model has 10 regions: EU (excl. Sweden and Finland), Rest of Western Europe, Eastern Europe and Former Soviet Union, North America, South America, Japan, China, Rest of Asia, Australia (including New Zealand), and Rest of world.
- Total steel demand in each region is represented by an aggregate, constant elasticity steel demand function. Two types of steel are consumed in each region; oxygen blown steel (BOF steel) and electric arc steel (EAF steel). These are treated as imperfect substitutes, because both the steel quality and the product mix differ between integrated steel mills and mini-mills.

[2] The average energy consumption for bulk transport in open sea is 0.2 MJ/tonne km (Ecofys, 2000). Using the IPCC guidelines for emissions per energy unit of oil, this implies an emission factor of 0.0269 million ton CO_2 per billion tonne-miles. With the transport volumes reported above, emissions from seaborne trade of iron ore, coal and steel products amount to 100-110 million tons CO_2 a year, or 0.14 ton CO_2 per ton steel.

- Steel from different regions is treated as imperfect substitutes (Armington, 1969)[3]. The import price of steel is the sum of producer prices in the exporting region, export taxes, transport costs and import duties.
- In each region, steel may be produced by three technologies: (1) Basic Oxygen Furnace (based on a mix of pig iron and scrap), (2) Standard Electric Arc Furnace (based on scrap), (3) DRI based Electric Arc Furnace (based on a region-specific mix of directly reduced iron and scrap). The outputs from the two EAF processes are treated as perfect substitutes.

[3] The assumption of imperfect substitution between steel from different regions is needed for technical reasons in order to reproduce the bilateral trade flows in the base year.

Figure 3.1.1. The Steel Industry Model (SIM)



- The production of oxygen blown steel is modelled in several stages. At the first stage, coal (or coke) and iron are combined in order to produce pig iron. At the next stage pig iron and scrap are combined in order to produce steel. Electricity is used in proportion to the amount of steel produced. DRI based steel making has a similar conceptual structure as the blast furnace-BOF process, except that natural gas is used rather than coal in the iron making process. The standard electric arc furnace has a simpler structure, with only scrap and electricity as the major inputs. The model also accounts for some additional fossil fuels beyond those mentioned in Figure 3.1, such as some coal powder in the EAF process and some heavy fuel oil and natural gas in the blast furnace. These inputs are used in fixed proportions.
- The model allows for substitution between pig iron and scrap in the basic oxygen furnace. In the other processes and process stages, inputs are used in fixed proportions (Leontief technology)[4]. The actual input mix per tonne steel may, however, differ between regions. Some differences may be explained by relative input prices that differ between regions. Other differences may result from managerial competence, experience and different vintages of capital. Such differences are taken as given.
- Due to differences in input mix and input prices, production costs vary across regions. Production costs also vary within each region due to variations in productivity across plants. The profile of production costs for a given technology within a region is described by an industry cost curve, $c_{ti}(\mathbf{w}_i;Q_{ti})$, where Q_{ti} is the output of technology t in region i and $\mathbf{w}_i$ is a vector of factor prices in region i. The industry cost curve is treated as additively separable in output and factor prices, i.e., $c_{ti}(\mathbf{w}_i;Q_{ti}) = g_{ti}(\mathbf{w}_i) + h_{ti}(Q_{ti})$, where $g(\cdot)$ is homogenous of degree one and $h(\cdot)$ is increasing and convex ($h' > 0, h'' > 0$). This formulation implies that a shift in factor prices will have an equal effect on all firms with a given technology in a given region. All observed differences in production costs are thus, somewhat arbitrarily, ascribed to factors that are not explicitly modelled, such as labour, maintenance, administration etc.
- There are global markets for iron ore, coal and scrap. The world prices of these goods are determined by world supply and demand. Local input prices may however vary due to differences in input qualities and transport costs.

- There are local markets for natural gas and electricity in each region. The prices of these factors are assumed to be exogenous to the steel industry. These input prices typically differ across regions, and they may change as a result of climate policies.
- Steel producers take steel prices as given. Steel prices are calibrated under the assumption that the marginal cost pricing rule applies.
- The model is a short to medium term equilibrium model. All changes in production volumes are assumed to take place within the limits of existing capacities.
- The regional pattern of steel consumption and production determines the steel transport demand. The transport demand of iron ore and coal is determined by steel production volumes, the input mix in steel production, and the regional location of steel production. The share of each exporting region in the trade of ore and coal to a given importing region is assumed to be fixed. A freight rate index, and thus the costs of transportation, is determined by the equalisation of aggregate transport demand with the supply of dry bulk transport services.

Key model parameters

The consequences of climate policy for steel production depend on several model parameters that are difficult to determine. Parameters of an equilibrium model can roughly be categorised into two classes; levels and price sensitivities. While the levels of variables are observable from yearly statistics, their price sensitivities are notoriously more difficult to get at. We have obtained empirical estimates of some of the most crucial parameters of the model. Other price sensitivity parameters are based partly on the literature and partly on advice from industry experts. The industry experts were given the opportunity to reconsider their initial beliefs based on the results of the model simulations.

In the SIM model, price sensitivity parameters appear at six levels: 1) the price sensitivity of steel demand, 2) the degree of substitutability between oxygen blown and electric arc steel, 3) the degree of substitutability between steel from different regions, 4) the degree of substitutability between inputs in the production processes, 5) the price sensitivity of steel supply, and 6) the price responsiveness of the supply of the major inputs (iron ore, coal, scrap and transport services). A few comments on each of these are needed in order to get a better understanding of the simulation results.

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[4] The model does not incorporate the substitution between scrap and DRI in DRI based steel making although a high degree of substitution is achievable in this process. This weakness is partly adjusted for by treating scrap based and DRI based steel as perfect substitutes.

1) Steel demand is normally considered to be relatively irresponsive to changes in steel prices. Winters (1995) uses a demand elasticity of –0.3 for Europe. As we do not have estimates of the demand elasticity in other regions, a uniform steel demand elasticity of –0.3 has been imposed across all regions.

2) Over time EAF steel producers have been able to substantially increase their market share at the expense of the integrated steelworks. Still, the range of products where actual competition between electric arc and oxygen blown steel products takes place at present is quite narrow. This implies a rather low degree of substitutability between the two steel types, at least in the short run. Based on an assessment by industry experts, the elasticity of substitution between steel types has been stipulated to 0.5.

3) The degree of substitutability between steel from different regions is, however, quite high. The elasticity of substitution between steel from different regions (i.e., the Armington elasticity) in the SIM model has been set to 8. This figure is somewhat higher than the Armington elasticity of 5.6 employed for the sector “ferrous metals” in the GTAP model (Hertel, 1997). We have chosen a higher elasticity in order to reflect the fact that the sector “ferrous metals”, which includes iron ore, scrap, as well as steel, is a more heterogeneous product category than the steel products that are traded in our model.

4) The SIM model recognises the substitution possibilities between scrap and pig iron in the BOF process. The technological possibilities to substitute between scrap and pig iron are reasonably good. However, the energy balance of the process does not allow the share of scrap to increase much beyond 30%. Based on a sample of 25 integrated steel mills, Mæstad (2002) estimated the elasticity of substitution between pig iron and scrap to 1.7. This estimate probably overstates the real substitution possibilities, because the estimation procedure does not take into account that technological differences between converters may imply smaller substitution possibilities for a given converter than across different converter types.

The SIM model uses substitution elasticities between pig iron and scrap of 1.5 in all regions, except in North America, China, Rest of Asia and Rest of World, where the elasticity of substitution is set to 0.5. In all simulations, the scrap rate tends to increase in North America and tends to fall in the three other regions. However, the scrap rate in North America is so high at the outset that the energy balance of the process will constrain a further increase. In the three other regions, the scrap rate is so low at the outset that only very small reductions are likely, because a certain amount of scrap is needed in order to control the temperature of the process.

5) Due to a more flexible cost structure, EAF steel producers tend to respond more easily to changes in steel prices than do BOF steel producers. This is reflected in the model by attaching a higher price sensitivity of steel supply to EAF producers. The price sensitivity of steel supply was determined based on assessments by industry experts. They were confronted with various price paths and were then asked to assess how the output from the industry would respond within one to two years' time. Due to large overcapacity in the steel industry, increasing steel prices may have a significant impact on output, even within such a short time horizon. The supply elasticity, i.e., the percentage increase in output following a 1% increase in steel producer prices, was set to 0.7 for basic oxygen furnaces and 1.2 for electric arc furnaces.

6) Finally, consider the price responsiveness of supply of the major inputs to steel production. The supply of scrap is quite insensitive to price changes. The total amount of scrap is more or less given, and strong price incentives are needed in order to increase the collection rates. The low supply elasticity of scrap leads to substantial volatility of scrap prices over time as scrap demand fluctuates. Based on advice from industry experts, the SIM model uses a scrap supply elasticity of 0.5. The supply elasticity of coal, on the contrary, is quite high. Low cost coal reserves are huge, and higher coal prices therefore easily stimulate coal supply. Following Golombek *et al.* (1995), the SIM model uses a coal supply elasticity of 2.0. Less is known about the supply elasticity of iron ore, but industry experts consider the price responsiveness of ore supply to be greater than for scrap supply and smaller than for coal supply. The SIM model uses an iron ore supply elasticity of 1.0. The supply elasticity of dry bulk shipping of 0.27 was taken from the shipping model NORBULK (see Wijnolst and Wergeland, 1997).

The parameter values in our base scenario are summarised in Table 3.2.

Table 3.2.1. Parameter values in the SIM model.

Parameter	Value
Price elasticity of steel demand	-0.3
Elasticity of substitution between BOF and EAF steel	0.5
Elasticity of substitution between steel from different regions (Armington elasticity)	8.0
Elasticity of substitution between pig iron and scrap in BOF steel production	1.5/0.5
Supply elasticity of steel production	BOF steel: 0.7 EAF steel: 1.2
Supply elasticity of major inputs	Scrap: 0.5 Coal: 2.0 Iron ore: 1.0 Transport: 0.27

4. Simulation results

Our goal is to shed some light on potential reductions in emissions of greenhouse gases from the steel industry as a result of a climate policy that is implemented in the industrialised countries only, resembling the structure of the Kyoto agreement. Climate policies are implemented in the model by a uniform tax on CO_2 emissions across all industrialised regions. The tax can alternatively be interpreted as the price of an internationally traded emission certificate. The tax rate is set to \$25 per tonne CO_2. This is in line with estimates of the price of emission permits under the Kyoto Protocol before the US withdrawal from the agreement and under assumptions about perfect competition in the permit markets (e.g., Weyant *et al.*, 1999). The US withdrawal has lead to a reduction in the estimated permit price, but the potential market power of Russia in the permit market pulls in the opposite direction. Perhaps even more importantly, the opportunity of "banking", i.e., to save unused permits for later periods might significantly increase the permit price also in the first period (e.g., Manne and Richels, 2001). Anyway, our purpose is not to predict the exact consequences of the Kyoto Protocol for the steel industry, but rather to reveal the underlying mechanisms when climate policies are implemented in the steel industry in the industrialised world.

In order to appreciate the simulation results, we will first describe and interpret the consequences of climate policies for the pattern of world steel production.

4.1. Steel production

Table 4.1 summarises the consequences for global steel production of a \$25 tax on CO_2 emissions in Europe and Former Soviet Union, North America, Japan and Australia, which is almost identical to the list of countries in the Annex B in the Kyoto Protocol. The first order effect of the tax is to increase variable production costs by 20-30% in BOF steel production, by 2-7% in standard EAF steel-making, and by 9-10% in DRI based processes. In equilibrium, world steel production will be reduced by 24 million tonnes (-3.2 %). The change in the total production of EAF steel is small, while changes in the production of BOF steel are large; production of BOF steel declines by 32 million tonnes in the Annex B countries (-9.3%). Part of this reduction is compensated by an increase in BOF steel production of 11 million tonnes (+6.7%) in non-Annex B countries. They enjoy improved competitiveness as production costs increase in the Annex B region, while at the same time factor costs are reduced because overall BOF production is down, whereby the prices of coal and iron ore decline (by 5% and 8% respectively).

The \$25 tax on CO_2 emissions induces only a modest shift away from BOF steel towards EAF steel in the Annex B countries. The low elasticity of substitution between steel types is not the only explanation for this result. Another important reason is that CO_2 taxes make it attractive to increase the share of scrap in the BOF process, leading to higher scrap prices (+10% in our simulations). Higher scrap prices imply that the gain in competitiveness for EAF steel relative to BOF steel is much smaller than what we would expect based on a comparison of emissions factors alone. If there were no factor substitution in the BOF process, EAF production would increase both in the Annex B and in the non-Annex B countries.

Table 4.1. Percentage changes in steel production

	BOF	Standard EAF	DRI based EAF	Total
Annex B	-9.3	-2.1	-6.5	-7.1
Non Annex B	6.7	1.1	5.2	5.3
Total	-4.3	-1.3	1.1	-3.2

The relative reduction in BOF steel production across Annex B regions is determined by a number of factors, such as relative emissions per tonne steel, relative production costs at the outset, and the shape of the industry cost curve. Relatively high emissions of carbon dioxide per tonne steel in Australia, Japan and Eastern Europe contribute to large reductions of production there. But the relative fall in production is smaller in Japan than in Eastern Europe because Japan has much higher production costs at the outset. The climate policy therefore induces a smaller percentage increase in the marginal costs of production in Japan. While BOF production in most Annex B regions is reduced by 8-12%, the production in EU13 falls less (-3%). This happens even though emissions are higher in Europe than for instance in North America, where BOF steel production is reduced by 8%. The shape of the industry cost curves can explain this pattern[5]; European producers seem to be in a better position to withstand a cost increase than their North American competitors.

Sensitivity analysis

We have investigated the robustness of our results with respect to changes in the elasticity parameters of the model. The results for four of the elasticity parameters are reported in Table 4.2. The simulations show that the production of BOF steel is reduced in all cases. This is the most emission intensive technology. Whether EAF steel production increases or decreases depends on the parameters. EAF steel production tends to increase when the elasticity of substitution between BOF and EAF steel is high. But even with a high substitution elasticity, the increase in EAF steel production is not very large, because the increase in scrap prices makes the gain in competitiveness for EAF steel smaller than we would expect on the basis of relative emission intensities. With a low degree of substitution towards scrap in BOF steel-making, the increase in scrap prices will be much smaller, and the increase in EAF steel production will then be larger.

EAF steel production also tends to increase as the price elasticity of steel demand falls. The reason is that the substitution effect away from BOF steel and towards EAF steel then dominates the negative output effect. As expected, the decline in steel production will be larger when steel demand becomes more price elastic than in the base scenario. This pattern is observed for all three production technologies.

[5] Although the supply elasticity is the same in all regions, both marginal and average costs may differ. Hence, the shapes of the industry cost curves differ across regions.

Table 4.2. Sensitivity analysis. Change in steel production (%).[*]

Price elasticity of steel demand					
	0	*-0.15*	***-0.3***	*-0.45*	*-0.6*
BOF	-1.0	-2.9	**-4.3**	-5.4	-6.3
Standard EAF	1.6	-0.1	**-1.3**	-2.2	-2.9
DRI based EAF	4.6	2.6	**1.1**	-0.1	-1.2
Elasticity of substitution between BOF and EAF steel					
	0	*0.25*	***0.5***	*1*	*2*
BOF	-3.0	-3.7	**-4.3**	-5.1	-6.0
Standard EAF	-3.5	-2.2	**-1.3**	0.0	1.5
DRI based EAF	-1.3	0.1	**1.1**	2.5	4.0
Elasticity of substitution between regions (Armington)					
	0	*4*	***8***	*16*	*32*
Annex B	-3.4	-6.4	**-7.1**	-7.8	-8.4
Non Annex B	-1.0	4.4	**5.3**	5.9	6.3
Elasticity of substitution between pig iron and scrap					
	0	*0.75*	***1.5***	*2*	*2.5*
BOF	-4.6	-4.4	**-4.3**	-4.2	-4.1
Standard EAF	1.1	-0.3	**-1.3**	-1.8	-2.2
DRI based EAF	-1.0	0.2	**1.1**	1.6	2.0

[*]Bold figures represent the base scenario.
[**]The elasticity in regions where the initial figure differs from 1.5 has been adjusted proportionally.

We would expect that if steel from different regions becomes more homogenous (i.e., a higher Armington elasticity), a CO_2 tax in the Annex B regions would cause more extensive relocation of production towards Non-Annex B countries. The analysis confirms this pattern, but the changes are quite modest. Setting Armington elasticity to zero shows that the possibility to substitute steel from various regions explains much of the fall in Annex B production levels.

An increase in the elasticity of substitution between pig iron and scrap in BOF steelmaking does not have a large impact on the volume of BOF steel. However, it leads to a structural shift in EAF steel production away from standard EAF production towards DRI based production. Part of the reason is that better opportunities to substitute towards scrap in BOF steel making drive the scrap price further up. This hurts standard EAF steel producers more than the DRI based ones, since the share of scrap is much smaller in DRI based processes.

4.2 CO_2 emissions

Our simulations suggest that emissions of carbon dioxide from the steel industry will decline more than twice as much as global steel production (-7.8% compared to –3.2% in the base scenario). This happens despite the fact that steel production increases in regions that are relatively energy inefficient. The main reason is less input of coal in BOF steel production in the Annex B countries. In addition, the market share of low polluting standard EAF steel increases by 1.5% in the Annex countries and by 0.5% globally.

At the outset, average emissions of CO_2 per tonne BOF steel are 2.26 tonnes in the Annex B regions and 3.16 tonnes in the non-Annex B countries. A reallocation of production from Annex B countries to non-Annex B countries might therefore lead to an increase in global emissions. This effect is however more than outweighed by the reduction in the share of pig iron (and coal) in the BOF process in Annex B countries, leading to a reduction in the average emission factor of BOF steel from 2.26 to 2.02 in the Annex B. Admittedly, production of BOF steel becomes even dirtier than before in the non-Annex B countries, due to lower world market prices of coal and ore and higher prices of scrap. But the increase in the average emission factor is small; from 3.16 to 3.18. The reason is partly that coal supply is relatively elastic, so that the decline in the world market price of coal is quite small. In addition, the share of scrap is low at the outset in many non-Annex B countries due to limited availability of local scrap. A further reduction in the scrap rate will often not be a viable option because a certain amount of scrap is needed in order to control the temperature of the process.

Table 4.3. Change in emissions of carbon dioxide (%).

	BOF	Standard EAF	DRI based EAF	Total
Annex B	-18.9	-2.4	-6.9	-17.2
Non Annex B	7.4	0.9	5.2	6.8
Total	-8.7	-1.3	1.5	-7.8

The emission reduction of 153 million tonnes CO_2 in Annex B countries (-17.2%) is partially outweighed by a 39 million tonne (6.8%) increase in emissions in countries that do not implement climate policies. The leakage rate is thus 25%. It is interesting that the model would predict a much higher leakage rate (53%) if there were no substitution between pig iron and scrap and no substitution between BOF and EAF steel in the model. This demonstrates the importance of a richer description of the structure of industries than what is the case in most CGE energy-economy models. Due to substitution away from the taxed commodity (coal) the cost burden on Annex B producers is reduced and less production is therefore relocated to non-Annex B countries. In addition, factor substitution in itself contributes to higher emission reductions in the Annex B at the same time as the factor market effects induce only a small increase in the emission factor of non-Annex B countries.

Note that the calculated leakage rate assumes that the energy efficiency of the incremental production in non-Annex B countries is equal to the regional average. If the best available technology were used to expand production, the increase in emissions in non-Annex B countries would be considerably lower. For instance, if incremental production in non-Annex B countries has the same emission factor as an average Annex B plant, the increase in emissions in non-Annex B countries would be no higher than 2/3 of our estimate.

A comparison of Tables 4.1 and 4.3 reveals that it is not only BOF production that becomes cleaner in the Annex B regions. Emission reductions are larger than output reductions also for the two EAF processes. Since there are no factor substitution possibilities in the EAF technologies, the explanation is a change in the market shares of different Annex B regions; countries with relatively low emissions per tonnes steel expand their share at the expense of the more polluting ones. Obviously, effects of this kind are also part of the explanation for the decrease in the average emission factor in Annex B BOF steel production.

One might worry that CO_2 taxes in the Annex B region would increase CO_2 emissions from the transport of steel, because Annex B countries will have to import a larger share of their consumption. Our simulation confirms this effect but also shows that the increase in steel transport by far will be outweighed by reductions in the transport of iron ore and coal. According to our estimates, steel transport will not increase by more than 4 billion tonne miles (0.5%), while the transports of metallurgical coal and iron ore are reduced by 92 and 209 billion tonne miles, respectively, representing a decline of almost 10%. In sum, therefore, the transport work related to the steel industry will decrease, leading to a fall in CO_2 emission by another 8 million tonnes (-8%). The total emission reduction in our base case is thus 122 million tonnes CO_2. In order to put this figure in perspective, this is equivalent to 1/3 of total CO_2 emissions in France in 1999 (OECD, 2001b).

Sensitivity analysis

There is considerably uncertainty attached to several of the parameter values in the model. Sensitivity analysis is therefore appropriate. Table 4.4 reports the results from our sensitivity experiments.

The overall picture is that the estimated changes in emissions are remarkably stable with respect to changes in the underlying parameters. Not surprisingly, however, the elasticity of substitution between pig iron and scrap is quite important for the emission level in the Annex B countries; better substitution possibilities induce larger emission reductions. Global emissions are also reduced more, as the increase in emissions in Non-Annex B countries is relatively small. The reason is that the supply of polluting inputs (coal) on the world market is relatively elastic, implying relatively small factor price changes in Non-Annex B countries.

The price elasticity of steel demand also plays an important role for the total reduction in emissions. While for the three other parameters it is typically the case that larger emission reductions in the Annex B are counteracted by a larger increase in emissions in Non-Annex B (and vice versa), this is not the case when it comes to the price elasticity of demand. As the price elasticity increases, emissions will be reduced in all regions, simply because a given rise in prices induces a larger overall reduction in steel demand.

Table 4.4. Sensitivity analysis. Change in emissions (%). Leakage rates (%).[*]

Price elasticity of steel demand					
	0	*-0.15*	***-0.3***	*-0.45*	*-0.6*
Annex B	-12.7	-15.3	**-17.2**	-18.8	-20.0
Non Annex B	8.0	7.3	**6.8**	6.5	6.2
Leakage rate	41	31	**26**	22	20
Elasticity of substitution between BOF and EAF steel					
	0	*0.25*	***0.5***	*1*	*2*
Annex B	-16.4	-16.9	**-17.2**	-17.8	-18.5
Non Annex B	6.7	6.8	**6.8**	6.9	7.0
Leakage rate	27	26	**26**	25	25
Elasticity of substitution between regions (Armington)					
	0	*4*	***8***	*16*	*32*
Annex B	-12.6	-16.3	**-17.2**	-18.1	-18.9
Non Annex B	0.0	5.9	**6.8**	7.4	7.7
Leakage rate	0	24	**26**	27	27
Elasticity of substitution between pig iron and scrap					
	0	*0.75*	***1.5***	*2*	*2.5*
Annex B	-9.0	-13.5	**-17.2**	-19.3	-21.2
Non Annex B	5.8	6.2	**6.8**	7.3	7.9
Leakage rate	42	30	**26**	25	24

[*]Bold figures represent the base scenario.
[**]The elasticity in regions where the initial figure differs from 1.5 has been adjusted proportionally.

It may be somewhat surprising that changes in the elasticity of substitution between EAF and BOF steel do not affect emissions more than they actually do. The main explanation is that the increase in the scrap price is so large that the relative competitiveness of the two production technologies does not change as much as we would expect based on relative emission intensities alone.

It is not surprising that an increase in the Armington elasticity leads to larger emission reductions in the Annex B countries and a larger emission increase elsewhere. Increased substitutability between steel from different regions implies that the cost increase in the

Annex B countries will affect their competitiveness more negatively, thus inducing more relocation of production towards the Non-Annex countries. What is more surprising is that a larger Armington elasticity causes a greater reduction in global emissions, despite the fact that Non-Annex B countries have a relatively high average pollution intensity. The main explanation is that an increase in the Armington elasticity causes a reduction in world production of BOF steel. This reduction is large enough to more than outweigh increased emission from the relocation of production from Annex B to Non-Annex B countries.

In all experiments but one, the reduction in global emissions is at least twice as large as the reduction in world steel production. The only exception is the unrealistic border case when the elasticity of substitution between pig iron and scrap is set to zero; then the emission reduction is only 10% larger than the fall in global steel production.

5. Border tax adjustments

In the environmental economics literature, the question of how to deal with leakage problems has been addressed in articles by Markusen (1975), Hoel (1996) and Mæstad (1998), among others. The general policy recommendation in this literature is that a country or a region that is trying to deal with a transboundary environmental problem by unilateral measures should implement a domestic emission tax at the Pigouvian level and use trade taxes or subsidies in order to reduce the leakage problem. When leakage is caused by the fact that domestic goods become more expensive relative to foreign goods, trade measures are the most direct way of dealing with the problem.

Whether or not the use of border tax adjustment in combination with environmental policies is legitimate according to WTO rules, is a controversial question. At the Rio+10 summit in Johannesburg, a formulation implying that WTO rules would take precedence of environmental policies was turned down, and the principle that WTO rules and international environmental agreements should be placed on the same footing was established. In consequence, future climate agreements may include provisions about border tax adjustments, despite potential conflicts with the WTO framework. Whether and how such policies will be implemented is of course highly uncertain, but since the issue attracts considerable political attention, we have chosen to run some illustrative simulations.

What should determine the size of any border taxes and subsidies, and should the taxes be differentiated across regions? The theoretical literature can help answering these questions. First, there should be free trade among the Annex B countries, because leakage is not a problem when all countries implement the same environmental policy. Secondly, as long as the purpose of the trade measures is to reduce the leakage problem, tax rates and subsidies should be scaled in accordance with the level of pollution in the Non-Annex B countries, because this is what determines the severity of the leakage problem. It follows that all Annex B countries should use the same tax rates. In principle, it will be desirable to differentiate tax rates between different technologies and different trading regions, because it is not arbitrary from a leakage point of view where production increases take place. However, problems with implementation might put limitations on the degree of such differentiation.

The reasoning above might lead us to the conclusion that the Annex B countries should implement a common import tax and export subsidy schedule, where the tax rates are determined by the emission level per unit of production for a given technology in a given region. However, the theoretical literature has shown that the efficient level of border tax rates is lower than this[6]. The reason is that border taxes are at best a second best instrument for achieving emission reductions in a foreign country. Following Mæstad (1998), the efficient level of import taxes and export subsidies, *T*, takes the following form

$$T = E\frac{S'(p)}{S'(p) - D'(p)} \leq E\,,$$

where E is the marginal environmental costs per unit of output, and S' and D' denote the slopes of demand and supply functions in the relevant Non-Annex B country. The intuition why $T \leq E$ is that an import tax or export subsidy, by lowering the world market price of steel so that steel production decreases in Non-Annex B countries, at the same time will stimulate steel demand in these countries. Trade provisions are thus imperfect policy instruments for achieving emission reductions in a foreign country.

We have run two illustrative border tax experiments. In the first one, an “optimal” border tax schedule is implemented, where the import tax and export subsidy in the Annex B are differentiated both across different Non-Annex B regions and between steel types (EAF and BOF steel). Moreover, the levels of the taxes and subsidies are adjusted in accordance with the second best considerations discussed above. In the second experiment, there is no differentiation across Non-Annex B regions and no second best adjustment. Hence, the border tax is equal to the average emissions per unit of output in the Non-Annex B countries, multiplied by the tax rate of $25 (which is taken to be the marginal costs of emissions). This implies import taxes and export subsidies of $80 and $23 per tonne of BOF and EAF steel, respectively.

Table 5.1. The effect of border taxes. Changes in %.

	No border tax	"Optimal" border tax	Simple border tax
Production			
Annex B	-7.1	-4.4	-1.7
Non-Annex B	5.3	1.0	-3.8
World	-3.2	-2.6	-2.4
Emissions			
Annex B	-17.2	-14.0	-10.6
Non-Annex B	6.8	2.2	-3.3
World	-7.8	-7.6	-7.7

As shown in Table 5.1, border tax adjustments will significantly reduce the leakage problem. In the latter experiment, emissions are even reduced in the Non-Annex B countries. Border taxes result in a smaller reduction in production levels in the Annex B countries, at the same time as Non-Annex B production does not reach the same levels as before. Nevertheless, the reduction in global emissions is almost at the same level as without border taxes. In other words, border taxes make it possible to achieve the same reduction in global emissions at significantly lower costs for the Annex B countries. The use of border taxes might therefore induce these countries to implement more ambitious environmental targets than they would otherwise do.

6. Conclusions

This analysis is based on a partial equilibrium model of the global steel industry. The model predicts that a carbon tax on emissions from steel production in the industrialized countries will reduce emissions by more than twice the percentage of reductions of steel production. More specifically, in the central scenario global production is reduced by 3.2% while emissions are reduced by 7.8%. This robustness of this pattern is confirmed by the sensitivity analysis.

As always, the value of this kind of simulation experiment lies more with the insights than the exact figures. The analysis indicates that the modelling of factor substitution possibilities in

[6] If the incentives for raising tariffs in order to generate positive terms of trade effects are taken into account, it might de desirable for the home country to raise tariffs above this level (Markusen (1975), Hoel (1996)). Such pure protectionism is ignored here.

Basic Oxygen steel making has important implications for the issues that we are concerned with. First, the substitution of scrap for pig iron contributes to a larger reduction in emissions, both in the industrialized countries and globally. Second, the substitution towards scrap drives up the scrap price, inducing less substitution towards low-polluting and scrap-intensive production technologies than one would expect based on relative emission intensities alone. The analysis finds that the inclusion of substitution possibilities between different types of steel and between inputs in steel production reduces the predicted rate of emission leakage in the steel industry significantly (from 53% to 26%).

The global reallocation of steel production in our results implies increased transport of steel products, which by far, however is outweighed by reduced transport of inputs to steel production. Thus, total emissions from transport related to the steel industry are clearly reduced.

Finally, we have simulated the impact of implementing border taxes as suggested by the theoretical literature. We find that such taxes on steel products in combination with carbon taxes on emissions from the steel industry are potentially powerful policy instruments that may bring about almost the same global emission reductions as without border taxes, but with considerably less restructuring of the steel industry in the industrialized countries.

Appendix 1. The calibrated share form of the CES function.

We use the CES (constant elasticity of substitution) function in order to model imperfect substitution possibilities between inputs and between steel products. Such substitution appears at three levels in the model; i) the combination of pig iron and scrap into steel, ii) the aggregation in each importing region of steel of type s from different exporting regions (the Armington aggregation), and iii) the aggregation in each region of the two steel types s into the top level steel composite.

Following Rutherford[7], we use the calibrated share form of the CES-function. Let y and x_i denote the level of output and inputs, respectively ($i = 1,..,n$). "Output" and "inputs" must here be interpreted widely to include not only traditional production activities, but also the "production" of a higher level aggregate from lower level product categories, for instance the "production" of the top level steel aggregate from the underlying Armington aggregates of steel type s.

Let p_i denote the price of input i and let σ be elasticity of substitution. Moreover, let boldface letters represent benchmark (observed) values of the variables in order to distinguish these parameters from the variables of the model. The calibrated share form of the CES production function can then be written

$$y = \boldsymbol{y}\,[\,\textstyle\sum_i \theta_i\,(x_i / \boldsymbol{x}_i)^{\rho}\,]^{1/\rho},$$

where θ_i is the benchmark value of input i, $\theta_i \equiv \boldsymbol{p}_i\,\boldsymbol{x}_i / \sum_i \boldsymbol{p}_i\,\boldsymbol{x}_i$ and $\rho = (\sigma\text{-}1)/\sigma$. The corresponding unit cost function is

(A1.1) $$C(p_1,\ldots,p_n) = \boldsymbol{C}\,[\,\textstyle\sum_i \theta_i\,(p_i / \boldsymbol{p}_i)^{1-\sigma}\,]^{1/(1-\sigma)},$$

where $\boldsymbol{C} \equiv \sum_i \boldsymbol{p}_i\,\boldsymbol{x}_i\,/\,\boldsymbol{y}$. Factor demand functions may be obtained from (1) by Shepard's lemma:

(A1.2) $$x_i(p_1,..,p_n,y) = \mathrm{y}\,\partial C/\partial p_i = (y/\boldsymbol{y})\,\boldsymbol{x}_i\,[\,\textstyle\sum_i \theta_i\,(p_i/\boldsymbol{p}_i)^{1-\sigma}\,]^{\sigma/(1-\sigma)}(\boldsymbol{p}_i/p_i)^{\sigma}, \qquad i = 1,..,n.$$

This formulation is employed both in order to describe the demand for pig iron and scrap and the demand for steel type s from a particular region.

The demand for steel type s in each region is derived from the top-level steel demand function, which is postulated as a constant elasticity demand function. Interpret now C as the price index of final demand. The top level demand function then takes the following form; $y = \beta C^{\varepsilon}$, where ε is the price elasticity. The constant β is calibrated as $\beta = \boldsymbol{y}/\boldsymbol{C}^{\varepsilon}$, whereby final demand can be written

(A1.3) $$y = \boldsymbol{y}(C/\boldsymbol{C})^{\varepsilon}.$$

By substituting (3) into (2) while utilizing (1), the demand for steel type s takes the form

(A1.4) $$d_s(p_1,..,p_S) = \boldsymbol{x}_s\,(C(p_1,..,p_S)/\boldsymbol{C})^{\sigma+\varepsilon}\,(\boldsymbol{p}_s/p_s)^{\sigma}, \qquad s = 1,..,S.$$

[7] http://www.gams.com/solvers/solvers.htm#MPSGE. CES-functions: Some hints and useful formulae.

Appendix 2. The Steel Industry Model (SIM) details

The model is formulated as a complementarity problem and solved by GAMS.[8] Equations (A1.2) and (A1.4) are central parts in the following formulation. There are five sets in SIM:

- f denotes factor inputs, $f = 1,..,5$
- t denotes steel producing technology, $t = 1,2,3$
- s denotes steel type, $s = 1,2$
- i denotes steel producing region, $i = 1,..,10$
- j denotes steel consuming region, $j = 1,..,10$.

Three factors (coal, iron ore and scrap) are traded in world markets at the world market price v_f. These factors are transported to the consuming regions. These shipments together with steel shipments and the supply of shipping capacity determine the freight rate, r. Next, region specific carbon taxes and local costs[9] are added to the *cif* factor price in order to arrive at regional specific factor prices, w_{fi}. These factor prices are arguments of cost functions that describe how a given level of factor inputs, a_{fti}, can be combined into steel within a specific technology t at unit costs c_{ti}, yielding an output level of Q_{ti}. Within each region, steel is produced in a cost minimizing way such that the cost of steel of type s, $\hat{c}_{si}$, is the lowest cost over the available technologies. This is the supply price of steel type s out of region i. Next, transportation costs, tariffs, etc. are added to obtain the price in region j of steel of type s originating in region i, p_{sij}. Shipments of steel type s from region i to region j, x_{sij}, are aggregated, first by region of origin into aggregates Y_{sj} with corresponding prices P_{sj}, and finally by steel type into aggregate steel consumption of region j, Y_j, with price P_j.

Let d_{fi} be the average distance of transportation of factor f used in region i.[10] The user-cost of factor f, is then

$$w_{fi} = v_f + d_{fi}\, r + \tau_{fi},$$

i.e., the sum of the world market price (v_f), the transportation cost (distance times freight rate) and a local cost component (τ_{fi}) that might include a carbon tax.

The unit cost function of steel technology t in region i is

$$\text{(A2.1)} \qquad c_{ti}(w_{1i},..,w_{5i}, Q_{ti}) = h(Q_{ti}) + \alpha_{ti}\,[\textstyle\sum_f \kappa_{fti}\,(w_{fi} / \mathbf{w}_{fi})^{1-\gamma}]^{1/(1-\gamma)},$$

where γ denotes the elasticity of substitution between factors of production and κ_{fti} denotes the benchmark value shares of the input factors. α_{ti} is the benchmark unit cost coming from the five production factors that are explicitly modeled, while $h(\cdot)$ is increasing and convex ($h' > 0, h'' > 0$).

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[8] See Mathiesen (1985) and Rutherford (1995).

[9] The cost of non-traded factors (electricity and natural gas) is captured by this local cost component, but there are also regional specific costs related to the traded factors.

[10] As argued by Ellerman (1995) and Light (1999), the average distances in the coal trade may differ from the distances on the marginal trades. By using average distances in our model, the estimates of the changes in shipping demand and freight rates may be somewhat biased.

Supply of and demand for (traded) factors of production:
According to Eq. (A1.2), the cost minimizing (conditional) input of factor f per unit of output at the prevailing user costs w_{fi} is

(A2.2) $$a_{fti} \equiv \partial c_{ti}(w_{1i},.., w_{5i}, Q_{ti})/\partial w_{fi} = \boldsymbol{a}_{fti}\, [\sum_f \kappa_{fti}\, (w_{gi}/\boldsymbol{w}_{gi})^{1-\gamma}\,]^{\gamma/(1-\gamma)}\, (\boldsymbol{w}_{fi}/w_{fi})^{\gamma}.$$

Total demand of factor f is obtained by summing over all technologies and regions, where factor usage is the product of the input use per unit a_{fti} and the output level Q_{ti}.

Non-traded factors are supplied at a constant price, while the supply of traded factors is an increasing (linear) function of the world market price. Let $s_f(v_f)$ denote the factor supply function. In equilibrium, we must then have:

(A2.3) $$s_f(v_f) \geq \sum_i \sum_t a_{fti}\, Q_{ti}, \qquad \perp^{11} \quad v_f \geq 0.$$

Supply of and demand for dry bulk shipping:
Supply of dry bulk shipping services s_s is postulated as an increasing (and linear) function of the freight rate index; $s_s = s_s(r)$.

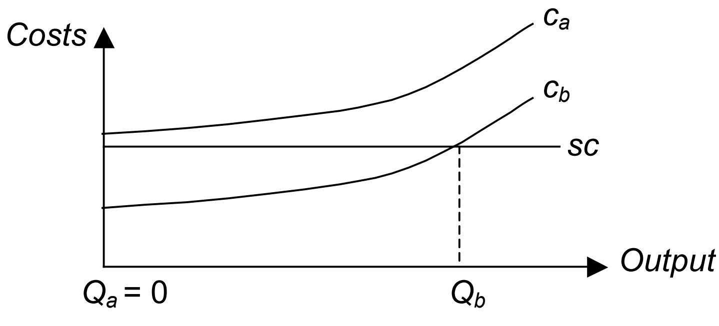
Demand for shipping services (measured in tonne-miles) is obtained first by summing the world demand for transport of input factors and then adding the transport demand generated by steel trade. Let d_{ij} be the distance between regions in the steel trade. The equilibrium in the freight market can then be described as follows:

(A2.4) $$s(r) \;\geq\; [\sum_f \sum_i \sum_t d_{fi}\, (a_{fti}\, Q_{ti})] + [\sum_s \sum_i \sum_j d_{ij}\, x_{sij}] \qquad \perp \qquad r \geq 0.$$

Marginal cost of producing steel type s:
Two types of steel are produced by three different technologies. Let the set TS denote the set of feasible technology / steel type combinations. The marginal costs of steel type s is then given by

(A2.5) $$c_{ti} \;\geq \hat{c}_{si}, \qquad \perp \qquad Q_{ti} \geq 0. \qquad \forall (t,s) \in TS$$

Figure A1. Two technologies for producing the same type of steel



The complementary slackness condition states that if technology t is employed (i.e., $Q_{ti} > 0$), then marginal cost of production equals the marginal cost of its steel. If, on the other hand the marginal cost of employing technology t to produce steel type s, exceeds the marginal cost of providing steel type s (because another technology provides this steel at a lower cost),

[11] The orthogonality symbol is used to denote the variable associated with an equation. In equilibrium, at least one of the inequalities must hold as strict equality.

technology t is not used, i.e., $Q_{ti} = 0$. Figure A1 illustrates these cases. Consider two technologies a and b. Technology b is operated, i.e., $Q_b > 0$, whereby $c_b = c_b\ (Q_b) = \hat{c}$. Technology a, however, has a too high cost; $c_a = c_a\ (0) > \hat{c}$, and hence $Q_a = 0$.

Output and supply of steel type *s*:

(A2.6) $\sum_{t\in TS} Q_{ti} \geq \sum_j x_{sij}$, $\perp$ $\hat{c}_{si} \geq 0$.

The summation on the left is over technologies t that produce steel type s, and the summation on the right is over shipments of steel type s to consuming regions.

Supply and conditional demand for steel type *s* from region *i*:

Let D_{sij} denote the demand of steel type s from region i in region j for a given level of demand for steel type s, Y_{sj}. In equilibrium

(A2.7) $x_{sij} \geq D_{sij}(p_{s1j}, .., p_{s10j}, Y_{sj})$, $\perp$ $p_{sij} \geq 0$.

Unit profit of supply:

(A2.8) $\hat{c}_{si}(1 + T_{ij}) \geq p_{sij}$, $\perp$ $x_{sij} \geq 0$.

T_{ij} aggregates all costs of transporting steel from region i to region j, including tariffs. The condition states that if shipment (x_{sij}) is positive, the price in region j exactly covers the cost of supplying this region from region i. If supply cost exceeds price, however, there is no shipment.

Demand for Armington aggregate *s*:

(A2.9) $Y_{sj} \geq D_{sj}(P_{1j}, P_{2j})$, $\perp$ $P_{sj} \geq 0$.

D_{sj} is final demand for steel type s in region j (see Eq. (A1.4)) and P_{sj} is its price.

Unit cost of Armington aggregate *s*:

(A2.10) $C_{sj}(p_{s1j}, .., p_{s10j}) \geq P_{sj}$, $\perp$ $Y_{sj} \geq 0$.

C_{sj} denotes the unit cost of the Armington aggregate Y_{sj}.

The equilibrium conditions A2.2 – A2.10 are solved simultaneously. They are, however, related to each other in a circular manner that is quite illustrative for the interpretation of the results from this type of model. Starting (arbitrarily) with the unit demand for factors of production (a_{fti}), we have the sequence of causal relations laid out in the following table.

Table A2.1. Causal relationships in the model

	Variables
(A2.2) determines factor demand per unit of output from factor prices	v_f, $r \rightarrow a_{fti}$
(A2.3) determines factor prices (v_f) from unit factor demand (a_{fti}) and output of steel (Q_{ti})	$a_{fti}\, Q_{ti} \rightarrow v_f$
(A2.4) determines the freight rate (r) from factor demand and steel shipments (x_{sij})	$a_{fti}\, Q_{ti}$ & $x_{sij} \rightarrow r$
(A2.5) determines marginal cost ($\hat{c}_{si}$) of steel type s from production volumes and factor prices (see also A2.1)	Q_{ti} , v_f, $r \rightarrow \hat{c}_{si}$
(A2.8) determines supply price (p_{sij}) of steel type s	$\hat{c}_{si} \rightarrow p_{sij}$
(A2.10) determines price (P_{sj}) of Armington-aggregate	$p_{sij} \rightarrow P_{sj}$
(A2.9) determines the level (Y_{sj}) of the Armington-aggregate	$P_{sj} \rightarrow Y_{sj}$
(A2.7) determines demand (x_{sij}) for steel type t from region i	Y_{sj} & $p_{sij} \rightarrow x_{sij}$
(A2.6) determines production (Q_{ti}) from total demand for steel	$x_{sij} \rightarrow Q_{ti}$

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