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# Impacts of Market-Based Climate Change Policy on the U.S. Iron and Steel Industry

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*This article presents an assessment of the impacts that policy-induced increases in cost of energy or carbon may have on energy use and emission profiles of the U.S. iron and steel industry. Time series data and engineering information are combined within a dynamic computer model to endogenously specify changes in technologies, fuel mix, and production processes. Results indicate that energy taxes shift production to electric arc furnaces and reduce total energy use more than policies that raise costs of carbon. However, both energy taxes and costs of carbon will result in a similar decrease in carbon emissions when compared to the absence of those policies.*

**Keywords** climate change policy, cost of carbon, dynamic modeling, energy tax, energy use, industrial policy, iron and steel industry, technology change

The U.S. iron and steel industry accounts for approximately 2.3% of all energy used in the United States, or 21 million BTUs per ton of product (OTA, 1993). Iron and steel production is a significant contributor of carbon emissions because the industry relies heavily on fossil fuels as an energy source, and on limestone for the purification of iron oxides. Several major changes occurred in the industry and its economic environment that led to reductions in its energy use and emissions. Significant advances in existing technologies, the emergence of entirely new processes since World War II, and toughened environmental standards prompted adoption of new technologies, and changes in the mix of materials and fuels (Adams, 1995; Ruth, 1995). Changes in the structure of the economy, most notably a move toward increased importance of the service sector, a reorientation of manufacturing from infrastructure to consumer goods, and increased competition

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from foreign producers, have all altered the U.S. market for steel (Ruth, 1998). Given the technological, regulatory, and economic parameters under which the U.S. iron and steel industry operates, what are likely development paths for the industry if new, global climate change policies are introduced into the picture? In this article we address this question and focus on the industry's material, energy, and carbon emissions profiles. We support our arguments with the results of a dynamic computer model (Ruth & Hannon, 1997) of the industry.[1]

## Dynamic Modeling of Technology Change in U.S. Iron and Steel Production

### *Model Structure and Specification*

To assess impacts of energy taxes and cost of carbon on the U.S. iron and steel industry we developed a dynamic computer model that captures the main production stages and technologies (Figure 1). In the United States, steel is produced using two different processes. Basic oxygen furnaces (BOFs) produce steel primarily from pig iron, which in turn is produced in blast furnaces (BF) from ores. Electric arc furnaces (EAFs) produce steel primarily from scrap.

Engineering information was used to specify material and energy efficiencies of individual technologies at any point in time, limits to those efficiencies, and conversion factors. Time series analysis was used to quantify change in technologies and production rates. The choice between different functional forms and which variables to include as regressors was guided by conventional hypothesis test statistics and, within the context of the dynamic computer model, by a battery of sensitivity and robustness analyses. Special attention was given to regression diagnostics used to detect sources of inefficiency and bias in regression equations. Specifically, we tested for presence of serial correlation, heteroscedasticity and unit roots, applying Lagrange multiplier tests (Breusch & Pagan, 1979; Godfrey, 1978) and unit root analysis (Dickey & Fuller, 1981). All results presented below meet the respective test criteria at the 95% confidence level. When running the resulting model over historic time and comparing model output to actual observations, mean absolute error rates of less than 2% are observed.

The structure of the computer model is shown in Figure 2. Forecasts of future steel production rates and energy prices drive the model for the years 1994 to 2020. Changes in material and energy efficiencies, technology mix, and fuel mix are determined endogenously. As technology mix changes, the differences in material and energy use that are associated with differences between the BOF and EAF routes of steel production determine the industry's overall material, energy and emissions profiles. Specifically, BOF production determines pig iron demand, and—given changes in BF and coke oven (CO) efficiencies—production of coking coal and limestone use. Changes in relative production shares of BOFs and EAFs also determine the rate at which electricity can be self-generated in the industry. Electricity that is not self-generated is purchased from the U.S. electricity sector and generated, by assumption, at the national average efficiencies and fuel mix. Changes in efficiencies and fuel mix of *purchased* electricity are exogenous to the model and follow projections by the Energy Information Administration (EIA, 1998). Carbon emissions are calculated for direct combustion of fossil fuels,

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[1] To request a copy of the model send E-mail to mruth@bu.edu.

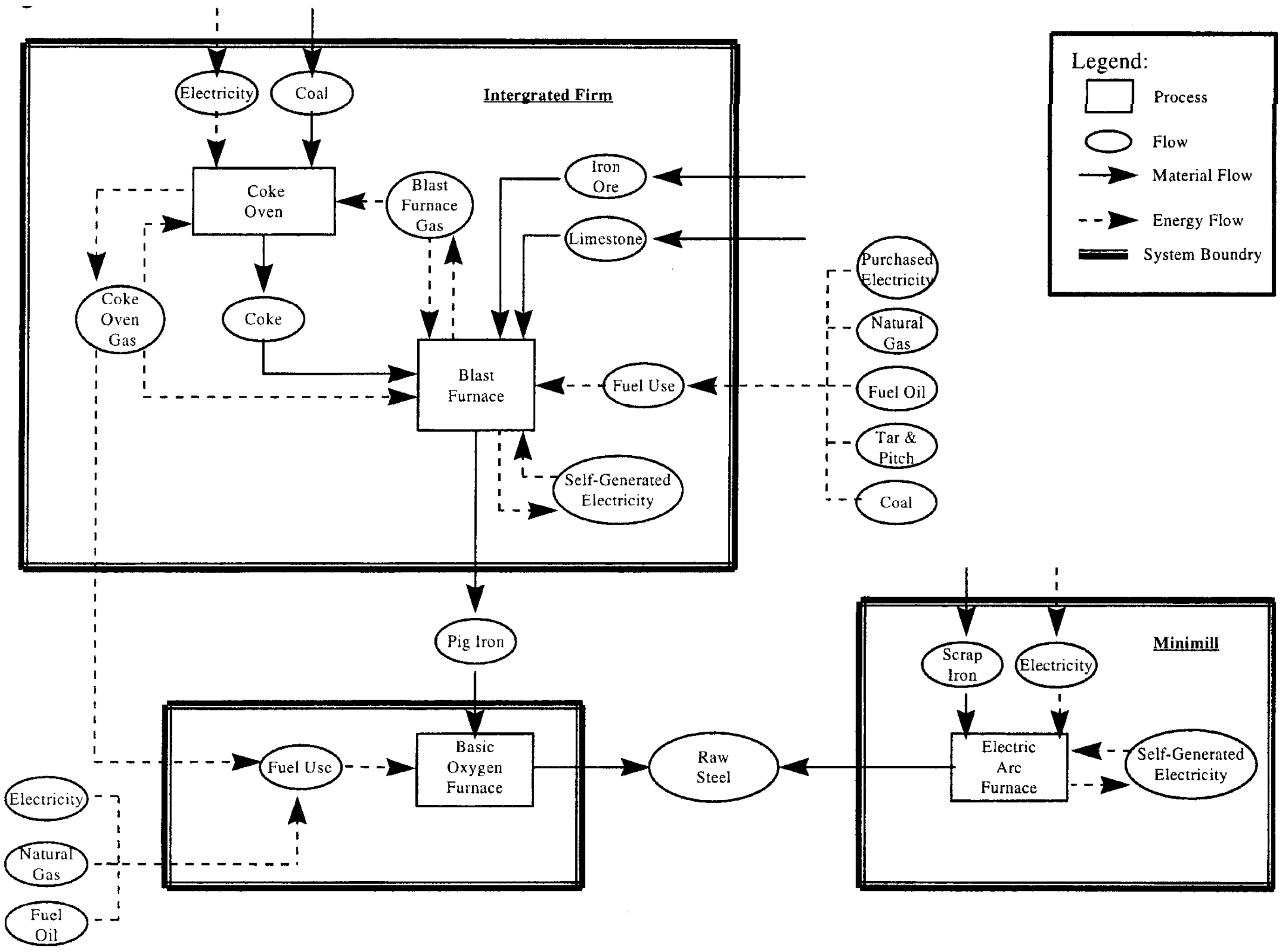

**Figure 1.** Steel production processes.

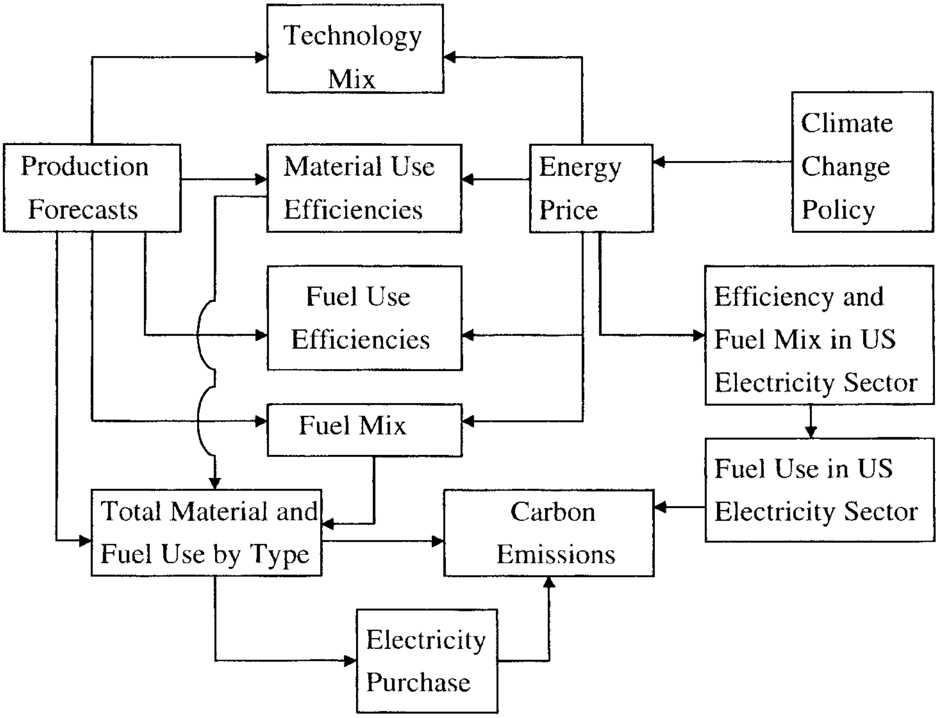

**Figure 2.** Model structure.

indirect fossil fuel use through the demand for electricity, and use of limestone for removal of impurities in iron ores. The model can also be run to "backcast" policy and technology conditions that meet, e.g., specific carbon emissions goals.

### *Steel Production*

Material use, energy use, and carbon emissions by the U.S. iron and steel industry depend on production rates. Higher production rates tend not only to increase input requirements and emissions but are accompanied by higher capacity utilization, greater opportunities for learning-by-doing, and, when associated with higher profits, can provide the capital and confidence to invest in new technologies. It is through these latter effects that higher production rates provide industry with possibilities for reduced environmental impact per ton of steel produced.

The base scenario discussed below is derived from projections of gross domestic product, GDP (Congressional Budget Office, 1998), population (U.S. Bureau of the Census, 1996), and estimated relationships between per-capita GDP and per-capita steel consumption (Table 1). Historical data of production rates comes from the American Iron and Steel Institute (AISI, various years). Following suggestions by Roberts (1990), steel imports and exports are calculated on the basis of the trade-weighted value of the U.S. dollar to account for the relative strength of the dollar against currencies of many of America's trading partners.

Expansion of EAF production is specified as a function of the price of electricity relative to the price of primary energy and cumulative EAF production

**Table 1**
Regression results for steel production forecast module
($t$-statistics in parentheses)

| | | Dependent variables | | |
|---|---|---|---|---|
| Regressor | Function form and lags | Per-capita steel consumption (log) | Percent imports (log) | Percent exports (log) |
| Constant | | 10.3248<br>(16.17) | −5.2580<br>(−2.17) | 20.1552<br>(3.37) |
| GDP per person | (log) | −0.3525<br>(−5.29) | | |
| Trade-weighted value of dollar | log($t-1$) | | | −4.4253<br>(−3.22) |
| | log | | 1.8557<br>(3.35) | |
| LM$\chi^2$[a] | | 0.2741<br>(0.9864) | 0.0133<br>(0.7258) | 0.6408<br>(0.7258) |
| LM$\chi^2$[b] | | 0.1675<br>(0.6822) | 1.1766<br>(0.2780) | 0.1738<br>(0.6767) |
| Adjusted $R^2$ | | 0.71 | 0.77 | 0.70 |

[a] Lagrange multiplier estimate of heteroscedasticity (Godfrey, 1978); significance level in parentheses.

[b] Lagrange multiplier estimate of serial correlation (Breusch & Pagan, 1979); significance level in parentheses.

(Table 2). Cumulative production is defined here and elsewhere in this study as an index set to 1 for the initial year of the respective time series. It is used as an indicator of experience (Ruth, 1993).

The split between EAF and BOFs influences the industry's energy profile. More than 99% of energy input into EAFs is in the form of electricity. The efficiency at which the energy is used depends on cumulative production (Table 2). Efficiency is measured in BTU per ton output because physical efficiency measures are more robust indicators of energy requirements than measures based on monetary values (Patterson, 1996).

### *Pig Iron Production*

Six sources are considered to supply energy necessary for pig iron production. Blast furnace gas and coke oven gas are self-generated by-products of BFs and COs, respectively. Their availability depends on the production rates of these furnaces. Fuel oil, coal, natural gas, and electricity are used in pig iron production alongside blast furnace and coke oven gas. Fuel oil use has historically been decreasing. Its decline has been driven to a significant extent by changes in its relative price (Table 2). Similarly, the price of coal relative to the average fossil fuel price significantly influenced the choice of coal as an energy source. In the model, the

## Table 2

Summary of regression results (*t*-statistics in parentheses)

| Regressor | Function form and lags | Dependent variables: Coal use efficiency in coke ovens log (ton/ton) | Share of EAF log(share/0.8-Share)[a] | EAF efficiency (log) (million BTU/ton)[a] | BF efficiency (million BTU/ton)[b] | BF coal (% of total BTU in BF)[b] | BF Fuel oil (% of total BTU in BF)[b] | Electricity self-generated |
|---|---|---|---|---|---|---|---|---|
| Constant | | −0.8521<br>(−4.77) | −3.3468<br>(−7.06) | 3.2193<br>(30.48) | 83.1923<br>(7.49) | 17.4311<br>(7.69) | 24.5848<br>(11.31) | 1.5433<br>(2.652) |
| Coke production rate | Log | 0.0543<br>(5.63) | | | | | | |
| Cumulative blast furnace production | Log | | | | −16.5669<br>(−5.17) | | | |
| | ($t$) | | | | | −0.2096<br>(−4.94) | | |
| Cumulative electric arc production | Log | | 1.0522<br>(14.11) | −0.4065<br>(−14.08) | | | | |
| (Electricity price-PEP)/electricity price ($/million BTU) | ($t-3$) | | 2.0663<br>(−4.18) | | | | | |
| BF production rate (% from $t-1$) | ($t$) | | | | −6.7437<br>(−6.90) | | | |
| Coal price/PEP[c]($t-1$) | | | | | | −10.1019<br>(−6.18) | | |
| Fuel oil price ($/million BTU) | ($t-2$) | | | | | | −2.9226<br>(−5.09) | |
| EAF share (% of total steel) | ($t$) | | | | | | | 10.4117<br>(4.90) |
| LM $\chi^2$[d] | | 1.7328<br>(0.1880) | .2474<br>(0.6189) | 0.8402<br>(0.3593) | 0.6601<br>(0.4165) | 0.6111<br>(0.4343) | 0.7305<br>(0.3927) | 0.1042<br>(0.7468) |
| LM $\chi$[e] | | 3.9452<br>(0.1391) | 1.6050<br>(0.6583) | 4.0227<br>(0.1338) | 5.1114<br>(0.1638) | 2.2024<br>(0.5315) | 0.9256<br>(0.62951) | 3.5479<br>(0.1696) |
| Adjusted $R^2$ | | 0.88 | 0.98 | 0.97 | 0.96 | 0.75 | 0.73 | 0.86 |

[a] EAF, electric arc furnace.

[b] BF, blast furnace.

[c] PEP: Primary energy price is a nonweighted average of primary energy prices.

[d] Lagrange multiplier estimate of serial correlation (Breusch & Pagan, 1979); significance level in parentheses.

[e] Lagrange multiplier estimate of heteroscedasticity (Godfrey, 1978); significance level in parentheses.

share of energy supplied by natural gas is set as the remainder that is not supplied by the other five energy sources, whose contribution is estimated with a seemingly unrelated regression model (Table 2).

### *Coke Production*

Coal use efficiencies in U.S. coke production remained virtually constant over the last three decades. Coal consumption per ton of coke depends primarily on the rate of coke production. Increased production rates frequently lead to higher efficiencies because of reduced heat losses per ton of product. This relationship is confirmed by the regression analysis (Table 2).

### *Electricity Generation*

To properly reflect the industry's fuel requirements and carbon emissions, the model includes fuel requirements by the U.S. electricity sector to supply electricity for iron and steel production. The respective module uses actual data and forecasts of fuel mix in the electricity sector that are reported in the *Annual Energy Outlook* up to the year 2020 (EIA, 1998).

### *Carbon Emissions*

Carbon emissions accrue from burning fossil fuels and from using limestone to reduce the impurity content of pig iron produced in BFs. Carbon emissions are calculated by multiplying the carbon content per BTU of a fuel with the industry's use of the respective fuel. Fixed carbon coefficients are applied and listed in Table 3. To avoid double-counting, only the carbon content of purchased fuels and of fuels used to generate purchased electricity are taken into account. For the decarbonization of limestone we assume average emissions of 0.0205 metric tons of carbon per ton of steel (Gielen, 1997).

**Table 3**
Carbon content of fuels.

| Fuel type | Metric tons of carbon per billion BTUs (1994 value) |
|---|---|
| Coal | 25.61 |
| Coal (electricity generation) | 25.71 |
| Natural gas | 14.47 |
| Residual fuel oil | 21.49 |
| Oil (electricity generation) | 19.95 |
| Liquid petroleum gas | 17.02 |
| Distillate fuel oil | 19.95 |

*Source*: EIA (1994).

## Model Results

### *Base Scenario*

For the base scenario of our model we assume future growth of GDP at an annual rate of 1.9% and a trade-weighted value of the dollar, measured as an index, fixed at 78. The former is based on Congressional Budget Office forecasts (Congressional Budget Office, 1998). The latter is the mean value for the years 1970–1996 (Federal Reserve Board Dallas, 1998). Under these assumptions, raw steel production rates increase only 1.1% for the years 1997–2020. At these lower production rates, fossil fuel use declines. Our base case results assume a penultimate market production share of 80% for EAF output and an S-shaped asymptotic approach toward that maximum. Concomitant with an increase in EAF production are technology changes that increase electricity use. However, since much of the electricity is produced from fossil fuels, total carbon emissions decline more slowly than total energy use (Table 4).

### *Market-Based Climate Change Policies*

To investigate impacts of market-based climate change policies on carbon emissions and energy use we assume that one of two policies are implemented in the year 2000. Either $100 are charged per ton of carbon, for example, in the form of a permit or tax, or alternatively, an energy tax of 77% per BTU is levied. This energy tax rate has been chosen to generate the same cumulative present value of tax revenues over the time frame 2000–2020 as the carbon cost (Table 4).

Implementation of climate change policies provides incentives for industry to reduce energy requirements per ton of steel, though the rate at which policy-induced efficiency improvements occur declines over time (Figure 3). Trends in carbon emissions per ton of steel mirror those of energy efficiency improvements (Figure 4). Expansion of EAF production will be hastened by cost of carbon and energy tax increases (Table 2) because of the EAF's significantly smaller energy requirements per ton of steel relative to the BOF route.

An increased share of production by EAFs has marked effects on carbon emissions and carbon per ton of output. As EAF production is expanded, a shift toward cleaner processes takes place. Declines in pig iron production and BOF output, in turn, are associated with higher energy requirements and carbon emissions per ton of product. If furnaces are operated at lower capacity, heat loss per ton of furnace charge is high, and thus efficiency is low. That furnaces are operated at low output rates during a recession, rather than temporarily closed, has been observed by Boyd et al. (1993) on the basis of firm-level data. Since the policies introduced here are not temporary, but fixed throughout the 2000–2020 period, adjustments continue to take place in the industry.

The introduction of a cost of carbon policy causes an immediate, although short-run, reduction in carbon emissions relative to a comparable energy tax. This is due to a less drastic shift away from the BOF route, where lower production rates result in higher energy requirements per ton of steel. The BOF route is given more time to adjust to the changing structure of the industry such that smaller inefficiencies occur in its production processes.

**Table 4**
Summary of model results for base case, energy tax, and cost of carbon scenarios

| | Base scenario | 77% energy tax | $100 per ton carbon |
|---|---|---|---|
| Total energy use (% change from 1994 levels to 2020) | −26.79 | −32.46 | −31.54 |
| BOF production (% change from 1994 levels to 2020) | −16.52 | −32.23 | −29.95 |
| BF energy use per ton of product (% change from 1994 levels to 2020) | −31.42 | −27.68 | −28.17 |
| Years lost in improvement in energy use per ton of product from BF (policy scenario vs. base scenario in 2020) | | 3 | 2 |
| EAF production (% change from 1994 levels to 2020) | +38.96 | +59.68 | +59.68 |
| EAF energy use per ton of product (% change from 1994 levels to 2020) | −25.63 | −27.58 | −27.39 |
| EAF share of production in 2020 (%) | 51.90 | 60.95 | 59.63 |
| Years gained in improvement in energy use per ton of product from EAF (policy scenario vs. base scenario in 2020) | | 2 | 2 |
| Total carbon emissions (% change from 1994 levels to 2020) | −21.10 | −26.10 | −25.97 |
| Cumulative present value of energy expenditures, 2000–2020 (billion 1994 $, 5% discount rate) | 37.44 | 63.89 | 63.42 |
| Cumulative present value of payments, 2000–2020 (billion 1994 $, 5% discount rate) | | 27.81 | 27.88 |
| Energy expenditure in 2020 (billion 1994 $) | .89 | 1.56 | 1.59 |
| Policy-induced payments in 2020 (billion 1994 $) | | 0.68 | 0.69 |

## Discussion

Market incentives are one way for the United States to promote strategies that help meet the Kyoto summit obligations of decreasing emissions by 7% below 1990 levels in the years 2008–2012. The iron and steel industry is a key element of this reduction because it is a large single end user of fossil fuels. The analysis above shows that implementation of energy taxes or increases in cost of carbon significantly alters technology mix, energy profiles, and emissions in the U.S. iron and steel industry. A shift is expected away from BOF to EAF production of steel. Reductions in output from BFs are likely to translate into reduced BF energy efficiency, but such efficiency losses are outweighed by improvements of EAFs.

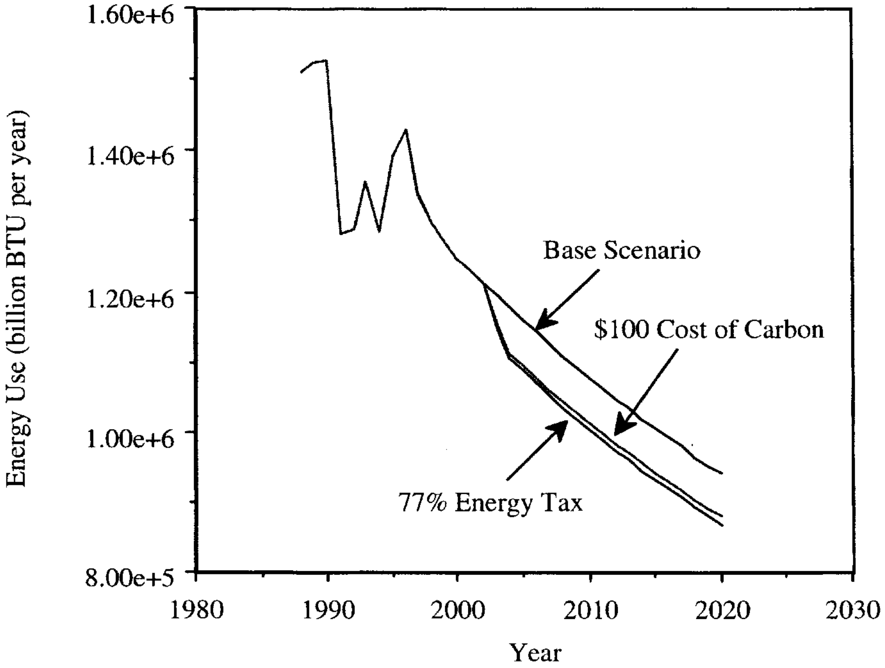

**Figure 3.** Energy use under alternative scenarios.

The higher the energy tax or cost of carbon, the larger the corresponding efficiency disimprovements in the BFs and efficiency improvements in the EAFs.

From a climate change perspective, both policies produce the desired reductions in energy use and carbon emissions over the base scenario, but with differences in short- and long-run effects on the industry. Costs of carbon policies cause a smoother transition to EAF production with more immediate short-term reduction in carbon emissions over comparable energy taxes. The long-run results of the model demonstrate that energy taxes help curb energy use to a greater extent than equivalent cost of carbon because energy taxes stimulate a larger expansion in EAF production.

These observations point to three main conclusions. First, to assess market-based climate change policy impacts on U.S. iron and steel requires explicit consideration of the dynamics that describe its technology change and fuel choice. Intermediate responses by the industry may differ from long-term trajectories, making it necessary for policy and industry decision makers to take the entire time profile of industry behavior into account rather than focus on short-term trends. Second, responses of individual establishments will vary between basic oxygen and electric arc producers. Effectiveness of the policies depends on the technical details of the production processes, as the example of efficiency declines with lower furnace charge illustrates. These technical issues need to be taken into account in the choice among policies. Third, because of large sunk investments in the industry, significant changes in overall energy use and emissions are difficult to achieve if

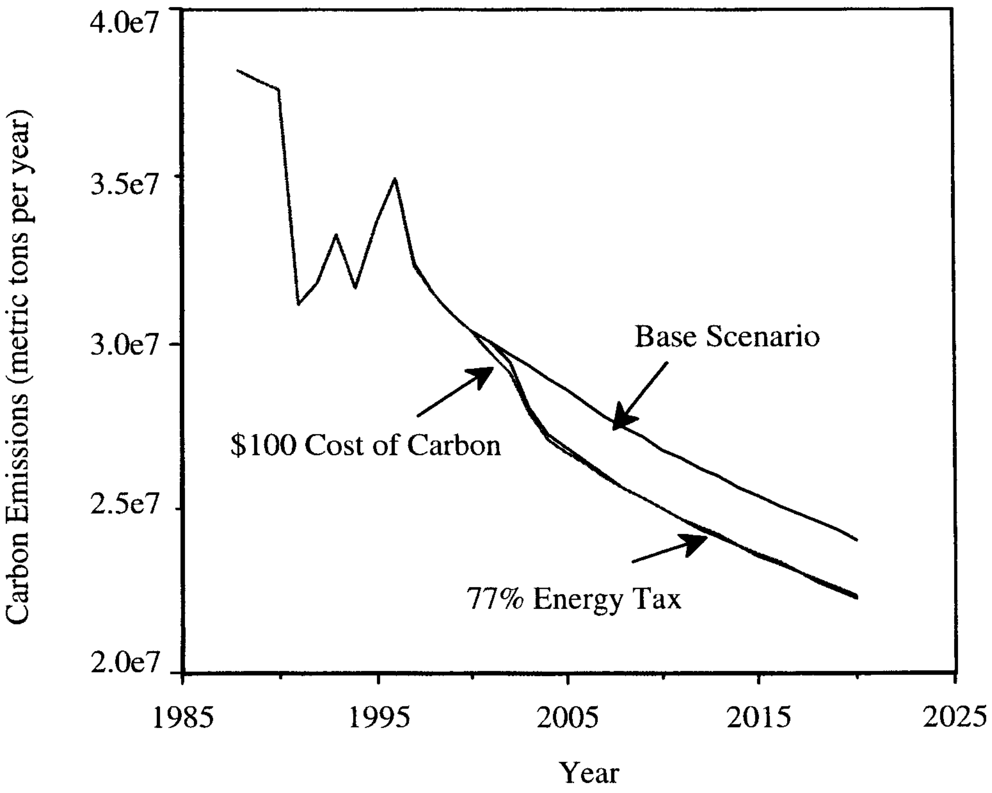

**Figure 4.** Carbon emissions under alternative scenarios.

the only incentives are through energy price signals. Combinations of market-based and investment-led policies may be required to overcome past technology lock-in.

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