Final Report

"Assessment of the Incentives, Disincentives, and Alternatives for Steel Industry CO_2 Reduction"

Contract No. DE-AC07-0013833

Submitted to

United States Department of Energy
1000 Independance Avenue S.W.
Washington D.C. 20585-0121

Submitted by

Charles River Associates
200 Clarendon Street
Hancock Tower, T-33
Boston, Massachusetts 02116-5092

March 31, 2002

CRA No. D02559-00

Table of Contents

1. Executive Summary 1
Figure S1a. Carbon Dioxide Emission Level: Final Annealed and Tempered Product from Blast Furnace/BOF 4
Figure S1b. Carbon Dioxide Emission Level: Final Annealed and Tempered Product from Conventional Charged EAF 5
Figure S2. Carbon Dioxide Emission Level: Smelting Processes 7

2. Introduction and Background and Methodology 13
DOE Program 13
CRA Approach and Methodology 14
Task 1—Review Relevant Technical Analysis and Policy Literature 15
Task 2—Review Insights with Relevant Industry, Government, and Outside Officials and Experts 17
Task 3—Analysis 19
Task 4—Review Preliminary Conclusions and Prepare Final Report 22

3. Industry Structure, Steel Making Technologies, and Financial Performance 23
Introduction 23
Table 1. U.S. Steel Production and Associated Carbon Dioxide Emissions in 1990 and 1998 23
Figure 1. Historic Blast Furnace Coke Rate in the United States 1976–1999 24
Current Industry Structure 24
Figure 2. Overall Steel Industry Sectoring 25
Figure 3. Profile of Current CO_2 Emissions per Ton of Steel 28
Figure 4. The Share of Steel Produced in EAFs Is Projected to Increase 29
Financial Position of the Steel Industry 29
Figure 5. Return on Assets in Steel Manufacturing 30
Figure 6. Median Z-Scores in Steel Manufacturing 31
Table 2. Recent Bankruptcies in the US Steel Industry 32
Steel making Technologies: Their Carbon Dioxide Potential and Cost-Effectiveness 33
Table 3. 1998 Consumption of Materials and Fuels; Production of Intermediate Products and Imports of Semifinished Steel[1] 34
Table 4. Conversion of Consumables to Carbon Dioxide Equivalents 36
Figure 7a. CO_2 Emission Level (lbs per Ton Coke) 40
Figure 7b. CO_2 Emission Reduction/Increase (Pounds per Ton Coke) 40
Figure 8a. CO_2 Emission Level (Pounds per Ton Hot Metal) 41
Figure 8b. CO_2 Emission Reduction/Increase (Pounds per Ton Hot Metal) 41
Figure 9a. CO_2 Emission Level (Pounds per Ton Hot Metal) 42
Figure 9b. CO_2 Emission Reduction/Increase (Pounds per Ton Hot Metal) 42

Table of Contents

Figure 10a. CO_2 Emission Level (Pounds per Ton Reduced Iron Feed DRI) 43
Figure 10b. CO_2 Emission Reduction/Increase (Pounds per Ton Reduced Iron Feed) 43
Figure 11a. CO_2 Emission Level (Pounds per Ton Liquid Steel) 44
Figure 11b. CO_2 Emission Reduction/Increase (Pounds per Ton Liquid Steel BF/BOF Process) 44
Figure 12a. CO_2 Emission Level (Pounds per Ton Liquid Steel Electric Arc Furnace Process) 45
Figure 12b. CO_2 Emission Reduction/Increase (Pounds per Ton Liquid Steel) 45
Figure 13a. $C0_2$ Emission Level (Pounds per Ton Hot Rolled Steel) 46
Figure 13b. CO_2 Emission Reduction/Increase (Pounds per Ton Hot Rolled Steel) .. 45
Figure 14a. CO_2 Emission Level (Pounds per Ton Cold Rolled Steel) 47
Figure 14b. CO_2 Emission Reduction/Increase (Pounds per Ton Cold Rolled Steel). 47

Conclusions from the Technology Evaluations 48

Figure 11a. CO_2 Emission Level (Pounds per Ton Liquid Steel) 48
Figure 12a. CO_2 Emission Level (Pounds per Ton Liquid Steel Electric Arc Furnace Process) 49
Figure 12b. CO_2 Emission Reduction/Increase (Pounds per Ton Liquid Steel) 49
Figure 8a. CO_2 Emission Level (Pounds per Ton Hot Metal) 50
Figure 8b. CO_2 Emission Reduction/Increase (Pounds per Ton Hot Metal) 51
Figure 10a. CO_2 Emission Level (Pounds per Ton Reduced Iron Feed DRI) 51
Figure 10b. CO_2 Emission Reduction/Increase (Pounds per Ton Reduced Iron Feed) 52
Figure 9a. CO_2 Emission Level (Pounds per Ton Hot Metal) 53
Figure 9b. CO_2 Emission Reduction/Increase (Pounds per Ton Hot Metal) 53
Figure 11a. CO_2 Emission Level (Pounds per Ton Liquid Steel) 54
Figure 11b. CO_2 Emission Reduction/Increase (Pounds per Ton Liquid Steel BF/BOF Process) 55
Figure 12a. CO_2 Emission Level (Pounds per Ton Liquid Steel Electric Arc Furnace Process) 56
Figure 12b. CO_2 Emission Reduction/Increase (Pounds per Ton Liquid Steel) 56
Figure 14a. CO_2 Emission Level (Pounds per Ton Cold Rolled Steel) 57
Figure 14b. CO_2 Emission Reduction/Increase (Pounds per Ton Cold Rolled Steel). 58
Figure 13a. $C0_2$ Emission Level (Pounds per Ton Hot Rolled Steel) 58
Figure 13b. CO_2 Emission Reduction/Increase (Pounds per Ton Hot Rolled Steel) .. 59

Estimated Costs, Emissions Reductions, and Economic Impacts of Policy Options to Reduce CO_2 Emissions in the Iron and Steel Industry 59

4. Survey of The Industry and Outside Experts 65
Survey Methodology 65
Interview Results—Technology and Economic Issues 65
Table 6. Summary of Interviews with Steel Industry Executives (I stands for integrated mills) 69
Interview Results—Policy Issues 77

5. Policy Analysis of Options To Reduce Carbon Dioxide Emissions in The U.S. Steel Industry 81
Hidden Costs As Barriers to Energy Efficiency Investment 81
Shutdown Risk 82
Table 7. Expected Cash Flows When Shutdown Is Possible 83
Scarce Engineering Resources 83
Risks of Interrupted Production 84
Market Failures, Market Barriers, and Public Policy 84
Market Failures and No-Regrets Market Barriers Identified in the Literature 86
Other Potential No-Regrets Market Failures 87
Market Failures in Research and Development 88
Principal/Agent Issues 88
Pricing Carbon Emissions to Correct Market Failure 89
Policies Appplicable to the Steel Industry 90
What Prevents Apparently Cost-Effective Investments in Energy Efficiency? 91
Poor Financial Condition 92
Site-Specific Costs and Loss of Revenue 92
Environmental Regulations 93
Risk Avoidance 93
Development and Introduction of New Technologies 94
What Measures are Feasible, But Not Cost-Effective at Current Prices and Under Current Policies? 94
Differences Between Integrated and EAF Operations 95
CRA Analysis of Policy Options 95
Reform Environmental Regulatory Process 95
Improve the Financial Condition of the Industry Through Trade Policy 97
Addressing Market Failures Associated with Information and Innovation 98
R&D Support 98
Cooperative R&D 98
First Mover Incentives 99
Technical Advisory Programs 99
Policies that Require Incurring Net Costs 100

Table of Contents

Targeted Tax Incentives 100
Targeted Loan Guarantees 101
Broader, Cost-Effective Approaches 101
Higher Energy Prices 102
Kyoto Protocol 103

6. Bibliography 105

Appendix A 109
Appendix B 143

1. Executive Summary

INTRODUCTION AND SCOPE

This report presents the results of the third element of a trilogy of studies sponsored by the U.S. Department of Energy's Office of Industrial Technologies on the consumption of energy and the emissions of carbon dioxide in the U.S. steel industry. The studies have sought to address the following issues:

- What is the current structure of energy use patterns in and carbon dioxide emissions from the domestic production of iron and steel?
- What are the theoretical minima in the consumptions of energy and emissions of carbon dioxide in the major process steps in iron and steelmaking?
- What are the applicable technologies, market barriers, R&D approaches, and policy instruments that need to be addressed to help the industry move from its current state toward reduced energy consumption and carbon dioxide emissions of the minimum benchmark?

The first two issues have been addressed in reports prepared by Dr. John Stubbles[1] and Professor Fruehan et al.,[2] respectively. CRA's analysis of the third issue is presented in this report.

CRA has carried out its analysis by executing four major tasks. In the first task, we reviewed relevant literature on the historical and current technology of the production of iron and steel and the economic forces that have driven technology evolutions, as well as literature on policy measures potentially relevant to the iron and steel industry. Preliminary analyses of the data and information obtained from these reviews were summarized in a report of the results of this task. The preliminary results were also used as key discussion points for the second task: a review of the insights gained from the discussions with relevant industry, governmental, and outside officials and experts. Face-to-face and telephone interviews were held with knowledgeable staff and decision makers from a variety of organizations to solicit their views and opinions on the technology and economics of reducing greenhouse gas emissions in the industry, and to test our preliminary analyses of policy measures and potential solutions developed in the first task. The third task constituted an analysis of the results of the first two tasks. The objective was to identify market failures that might be corrected through creative policy design, and to suggest policies that could correct the failure or provide incentives to overcome them; characterize the energy savings, costs, and economic impacts of such policies; and develop a rough estimate of

---

1 Energy Use in the U.S. Steel Industry: An Historical Perspective and Future Opportunities, U.S. Department of Energy, Office of Industrial Technologies, September 2000.

2 Theoretical Minimum Energies to Produce Steel for Selected Conditions, U.S. Department of Energy, Office of Industrial Technologies, March 2000.

the costs of reducing energy consumption that are realized by adoption of the technologies. The fourth task was to summarize the results and prepare a final report presenting the findings. This document constitutes CRA's final report of the findings of our analyses.

SUMMARY OF FINDINGS

The iron and steel industry is a significant emitter of carbon dioxide, with emissions totaling 185 million tons in 1998. In the last decade, the industry has made significant progress in decreasing the specific carbon dioxide emission rate from almost 210 million tons, or 2.2 tons per ton of steel to 1.7 tons per ton of steel. Further reductions in carbon dioxide emissions may be possible through judicious adoption of various proposed technologies.

There are two major sectors of the iron and steel industry: the integrated sector and the minimill sector. The integrated sector is based on producing steel from virgin iron ore by reducing the ore by carbon in coke. The minimill sector is primarily based on producing steel from steel scrap, thereby avoiding the emission of carbon-containing gases required in the reduction of iron ore. The liquid steel from both sectors is solidified and rolled into final products. Therefore, a shift in the share of steel produced from the integrated sector to the minimill sector would also result in a reduction of carbon dioxide emissions, even in the absence of adoption of new technologies.

Financially, the minimill sector is healthier than the integrated sector because it has newer plants, which have capital and operating costs that are lower than in the integrated sector. However, the fact is that, overall, the steel industry is in a precarious financial condition. Still, the decisions in some cases not to undertake seemingly profitable investment in new or even demonstrated technologies require an analysis of hidden costs and barriers.

CRA's evaluation of the process technologies that could reduce emissions consisted of the following steps.

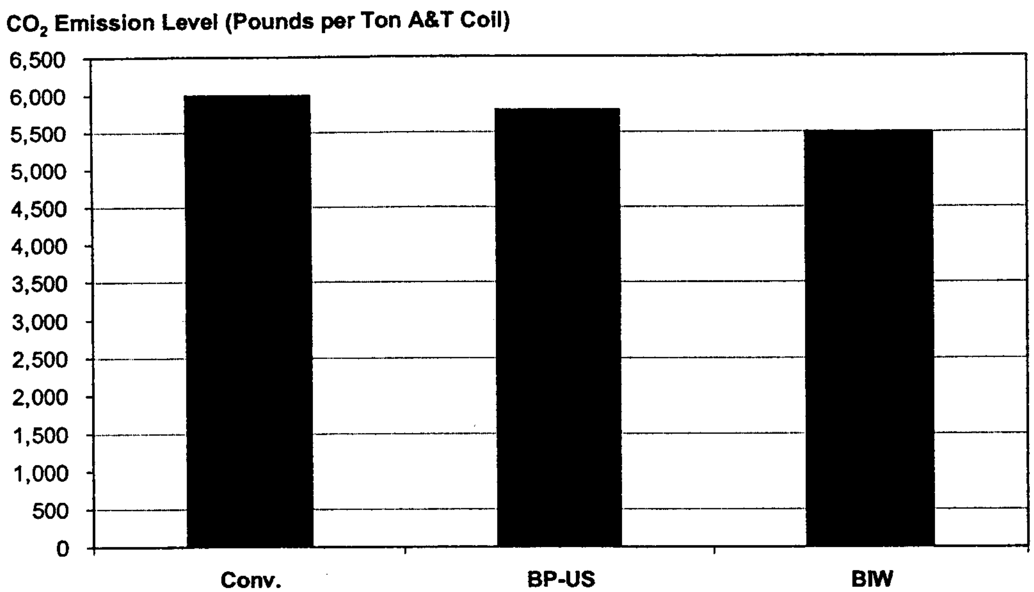
- Estimating the current average amount of carbon dioxide emitted across the U.S. steel industry in various unit process steps, starting with agglomeration of iron ore and ending with the finishing process steps to produce the final product. As a comparison, we also displayed the carbon dioxide emissions in the best practice processes in the United States and the world. This comparison indicates the decrease in carbon dioxide emission that has already been demonstrated with existing technologies in operating plants.
- Assigning the new and proposed technologies to the appropriate process steps, starting with agglomeration and continuing through to finishing operations.

- Sorting the technologies into four classifications, namely:
  - Process improvement.
  - Process replacement or substitution.
  - Energy source replacement.
  - Recycling.
- Identifying the current status of the development of these technologies
- Finally, estimating the economic criteria that permit a preliminary screening of these technologies. The criteria are:
  - Those technologies where engineering judgment suggests that the adoption of the technology can be justified on the energy or productivity savings alone under current conditions.
  - Those technologies where additional engineering analyses or additional development are needed to make a decision.
  - Those technologies where engineering analyses suggests that the savings will not be enough to justify the additional investment required under essentially all of the foreseeable circumstances.

In the absence of market barriers, market failures, or misestimates of the costs and benefits involved, those technologies that have been demonstrated and are estimated to be justifiable under current conditions should be adopted throughout the industry to reduce energy consumption and the attendant carbon dioxide emissions. A key objective of this study was to determine the extent and reasons to which those technologies have not been adopted. This would assist in evaluating policy options that could be developed to facilitate more widespread adoption of technologies, and to provide the necessary conditions to provide adoption of emission-reducing technologies that are not cost-effective under current circumstances.

Generally, the steel industry has made significant progress during the last decade in decreasing CO_2 emissions in both the integrated and minimill sectors of the industry. Figures S1a and S1b show that an approximately 10 percent decrease in CO_2 emissions, compared with current conventional U.S. practices has already been demonstrated in at least one operating plant somewhere in the world. Presumably, domestic producers could be given incentives to adopt these technologies with properly designed policies. Other incremental technology improvements could decrease emissions by perhaps an additional 10 percent, but they would come more slowly because additional development and economic incentives may be required.

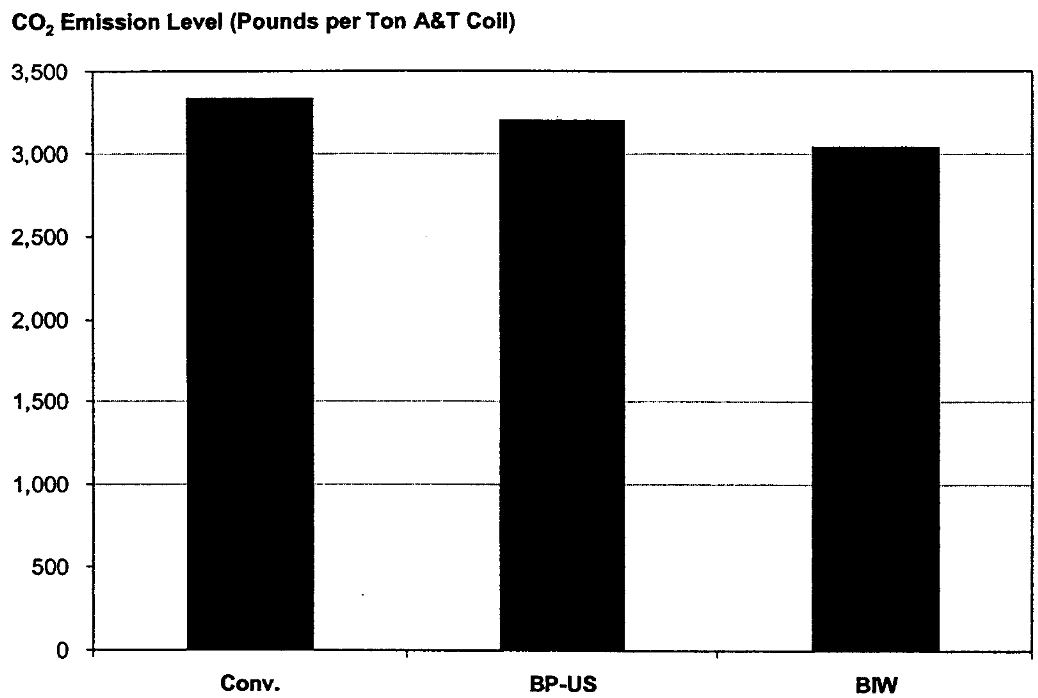
Figure S1a. Carbon Dioxide Emission Level: Final Annealed and Tempered Product from Blast Furnace/BOF



BP-US: Best Practice U.S.
BIW: Best Practice in the World

Source: Charles River Associates, 2001.

Figure S1b. Carbon Dioxide Emission Level: Final Annealed and Tempered Product from Conventional Charged EAF



BP-US: Best Practice U.S.
BIW: Best Practice in the World

Source: Charles River Associates, 2001.

There always exists the possibility that discrepancies among various engineering analyses of energy consumptions and emissions arise from excluding or including energy requirements in certain precursor operations or in other raw materials used, such as oxygen. For example, Stubbles[3] reports that the best U.S. practice in the production of hot metal—the largest emitter of carbon dioxide in the chain of various steps in steel production—is 20.08 million BTU per ton of hot metal. This is equivalent to an emission rate of 4,249 pounds of carbon dioxide per ton of liquid iron, as compared with the value calculated by CRA of 4,412 pounds per ton. CRA's value is based on actual results at the best operating blast furnace at the US Steel plant in Gary, Indiana. (By contrast, the average value for all U.S. blast furnaces is 4,525 pounds of CO_2 per ton of liquid iron.) Most of the difference can be attributed to noninclusion of the carbon dioxide emissions attributed to factors such as the consumption of lime, the use of natural gas in the blast furnace stoves, and the oxygen required in the injection of coal. These omissions alone would account for 288 pounds of CO_2/ton of hot metal giving a corrected total

[3] Op cit.

of 4,537 pounds of CO_2/ton of hot metal in the Stubbles estimate, which is essentially the same as estimated by CRA.

Fruehan[4] et al. analyzed the CO_2 emissions for various unit process steps in the production of steel. This analysis was designed to put a theoretical, lower limit on the carbon dioxide emissions and is a good road map. However, there are practical considerations, such as heat losses, process inefficiencies, and other unavoidable losses, which preclude the achievement of theoretical values.

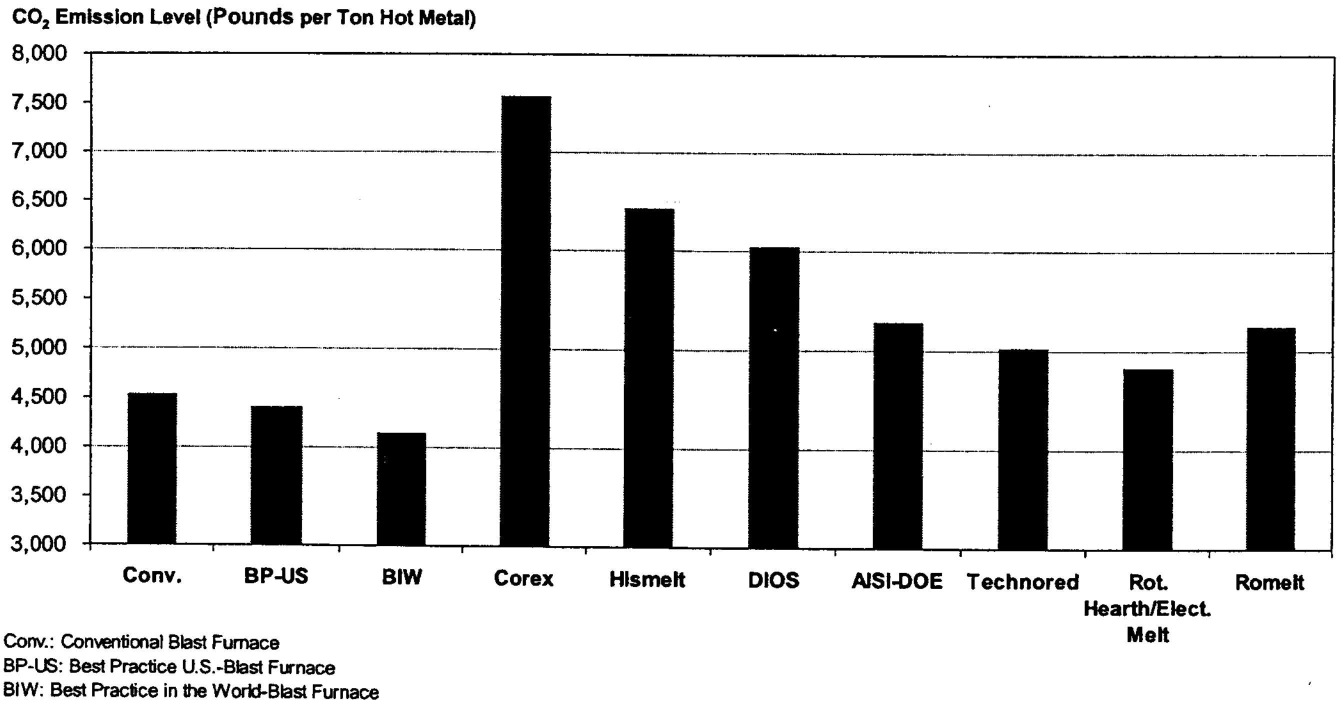
Scrap-based electric furnace steel making has much lower CO_2 emission per ton of steel than that based on the virgin iron ore reduction as shown in charts S1a and S1b above. Most industry observers expect that the trend of increasing production share being captured by the minimill sector will continue, and that this alone will reduce average energy consumption and, therefore, carbon dioxide emissions by the industry. For example, Stubbles[5] projects an industrywide reduction in specific energy consumption of about 14 percent, from about 17.4 to about 15 million BTU/ton, from practice in 2000 to 2010 conditions. However, only about 35 percent of the total is attributed to the structural change in the industry caused by the loss of share in the integrated sector, so that about 9 percent must be technology-driven. There is a finite supply of high-quality scrap, and additional iron units must be generated from the reduction of virgin iron ore to satisfy the overall U.S. demand for high-quality, low-residual flat rolled steel, and this will mitigate the savings achievable by simple structural changes. Overall, CRA's projection of savings of up to 10 percent through new policy-driven incentives is only slightly more aggressive than that projected by Stubbles on a "business-as-usual" basis.

Incremental improvements in these two steel making routes will continue to occur and are evaluated and discussed more fully in the report. Our engineering analyses show that all newly proposed iron ore smelting processes or coal-based, direct reduction processes will emit more CO_2 per ton produced than existing technologies, as shown in Figure S2. The reason for this is that these processes have been proposed or developed to address conventional economic issues in the industry, not to reduce CO_2 emissions. Specifically, development objectives have been to eliminate the use of coke and, in some cases, to use ore fines instead of the more costly lump ore or pellets. These technologies were expected to reduce capital requirements and/or operating cost vis-à-vis conventional coke-based blast furnace reduction of pellets. Whether any of these processes are adopted by the steel industry depends on the market forces and the policies adopted, but our analysis excludes them from consideration.

[4] Op cit.
[5] Op cit.

Since CRA's estimate that up to 10 percent reductions in specific carbon dioxide emissions should be possible in the domestic industry, even in the absence of structural changes in the industry, and is based on practice demonstrated elsewhere in the world, the question arises: why haven't such changes already been adopted here?

Figure S2. Carbon Dioxide Emission Level: Smelting Processes



Source: Charles River Associates, 2001.

Market barriers and market failures can provide explanations for why economic and demonstrated or promising technologies apparently are not adopted. Some of the market barriers include higher-than-anticipated retrofitting costs, the perceived short life of the existing plant (i.e., the threat of shutdown), limitations on domestic engineering resources needed, the preferential deployment of the available capital to projects related to product improvements, and finally, the risk of interruption of production during the installation of the new technology.

Market failures arise from a misalignment of private and social incentives. An example of market failure is that created by the failure to price greenhouse gas emissions in a world where such emissions are believed to create environmental harm.

If greenhouse gas emissions are indeed creating environmental damage, then failing to control them represents a fundamental market failure. Pricing greenhouse gas emissions at a level equivalent to the environmental damage they create on the margin represents an ideal measure for dealing with this market failure. As a practical matter, however, it will be difficult, if not impossible, to assess the correct social cost of such emissions. Nonetheless, putting the correct equivalent price on all such emissions represents the lowest-cost strategy for reducing economywide emissions by any given amount. This pricing can be done through carbon taxation, a carbon permit trading, or by subsidizing avoided emissions. Any of these policies are likely to bring about wider use of some energy-saving technologies that are not economically viable at today's energy prices. However, such measures, if adopted unilaterally by the United States or even by the industrialized nations alone, would almost certainly have disastrous results for the U.S. steel industry.

In order to present our evaluation of these policy options, CRA prepared a summary of the findings of the technology evaluation presented above and of the range of policy options that might be considered. The summary was delivered to the staff of both integrated and minimill steel makers, industry trade groups (e.g., AISI), and relevant experts in government agencies (DOE, EPA) and sectors that support the steel industry (e.g., engineering firms). While there were differences in emphasis in the responses, there was broad agreement on a number of issues.

Four major reasons were given why apparently cost-effective technologies have not been adopted more widely:

- The poor financial conditions of the industry.
- High site-specific costs.
- The perceived risks of retrofitting technologies.
- Environmental regulations and permitting processes that block energy saving investments.

Three policies emerged from the interviews with strong and consistent support:

- Policies that would raise the price of steel imports.
- Targeted tax incentives.
- Removal of obstacles in environmental regulation.

All the respondents strongly supported policies to manage steel imports in a manner that would improve profitability without preserving weak competitors. Since many of the industry's financial problems were attributed to excess capacity worldwide, all stressed the need to reduce global overcapacity. A healthy industry was seen as having more financial resources and being more likely to be willing to invest in improving energy efficiency.

Targeted tax incentives were generally viewed with favor. However, the respondents were insistent that tax credits had to be certain, and not subject to IRS negotiation and interpretation. They were also quite clear that tax credits should not specify particular technologies and, at the same time, believed the incentives should be limited and targeted.

Better coordination between DOE and EPA, and removal of obstacles to energy-saving technology created by prevention of significant deterioration (PSD) rules and permitting processes, were also mentioned frequently. A number of clear examples of efforts to install energy-saving technologies that were blocked by existing EPA regulations and procedures was given. EPA staff involved with the industry acknowledge that such problems exist.

Policies with more limited but definitely positive support included first-mover assistance and cooperative R&D. First-mover assistance had some support, based on the observation that everyone in the industry wants to be second in adopting new technologies. Little detail was provided on what technologies might actually be developed or how such a program would be organized. R&D consortia were generally viewed favorably but seen as already in existence where needed, so that new initiatives in the cooperative R&D were not given high priority. Larger tax benefits for R&D, in general, were supported by some.

Two policies elicited an almost total lack of positive interest, though no opposition: technical assistance programs and targeted loan guarantees. Although many respondents identified an industrywide lack of engineering capability as a problem, few thought that bringing in outside advisors or experts on energy efficiency would be of any benefit. Skepticism regarding the ability of such programs to provide real expertise and a feeling that advisors would lack site-specific knowledge were given as reasons. Targeted loan guarantees were seen with much less enthusiasm than tax incentives, even if they were equally narrowly focused. There seemed to be a perception that loan guarantees were only helpful to failing firms, while tax credits were only valuable to profitable firms, and the respondents all gave high priority to getting rid of weaker firms.

Some policies were strongly and universally opposed, including general loan guarantees, higher energy prices, and adoption of the Kyoto protocol. General loan guarantees were universally criticized on the grounds that they would only aid failing firms and, in doing so, would tend to preserve excess capacity and prolong the financial problems of the industry. Their firm opposition to the Byrd bill was frequently brought up by the respondents, who pointed out that even companies now in bankruptcy had not had problems getting financing until very late. Higher energy prices were expected to stimulate improvements in energy efficiency. However, they were characterized as starting a vicious circle by raising costs and making U.S. steel makers even less competitive, which would further reduce funds available for investment and stimulate imports. In line with those observations, the Kyoto Protocol was seen as exporting production and emissions to Annex B countries, and was generally vigorously opposed.

Overall, industry executives did not see improvements in energy efficiency or reductions in carbon dioxide emissions as a high priority for the industry. They saw some conflicts between improving energy efficiency and improving economic efficiency, mentioning highly desirable operating strategies that would increase carbon emissions. They also did not believe that there was much potential for improvement, since new plants were state-of-the-art and retrofit was excessively costly for the rest. They were far more interested in whether a measure would be good for the overall health of the steel industry than whether it would be effective in reducing the energy use or emissions. In general, they only supported policies that were sufficiently voluntary that they would do no harm if not successful. The executives did strongly support reform of environmental regulations and processes to remove obstacles to investment in new technologies, and probably saw more effects on energy use and carbon emissions coming of this than anything else. There was no indication of a general belief that policies could produce very significant changes in emissions (except for policies like higher energy costs that would force additional plant closings and shift emissions offshore). They firmly rejected any policies that were seen as propping up weaker parts of the industry.

CRA ANALYSIS OF POLICY OPTIONS

The policy recommendation most likely to produce reductions in energy use and carbon emissions and at the same time provide direct economic benefits to the steel industry is the removal of unnecessary obstacles to investment created by environmental regulations. This change could, however, require reopening Title V of the Clean Air Act Amendments and replace New Source Review procedures and New Source Performance Standards with a more market-oriented and even-handed approach that addresses emissions rather than technology requirements.

If managing steel imports is desirable on other grounds, such policies are also likely to have beneficial effects on investments in energy efficiency that will reduce carbon emissions because increased margins will improve the overall health of the industry.

Two programs have sound economics, and could have net economic benefits but small overall effects: these include support for R&D into technologies and processes that could reduce energy use and greenhouse gas emissions, provide for exchange of information, decrease risk, include technical advisory programs, and provide for "first-mover" incentives. Although these programs would decrease the technological risks associated with new innovations, the commercialization would require significant amount of scarce capital.

None of the industry's other recommendations suggest serious market imperfections that could be removed to produce costless reductions in emissions. Programs favored in interviews, such as targeted tax incentives or loan guarantees, involve expenditures (in one form or another) to cover real costs incurred in reducing energy use or emissions. Identifying programs that provide the most reduction per dollar and deciding how much a unit reduction in emissions or energy use is worth are the remaining issues. Universal industry opposition to the measures that are globally cost-effective (such as emission trading and energy taxes) suggests that constructing a comprehensive, least-cost policy toward energy efficiency and carbon emissions will be very difficult.

2. Introduction and Background and Methodology

DOE PROGRAM

The Office of Industrial Technologies of the US Department of Energy has embarked on a program reviewing the energy consumption patterns and opportunities for reducing energy consumption and attendant greenhouse gas emissions in the energy intensive manufacturing sectors of the United States economy. As part of this program, the Office has sponsored a three-part study of the domestic steel industry. One part of the study, carried out by Dr. John Stubbles,[6] presents an overview of the structure of the industry; descriptions of the salient features of the technology it employs; a discussion of how the technology and energy consumption patterns have changed over the past 50 years; estimates of current levels of emissions of carbon dioxide; and projections of specific energy consumption changes out to 2010, due to continuing changes in both the structure and technology used by the industry. Stubbles' estimates are based on a general appreciation of the technology used in both integrated and minimill sectors, as well as production and consumption figures that companies have reported to the American Iron and Steel Institute (AISI). In projecting future energy consumption patterns, Stubbles has made a number of assumptions regarding the changes in production shares that will occur among the industry sectors, the change in total demand and import shares, and the rates of adoption of certain key technology changes (e.g., the fraction of EAF shops that will produce flat products from charges containing large amounts of scrap alternatives produced from iron ores).

Taking 1990 as a base year, Stubbles shows that the average specific energy consumption in the industry had been reduced by 50 percent since 1950, due mainly to greatly reduced blast furnace fuel rates; the replacement of open hearth furnace/ingot casting technology with basic, oxygen furnace/continuous casting technology; and the increased production of steel from scrap in electric arc furnaces. His projection of ongoing decreases in specific energy consumption of 13 percent by 2000 from the 1990 levels incorporates the suite of assumptions described above. However, only about 35 percent of the total is attributed to the structural change in the industry caused by the loss of share in the integrated sector, so that about 9 percent must be technology-driven. There is a finite supply of high-quality scrap, and additional iron units must be generated from the reduction of virgin iron ore to satisfy the overall U.S. demand for high-quality, low-residual flat rolled steel, and this will mitigate the savings achievable by simple structural changes. Overall, CRA's projection of savings of up to 10 percent through new policy-driven incentives is only slightly more aggressive than that projected by Stubbles on a "business-as-usual" basis. This holds true against either current, best-practice performances, as well as other new developments in technology in the U.S. or elsewhere.

---

[6] Op cit.

A second part of the study, carried out by Dr. Richard Fruehan and colleagues,[7] examines the minimum theoretical energy requirements for key process steps in steelmaking. The study includes reduction of ore to hot metal; its conversion to raw steel, by oxidizing impurities in a basic oxygen furnace; production of liquid steel, by melting scrap in an electric arc furnace; hot rolling of slab and further cold rolling. The objectives of these analyses were to estimate both the theoretical and practical minima in energy consumption for the selected steps, compare them to actual "typical" energy consumptions, and convert the energy consumption estimates to estimates of the amounts of carbon dioxide that would be emitted for each case.

Fruehan et al. had to make the usual basic assumptions to carry out the calculations, and these assumptions are not necessarily consistent with those used by Stubbles or by CRA in their analyses. For example, coke oven gas is treated in the same way as natural gas for computation of carbon dioxide emissions. Also, the energy consumption for pellet production, coke production, and production of consumables, such as alloys and oxygen, is not considered; this underestimates emissions by about 15 percent. Furthermore, the Fruehan study distinguishes between an absolute minimum energy requirement and a practical—but still theoretical—minimum that recognizes such factors as the unavoidable production of slags. The Fruehan study estimates that typical, actual energy requirements for the most energy-intensive operations in the production of liquid steel—blast furnace/BOF and electric arc furnace routes—exceed the estimated practical minima by 30–50 percent.

The actual requirements for hot and cold rolling exceed the estimated practical minima by far larger amounts, but the absolute amounts of energy consumed, and carbon dioxide emitted, are substantially lower than for production of liquid steel.

Taken together, these studies suggest that, while the domestic industry will continue to improve its energy efficiency and reduce specific carbon dioxide emissions, there should be room for even greater improvement. However, the Fruehan study does not consider the economic challenges and consequences of achieving or even approaching the "practical" minima, and the Stubbles study attributes a substantial fraction of the benefit to structural changes in the industry, as opposed to improvements in technology.

CRA APPROACH AND METHODOLOGY

The key objectives of this study are to identify and evaluate applicable technologies, market barriers to their adoption, R&D approaches to develop new technologies, and policy instruments to promote the reduction of carbon dioxide emissions in the iron and steel industry. To meet these objectives, CRA needed to examine the elements of steelmaking technology and economics in more detail than had been done in the two studies cited above. It also required that specific barriers to technology

---

[7] Op cit.

adoptions be identified, so that specific policy options could be evaluated. Also, our analysis of the potential effectiveness of the options needed to be communicated to the decision makers in the industry as well as others in government agencies and supporting industries with relevant background and experience. To accomplish this, CRA has executed a program consisting of four major tasks described below.

TASK 1—REVIEW RELEVANT TECHNICAL ANALYSIS AND POLICY LITERATURE

The first step in this task was to identify specific, technologies/process changes that are either currently available or potentially feasible for reducing energy consumption and greenhouse gas emissions from the iron and steel industry.

There are several "potentials" for reducing carbon dioxide emissions in the steel industry. These can be classified as follows:

- Decrease the amount of CO_2 emitted for required reduction of iron ore to produce virgin iron metallics by, e.g., using hydrogen instead of carbon for reduction.
- Decrease the amount of power required to produce liquid steel.
- Decrease the amount of power and heat required to produce sellable solid products by:
  - Increasing thruputs.
  - Eliminating unit processes such as breakdown rolling, cold rolling, etc.

For each technology and process change, we developed estimates of potential energy savings, implied greenhouse gas emissions (per unit and for industry based on penetration and applicability), stage of development, technical risks, capital investment requirements (both for development and implementation) and operating costs. The technologies were identified and analyzed based on CRA's extensive knowledge of the iron and steel industry, as well as via a detailed review of relevant literature.

Having identified and characterized relevant technologies, the next step was to identify barriers to energy efficiency improvements. There is a large amount of literature on this subject that CRA has participated in and reviewed in depth.[8] These studies, their references, and a search of the peer-reviewed literature were evaluated to determine what has been published specifically on technologies and market barriers in the iron and steel industry. In its review of the literature, CRA also collected conclusions about "barriers" to energy efficiency improvements that are cited in the

[8] Interlaboratory Working Group on Energy-Efficient and Low-Carbon Technologies, *Scenarios of U. S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond,* LBNL-40533 or ORNL/CON-444, September 1997 (http://www.ornl.gov/ORNL/Energy_Eff/labweb.htm); EMF 13 issue of Energy Journal.

different studies. CRA reviewed these studies critically, and classified "barriers" into the categories of possible market failures versus costs that someone has to bear.

CRA also reviewed and summarized the literature on market imperfections and their relation to energy efficiency investments. CRA staff have made significant contributions to this literature,and also participated in the study by the Energy Modeling Forum that brought together the leading groups studying this subject. As discussed in the paper by Cameron, Foster, and Montgomery,[9] market barriers need to be divided into two groups: those that are due to market failures and those that arise from "hidden costs." An important example of the first type of market barrier is the difficulty that inventors face in capturing all the economic benefits of innovations. In the second category fall the costs that are inevitably incurred when a technology or process is adopted, such as the risk of making large capital investments in a cyclical industry.

CRA also reviewed policy measures analyzed or suggested in the literature that are potentially relevant to the iron and steel industry. Following on the classification system described for separating market failures from hidden costs, we classified policies into measures intended to provide incentives for adoption of technologies that are not cost-effective at current energy prices and measures directed at repairing market failures so that measures that are cost-effective at current prices will be adopted.

CRA also drew on the literature in applied welfare economics to describe how the economics profession recommends measuring the costs and benefits of policies. The theoretical basis for these measures, and how they can be practically applied to the iron and steel industry, was explored in this first task. Some of the topics addressed included:

- Producer and consumer surplus.
- Full lifecycle cost.
- Influence of uncertain/cyclical demand on expected costs.
- Cost of bearing increased risk.
- Costs associated with premature retirement of productive capital.

Finally, our previous work on cost-effective policies to promote action to reduce greenhouse gas emissions suggests that cooperative R&D programs have great potential (see Montgomery, IPIECA

[9] Energy Policy Alternatives, CRA, 1991, for the MVMA; No Free Lunch, a review of a series of studies released through 1993, Jaccard and Montgomery; Energy Policy, Cameron, Foster and Montgomery, in Reviews of Energy; W.D. Montgomery, "The Economics of Conservation." In M. Kuliasha, A. Zucker, and K. Ballew (eds.), Technologies for a Greenhouse-Constrained Society. Chelsea, MI: Lewis Publishers, 1992.

and ACCF volumes).[10] Therefore, we surveyed the literature on cooperative R&D programs in the steel and other industries to identify good and bad ideas about how those programs could be designed. Examples of such programs are:

- Partnership between the American Iron and Steel Institute and DOE for smelting of iron ore with an objective to produce liquid iron by using injection of coal in a bath. There are numerous other cooperative projects between the steel industry and DOE.
- The Partnership for a New Generation of Vehicles (PNGV), including the U.S. auto manufacturers and DOE, jointly fund a systematic program designed to produce the technologies required for production of an affordable, attractive car with 80 mpg fuel economy.
- The Advanced Battery Consortium, composed of DOE and auto and battery manufacturers working to create the fundamental breakthroughs in battery technology required for electric and hybrid vehicles.
- Sematech, the Semiconductor Manufacturing Technology Institute, created to improve the competitiveness of the U.S. semiconductor industry.
- The Electric Power Research Institute (EPRI), the collaborative research arm of the U.S. electric utility industry.
- Center for metal production at Carnegie Mellon University, a collaborative research arm of EPRI and the Metal Industries.

The results of Task 1 were presented in a report, summarizing the literature and describing findings about applicable technologies, market barriers, possible policy instruments, and R&D consortia applicable to the iron and steel industry.

TASK 2—REVIEW INSIGHTS WITH RELEVANT INDUSTRY, GOVERNMENT, AND OUTSIDE OFFICIALS AND EXPERTS

Having developed our initial analyses in Task 1, we sought input from relevant industry, technology, and government experts. These discussions were focused on two different objectives:

- Solicit opinions of other experts to identify additional technical approaches to reduce greenhouse gas emissions and test our analyses from Task 1.

[10] "Framework for Short and Long-Term Decisions." In critical issues in The Economics of Climate Change, ed. B. Flannery and D. Kennedy, IPIECA, London, 1997 and "Developing a Framework for Short- and Long-Run Decisions on Climate Change Policies." In C. Walker, M. Bromfield, and M. Thorndike (eds.), *An Economic Perspective on Climate Change Policies*, Washington, D.C.: American Council for Capital Formation, 1996.

- Test analyses of policy measures and potential solutions developed in Task 1.

As a first step, CRA prepared an executive summary of information, developed in Task 1, to share during interviews and provide a basis for further discussion. During the interview process, we solicited the opinions of a variety of industry experts, including:

- Iron and steel company management personnel (technical, operating and corporate), such as CEOs, VP Operations, VP Technology, Equipment and technology suppliers, Trade associations (including AISI, AISE, and SMA), Collaborative research organizations, such as EPRI-Center for Metal Production (CMP), GRI, etc., and Government Agencies (e.g., EPA and DOE).

Depending on the interests and expertise of the individuals we interviewed, we expected to discuss the following topics:

- What are the technical risks in the major technologies identified in Task 1?
- How realistic are the energy savings and costs for major (large potential applicability and low cost) technologies identified in Task 1?
- Why are apparently attractive measures not used? For example, in many steel plants, significant quantities of blast furnace off gases are flared which produce carbon dioxide without the recovery of the contained energy.
- What other approaches to reducing greenhouse gas emissions in the iron and steel industry should be evaluated?
- What other (hidden cost) barriers to implementation exist?
  - Incremental labor and management costs of installing, training and operating new equipment or practices.
  - Changes in health, comfort, or safety in the workplace.
  - Risks of failure, malfunction, or interaction with existing processes that could interrupt production.
  - Market acceptance of the new products produced by more efficient processes.
- How could a cooperative research program be designed to be effective in light of the industry's structure, R&D processes, and financial condition?

TASK 3—ANALYSIS

The third task was to analyze the information on technologies, costs, market barriers, and potential policies developed in the first two tasks to:

- Identify market failures that could be corrected through creative policy design and lead to greater reduction in green house gases.
- Estimate the cost of reducing energy consumption in the iron and steel industry further through adoption of technologies and process changes that have costs, including both hardware and hidden costs, greater than the value of energy savings.
- Design policies that correct market failures or provide incentives for greater efforts.
- Characterize the energy savings, costs, and economic impacts of these policies.

Since this is a somewhat different methodology than is typical of so-called bottom-up studies of energy efficiency (which typically conclude that significant improvements in energy efficiency can be achieved without cost) an important part of CRA's analysis was to explain the methodology we used. We needed to explain how it is derived from the economics literature surveyed in the first task and the industry insights gained in the second task. One of the important parts of this explanation involved drawing distinctions between market imperfections (which provide opportunities to find policies that bring about cost-effective improvements) and hidden costs (which can be overcome with adequate incentives, but which remain costs that must be borne by someone—the business, the taxpayer, or some other party).

This distinction is important because there appear to be market imperfections in the area of R&D that might enable efficient policies designed to stimulate appropriate R&D (such as cooperative research programs), to produce reductions in greenhouse gas emissions at costs less than the value of energy saved. When these market imperfections are not present, policies must overcome the fundamental problem of no market incentives—other than potential savings on energy costs—to reduce greenhouse gas emissions. Also, energy costs have been low and stable for some time, despite recent spikes in the costs of natural gas and electricity. Lacking broad measures in the United States to control greenhouse gas emissions—such as a broad tax on the carbon content of fuels, or a permit trading system—it is necessary to look for substitute incentives to encourage greater energy efficiency. Moreover, since there are generic market failures in the case of R&D, stimulating adequate research on technologies to reduce energy use in iron and steel could require additional policies, even if there were an adequate carbon tax or permit trading system.

An important part of our analysis was to estimate any hidden costs that were likely to occur, so we could more accurately predict whether policies could effect emission reductions. Many of these hidden costs will emerge in investigating subtleties about the iron and steel market that may discriminate against some technologies. For example, the cyclical nature of industry makes capital-intensive solutions more costly. Capital replacement cycles, and the relative growth or decline of industry segments that might use them need to be taken into account in economic comparison of technologies.

Many technologies have significant risk associated with the scale-up from a pilot plant to a commercial plant. These risks need to be addressed, as do the more "normal" risks to production associated with the adoption of "known" technologies in a new setting.

In addition, it is important to discuss, and where possible estimate, the administrative or "transaction" costs of policies, including structural measures designed to reduce market imperfections.

The next step was to review the candidate policy measures, including both those listed by DOE and others that appear in our review of the literature and discussion with industry leaders and experts. This step required us to address a number of questions: How important are different types of policies? Which areas are worth giving the most attention to? Which types of "impediments" are most likely to be true market failures? Which "impediments" can be addressed by policies that have some potential of producing large beneficial effects? What are the characteristics of undesirable policies (limited scope, lack of problem to solve high cost)?

Based on this review, the policies were divided into three groups:

- Policy measures that address market imperfections, such as policies to stimulate R&D.
- Policies that that can be reasonably expected to be effective and efficient in bringing about additional, admittedly costly, improvements in energy efficiency when market imperfections do not exist or cannot be removed.
- Policies that are likely to be excessively costly, because of administrative burden, creation of perverse incentives, or minimal effectiveness in inducing changes.

We concentrated on policies in the first two categories, and developed estimates of costs, emission reductions, and economic impacts for these policies.

The first step in this analysis was to estimate emission reductions and cost. There are three important steps in this estimation: First, estimate the emission reductions and cost per unit of output or capacity in the industry. Second, estimate how large the potential applicability of the technology is. This calculation has to take into account how that capacity will grow or shrink over time. Third, estimate the penetration rate of the new technology, as a percent of the total potential market achieved each year. For example, if a technology or process is most economical as capital equipment is replaced, what is the normal replacement cycle for the type of equipment in question? Finally, emission reductions and direct costs are estimated as the product of the per unit emission reduction (or unit cost) times the potential market times the penetration rate.

One of the areas most likely to produce cost-effective policies is in cooperative research programs. Cooperative R&D provides an effective answer to the question of how to change the direction of R&D toward improvements in energy efficiency when market signals (in the form of high energy prices) are not there.

There are several reasons for starting with cooperative R&D through research consortiums:

1. They have worked in other industries, as the PNGV example demonstrates.

2. They are a reasonably efficient way of providing incentives in advance of full permit trading and of sharing risks associated with scale-up to large capital- intensive projects.

3. Additional incentives for R&D are needed even with comprehensive economic incentives for reducing emissions, because of the difficulties of fully capturing profits from and simultaneously encouraging maximum use of innovations.

4. Cooperative research programs need to be designed carefully to be effective.

Investigation of cooperative research programs included the following steps:

- Identify possible future technologies/processes for the iron and steel industry based on Tasks 1 and 2.

- Discuss R&D history, practices and levels of funding in the industry.

- Discuss incentives for R&D in the industry practices for licensing of technology, existing cooperative research arrangements, etc.

- Discuss what economic characteristics a technology requires to be a winner (size of potential market, cost, etc). This is much the same analysis a venture capitalist might undertake in investigating the market for innovations—the information required to estimate potential profits from using or licensing the technology. It includes such issues as the amount of production affected by an innovation, how that market will change over time, the kinds of risks associated with adopting the technology replacement cycles for equipment, and absolute cost advantage over competitors. The lack of market signals for more efficient technologies complicates the analysis of programs to stimulate R&D. In thinking about candidate technologies, it is useful to keep in mind the principles of dynamic programming. These principles suggest the need to work our way back from ultimate market acceptance for a technology to address the best current decisions about the speed and direction of R&D, recognizing uncertainties and decision points along the way.

CRA then applied the lessons learned from cooperative R&D programs in the steel and other industries to propose a form for cooperative R&D in the iron and steel industry. There are a number of design issues in regard to R&D consortiums that must be addressed. These include how to identify efficient means of combining government and private funding, provide incentives for participating companies and universities to bring their best and brightest engineers and scientists to the consortium, and how to keep "picking winners" out of government hands.

Cooperative R&D is not the only approach to stimulating additional R&D. There are other financial measures that could be applied to stimulate investment in energy efficiency R&D:

- Government procurement of specific R&D.
- Establishment of entitlements, such as tax credits for R&D in relevant areas.
- Winner-takes-all competitions for the best idea.

In evaluating these alternatives, one of the important issues is whether eligibility for incentives should be broad or narrow. The trade-off here is that broad eligibility (such as an R&D tax credit) gives industry the maximum flexibility to find the best solution, but studies of tax credits have demonstrated that most of the taxpayer funding goes to projects that would have been undertaken anyway. Narrower eligibility—with direct funding of specific technologies being the narrowest—avoids creating windfalls, but substitutes the government's judgment in "picking winners" for the judgment of investors and entrepreneurs in the industry itself, and is likely to be rejected hands-down in Task 2 of this project.

There are also issues that deal with what kinds of research should be supported, with the distinction between precompetitive and competitive R&D the most common dividing line.

TASK 4—REVIEW PRELIMINARY CONCLUSIONS AND PREPARE FINAL REPORT

The final task consisted of drawing all this analysis together into a set of findings and recommendations, which are presented in this final report.

3. Industry Structure, Steel Making Technologies, and Financial Performance

INTRODUCTION

The iron and steel industry in the United States (SIC 331) is a significant emitter of greenhouse gases, mainly in the form of carbon dioxide. Stubbles estimated that, in 1998, the industry emitted about 185 million tons of CO_2, which amounted to a specific CO_2 emission rate of about 1.7 ton/ton of steel produced.[11] The industry has made significant progress since 1990 in decreasing carbon dioxide emissions as shown below (see Table 1).

Table 1. U.S. Steel Production and Associated Carbon Dioxide Emissions in 1990 and 1998

Year	1990	1998
Total raw steel produced (million tons)	95.4	108.8
Electric arc furnace-based production	36.9	49.1
Blast furnace/BOF-based production	58.5	59.7
Tons of CO_2 emitted (million tons)	209	185
Tons of CO_2/ton of steel	2.2	1.7

Source: CRA estimates based on 1990 and 1998 AISI data and reference 1.

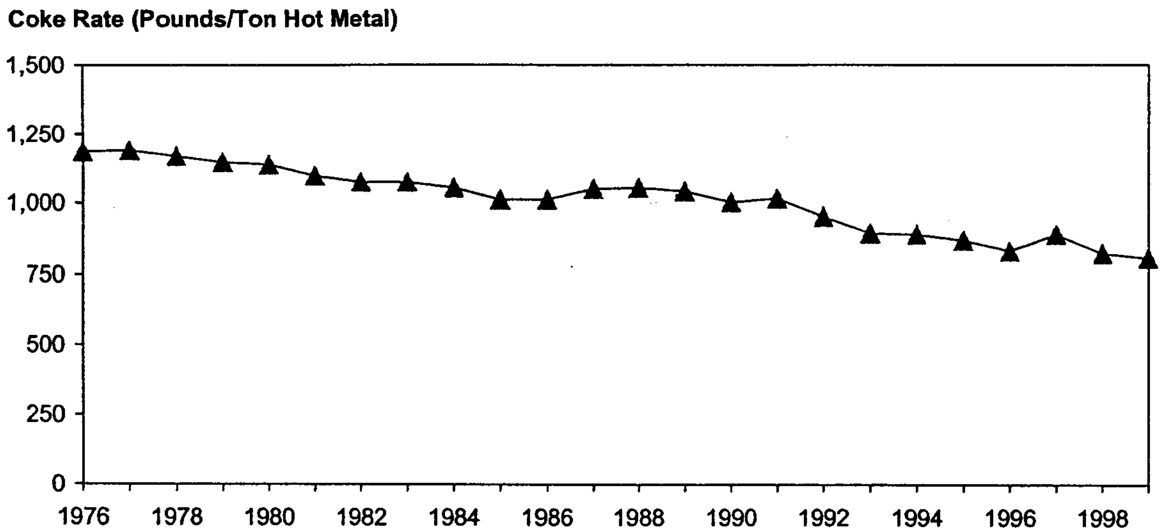
The specific rate of CO_2 emission has been decreased by more than 20 percent for a variety of reasons. A major contributing factor in the integrated sector has been a decrease in the coke required to produce a ton of iron, from approximately 1,000 pounds of coke per ton of iron to approximately 850 pounds of coke per ton of iron over this period (see Figure 1). In addition, the growth of EAF production share, with its inherently lower CO_2 emissions per ton, has been an important factor.

While this achievement has been substantial, the specific energy consumption and carbon dioxide emission rates can still be improved by using both demonstrated technologies and some improved technologies that require additional R&D.[12]

[11] Op cit.

[12] *Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the US Iron and Steel Sectors,* LBNL-41724, July 1999.

Figure 1. Historic Blast Furnace Coke Rate in the United States 1976–1999



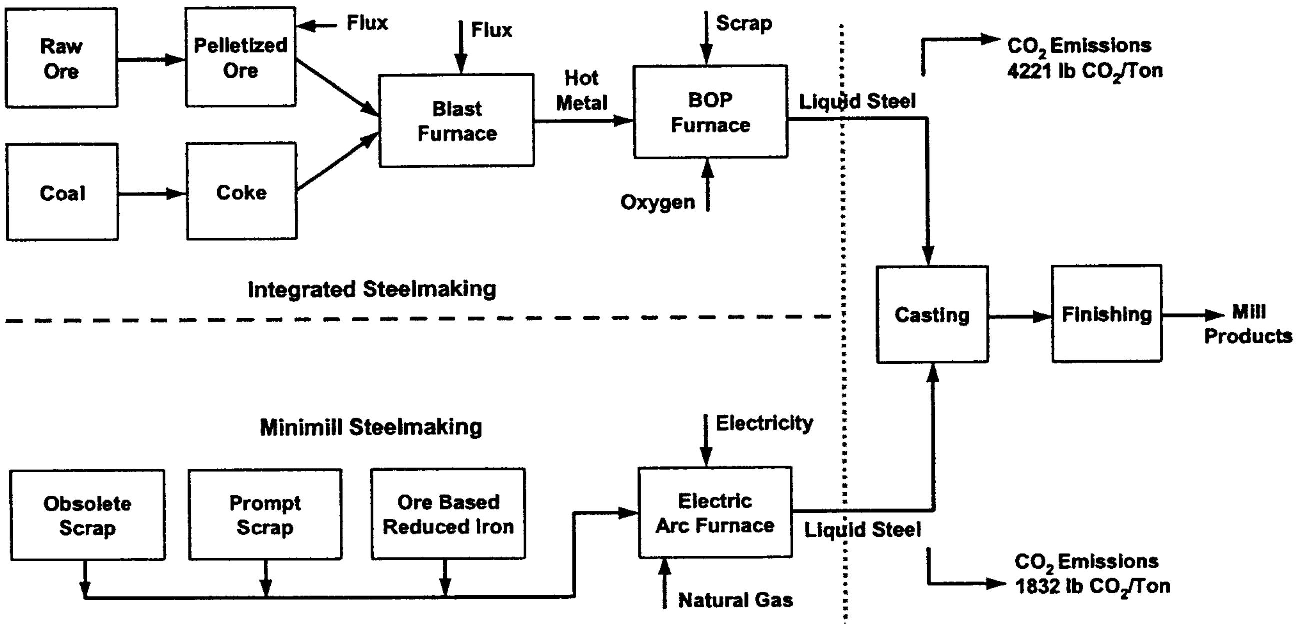
Source: Charles River Associates, based on AISI Annual Statistical Reports.

In this chapter, we first describe the current structure of the industry and the salient features of its production technologies, with an emphasis on the characteristics of the technologies that lead to CO_2 emissions. We then review and characterize the technologies that are available now to improve process energy efficiency and reduce CO_2 emissions, as well as those that have been proposed or are in various states of development but have not as yet been commercialized.

CURRENT INDUSTRY STRUCTURE

For some time, it has been customary to refer to the steel industry as having two major segments or sectors: the integrated sector and the minimill sector. The production processes used for steel making are what differentiate these sectors (see Figure 2), but product-specific differences in the technologies used in converting crude steel to finished steel mill products, as well as variations in the steel making processes within each sector, will also be described in more detail below. For this analysis, a third segment of the industry, independent processors who transform semifinished products to finished ones, can be looked upon as an extension of the two major segments because the same manufacturing processes are used.

Figure 2. Overall Steel Industry Sectoring



Integrated steelmaking is based on virgin iron units that are produced from ore. In the United States, most ore is ground to a fine size, beneficiated to upgrade its iron content and then pelletized to produce a suitable blast furnace feed. Acid pellets contain much more acidic gangue constituents (i.e., more SiO_2 than CaO) and limestone flux must be added at the furnace to produce slag of the required composition. Fluxed pellets have lime added to them in a more energy-intensive manufacturing step, but they decrease the energy consumption in the blast furnace. Some furnaces charge a mix of pellets and sinter, which is a product made by high-temperature induration of ore fines with coke, and all furnaces charge relatively small amounts of iron-containing scrap reclaimed from mill operations or purchased from outside sources. Some furnaces may also charge larger amounts of prereduced materials, such as direct reduced iron (DRI), as a means of reducing direct energy consumption so as to increase furnace productivity.

The iron ore is reduced in the blast furnace by contact at high temperatures with reducing gases formed by combustion of the coke in the burden. Coke, produced by devolatilization of special grades of coal, provides mechanical support for the pellet/coke mix as well as the carbon for reduction. Currently, all operators also inject supplemental fuels into the furnace, including coal, natural gas, heavy fuel oil, or coke oven gas, in order to reduce coke consumption and increase furnace productivity. In most cases, the energy contents of coke oven and blast furnace offgases are at least partially recovered by burning them at various operations around the blast furnace and in the mill. In some cases, however, a portion of the gases is simply flared. These gases, intrinsic to the process, are by far the major sources of CO_2 emissions in integrated steel making. Mills that use purchased coke emit less CO_2 on site, since the coke oven gases are generated and burned elsewhere.

The product of the blast furnace is hot metal, a carbon-saturated liquid iron that also contains silicon, sulfur, and other elements. It is typically desulfurized and then converted to liquid steel in a high-temperature, basic oxygen process (BOP) furnace by contact with high-purity oxygen. While some scrap or reduced iron units are charged as well, the BOP process is autogeneous (i.e., requires no additional thermal energy), its needs being met by the heat of combustion of the silicon and carbon contained in the hot metal. The offgases from the BOP furnace contain significant amounts of CO, the energy content of which is currently not recovered in domestic practice. The liquid steel from BOP furnaces is then cast continuously into slabs for further processing.

Minimill steel making is based on melting scrap in electric arc furnaces (EAFs) to produce liquid steel. Typically, an EAF charge contains a variety of types of scrap, including home scrap, prompt scrap, and obsolete scrap, and may contain ore-based iron units as well. Home scrap is produced in the mill itself and is recycled internally. Prompt scrap, such as factory bundles, is returned to the steel mill directly from manufacturing operations and is usually of high and known quality, although it may contain objectionable impurities, such as the zinc applied in galvanizing. Obsolete scrap is postconsumer material that may be of variable quality and whose use must be limited to control objectionable impurities, such as copper in the steel. Minimills that produce high-quality products typically add some metallics derived from ore to "sweeten" the charge and dilute the level of impurities carried in with the scrap. The major ore-based metallics charged are cold pig iron (solidified hot metal) and direct reduced iron, which is made from iron ore that has been reduced in the solid state to produce a product whose iron content is typically about 90 percent.

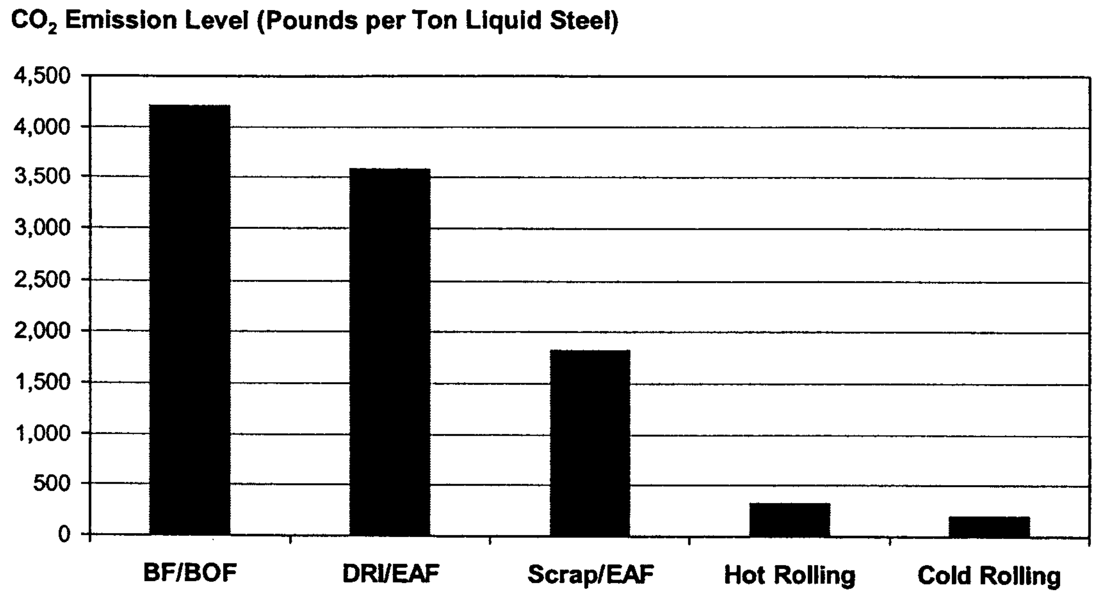
The EAF charge material may be introduced either cold or preheated to the furnaces. It is melted by application of electricity carried by carbon electrodes in either AC or DC furnaces. The EAF charge also includes fluxes to remove impurities and carbon to maintain a reducing environment in the furnace, so as to minimize the high-temperature reoxidation of the scrap and to complete the reduction of any DRI or oxidized scrap (rust) in the charge. Essentially all furnaces today practice injection of natural gas and oxygen to boost furnace thermal input, to reduce electricity consumption, and to improve furnace productivity. They employ the so-called foamy slag practice to assist in these goals and to reduce refractory consumption. EAF furnace off gases are thus a significant source of CO_2 emissions, as are the power plants in which the electricity consumed in the furnace is generated. The liquid steel produced in the EAF may then be transferred to a second, electrically heated ladle metallurgy furnace (LMF) for addition of alloying elements or composition adjustment, as required, before the steel is fed to a continuous caster for solidification.

The schematic diagram in Figure 2 simplifies the casting/finishing sequence for integrated and minimills; there are, of course, significant product-specific differences between the sectors and from mill to mill. Today, all stainless steels and long products (such as rebar, SBQ bar, wire bar, structural sections, and so forth) are produced from continuously cast forms made in what has been described above as the minimill sector. In general, the cast forms are reheated and then treated hot to form the final mill product, be it flat (for stainless), rod, or bar. However, over the last decade, this sector has adopted a new technology—thin-slab casting with in-line reheating furnaces and hot rolling mills—which permits the cost-effective production of hot-rolled products that had previously been produced only by the integrated mills. In fact, scrap-based EAF production of flat products in mills with capacities of two million tonnes per year really strains the definition of a "minimill." Since these types of mills are new and were carefully designed to serve a limited segment of the market, they are quite energy-efficient. The older minimills dedicated to long products production may not be as efficient because of their vintage and scale (some have capacities as small as 50,000 tons per year), and because they may produce a wider range of products.

Integrated mills with larger capacities produce thicker slabs in their casters, which are allowed to cool and then are reheated and passed through hot mills for the production of flat products. The mill equipment generally is not as efficient as that in the newer EAF flat mills, nor is it as effectively arranged. Furthermore, the integrated mills also generally produce a wider range of products (alloy, carbon content, width, gauge) than do the newer minimills, and product changeovers introduce an intrinsic inefficiency into the finishing operations. Some integrated mills also practice further finishing of the hot-rolled flat products. The energy consumption and CO_2 emissions from these operations, which include further gauge/width reduction, tempering, coating, and so forth, are process- and product-specific, and also depend on the layout and age of the equipment.

CRA estimates of the "typical" amounts of CO_2 emitted per ton of steel produced in blast furnace/BOF (integrated) and ore and scrap-based EAF (minimill) steel making through casting, as well as for the subsequent hot and cold rolling operations, are shown in Figure 3 below. It must be emphasized that there are significant mill-to-mill differences within each of these categories because of the differences in size and age of the equipment, as mentioned above. Therefore, technologies that are cost-effective in one mill setting may not be in another, particularly where the technology must be retrofit into an existing operation. Also, no mills in the United States minimill sector use 100 percent ore-based (DRI) charges, but most blend some in with the scrap.

Figure 3. Profile of Current CO_2 Emissions per Ton of Steel



DRI/EAF process based on 100% DRI charge.
Scrap/EAF process based on conventional scrap charge.

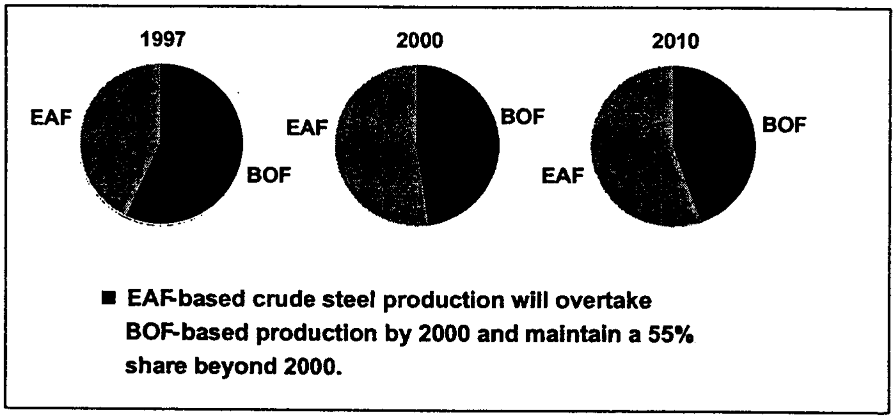
Source: CRA estimates.

Figure 3 shows that, for the production of a given product, the key determinant of specific CO_2 emissions in steel making is the source of the raw material used—ore or scrap. Thus, there are four types of strategies that might be followed in reducing the overall CO_2 emissions from the production of steel in the United States. They are:

- Implement "evolutionary" improvements to each of the basic technologies currently in use—the ore-based blast furnace/basic oxygen furnace route in the integrated sector and the scrap-based EAF route in the minimill sector.
- Develop "revolutionary" improvements to the basic technologies that will reduce emissions, particularly in the ore-based integrated sector.
- Promote a shift of steel making technology from ore-based to scrap-based processes.
- Promote the import of slabs and other semifinished products. This is an emissions export strategy, not a technology implementation one, and will not be discussed at length in this report except to the extent that it might occur as a consequence of some policy option.

In fact, a shift from ore- to scrap-based steel making has been under way for some time, driven by market forces, as shown in Table 1 and below in Figure 4. Since the minimill sector has already captured essentially all long product production, increased production share can come only at the expense of current integrated flat product producers.

Figure 4. The Share of Steel Produced in EAFs Is Projected to Increase



Source: CRA estimates.

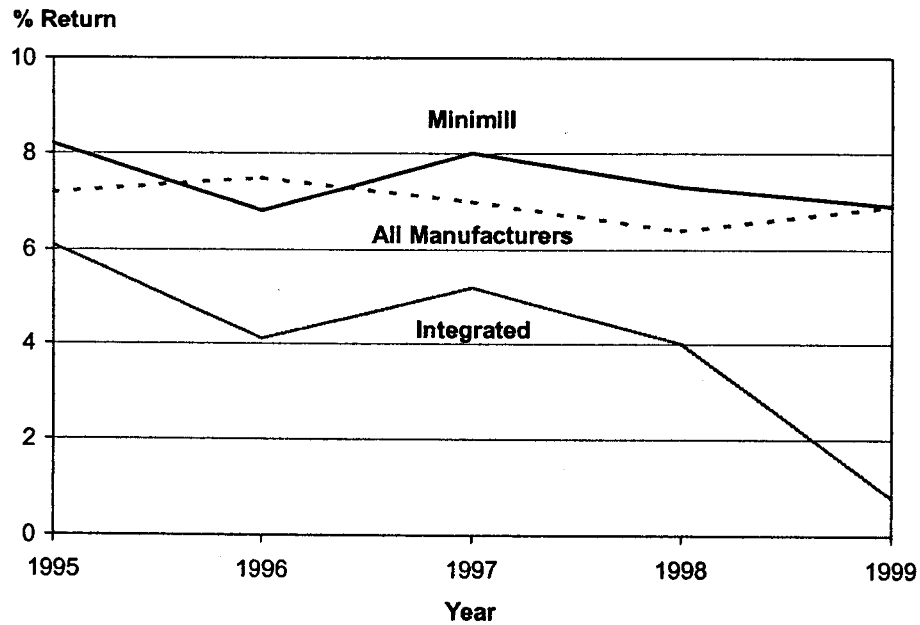
However, this projected shift in market share will not bring about the strictly proportional reductions in CO_2 emissions implied by the simple extrapolation of the values shown in Figure 3. This is because the integrated producers that will be displaced are generally the less efficient ones, so that the average specific CO_2 emissions of the remaining ones will be reduced. Also, production of the higher-quality flat products in an EAF demands a higher-quality scrap mix, the supply of which is limited. Thus, for a large share shift, the United States might have to import high-quality scrap (it is now and has historically been a scrap exporter), or—more likely—larger amounts of low-residual, ore-based materials (DRI and cold pig iron) would have to be charged. This will tend to increase the average specific CO_2 emissions in the minimill sector, since production of these charge materials emits large amounts of CO_2.

In a following section of this chapter we describe the characteristics of "evolutionary" and "revolutionary" technologies that can reduce specific CO_2 emissions in steel making, apart from simply changing the share of ore- and scrap-based processes.

FINANCIAL POSITION OF THE STEEL INDUSTRY

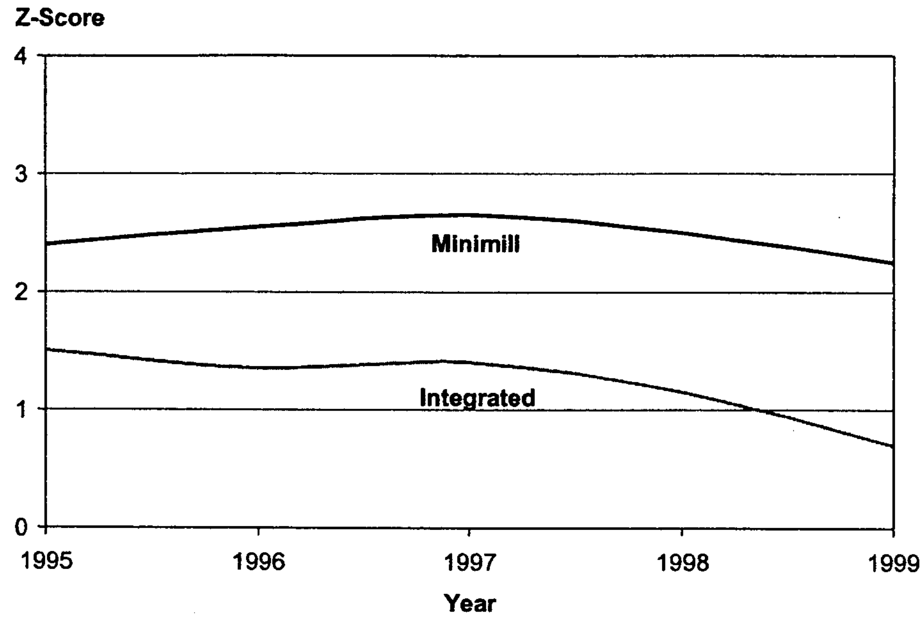
Throughout the 1970s domestic annual steel production fluctuated between about 100 and 130 million tonnes, three-quarters of which came from the integrated sector. The sharp recession in the early 1980s changed the industry, however, and by 1982, annual production had dropped to less than 70 million tonnes, with the loss coming primarily in the integrated sector. It took until the mid-1990s for annual domestic production to return to the 100-million-tonne-level, partly because the amount of imports has increased from the 10 to 20 million tonne per year range in the 1970s to the current range of 30 to 40 million tonnes per year. The domestic overcapacity created in the integrated sector by the loss of market has only slowly been worked off through consolidation and rationalization. Worldwide, there remains significant overcapacity in steel making, and the United States is regarded as the market of last resort. The pressure on operating margins has remained severe throughout this period, and this has resulted in a decline in the financial strength of the industry, particularly in the integrated sector. Recent financial performance is shown in Figures 5 and 6 below.

Figure 5. Return on Assets in Steel Manufacturing



Source: "An Analysis of the Vulnerability of the Industries Producing Corrosion-Resistant Carbon Steel Flat Products, Certain Cold-Rolled Steel Flat Products and Certain Cut-to-Tough Carbon Steel Plate Products." S.P. Kothani, August 2000.

Figure 6. Median Z-Scores in Steel Manufacturing



Source: "An analysis of the Vulnerability of the Industries Producing Corrosion-Resistant Carbon Steel Flat Products, Certain Cold-Rolled Steel Flat Products and Certain Cut-to-Tough Carbon Steel Plate Products." S.P. Kothani, August 2000.

The levels of returns on assets shown in Figure 5 for the integrated sector are in the lower quartile of all manufacturing, whereas the minimill sector has performed about as well as the median for all manufacturing. The equity markets realize this distinction, and the ratio of market capitalization to assets is far lower for the integrated sector than for the minimill sector. The Z-scores shown in Figure 6 are a composite measure of a firm's (or industry's) financial health. Values of this parameter below about 1.8 indicate a high probability of bankruptcy, while values above 3 indicate a low probability of bankruptcy. The Z-scores suggest that both sectors of the industry are at risk, and this is confirmed by the list of recent bankruptcies summarized below.

Table 2. Recent Bankruptcies in the US Steel Industry

Minimill or EAF-Based Sector	Integrated Sector
CSC	Acme Steel
Empire Specialty Steel	Bethlehem Steel
G.S. Industries	Geneva Steel
J&L Structural	Gulf States Steel
Laclede Steel	LTV Steel
Northwestern Steel and Wire	Wheeling Pittsburgh Steel
Qualitech	Republic Technologies
Sheffield Steel	
Trico	

Financial performance this poor has a debilitating effect on the ability of the industry to adapt to technological change. Cost-cutting measures decrease both R&D and in-house engineering capabilities, making it more difficult to evaluate, plan, and manage capital projects that otherwise might be justified. Management gives priority to projects that must be implemented to remain in operation, such as blast furnace relines, or that are required to maintain a customer base, such as upgrading the finishing mills to improve product quality. Some projects are undertaken using off-balance-sheet financing, but this may simply lock a company into a take-or-pay contract that is not advantageous in the long run. The lack of regular, significant capital projects also has deleterious effects in the engineering/design/construction industry that supports these activities, which gradually loses its experience base and reduces its own capabilities. These influences are revealed in the post mortems on such routine projects as blast furnace relines or rolling mill upgrades that go over budget and miss completion deadlines.

Over the past few years, there have been relatively few expansions of productive capacity in the steel industry, and most of these have been in the minimill sector, including Ipsco's new plate mills at Montpelier and Mobile, Nucor's Berkeley and Hertford mills, and those of Northstar BHP and Trico. Among the integrated producers, AK Steel has invested significantly in new capacity at its Rockport finishing mill, but even this company does not have an investment-grade bond rating. Acme attempted a major project (new thin slab caster and rolling mill), the failure of which has resulted in Acme's bankruptcy.

Thus, management is risk averse with respect to investments that may offer what appear to be reasonable paybacks, because poor financial strength forces them to have an extremely short time horizon. Furthermore, the integrated sector's high fixed-cost structure leads it to discount strongly any project that carries the risk of decreasing production, even temporarily, because of the need to maintain sales and cash flows. This problem is exacerbated by the fact that almost all energy savings or carbon dioxide reduction projects would have to be retrofit into existing operations, and retrofit projects are notorious for carrying large hidden costs and being subject to uncontrollable delays.

The practical result of all these factors is to impose very high hurdle rates for "nonessential" projects, which delays the adoption of both new and incremental technologies in the industry.

STEEL MAKING TECHNOLOGIES: THEIR CARBON DIOXIDE POTENTIAL AND COST-EFFECTIVENESS

It is important to establish the bases that are being used to estimate both current CO_2 emissions and the emission reduction potential of the "evolutionary" and "revolutionary" technologies being evaluated, since various sources can use different values. Some overall production and consumption data obtained from AISI for 1998 are summarized in Table 3.

Table 3. 1998 Consumption of Materials and Fuels; Production of intermediate Products and imports of Semifinished Steel[1]

Process	Units	
Cokemaking		
Coal for Cokemaking	M Tons	20,174
Coke Oven Underfiring		
Natural Gas	MM ft^3	275
Coke Oven Gas	MM ft^3	88,386
Blast Furnace Gas	MM ft^3	23,115
Coke Production	M Tons	15,591
Blast Furnace Ironmaking		
Consumptions		
Coke	M Tons	21,874
Natural Ore	M Tons	866
Pellets	M Tons	69,278
Sinter, Briquettes, Nodules, & Other	M Tons	11,731
Oxygen	MM ft^3	98,472
Fluxes	M Tons	3,987
Refractory	M Tons	172
Fuels		
Fuel Oil	M Gallons	144,479
Natural Gas	MM ft3	95,265
Coke Oven Gas	MM ft3	17,336
Blast Furnace Gas	MM ft3	596,329
Pig Iron Production	M Tons	53,164
BOP Steelmaking		
Consumptions		
Scrap	M Tons	15,000
Pig Iron	M Tons	51,000
DRI	M Tons	120
Total Fluxes	M Tons	4,090
Oxygen	MM ft3	115,595
Refractory	M Tons	501
Ferroalloys	M Tons	448
Fuels		
Fuel Oil	M Gallons	24
Coke Oven Gas	MM ft3	847
Raw Steel by BOP[2]	M Tons	59,686
EAF Steelmaking		
Consumptions		
Scrap	M Tons	46,000
Pig Iron	M Tons	3,700
DRI	M Tons	1,000
Total Fluxes	M Tons	1,403
Oxygen	MM ft3	62,042
Refractory	M Tons	534
Ferroalloys	M Tons	245
Electrodes	M Tons	98
Fuels		
Natural Gas	MM ft3	28,819
Raw Steel by EAF[2]	M Tons	49,067

Table 3. 1998 Consumption of Materials and Fuels; Production of intermediate Products and imports of Semifinished Steel[1] (continued)

Heating & Annealing Furnaces		
Fuels		
Fuel Oil	M Gallons	4,103
Natural Gas	MM ft3	206,047
Coke Oven Gas	MM ft3	38,437
Consumption of Pig Iron in Steelmaking	M Tons	52,327
Net Imports of Ingots, Blooms, Billets, Slabs, Etc	M Tons	6,543
Net Shipments of Steel Mill Products[3]	M Tons	102,420

[1] AISI data are adjusted data that comprehends non-reporting compa
Data may not agree with other sources.
[2] Steelmaking production includes carbon, alloy, and stainless steels.
[3] Includes carbon, alloy, and stainless steel products.
Sources: Charles River Associates and 1998 and 1999 AISI Annual Statistical Reports.

Note that AISI reports blast furnace production as pig iron, but in fact, the great majority is produced as hot metal, which is charged directly to the BOP furnace along with about up to one-third of its own weight in scrap plus DRI. It is also significant that more than 6 million tons of coke were consumed in domestic blast furnaces than were produced by the integrated sector: the difference was obtained from inventories, independent coke makers, and imports. The United States has been importing coke for a number of years. For example, Japan and China exported approximately 1.9 million tons and 2.0 million tons, respectively, to the United States in the year 2000. Small amounts have come from Eastern Europe and other countries, but China has become a major exporter in recent years even though some of the Chinese coke is of poor quality and its use reduces blast furnace efficiency noticeably. It is purchased because of its low price.

A large amount of fuel is consumed to raise steam for process and general plant consumption and to generate electricity. About 15 percent of the electricity consumed was generated internally, almost all of it in the integrated sector. Finally, while the total consumption of pig iron and DRI was less than 10 percent of the scrap consumed in EAFs, the ratio was significantly higher in minimills making higher-quality flat products than in mills making lower-quality long products. It is required to control the levels of "residuals" in the flat products, which are considerably lower than those allowed in long products. As will be shown, this increases the levels of CO_2 emissions from EAF steel production considerably.

Table 4 summarizes the energy, carbon, and CO_2 contents of the most significant materials and energy used in steel making. This summary is not meant to be exhaustive, nor does it recognize site-specific differences in these consumables that arise from differences in composition, transportation, or, especially, the energy sources used to generate electricity. However, they are useful in obtaining an overall estimate of the consequences of changing the technology of steel making.

Table 4. Conversion of Consumables to Carbon Dioxide Equivalents

Fuel or Consumable	Unit	Density lbs/Unit	Equivalent Energy Content Btu/Unit	Equivalent Carbon Content lbs/Unit	Equivalent CO_2 Content lbs/Unit	Comments
Electricity	kWh		10,300	0.66	2.4	Coal Based[1]
Steam Coal	lb		12,500	0.80	2.9	
Coking Coal	lb		13,500	0.80	2.9	
Natural Gas	SCF	0.045	1,000	0.033	0.12	
Oil	Gal	8.2	150,000	7.05	26	
COG	SCF	0.031	500	0.014	0.052	
BFG	SCF		95	0.00	0.00	
Charge Carbon	lb		13,500	0.80	2.9	
Coke	lb		13,000	0.92	3.4	
Coke Breeze	lb		13,000	0.92	3.4	
Oxygen	SCF	0.083	171	0.011	0.040	Electricity/coal based[2]
Lump Ore	lb		26	0.002	0.01	Electricity/Coal Based
Ore Fines	lb		52	0.003	0.01	Electricity/Coal Based
Cold Pig Iron	lb		6,400	0.50	1.8	Coke Based
Prompt Scrap	lb		100	0.005	0.02	Fuel Oil Based
Obsolete Scrap	lb		152	0.008	0.03	Electricity/Coal and Fuel Oil Based
Grinding Balls/Rods	lb		10,000	0.26	0.9	EAF Based
Flux Agent	lb		3,100	0.20	0.73	Coal Based
Refractory	lb		4,000	0.14	0.50	Electricity/Coal and Natural Gas Based
Desulfurizing Agent	lb		21,000	1.3	4.6	Electricity/Coal and Natural Gas Based
Ferroalloy Agent	lb		20,000	1.3	4.7	Electricity/Coal Based
Carbon Electrodes	lb		37,000	2.5	9.0	Electricity/Coal Based

[1] Maximum CO2 emissions. May be lower because of actual energy mix for electricity generation (e.g., coal, oil, hydro, nuclear, etc.)

[2] Based on vaporization of liquid oxygen. Some sites may use low purity oxygen.

Source: Charles River Associates, 2001.

Based on these conversion factors (see Table 4) and unit consumptions (see Tables 5 through 21, which are presented in the Appendix A to this report), various elements of steelmaking technologies that are currently in use and the potential improvements that might be used to reduce energy consumption and CO_2 emissions have been characterized. In general, the technologies are presented serially from the first steps in the steel making process (e.g., ore and scrap treatment) through the final steps in the production of mill products (e.g., coating or annealing and tempering). Table 22 in Appendix A summarizes the CO_2 emissions by the two major routes.

Listed first are the key unit consumptions of energy and materials, and their equivalent unit CO_2 emissions, for current "typical" or "average" practice conditions in the United States. The next two columns list the best practice consumptions under both U.S. and foreign steel making conditions. The subsequent columns in each table list the same characteristics for potential technologies that might be adopted for both conventional economic reasons (e.g., to reduce materials and energy consumption in a cost-effective manner) and to reduce CO_2 emissions. The results are shown in Tables 5 through 21 in Appendix A.

In addition, the nature of each of the potentially improved technologies has been classified according to its impact as follows:

1. An improvement of current technologies
2. A replacement of current technologies
3. A replacement of existing energy sources
4. A recycling technology

The current status of the potential improvements has also been indicated and classified accordingly as:

1. In R&D stage that will require additional time and funds for technology development prior to commercialization.
2. "First mover" that has further developed the technology but will require some inducements or risk-mitigation policies to spur the commercialization.
3. Layout constraint in which the technology has been demonstrated but a retrofit situation is constrained by the existing configuration or layout.
4. Demonstrated

The "typical" or "average" practice, current best practice and potential future average practice conditions for these elements of the steel making process are all based on the use of demonstrated technologies.

Many of these technologies have been evaluated by others to assess their cost-effectiveness under typical conditions in the United States.[13] These evaluations have been based on cost and performance data reported in the literature and the authors' best estimates where data were not available. These evaluations focused on the economic costs and benefits that could be obtained through their potential to reduce consumption of energy, not from reductions in CO_2 emissions. The primary economic figures of merit used were the estimated project internal rate of return, the simple payback time, and the estimated cost of the conserved energy. The first two of these require that the

[13] *Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the US Iron and Steel Sectors*, LBNL–41724, July 1999.

unit cost of the energy saved be stipulated, along with the capital requirements and any changes in other components of operating cost, while the discount rate appropriate for annualizing investments must be stipulated to calculate the cost of conserved energy.

Properly calculated, each of these figures of merit could serve as an indication of the attractiveness of an energy-saving investment. However, it is not at all clear that the authors of these studies have comprehended the real investment requirements and operating costs of these options, because costs are so site-specific and difficult to estimate, particularly in retrofit situations. Furthermore, in making these calculations, the authors have estimated savings from an "average condition," and there is no such thing in the industry. Each energy-saving investment must be justified in terms of the specific conditions at an existing plant, not against some hypothetical average. In some cases, energy savings will be higher and investment requirements lower than "average," and in other cases, the reverse will be true. Furthermore, estimates of the sector average fuel costs have been used, and such an approach cannot comprehend either the highly site-specific unit costs of natural gas, electricity, and coke, or the impact of a technology change on the energy mix used in a mill. Nor can such an approach be used with any certainty to estimate the attractiveness of an energy-saving technology that has not yet been fully developed. In that case, one can develop an estimate based on the cost and performance goals targeted for the technology, but some element of judgment is still required to project the actual outcome of the targets still under development.

Because neither the actual economic performance of these potential improvement technologies nor the specific investment criteria that the industry would apply to their justification can be determined with a high degree of certainty, we have applied a rough economic screen to the technologies enumerated in Tables 5 through 21 of Appendix A. The classification adopted is as follows:

1. Likely to have a return on investment high enough (or payback time short enough) to meet likely industry investment criteria for energy-saving projects because the technology would appear to be economically efficient to introduce.

2. The return is uncertain or the energy cost saving justification is unclear.

3. Likely to have an unacceptable return without extraordinary high-energy prices since it would appear to be economically inefficient.

In order to simplify the analyses, we have grouped the various process steps in the following major carbon dioxide emitting unit operations.

- Coke making (Figures 7a and 7b).
- Iron making and blast furnace process (Figures 8a and 8b).
- Smelting process (Figures 9a and 9b).

- Direct reduction processes (Figures 10a and 10b).
- Steel making.
  - Basic oxygen process (BOP) (Figures 11a and 11b).
  - Electric Arc furnace process (Figures 12a and 12b).
  - Casting and hot rolling (BOP source) (Figures 13a and 13b).
  - Cold rolling (BOP source) (Figures 14a and 14b).

In all of these major unit processes, we show the current levels of CO_2 emissions that are generated in the production process or would be generated if the product was used subsequently. For example, coke that is used in the production of liquid iron would generate CO_2 resident in the carbon content of the coke used in the production of liquid iron. Also shown are the best U.S. practice, as well as the "Best in the World" practice. Besides these bar graphs, there are shown the impacts of the proposed technologies in these major sectors on the carbon dioxide emissions. Those technologies that are estimated to increase the CO_2 emissions are shown as negative numbers with appropriate shading and status coding to indicate their preliminary economic and developmental status.

We have three objectives in grouping the technologies in this fashion. First, we seek to determine "what we will win if we win." That is, we seek to determine the extent to which specific CO_2 emissions will be reduced (or in some cases actually increased) if these technologies are adopted. This requires that we make an estimate of the extent to which the technologies can penetrate the industry. Second, we seek to determine why the technologies estimated to be of the first economic rank have not been more widely adopted. This forces us to question the existence of unrecognized barriers in the industry or of market failures that might be overcome through changes in policy. Finally, we seek to estimate, at least qualitatively, the extent to which policy measures, such as energy taxes or carbon emission taxes, would have to be implemented to change the outcomes now dictated by market forces.

Figure 7a. CO_2 Emission Level (lbs per Ton Coke)

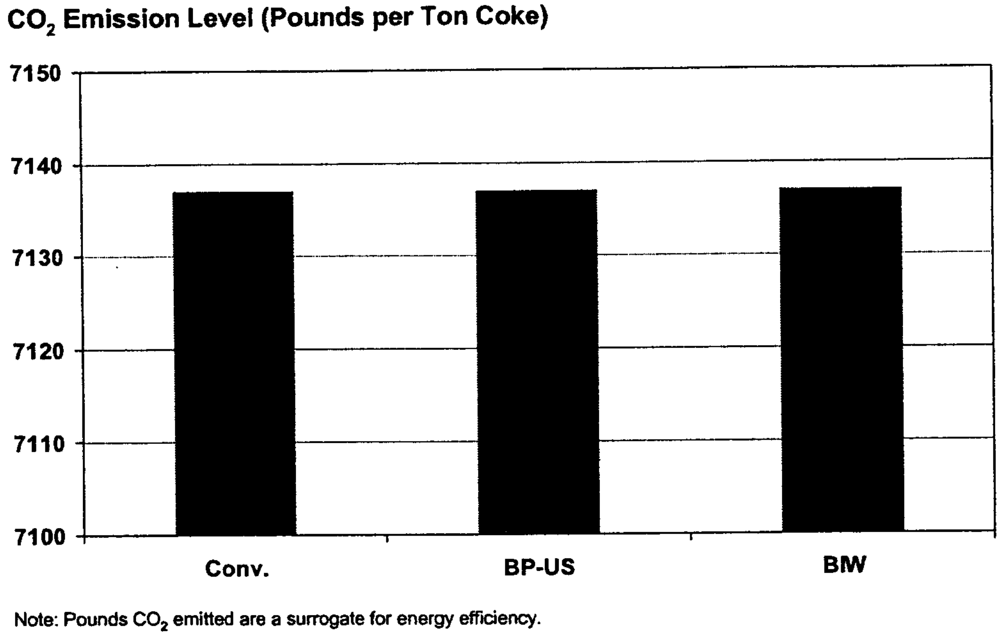
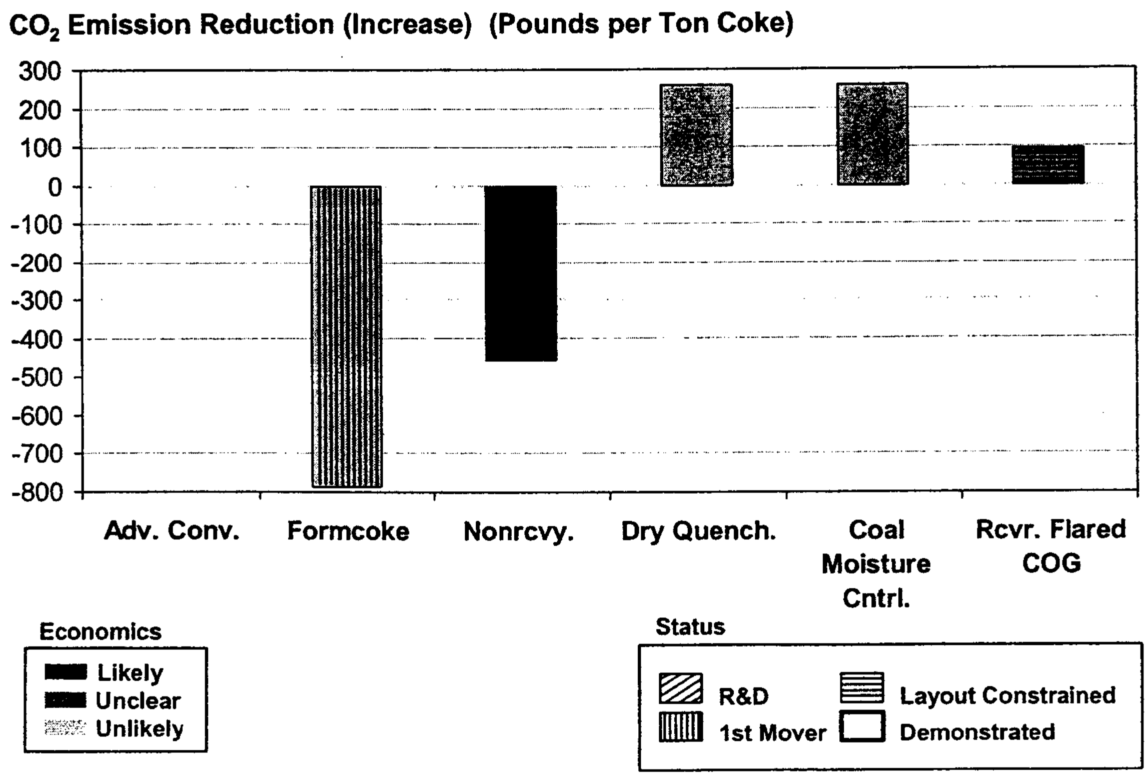
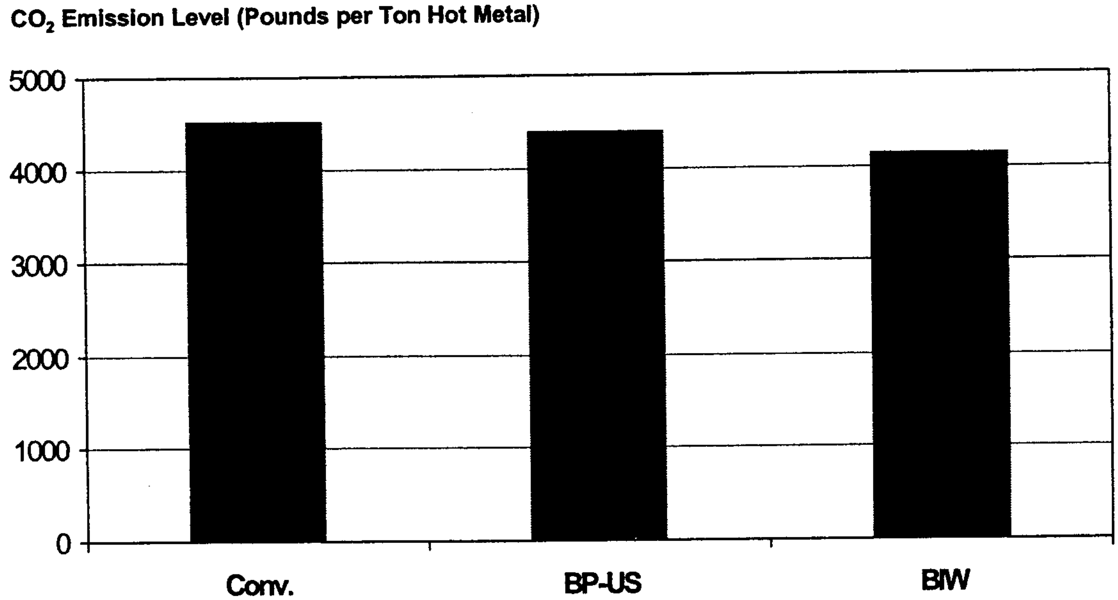


Figure 7b. CO_2 Emission Reduction/Increase (Pounds per Ton Coke)



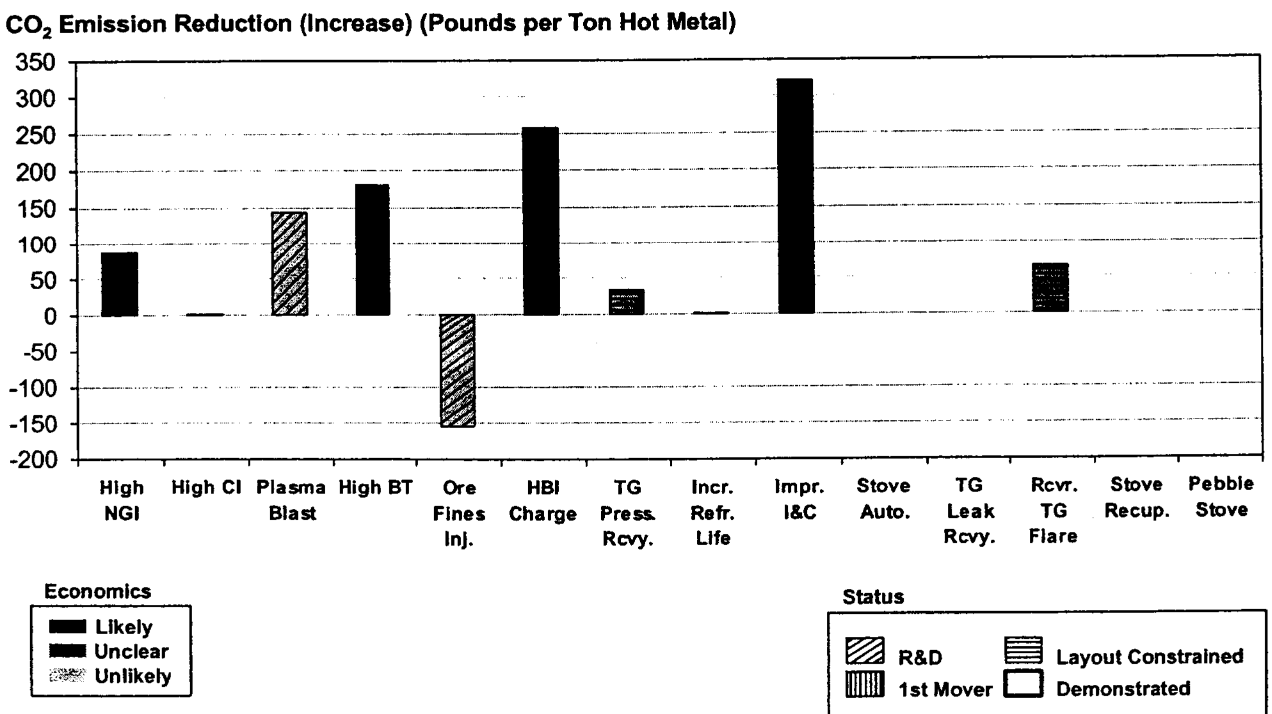
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 8a. CO_2 Emission Level (Pounds per Ton Hot Metal)



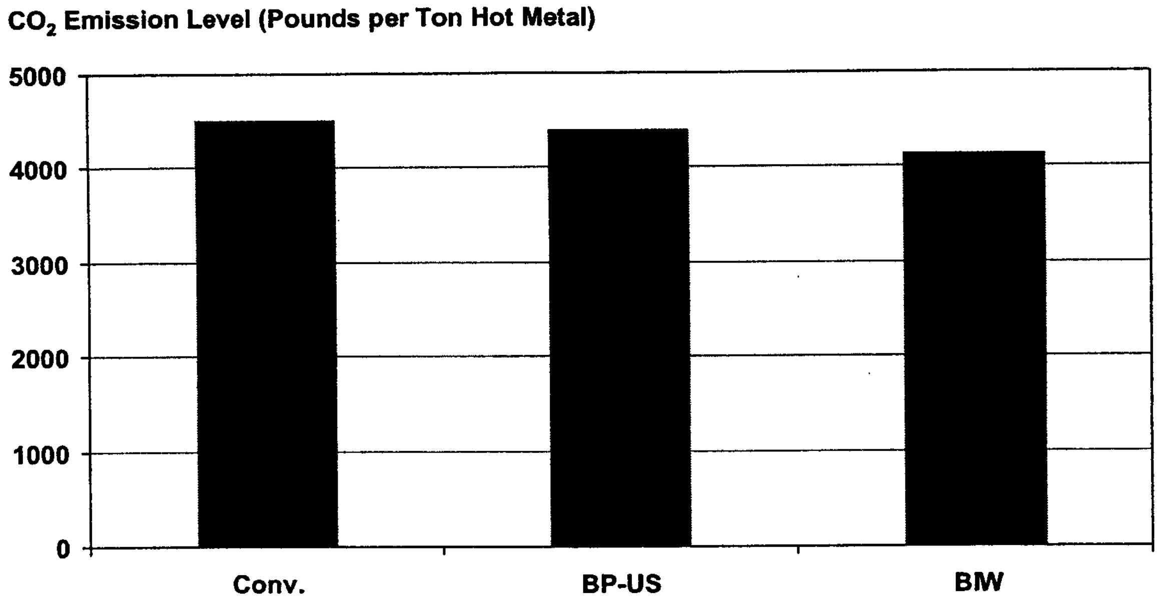
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 8b. CO_2 Emission Reduction/Increase (Pounds per Ton Hot Metal)



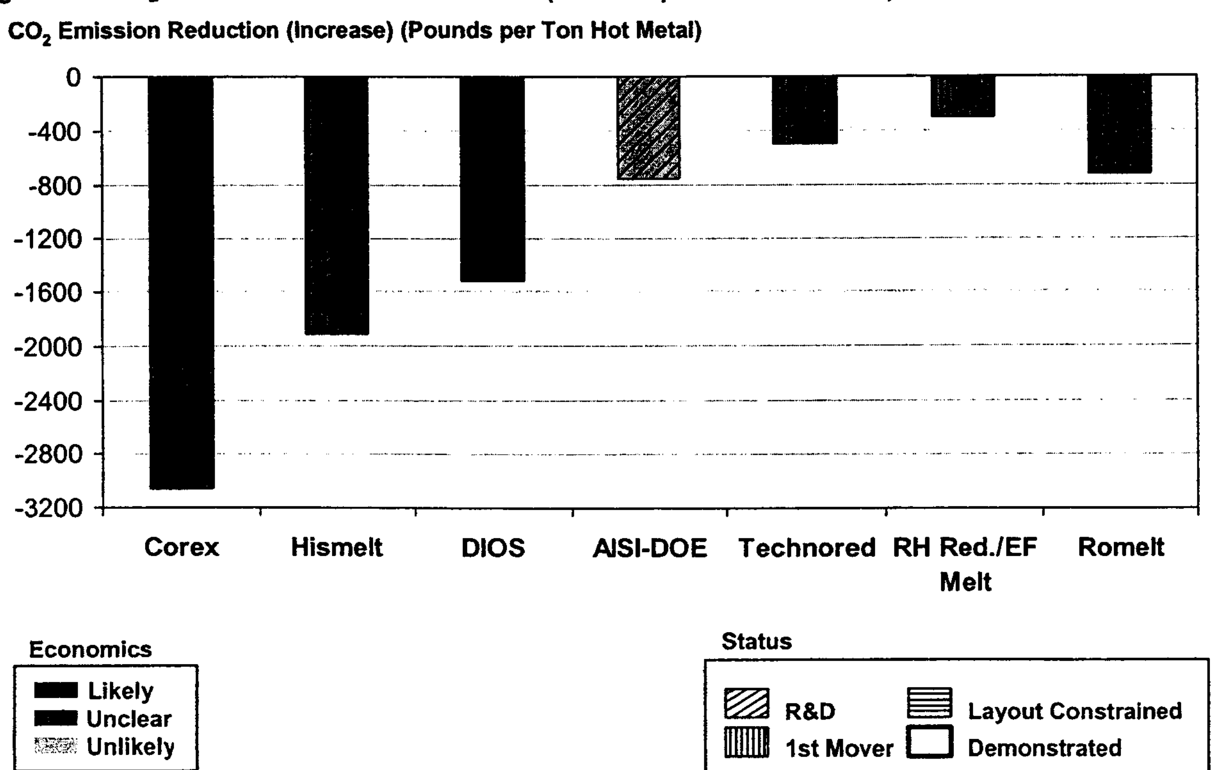
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 9a. CO_2 Emission Level (Pounds per Ton Hot Metal)



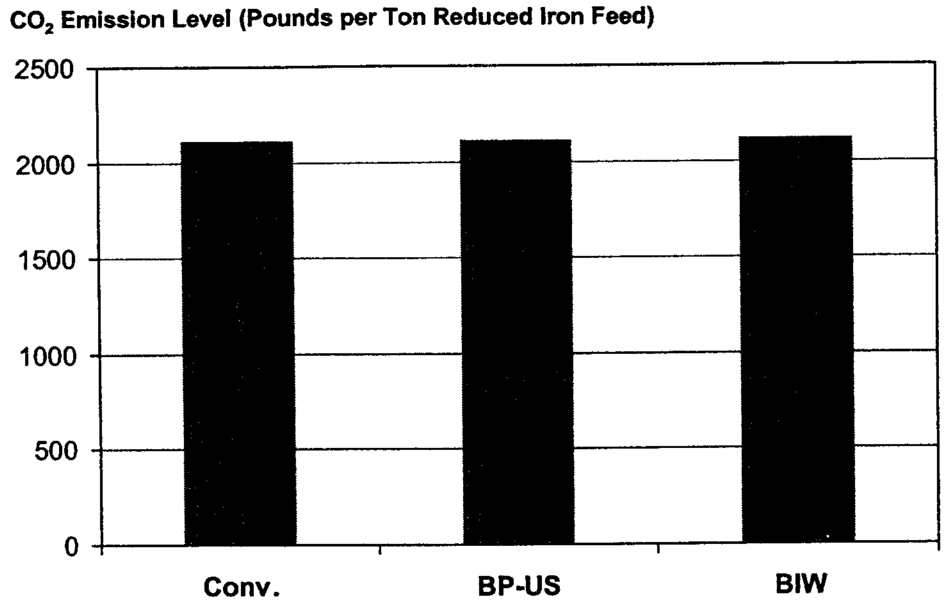
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 9b. CO_2 Emission Reduction/Increase (Pounds per Ton Hot Metal)



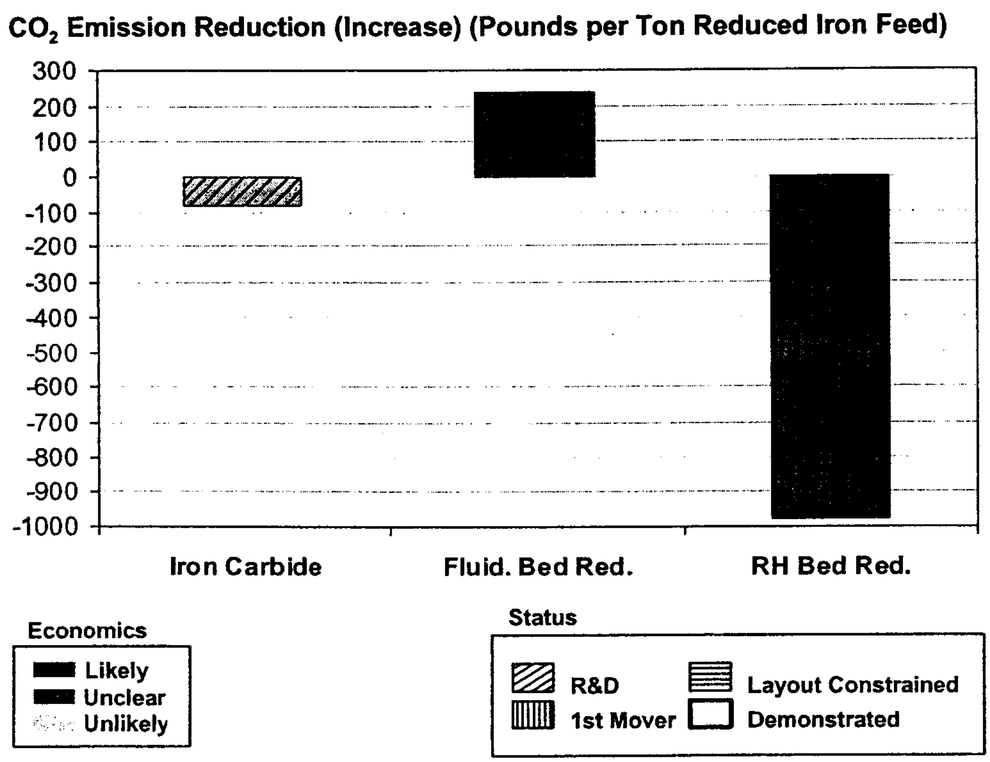
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 10a. CO_2 Emission Level (Pounds per Ton Reduced Iron Feed DRI)



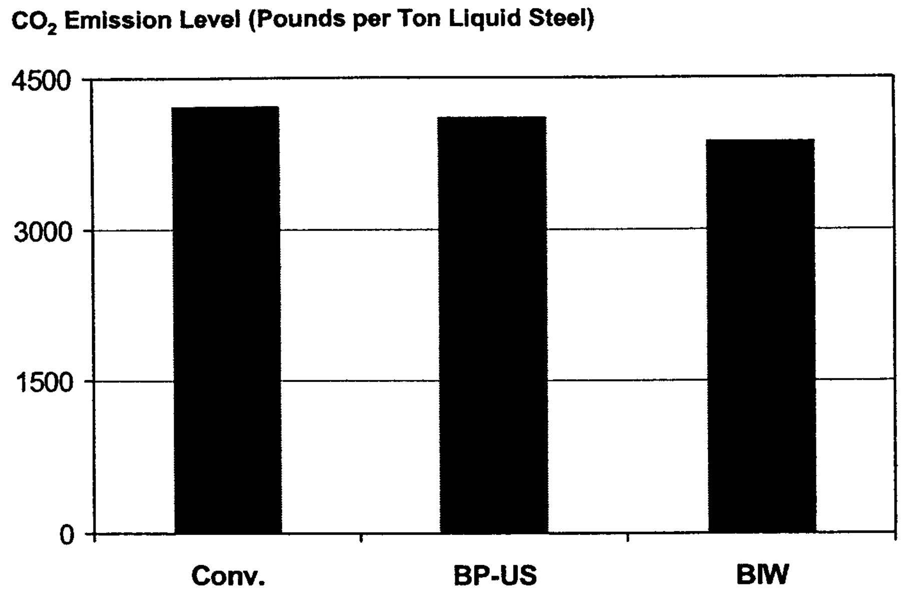
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 10b. CO_2 Emission Reduction/Increase (Pounds per Ton Reduced Iron Feed)



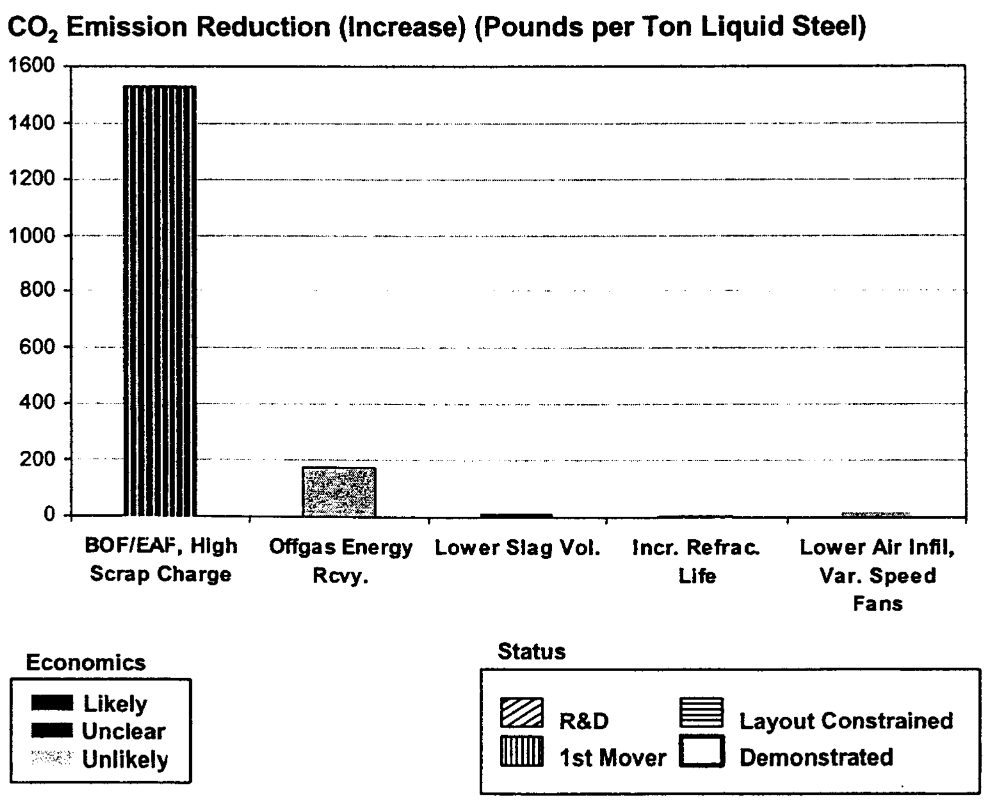
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 11a. CO_2 Emission Level (Pounds per Ton Liquid Steel)



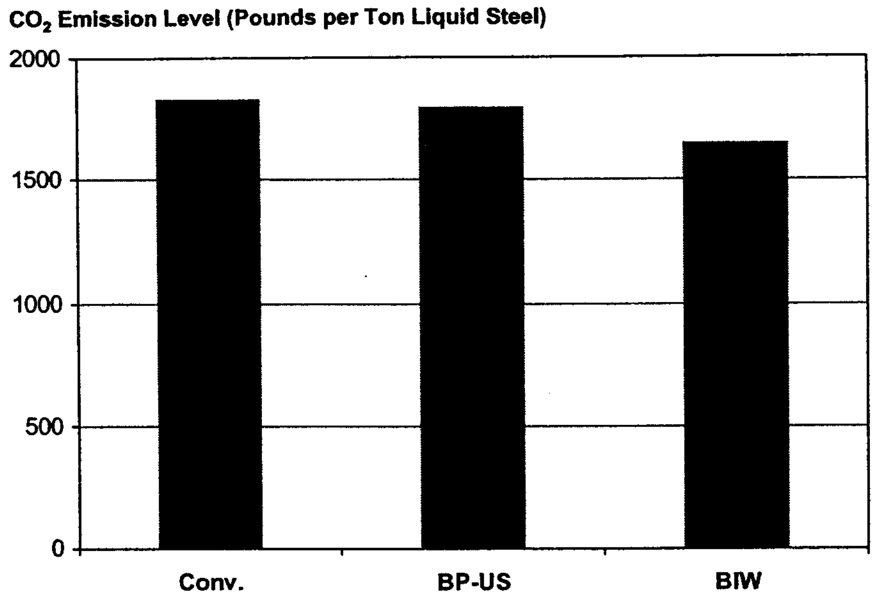
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 11b. CO_2 Emission Reduction/Increase (Pounds per Ton Liquid Steel BF/BOF Process)



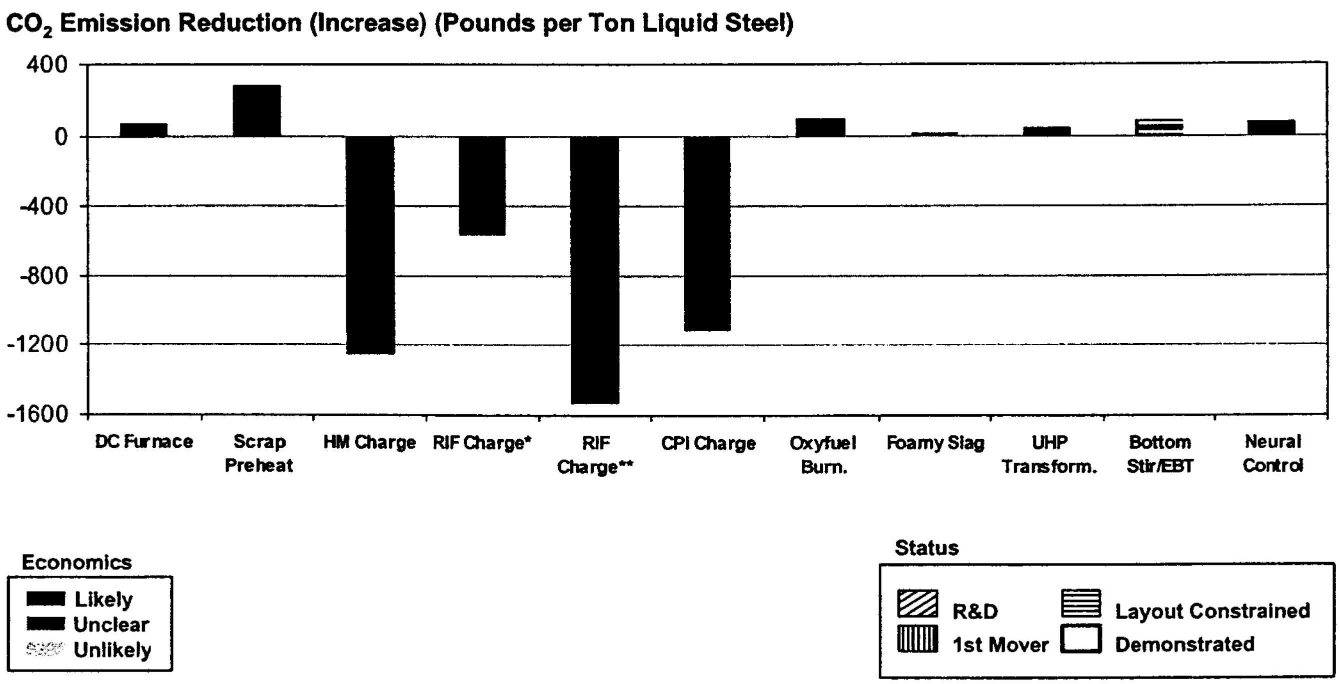
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 12a. CO_2 Emission Level (Pounds per Ton Liquid Steel Electric Arc Furnace Process)



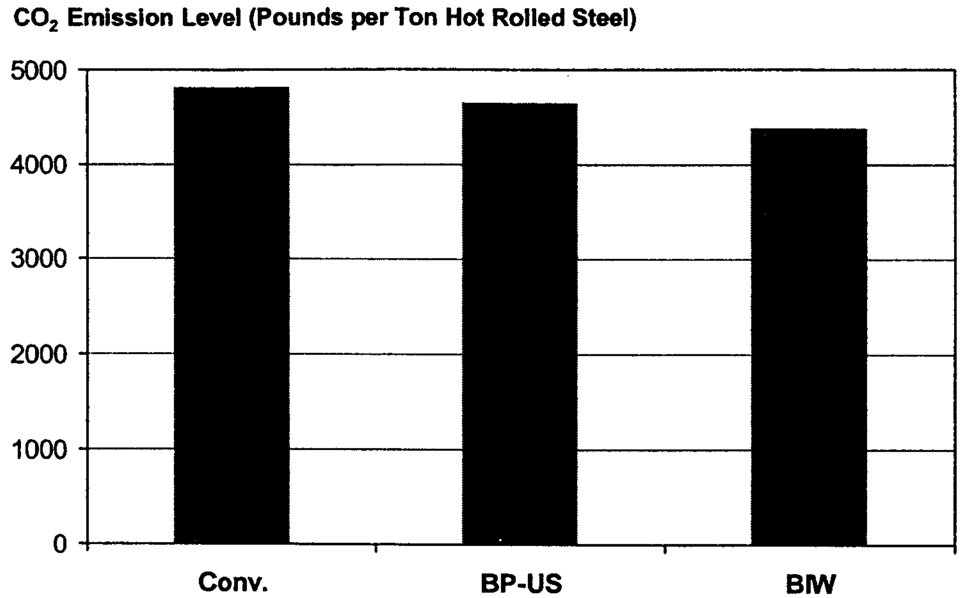
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 12b. CO_2 Emission Reduction/Increase (Pounds per Ton Liquid Steel)



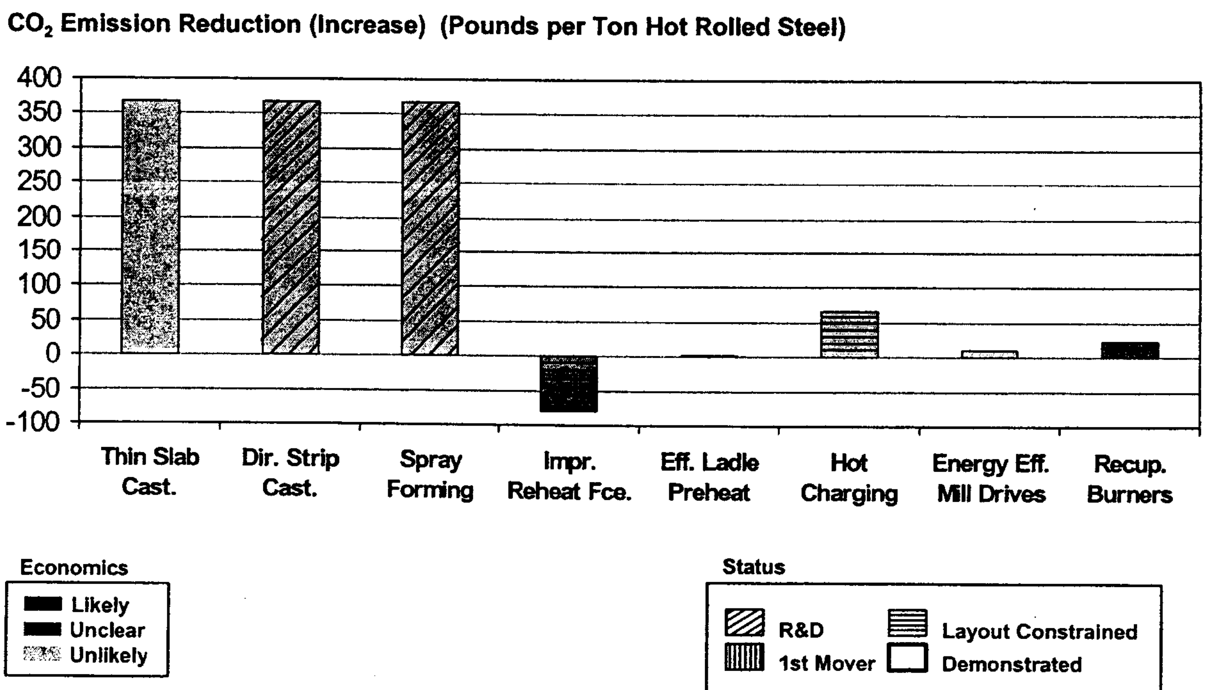
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 13a. CO_2 Emission Level (Pounds per Ton Hot Rolled Steel)



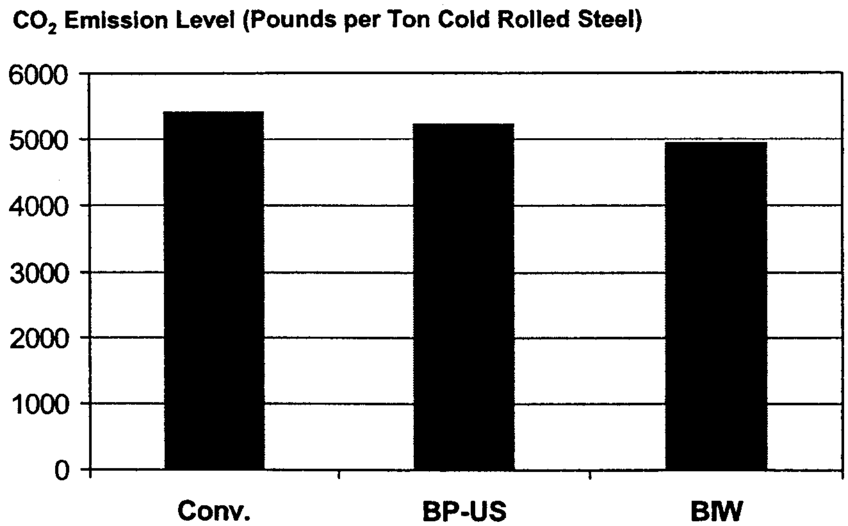
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 13b. CO_2 Emission Reduction/Increase (Pounds per Ton Hot Rolled Steel)



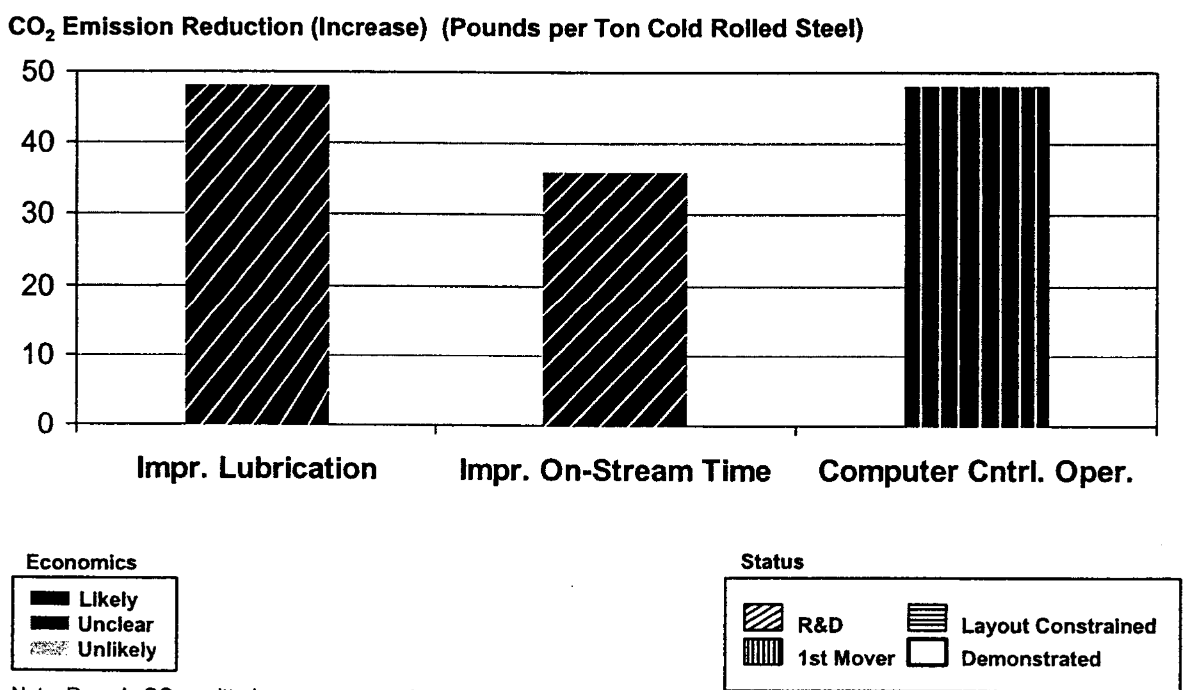
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 14a. CO_2 Emission Level (Pounds per Ton Cold Rolled Steel)



Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 14b. CO_2 Emission Reduction/Increase (Pounds per Ton Cold Rolled Steel)



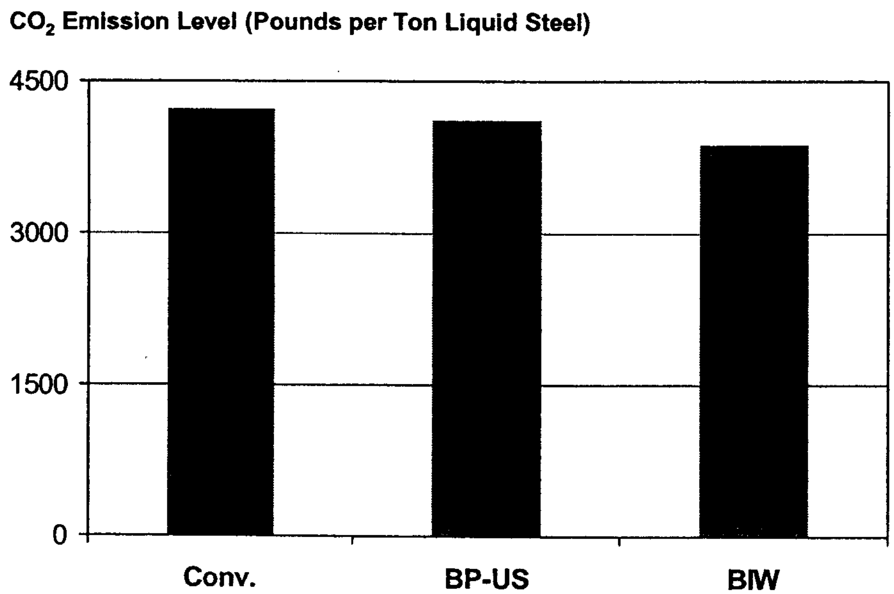
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

CONCLUSIONS FROM THE TECHNOLOGY EVALUATIONS

Generally, the steel industry has made significant progress during the last decade in decreasing CO_2 emissions, from iron ore agglomeration and reduction to the production of final steel products. Further decreases based on technology improvement alone would be in the range of an additional 10 percent and would come more slowly. Most of these further improvements could be attributed to evolutionary process improvement that occurs normally in any mature industry.

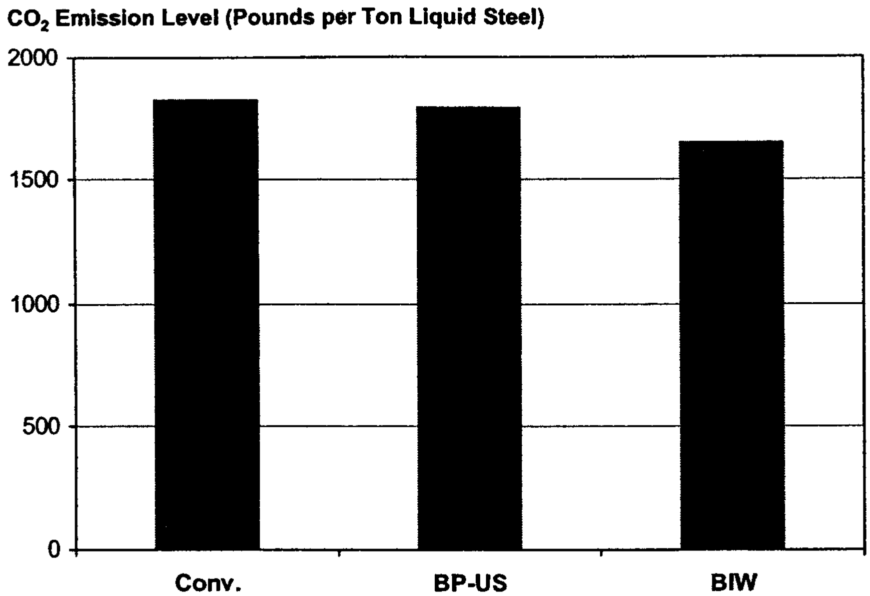
As expected, the conventional virgin iron ore-based production of hot-rolled steel emits nearly 2.3 times more CO_2 than does the scrap-based electric arc furnace method (see Figures 11a and 12a). However, the amount of available high-quality scrap is limited and the practice of "sweetening" charges with ore-based RIF's and CPI additions greatly increases the amount of CO_2 emission as shown in Figure 12b. Therefore, these two routes to the production of EAF-based steel products must be evaluated separately because significant amounts of virgin iron ore must be processed to satisfy the overall demand for high-quality, flat products.

Figure 11a. CO_2 Emission Level (Pounds per Ton Liquid Steel)



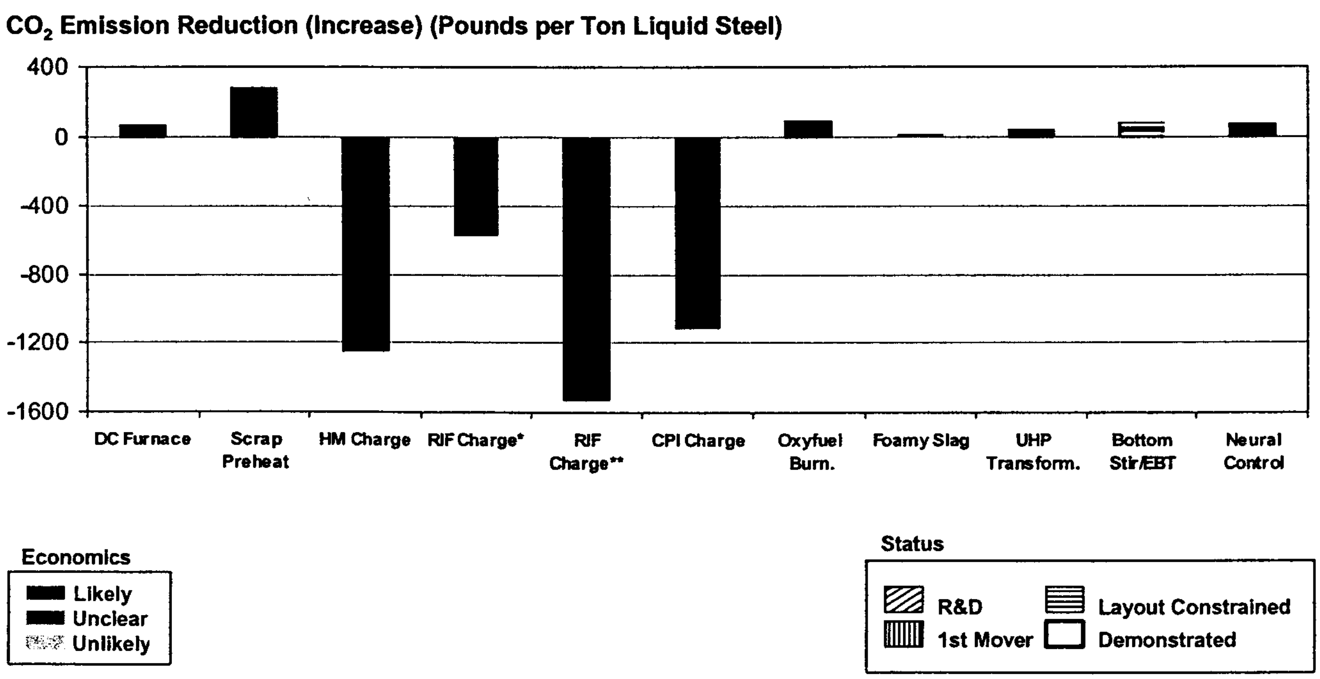
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 12a. CO_2 Emission Level (Pounds per Ton Liquid Steel Electric Arc Furnace Process)



Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

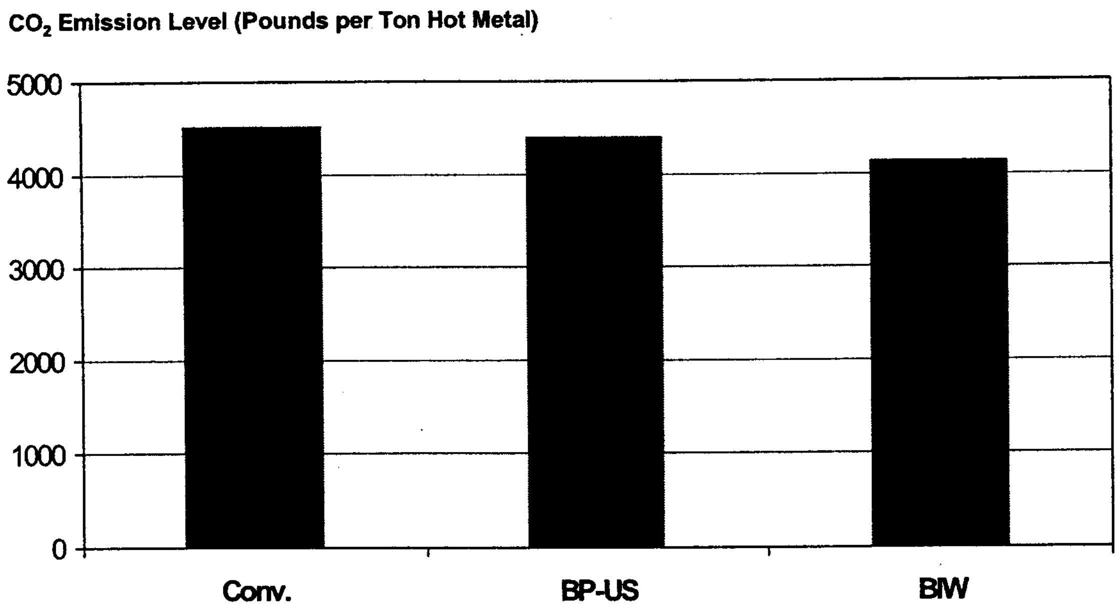
Figure 12b. CO_2 Emission Reduction/Increase (Pounds per Ton Liquid Steel)



Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

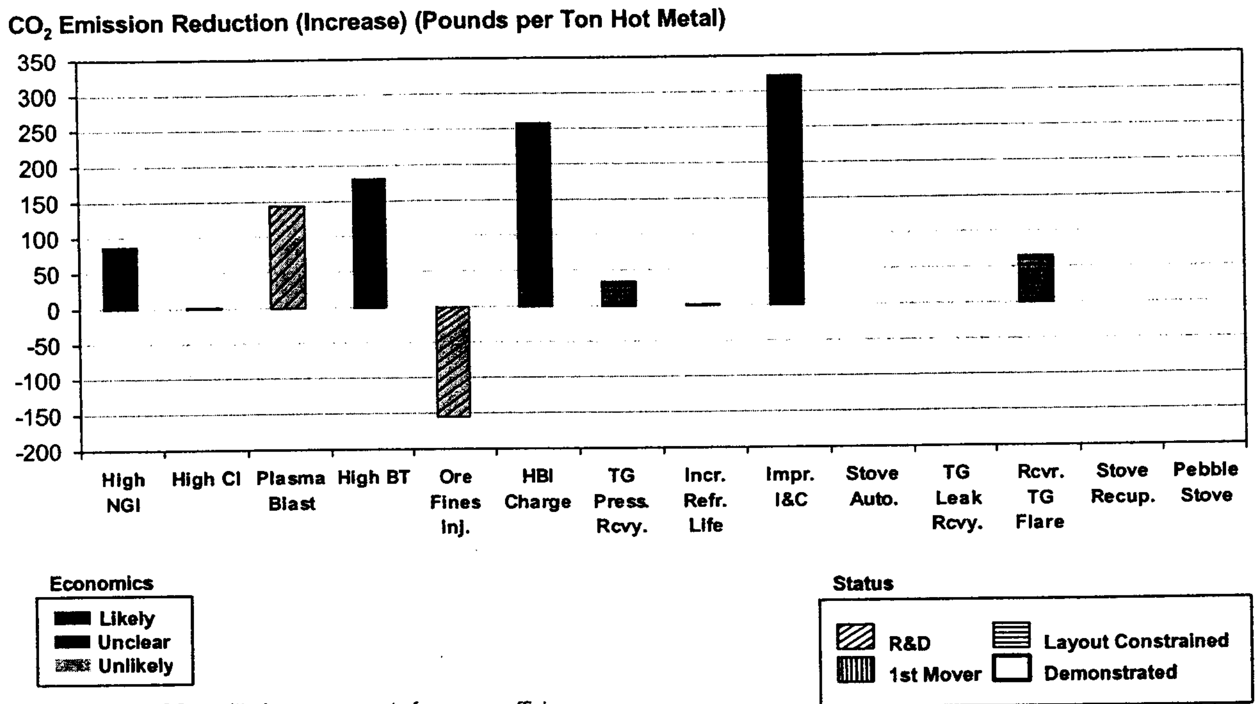
For the production of the required iron units from virgin iron ore, the natural gas-based direct reduction processes emit only one-half as much CO_2 (see Figures 8a, 8b, 10a and 10b; Tables 9 and 11 in Appendix A), as does the conventional coke-based production of liquid iron. Imposing a high CO_2 emission tax could change the economic incentives in favor of using the natural gas-based processes, but the stability of price and supply of natural gas would then become a key issue.

Figure 8a. CO_2 Emission Level (Pounds per Ton Hot Metal)



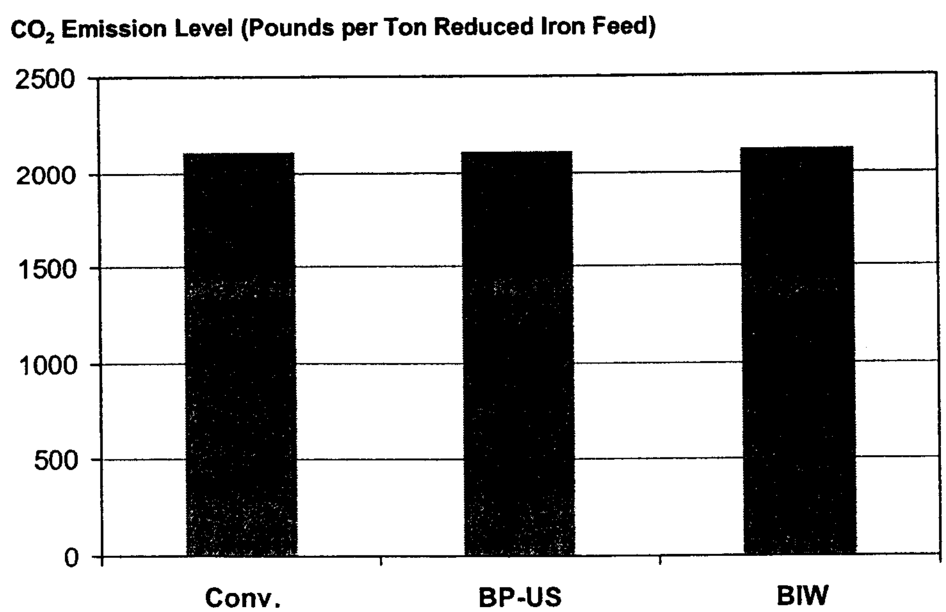
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 8b. CO_2 Emission Reduction/Increase (Pounds per Ton Hot Metal)



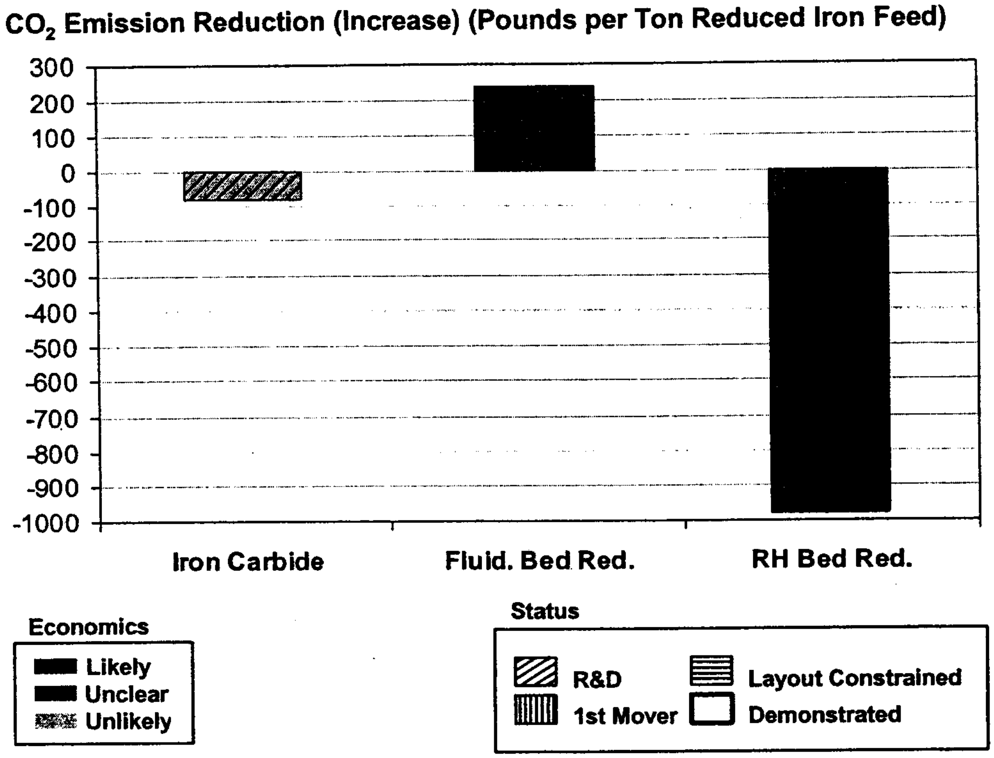
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 10a. CO_2 Emission Level (Pounds per Ton Reduced Iron Feed DRI)



Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

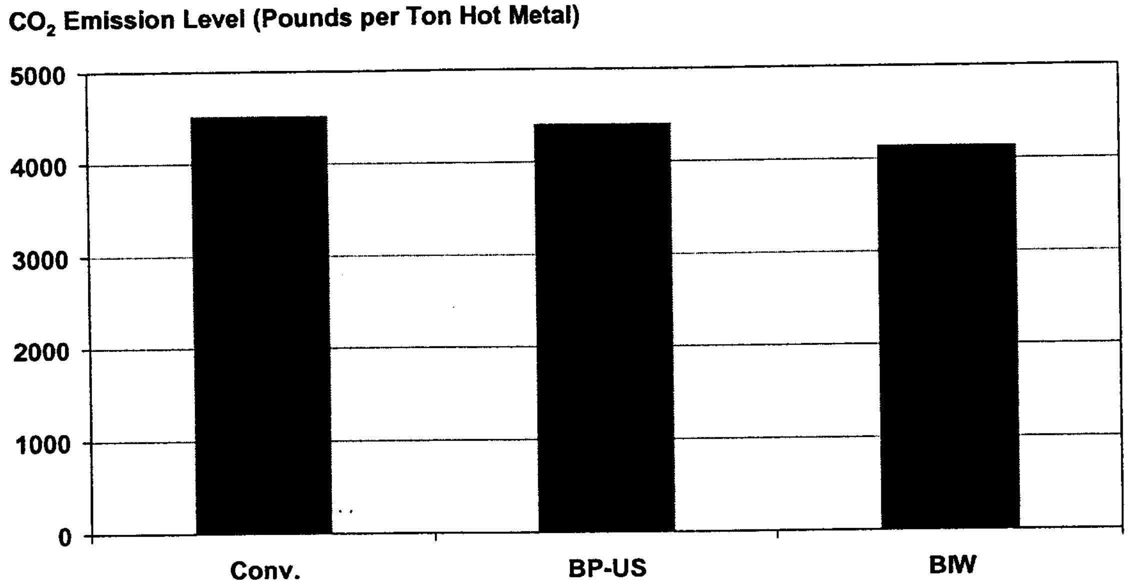
Figure 10b. CO_2 Emission Reduction/Increase (Pounds per Ton Reduced Iron Feed)



Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

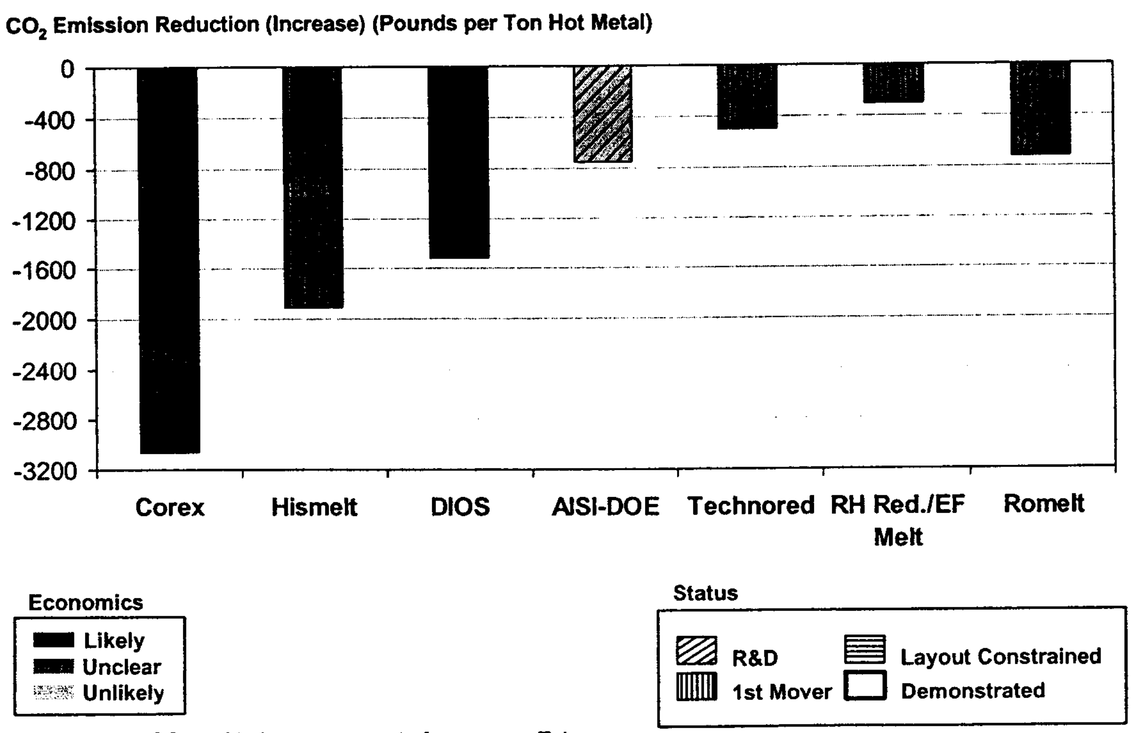
More than 75 percent of the total amount of carbon dioxide emissions per ton of steel produced in integrated plants and DRI plants occurs in the reduction of iron ore by carbon-containing reductants (see Figures 8a, 8b, 9a, 9b, 10a and 10b; Tables 9 and 22 in Appendix A). All proposed improvements to produce liquid iron by the blast furnace method (hot metal) offer less than 5 percent reduction in CO_2 emissions. The adoption of the best practice in the world could result in a decrease of up to 10 percent, but the extent would depend upon site-specific conditions. Although the decrease in CO_2 emissions may not be very significant, the economies of the production of hot metal could improve if site-specific conditions are satisfied.

Figure 9a. CO_2 Emission Level (Pounds per Ton Hot Metal)



Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 9b. CO_2 Emission Reduction/Increase (Pounds per Ton Hot Metal)

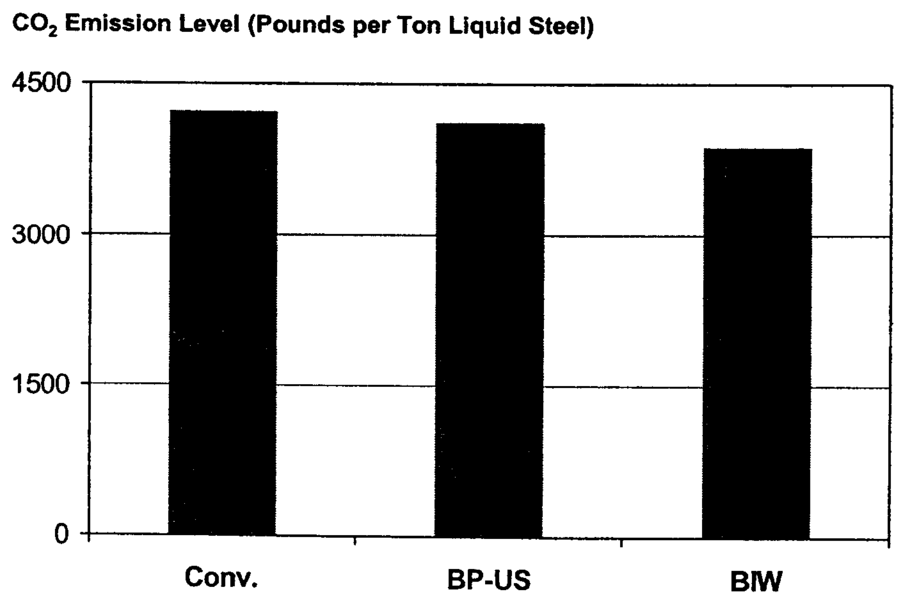


Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

All of the newly proposed iron ore smelting processes are likely to emit more CO_2 per ton of iron than the conventional blast furnace process (see Figures 9a and 9b and Table 10 in Appendix A). However, the total cost of producing the liquid iron could be lower, depending upon the cost assigned to the recovery of capital cost and other site-specific costs, particularly the cost of acquiring coke. Coal-based direct reduction processes emit nearly 50 percent more CO_2 than those based on natural gas (see Figures 10a and 10b and Table 11 in Appendix A). In addition, the product quality is low because of coal's generally high sulfur content. The authors of Scenarios for a Clean Energy Future[14] assert that development of new smelting technologies will provide substantial energy savings in the steel industry. The basis for their estimates are not given, but presumably rest on comparisons of direct fuel consumption estimated for the new technologies vis-à-vis an inefficient coke oven—blast furnace process. However, if one accounts for all CO_2 emissions, including those produced in generating oxygen, they generate more greenhouse gases than conventional technologies.

In the steel making process, a combination of electrically boosted BOF charged with a higher proportion of scrap could decrease CO_2 emissions by approximately 30 percent (see Figures 11a and 11b and Table 12 in Appendix A). In electric arc steel making, scrap preheating appears to offer the most improvement possible (approximately 5 to 10 percent) in CO_2 emissions (see Figures 12a and 12b and Table 13 in Appendix A).

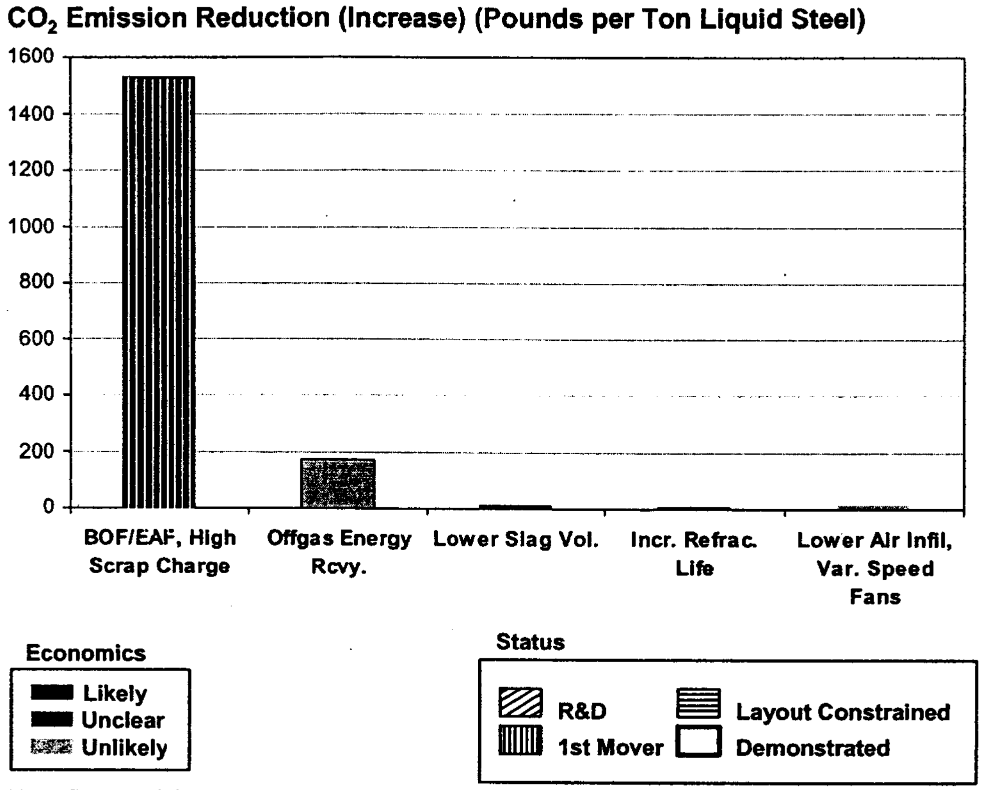
Figure 11a. CO_2 Emission Level (Pounds per Ton Liquid Steel)



Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

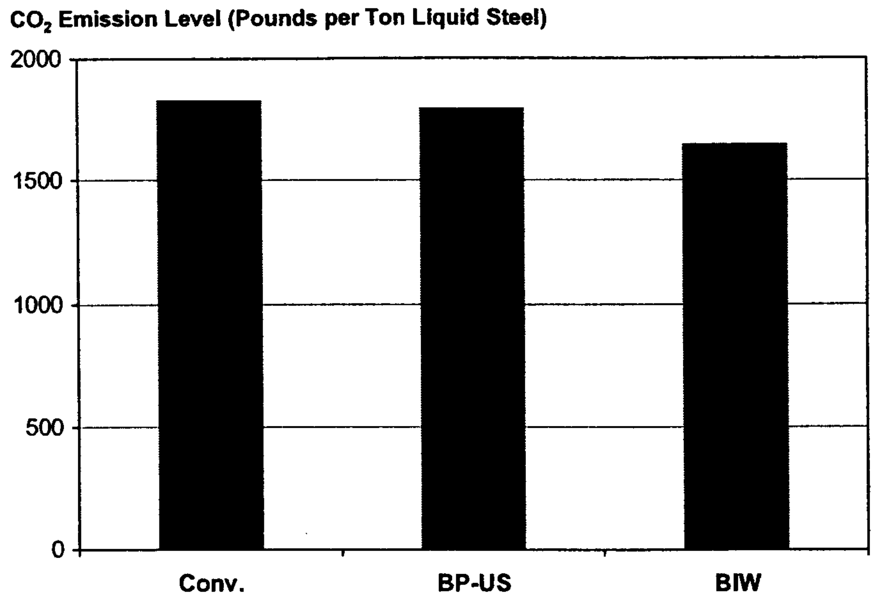
[14] *Scenarios for a Clean Energy Future* (Oak Ridge, TN: Oak Ridge National Laboratory and Berkeley, CA: Berkeley National Laboratory), ORNL/CON-476 and LBNL-44029, November 2000.

Figure 11b. CO_2 Emission Reduction/Increase (Pounds per Ton Liquid Steel BF/BOF Process)



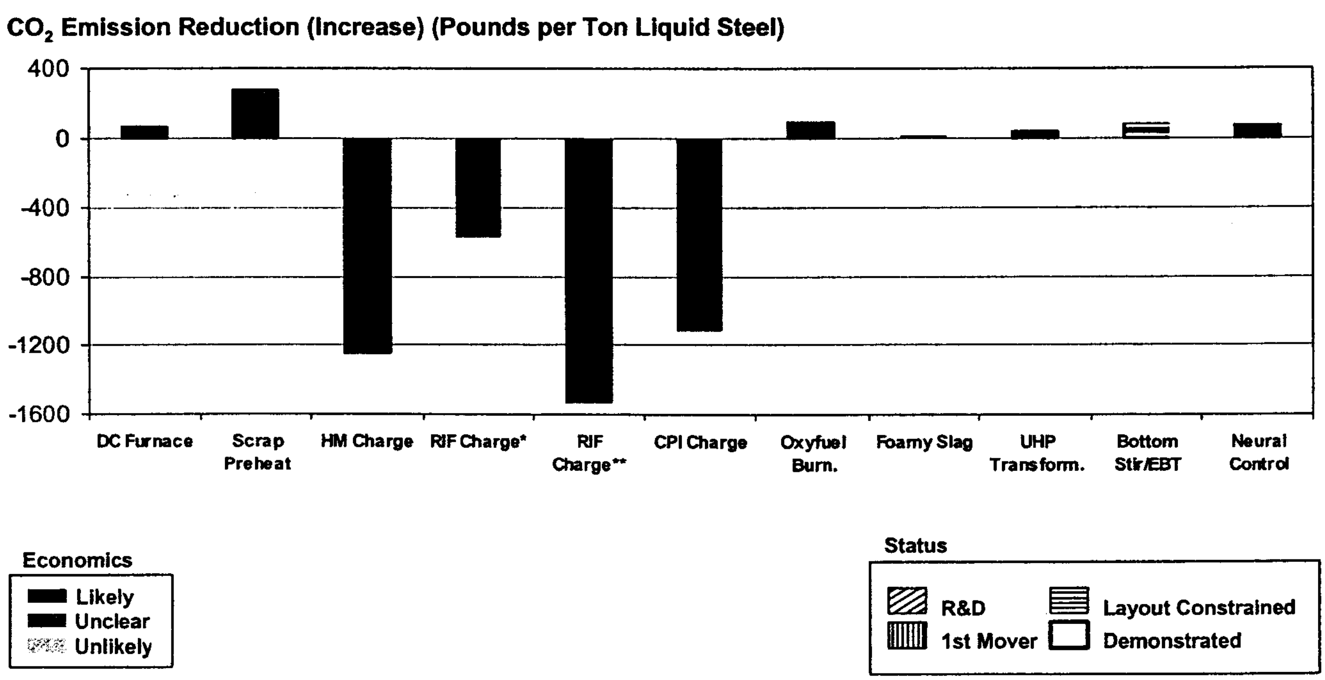
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 12a. CO_2 Emission Level (Pounds per Ton Liquid Steel Electric Arc Furnace Process)



Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

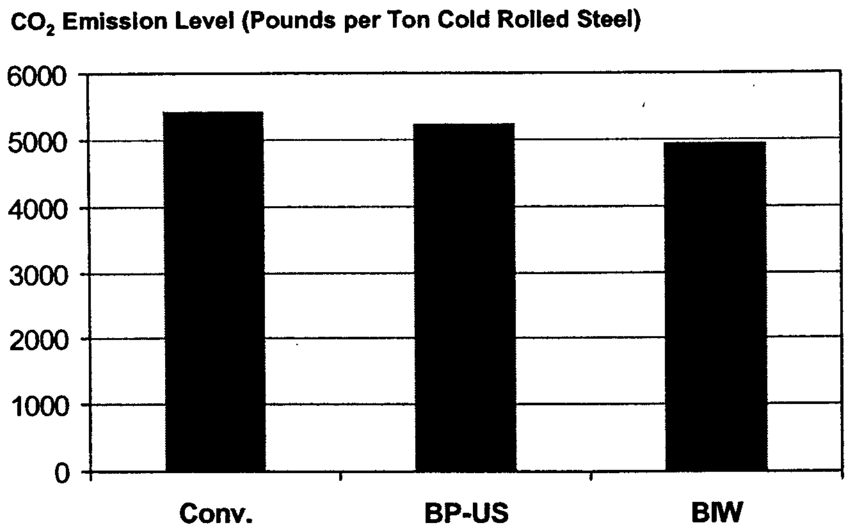
Figure 12b. CO_2 Emission Reduction/Increase (Pounds per Ton Liquid Steel)



Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

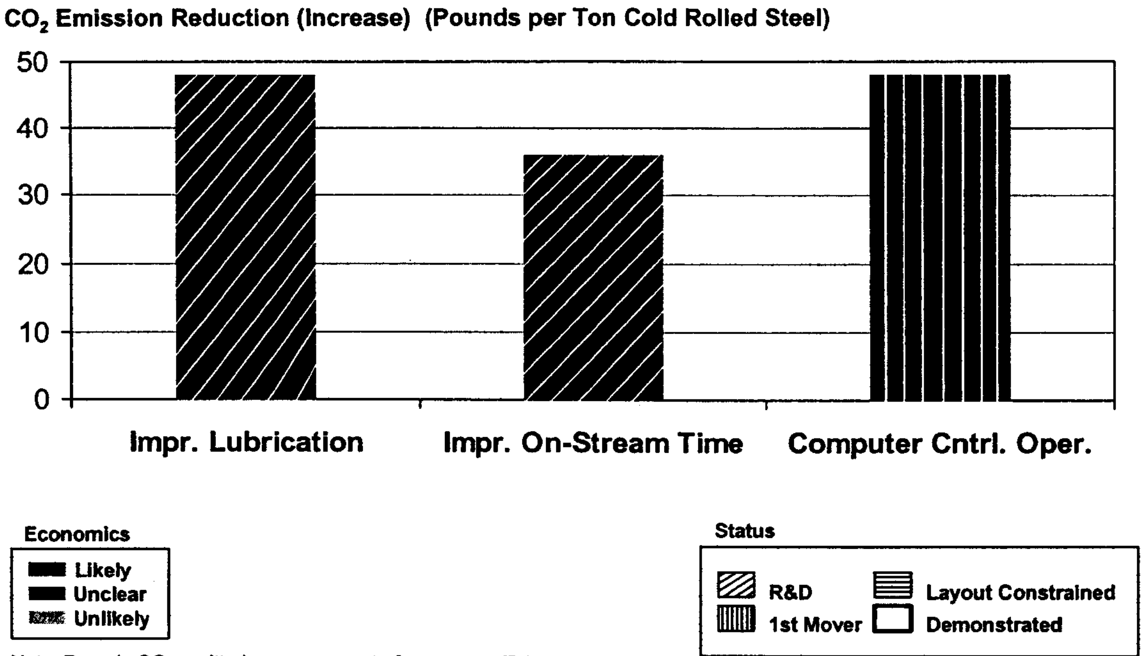
If thin slab casting were universally adopted, it would result in a 5 to 10 percent decrease in CO_2 emission per ton of steel. However, the insertion of thin slab casting in a conventional integrated shop would entail significant site-specific engineering problems. Improvements in process control to increase productivity, decrease scrap, etc., throughout the process flow sheet could offer approximately a 10 percent decrease in CO_2 emissions (see Figures 14a and 14b and Table 21 in Appendix A). None of the other currently developed proposed improvements are significant as far as CO_2 emissions are concerned (see Figures 13a and 13b and Table 14 in Appendix A).

Figure 14a. CO_2 Emission Level (Pounds per Ton Cold Rolled Steel)



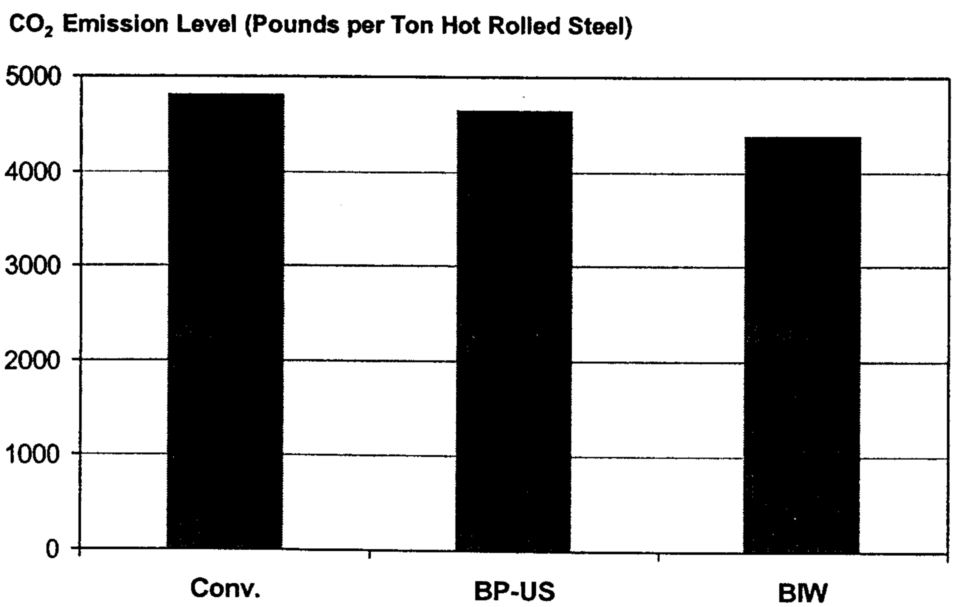
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 14b. CO_2 Emission Reduction/Increase (Pounds per Ton Cold Rolled Steel)



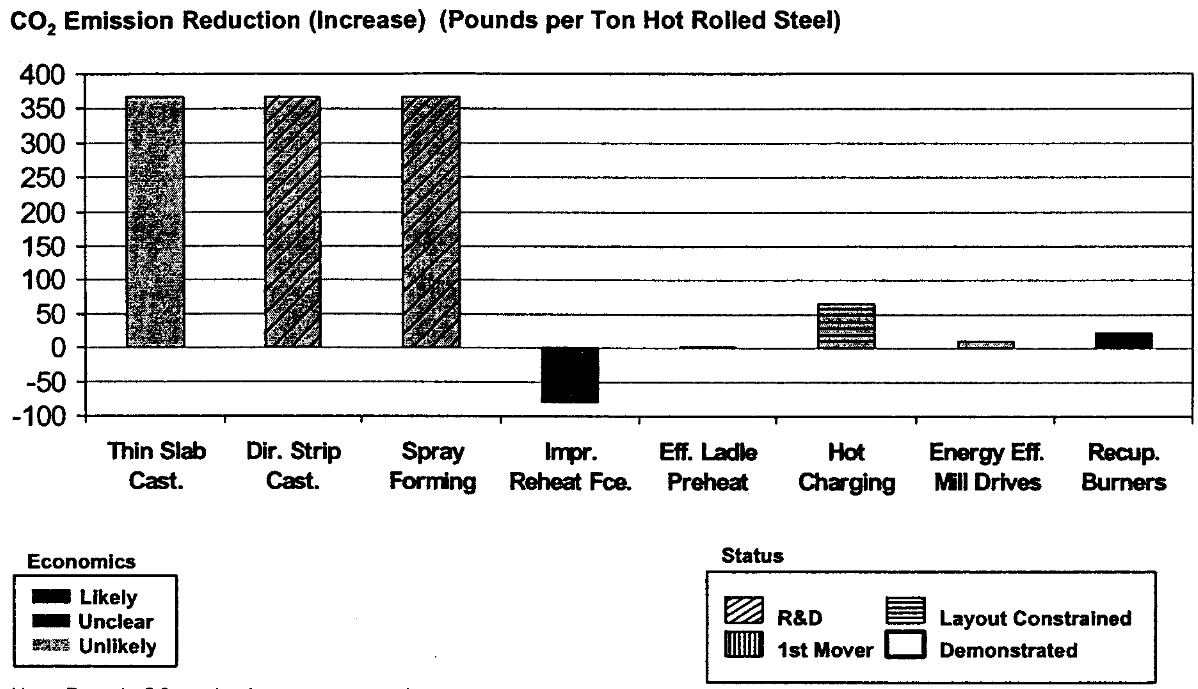
Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 13a. CO_2 Emission Level (Pounds per Ton Hot Rolled Steel)



Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

Figure 13b. CO_2 Emission Reduction/Increase (Pounds per Ton Hot Rolled Steel)



Note: Pounds CO_2 emitted are a surrogate for energy efficiency.

ESTIMATED COSTS, EMISSIONS REDUCTIONS, AND ECONOMIC IMPACTS OF POLICY OPTIONS TO REDUCE CO_2 EMISSIONS IN THE IRON AND STEEL INDUSTRY

The equipment and processes currently in use in the domestic industry are highly site-specific, and there is a high degree of uncertainty in site-specific costs to retrofit existing or new technologies into the mills. There are also wide variations in energy consumption and emission rates among the mills, and, therefore in the benefits that can be obtained by implementing the technologies. Given these considerations it is not possible to develop energy conservation supply curves—and the corresponding reductions in emissions curves—with any certainty in an analysis of this scope. We believe that previous attempts to do so (e.g., by Warrell, Martin, and Price, op cit.) have seriously overestimated the potential energy savings that can be obtained under the influence of market forces alone, that is, in the absence of any new policies, because they have underestimated the costs to implement the technologies on an industrywide basis. For example, these authors estimate that even at a very high real discount rate of 30 percent, cost-effective technologies exist that could reduce energy consumption by 16 percent and 25 percent in the integrated and minimill sectors, respectively, whereas we have shown that employing the best practice demonstrated worldwide would provide savings of the order of 10 percent in either sector. Savings of 10 percent would not be insignificant, however, since they would represent an improvement of the order of 30 percent of the amount that could be saved in moving from current averages to the theoretical practical minima (see Fruehan et al., op cit.).

However, many of the technologies used to obtain best practice results have been employed in regions with different economic drivers (e.g., higher energy costs) than are at play in the domestic industry, and retrofitting them into existing plants is of necessity more costly than designing them in ab initio. Therefore, these technologies may not necessarily be cost-effective under current conditions in the domestic industry, where capital for such projects is extremely scarce for the reasons described earlier. Nevertheless, we have estimated the capital requirements and cost savings that would attend the implementation of the technologies described in Appendix A, which would be required to reduce industrywide emissions by 10 percent.

Our estimates were developed using preengineering design techniques based on "typical" unit capital requirements and the "average" reductions in energy and materials consumption shown in the Appendix. Where appropriate, we have estimated the productivity improvements and yield increases that would accompany the technology changes for "typical" conditions. These are rough order of magnitude class estimates, which carry uncertainties of the order of -50 percent to +33 percent in capital requirements and -33 percent to +25 percent in operating costs or benefits. Since total carbon emissions are estimated in a chain or sequential type calculation across the production processes, reductions of less than 10 percent in one processing step must be offset by reductions of more than 10 percent in another step, and vice versa. Where large savings are possible in a step, e.g., in the recovery of energy from basic oxygen furnace off-gases, we have based our estimate on the use of the technology in only that fraction of production required to decrease the overall industry average emissions in that step by 10 percent.

In developing these estimates, we have not attributed the adoption of any particular technology to any specific policy option that might be considered. Rather, we have picked those technologies that, in our judgment, would be most likely to be adopted based on the recent structure of the industry, with a production of about 109 million tons of raw steel of which about 60 percent originates in the integrated sector. Benefits have been estimated on the basis that coke, fuel, and power saved are valued at $120/ton, $3/MMBtu, and $0.03/kWh, respectively. Increased productivity is estimated to return average revenue of $300 to $400/ton depending on the product. The results of this analysis are summarized in Table 5 below.

Table 5. Estimated Costs and Economic Impacts of Reducing Carbon Dioxide Emissions by Ten Percent in the Domestic Iron and Steel Industry

Process Step	Technology Required	Operating Benefits	Capital Requirements ($million)	Benefits ($million)/ Year
Integrated Sector				
• Pelletizing and sintering	Improved grinding; bed depth, and air control	Reduced specific power, improved recovery	300	84
• Cokemaking	Coal moisture control, dry quenching	Reduced specific coal consumption	320	52
• Blast furnaces	Higher blast temperatures on smaller furnaces; higher natural gas injection on larger furnaces	Reduced coke consumption, increased productivity	650	60
• Basic oxygen furnace	Off-gas energy recovery system	Increased on-site power cogeneration	200	23
• Casting, reheat, hot/cold roll, coat	More efficient drives, reheat furnaces, improved process control	Reduced specific power, energy consumption and increased yield	1,000	268
		Total Integrated Sector	**2,470**	**487**
Minimill Sector				
• EAF-long products	Larger, more efficient/productive furnaces	Reduced specific power, increased productivity	1,000	166
• Long products–casting, reheat/rolling	More efficient drives, reheat furnaces, improved process control; capacity increase to accommodate production	Reduced specific power, energy consumption, and increased yield	300	40
• Existing EAF-flat products	Improved process control and energy savings projects across the mills	Reduced specific power, energy consumption, and increased yield and productivity	450	80
		Total Minimill Sector	**1,750**	**286**
		Industry Total	**4,220**	**773**

Our estimates indicate that investments of the order of $4.2 billion would be required to reduce industrywide emissions by 10 percent, or by about 19 million tons of carbon dioxide per year, a specific investment requirement of about $225 per annual ton removed. Given the uncertainty in the estimating methodology, the required capital could range from $3 to $6 billion, or from about $160 to about $320 per annual ton. The projected benefits of about $0.8 billion per year amount to about $40 per ton of carbon dioxide removed, but given the uncertainty in the methodology, estimates could range from $0.6 to $1.0 billion per year or from about $30 to about $50 per ton of carbon dioxide removed.

The estimated simple pretax return from the cash benefits derived from these investments is about 18 percent per year, a level too low to justify major expenditures in an industry in such poor financial condition. For example, the current market capitalization of the U.S. and Canadian steel industry is in the range of $10 billion. Thus, the industry would be forced to seek financing for up to 40 percent of its total capitalization to implement such projects, and it is unlikely to be able to secure such financing based on the prospect of such meager returns. Assuming a two-year construction period, no start-up delays, and a 20-year life, the estimated net present value of the pretax cash flows from these investments, excluding depreciation expense, at a 20 percent real discount rate, is negative and amounts to about $1.2 billion. The present value estimation is sensitive to the assumed construction schedule, start-up rate, project life, and discount rate. The 20-year project life assumed here is based on typical equipment lives not on the investment time frame in the industry, which is much shorter. The 20 percent discount rate is significantly higher than the real cost of capital in financially healthy industries in the economy, which is in the range of 10 to 12 percent, but reflects the magnitude of the current opportunity cost of capital for nonessential investments in the steel industry.

In these estimates, about two-thirds of the projected benefits result from estimated improvements in yields and productivity gains, which are assumed to generate increased revenue at current average sales prices and margins. This may not be possible given the current state of the markets, and in the absence of these benefits, the simple pretax return on materials and energy savings alone drops to about 6 percent per year and net present value decreases to about negative $2.9 billion. Clearly, these investments would not be considered based on energy savings alone at current energy prices. Furthermore, these estimates do not recognize any real increased emissions of particulates or criteria pollutants, or the administrative and regulatory complications arising from their consideration, such as the need to repermit a facility. Such factors could impose significant additional costs that would reduce the projected benefits substantially.

It is interesting to note that while about 75 percent of current carbon emissions arise from the integrated steel making sector, we have estimated that only about 60 percent of the industry total capital requirements and benefits are associated with that sector. The implication is that it is more cost-effective to reduce emissions in the integrated sector than in the minimill sector. This is to be expected given the nature of the production processes and the condition of the facilities involved. The reduction targets are "fatter" in the integrated sector, and it is more difficult to make large improvements in the generally newer, simpler, and lower-emitting equipment and processes in the scrap-based minimill sector. The estimated net present value of the pretax cash flows from these investments, ignoring depreciation is about negative $0.6 billion in each sector.

If a carbon tax were imposed on the economy, avoidance of emissions would provide additional economic benefits beyond those estimated here from energy savings and productivity and yield improvements. Industrywide, imposition of a $70 per ton carbon tax would be sufficient to provide a 20 percent real discount rate on these investments. However, such a uniform tax would disadvantage the minimill sector vis-à-vis the integrated sector, since a tax of about $40 per ton would be sufficient to justify projects in the latter while a tax of $140 would be required in the former if the same 20 percent discount rate were used.

Since specific emissions are much higher in the integrated sector than in the minimill sector, about 2.2 tons CO_2 per ton crude steel versus about 1.0 tons per ton, industrywide average emissions can be reduced if production share is shifted from the integrated to the minimill sector. A share shift of about 15 million tons per year of flat products production would be required to decrease average emissions by 10 percent, but a shift this large would probably be constrained badly by the available supply of high-quality scrap. Either scrap or, more likely, cold pig iron or reduced iron feeds, such as DRI, would have to be imported to meet the requirements for high-quality metallics in flat products electric arc furnace shops. While these materials have high carbon emissions in their production, they would be manufactured offshore and so would not contribute to the domestic emissions calculation. Thus, shifting production share from the integrated to minimill sector to reduce average emissions is an emissions exporting strategy.

While a shift of such magnitude is not likely, most industry observers expect some ongoing shift to occur, driven by normal market forces—new flat-rolled minimills can be constructed relatively quickly and at far lower unit capital cost than integrated mills and can be located closer to developing markets, requiring only access to scrap and reasonably priced power. Investments of the order of $2.5 billion would be required to bring on an additional 5 million tons of capacity, which would reduce industrywide emissions by 3 to 4 percent. However, the developers of these projects would justify them on conventional economic grounds, not on the need to reduce emissions. Since the projects are expected to be profitable in their own right, the emissions reductions benefits overall would be obtained at no net cost to the economy. These considerations suggest that policymakers may have to view the integrated and minimill sectors differently when attempting to formulate economically efficient policies for reducing carbon emissions.

4. Survey of The Industry and Outside Experts

SURVEY METHODOLOGY

As the work on Task 1 was being concluded, CRA developed a list of key contacts in both the integrated and minimill sectors of the industry, in government agencies, and in other supporting industries to solicit responses to the preliminary conclusions and suggestions regarding policy options for greenhouse gas reduction. Letters soliciting meetings were sent to the senior executives of all of the integrated companies and to a number of the most important minimill companies. We chose not to survey most of the large number of small, local EAF- based long-product producers, and, instead, concentrated on the larger multishop long and flat-product producers. We received positive responses to our request for interviews from companies that had the capacity for more than 50 percent of domestic production, and these companies were sent a briefing document to prepare them. This document is presented in Appendix B. In addition, we sought interviews with the industry trade associations (AISI, SMA), and with experts in government agencies and organizations that support the industry, such as engineering firms, to discuss narrower issues that arose in our discussions.

The interviews with industry executives typically lasted two or three hours, depending on the time that could be made available, and were carried out both face to face and by teleconferences. All discussions were open and wide-ranging—CRA promoted the frankest possible discussions by agreeing not to attribute specific comments to specific organizations. Detailed meeting notes were taken and have been abstracted for presentation in this report. The same procedure was used in the other interviews that were made, but the durations were typically shorter because the topics under discussion were more focused.

INTERVIEW RESULTS—TECHNOLOGY AND ECONOMIC ISSUES

The results of our interviews with executives of both the integrated and minimill sectors of the industry are summarized in Table 6. We sought responses to suggestions about specific policy issues and to ask questions on the cost effectiveness of the various technologies, and the process of investment decision-making in the industry. Responses to the latter type of questions are summarized in the "other issues" responses in the table.

An overarching question posed in this analysis was: why don't all firms adopt the most energy efficient technologies used by the industry leaders, domestic or foreign, if the payback on returns on these types of investments appears to be so attractive? The respondents provided several answers to this question, often with specific examples from their firms' experiences.

All asserted that investment decision making for energy reduction projects was carried out in the same way as any other investment decisions, and, indeed, many such projects had been approved over the years. However, results of these projects were mixed, with a significant number not providing the returns expected, either because technical performance did not meet expectations, or because the economic premises on which the justifications were based were violated by cost overruns, schedule slippages, etc. One executive commented that, had all approved projects worked as planned, they could "make steel for free." While such problems are by no means unique to the steel industry, poor results accumulate in the corporate memory, those deemed responsible pay a personal price, and management becomes risk averse.

When asked if the technical problems resulted from lack of engineering resources or poor planning and evaluation procedures within the firms or the engineering/construction industry, the responses were mixed: the larger firms with more capability felt this was less of an issue than did the smaller firms. None of the participants seemed to feel there was a positive role that "outsiders" could play to remedy this situation. However, minimill companies often consider local skills levels and community commitments to support operator training in their plant siting decisions, and interviews with executives in the engineering/construction industry confirm that their collective capabilities have diminished in recent years because of the low level of capital spending in the industry.

Lower-than-expected economic returns can arise from purely technical problems, such as lower-than-expected energy savings or equipment reliability, or higher than expected costs, schedule slippages, or longer-than-anticipated commissioning times that lead to lost production. The authors of a study of Energy Efficiency and Carbon Dioxide Emissions Reductions Opportunities in the U.S. Iron and Steel Sectors gathered data on the cost effectiveness of a range of energy-savings technologies.[15] They were interviewed to gather more information on the bases for their conclusions and the extent to which they were validated through industry contacts, since CRA did not agree with all of their estimates. We believe that, while some validation was obtained, most of the estimated capital requirements are only qualitatively correct, because the authors had no way to comprehend the effects of site-specific constraints—especially plant layout—on costs. The individual technologies considered, and listed in Appendix A, would have to be retrofit into operating plants.

In the integrated sector, the plant layouts were fixed forty years or more ago, and are generally not conducive to major retrofits. While most EAF shops are of more recent vintage, they too were laid out with a specific technology and operating practices in mind and are generally not amenable to major retrofitting.

[15] Op cit.

Retrofitting a scrap preheater, for example, poses major problems of access, altered material handling and gas handling, and even in acquisition of the type of scrap that can be charged to the furnace. An interesting example of such problems was cited at a BOF shop in the integrated sector. One vessel was laid out quite differently than the other, and while off-gas energy recovery was economically feasible conceptually for one, it was unfeasible for the other because of the changes that would be required to the structure. It was suggested that retrofitting energy-savings technologies in mills in western Europe and the Far East was generally more practical, because the facilities are newer than those in the US and, having been intended to operate in environments where energy costs are higher than in the United States, they are designed more flexibly, and to accommodate energy-efficient technologies. While this is undoubtedly true, there also exists a significant range between the most and least energy efficient mills in these regions, just as there is in the United States, because they were designed with different objectives and constraints applying and at different times.

However, a major factor in the apparent reluctance to adopt apparently cost-effective technologies is the scarcity of capital in the industry brought about by poor economic conditions. The general state of affairs has been shown in Figures 5 and 6, and many individual company's capital budgets are so low that only essential projects are justified. Essential projects include those that must be undertaken to permit continued operation, such as blast furnace relines, maintenance projects that are essential for environmental, safety, and occupational health reasons, and projects that are essential to improve product quality to maintain market position, such as mill upgrades. In effect, all other "nice to have" projects have almost impossibly high hurdle rates even though they may appear to be justified by conventional economic criteria. This consideration leads to much of the reaction to various suggested policy options (discussed below) to improve the overall health of the industry.

Unexpectedly, the issue of environmental constraints occurred in some of the discussions with industry participants, and examples were cited of projects that were not executed because of the consequences of the current permitting process. Anecdotal evidence was given of similar occurrences in Western Europe and Canada.

Subsequent interviews with members of the staff of the U.S. Environmental Protection Agency who are responsible for rulemaking, enforcement, and industry ombudsman capacities confirmed that such problems do exist. Thus, even though installation of a new technology might reduce CO_2 emissions, as well as the emissions of other pollutants, such as particulates, its installation could trigger a Title 5 review of the entire mills operations, and companies are unwilling to undertake such an exercise for marginal energy savings.

A careful reading of the response in Table 23 shows that there are some differences between the response of integrated producers and minimill operators. The latter, for example, have little concern over the handling of issues related to labor legacy costs that are a major problem for the integrated producers. On the other hand, they are much more sensitive to security of supply and price stability issues for electric power, since it is a far larger component of their costs than it is for the integrated producers. These differences need to be recognized in the formation of policy aimed at assisting the industry as a whole.

Finally, it is of interest to note the comment of one participant who pointed out that the most energy-efficient way to operate a plant is not necessarily the most profitable. For example, long runs of a single product may minimize downtime, scrap generation, and energy consumption. However, shorter runs of more profitable products may provide net revenues that more than offset the additional energy costs associated with their production. The implication clearly is that there is no universal or "best" approach to energy conservation to reduce emissions of CO_2, since economic optimization depends not only on the physical assets involved, but local costs and market-driven production requirements as well.

Table 6. Summary of Interviews with Steel Industry Executives (I stands for integrated mills)

ISSUE	I-1	I-2	I-3	I-4	I-5
Raise all boats -- import restrictions	Enforce existing trade laws instead of developing new ones.	Must manage imports so that there will be no price erosion. Use section 202 for both semis and finished.	The excess capacity problem is worldwide, not just in the United States.	Need timely enforcement of existing laws.	
Raise all boats -- nontargeted loan guarantees	Do not work because they go on the books as debt.	No- Government has no business helping weak companies. Not needed if 202 invoked.		Not in favor of nontargeted loans.	
Capital subsidies -- accelerated depreciation	Good if applied against alternative minimum tax.	Yes, and other tax credits for improving energy efficiency.	Helpful if there are earnings. Any policy improving EBITDA[1] would be helpful.	Favors for projects related to energy efficiency or CO_2 reduction	
Capital subsidies -- loan guarantees	Against. See above	No. See above.		See above	

[1]EBITDA = Earnings before interest, taxes, depreciation and amortization

Table 6. (continued) Summary of Interviews with Steel Industry Executives (I for integrated mills)

ISSUE	I-1	I-2	I-3	I-4	I-5
High energy costs	Provide a tax credit for the saved BTUs.	Would drive out producers and users causing them to locate elsewhere.	High energy costs or CO_2 taxes would have depressing effect across the board and lead to more imports.		Will simply promote more overseas production – same with CO_2 tax
Targeted spending - loan guarantees, energy savings projects		Good, as all projects are handicapped by lack of capital.		Favors loan guarantees or low interest loans for energy savings projects.	
Targeted spending - R&D consortia, cost savings	DOE Clean Coal Technology programs for coal injection were good. Supports R&D consortia (increased competitiveness has hindered cooperation).	Technical assistance would be useful as currently constrained by lack of capital.	Cost-sharing R&D would be helpful.		
Technical assistance – first mover assistance			There could be "cultural issues" with acting as a test bed for development of new technology because of risks.		

Table 6. (continued) Summary of Interviews with Steel Industry Executives (I for integrated mills)

ISSUE	I-1	I-2	I-3	I-4	I-5
Technical assistance -- dedicated PM teams			Uses outside resources extensively. They key to project success is through planning.		The causes of some past PM problems aren't clear- both internal and external issues.
Antitrust issues resolution	An internal industry ego issue, not matter of law per se.	Current fragmentation is hurting the industry. Mergers with stock transactions would improve efficiency.	Consolidations would be helpful, but only if obsolete plants are shut.	Consolidations with facilities closures should not be a problem under existing law.	
Labor issues -- legacy cost assistance		Not an issue. Perhaps some form of government assistance would be helpful.		Tax credits for firms that have already met legacy requirements, but no "general amnesty."	
Labor issues -- labor relations assistance					

Table 6 (continued) Summary of Interviews with Steel Industry Executives (I for integrated mills)

ISSUE	I-1	I-2	I-3	I-4	I-5
Labor -- training, other			The issue with skills is qualification/ competency on the shop floor. Work force is aging and jobs are filled by seniority. Training is an issue.		
Other issues	The most profitable operation is not always the most energy efficient. Capital for purely energy savings projects is practically nonexistent.		Reluctant to deviate from what is "known to work" because of down time risk and financial/personal consequences of failure.	Environmental laws may "impede" new investments in energy savings projects and are "barriers" -- need simplified laws.	First priority for capex[2] is market positions or quality improvement, regardless of ROI.
Other issues	Encourage development of N.G. supply and infrastructure.		High energy costs in other countries have led them to "build in" infrastructure for energy savings. Retrofitting costs are less of an issue there.	"Environmental" costs are $25/ton and, with occupational safety costs, are not borne in most exporting countries.	Energy efficiency is <u>very</u> product specific. Changing grades constantly introduces innefficiencies.
Other issues			Energy savings projects that must be retrofit or entail downtime risk are problematical. They do "all the Japanese stuff."		Retrofit costs in an old mill are high. They have some problems with basic energy measurement.

[2] Capex = Capital expenditure

Table 6. (continued) (M stands for mini-mills)

ISSUE	M-1	M-2	M-3	M-4
Raise all boats -- import restrictions	MOU on steel probably impractical - too many parties. Use licensing system (Canada). Make WTO compliant and anticipatory, not reactive.	Use import licensing system (Canada) -- be active not reactive.	Taxing imports based on CO_2 content would ameliorate effect of forcing production offshore. Need to get level playing field, not bans or quotas.	Favor AISI position. Overcapcity is a worldwide problem, not a US problem.
Raise all boats -- non-targeted loan guarantees	Against broad based subsidies -- let weak players die.	Against broad based subsidies and overt assistance.	Against -- need to let old/inefficient faclities go out of business. Strenghten the survivors will promote investment in more efficient plant.	Opposes Byrd bill, it subsidizes weak players. Most companies in Cha 11 have had financing.
Capital subsidies -- accelerated depreciation	Favor for energy-related projects.	Favor tax subsidies for energy projects. Additional credits would help implement some technologies.	Would be helpful.	Would be useful if well defined in advance and applicable at companies' discretion.
Capital subsidies -- loan guarantees	Against. See above.	Against. See above.	Targeted loan guarantees would probably help industry as a whole. Non targeted (Byrd) are bad.	

Table 6. (continued) (M stands for mini-mills)

ISSUE	M-1	M-2	M-3	M-4
Higher Energy costs	Would lead to a vicious cycle -- reducing earnings and amount of $ to invest.	Would lead to a vicious cycle -- energy projects better, but no earnings.	Would lead to a vicious cycle. Only work if all producers internationally were subject to the same increases.	Without a commensurate increase in product price, it is not clear that energy savings projects could be implemented.
Targeted spending - loan guarantees, energy savings projects	No real interest.	No interest.	Would help promote energy projects -- favor targeted loan guaranteees or tax benefit.	Targeted loan guarantees to energy projects would be OK if structured properly.
Targeted spending-R&D consortia, cost savings	Scrap preheating R&D could be an effective area for this.	Additional tax credits for R&D.	Already participate and will continue to do so.	Have used the results of prior AISI research effectively. Let industry set goals and targets, not government.
Technical assistance - First mover assistance	Could be helpful in removing mentality of wanting to be 2nd. Need to ensure against bureaurcracy and to allow advantage to be gained.	Could be helpful to mitigate risk.	Financial assistance for a new technology would be helpful as well as regulatory relief (EPA) during start-up.	Would probably be valuable, but potentially difficult to implement, to aid the entire industry.

Table 6. (continued) (M stands for mini-mills)

ISSUE	M-1	M-2	M-3	M-4
Technical assistance -- Dedicated PM teams		No role for government here. This done with equipment vendors.	Have strong internal capabilities -view as a competitive advantage.	Probably a bad idea - question the competence of government sponsored assistance in this area.
Antitrust issues -- resolutions		Set up something analogous to code-sharing deals among airlines for order swapping to better serve customers.	Not an issue yet.	
Labor issues -- Legacy cost assistance		Government should not play a role in relieving legacy costs.	Not an issue. Government should provide relief only if facility is closed permanently, otherwise it promotes continued operations of inefficient faclities.	Successful companies do not have onerous contracts.
Labor issues -- labor relations assistance		Not an issue.		The government could help legislate out the "dogs" in the contracts e.g., work rules.

Table 6. (continued) (M stands for mini-mills)

ISSUE	M-1	M-2	M-3	M-4
Labor issues – training, other			Cooperates with state/local governments for funding training programs.	Training assistance is valuable espcially for older workers and can effect siting decisions. Need support at the university level to train more technical people.
Other issues	Patchwork of state regulations leads to supply/price uncertainty. Feds should develop policy to insure cost effective supply of power. Coordinate FERC and State PUCS .	If "money were no object" would outfit furnaces with scrap preheat (consteel), but capex is high and scrap charge is limited (no bundles), and there are operability problems.	Need to get better coordination between EPA & DOE. EPA may discourage new energy savings technologies (e.g., scrap preheating).	New projects are being done with foregin equipment and engineers.
Other issues	Get rapid approvals of energy projects, promote cogeneration, reexamine Nuclear role, and deregulation philosophy.		EPA/DOE coordination is a major issue. Measures to "save" the industry will be counter productive unless some capacity closure occurs.	New projects are often justified on grounds other than energy (e.g., yield, productivity)- energy savings are a bonus. Energy savings per se has low priority in capex.
Other issues	Kyoto may simply export CO_2 generation not reduce global levels.			Giving EPA control over CO_2 is a bad idea. CO_2 tax would result in exported production and pollution.

INTERVIEW RESULTS—POLICY ISSUES

The briefing document shown in Appendix B lists some of the policy options CRA wished to bring up for discussion in the interviews, and we solicited the participants' suggestions as to others that should or should not be considered. As might be expected, there were varying degrees of uncertainty on the appropriateness and probable effectiveness of the measures suggested.

There was strong and consistent support for policies that would raise the price of steel imports, both for semifinished and finished products, although individual producers had different interests with respect to the treatment of the two types of imports. The producers were not suggesting that a widespread quota system be adopted, because it is recognized that current domestic capacity is far below domestic demand, and significant imports will be required for the foreseeable future. Rather, price protections were being sought as a means to increase revenues, and thereby improve the financial health of the industry. There was, however, no general agreement on the specific mechanisms that should be used to achieve this goal, and suggestions ranged from the simple enforcement of existing laws on a more consistent and vigorous basis, to the adoption of a licensing system for imports, to invocation of section 202 of the trade laws. The problem of global overcapacity in steel production was cited as the root cause of the problem, but there was also clear sentiment for further rationalization in the domestic industry. Enforcement of existing antitrust laws were not seen as an insurmountable obstacle in this regard.

Past experiences were cited in support of policies that would provide targeted tax incentives. The industry would seek regulations that amounted to "prior agreement" on the concept and would not be subject to ongoing interpretations and negotiations with the IRS. The industry would seek to maximize flexibility with respect to selection of the technologies it would adopt, not being tied to specific choices, but at the same time it was acknowledged that such incentives would have to be targeted and limited to prevent abuses. Suggestions as to how these requirements might be met were not forthcoming. In any case, achieving industry health was a prerequisite to the effective use of tax credits.

A clear concern was expressed at the apparent lack of "coordination" between DOE and EPA with respect to the environmental issues discussed above. Staff of the EPA cited an example of a cooperative DOE-EPA effort to promote clean coal technology development some years back. The agreement in effect at that time, which has apparently been accepted as a general model, could provide significant relief in efforts to demonstrate new technologies. Broader relief would, however, probably require revision to the PSD rules to remove the obstacles cited by industry participants.

There was more limited but still positive support for policies that would provide first-mover assistance, or support cooperative R&D efforts. Support for the latter, however, was qualified by the opinion that the R&D programs be defined in scope, and directed by the industry to satisfy their needs—not by the government. The past programs undertaken by DOE and AISI were viewed as good models, and there was no support for erecting new structures to support cooperative R&D, except for the desire for larger tax benefits. Since all participants acknowledged that the industry was generally risk averse, the potential benefits of first-mover assistance were recognized as a method of risk spreading. Still, some participants expressed doubts that it would be feasible to draw up agreements that would properly indemnify all parties from risks in a significant first-mover technology development program.

Policies supporting technical assistance programs attracted little support, and the proposal was met with great skepticism by some. The attitude seemed to be that no "outsider" could provide the necessary expertise or understand the real site-specific constraints of particular situations. This is a somewhat parochial attitude, given the relatively poor track record of the industry in recent years in bringing projects in on time and within budget, and also given the acknowledged ongoing reduction in the technical resources available within the companies. One participant had had a millwide energy audit performed for them by a local utility—not a small undertaking in so complex an operation, and well beyond the capability of existing staff, given their other responsibilities. However, mill management had not reacted yet to the implications of the study, which showed numerous opportunities for energy savings, because of the scarcity of capital.

The participants also showed far less interest in targeted loan guarantees than in the targeted tax incentives described above. The reasons for this are not entirely clear, since they might be structured to meet the needs of all parties more simply than could the analogous changes in the tax laws, and would be of benefit to firms that did not have significant tax liabilities. It appears that this reaction results from a perception that loan guarantees simply serve to prop up weak firms that should be allowed to fail.

The latter concern was expressed forcefully with respect to policies that provide general guarantees, such as the Byrd bill. The stronger players see no benefit in propping up weaker competitors, and would prefer to see them fail, either to take capacity off the market, or perhaps, to acquire it themselves, and rationalize their move in a way that would strengthen their business through a better match of their production capabilities and market requirements.

While it was acknowledged that higher energy prices should promote more investment in energy-savings technologies, policies to effect this were opposed uniformly. The rationale was that the increase in energy costs could not be passed on to customers, given the import pressures—margins would be reduced further, and an already distressed industry would have even less capital to commit to any projects. The net effect would be to export still more production.

The same logic was expressed with respect to oppositions to the Kyoto protocol. It was also pointed out that, by and large, the production of steel in Annex B countries is not as energy efficient as it is in the United States, so that the net effect would be an increase in the world's burden of CO_2 created in the production of steel. It does not appear, however, that the concept of carbon dioxide emissions trading is well understood in the industry, and that the reaction to the proposed Kyoto protocol was visceral, being viewed as a pure threat, with no opportunity to derive competitive advantage.

5. Policy Analysis of Options To Reduce Carbon Dioxide Emissions in The U.S. Steel Industry

HIDDEN COSTS AS BARRIERS TO ENERGY EFFICIENCY INVESTMENT

We have described above how, with financial conditions precarious in the steel industry, rational businessmen may choose not to undertake energy efficiency investments that might appear profitable to an outside observer. The reasons that those making investment decisions choose not to undertake seemingly profitable investments have long been the subject of debate in the energy policy literature.

Numerous engineering-based studies of energy efficiency technology point to the existence of highly energy-efficient products and technologies that appear to offer end users significant life cycle cost savings, yet are not widely used. Many contributors to the literature think the existence of these untapped opportunities demonstrates that significant improvements in energy efficiency, and reductions in greenhouse gas emissions, can be achieved at zero or negative cost. To others, including most economists, the existence of underutilized technologies with putative cost savings does not automatically lead to such a conclusion. These observers would point to hidden costs not captured in the engineering-based studies, as well as potential market imperfections, as reasons for nonadoption. Where hidden costs are significant, claims of technological "free lunches" fail.

A comprehensive analysis of the economics of energy-saving technologies must capture all the costs of implementing the technology. Of general relevance to most industries, including steel, are the additional costs, frequently omitted from engineering-economic analyses, of retrofitting new technologies into existing facilities or replacing existing equipment with the latest technologies before the end of the normal economic life cycle. These costs may explain why seemingly attractive technologies are used in some facilities and not in others. The facilities with low retrofit costs, or ones that have not recently undertaken major capital replacements, will have found installing the technology to be profitable, while those with high retrofit costs, or with relatively new equipment in place, will not.

The preceding analysis, however, suggests the existence of three other sources of hidden costs likely to be of great significance in the steel industry:

- Risk of premature shutdown of the facility in which the investment is being made.
- Scarcity of engineering resources.
- Risks of interrupted production.

We will discuss these in turn.

SHUTDOWN RISK

In the literature on the discount rates to be used in assessing investments designed to avert global warming, it has already been noted that individuals with short lifetimes, or no interest in the welfare of their descendents, will appear to use higher discount rates in evaluating investments than individuals with very long lifetimes, or with a strong interest in their descendents well-being.[16] A similar phenomenon is likely to characterize the steel industry, or any other industry in financial distress: firms facing significant risks of plant shutdowns may act as if they are facing very high discount rates, because they are reluctant to undertake investments that seem unlikely to provide benefits. For example, consider a hypothetical investment of $100 undertaken today that yields $50 in cost savings per year over a useful life spanning the next five years. Such an investment has a two-year simple payback, and, at an interest rate of 15 percent, has a positive net present value of $67, assuming the plant in which the investment is made stays in business throughout the life of the investment. Suppose, however, the firm faces a one-third chance of having to shut the plant every year, and that the investment is plant-specific and has no scrap value if the plant does shut down. The firm's expected returns on the investment in any particular year is no longer $50, but rather $50 multiplied by the probability that the plant will still be in operation in business in year i, which is given by:

$$P = (1-1/3)^i, \ i=1\ldots5$$

Table 7 illustrates that, under such circumstances, this hypothetical investment with a seeming two-year payback fails to yield an expected positive return at any nonnegative interest rate.

[16] P. Portney and J. Weyant, eds., *Discounting and Intergenerational Equality*, Washington, DC: RFF, 1999. See also R.C. Lind, *Discounting for Time and Risk in Energy Policy*, Baltimore: Johns Hopkins University Press, 1982.

Table 7. Expected Cash Flows When Shutdown Is Possible

Year	Cash Flow	Expected Value of Cash Flow
0	-100	-100.0
1	50	33.33
2	50	22.22
3	50	14.81
4	50	9.88
5	50	6.58
NPV at 0% Interest		-13.17
NPV at 15% Interest		-35.55

Given the precarious financial state of many of the firms in the steel industry, shutdown risk may well be a significant hidden cost acting as a barrier to investments in energy efficiency.

SCARCE ENGINEERING RESOURCES

Another source of hidden costs previously acknowledged in the literature may well be quite significant in the steel industry—the need to include the costs of scarce engineering resources when accounting for an investment's economic potential.[17] In most engineering-economic analyses, the opportunity cost of the engineering and management services needed to implement the investment successfully are inappropriately excluded from calculations of cost. Failure to include these costs in analyses of the steel industry is likely to lead to especially misleading assessments of the economics of various technologies, because there is reason to believe that engineering services are in short supply in the industry, and therefore carry a very high opportunity cost. One consequence of the poor health of the U.S. steel industry has been the erosion of in-house engineering staffs, and the availability of domestic contract engineering providers with experience in installing new facilities. There is a shortage of the locally available experienced engineers that would be needed to evaluate and implement any new investments.

[17] The need to account for engineering costs as a factor in explaining decisions about whether or not to adopt technology has been stressed most recently in a study of the potential for greenhouse gas reductions in the Canadian auto parts sector. Transportation Equipment Manufacturing Sector Working Group, National Climate Change Industry Table, *Greenhouse Gas Options, Policy and Measures for the Canadian Transportation Equipment Manufacturing Industry*, February 2000.

RISKS OF INTERRUPTED PRODUCTION

A final source of hidden costs particularly relevant to the steel industry relates to the economic risks taken when a firm faces the possibility that installing a new technology will lead to interruptions in production. Especially when the expected value of energy savings is small relative to the value of potentially lost output, firms may rationally choose not to adopt technologies that seem to offer energy cost savings. Considerations of such risks are likely to be especially acute in the steel industry for two reasons: First, the execution risk—the probability that the downtime associated with new investments will be unexpectedly large is likely to be especially significant in the industry because of the shortage of experienced engineering personnel. Second, with many companies in extremely precarious financial positions, an unexpectedly prolonged loss of a production line may expose firms to potentially fatal cash flow crises.

The risk is especially important because the expected energy savings are a relatively small percentage of total costs of production. Moreover, many studies explain that energy savings are seen by managers as being "too small to matter" even though they promise positive returns. Consider, for example, an investment made by a 5 million ton/yr integrated mill, to reduce emission by 10 percent. Earlier in this report, we estimated that such an investment might cost about $100 million, and have expected benefits (from associated improvements in productivity and lower energy costs) of about $4/ton of steel produced. Assuming average revenues of $440/ton, a margin of $40/ton, and a 50:50 split of fixed and variable costs, even a small amount of project downtime can wipe out the savings projected for a 20- year project. Either an 80-day zero production start-up delay or a reduction in production by a little over 1 percent (4 days/yr) would result in no net savings at a 0% discount rate. Any linear combination would have the same effect, e.g., a 40-day start-up delay plus a ½ percent loss in production. These considerations are powerful barriers in decision-making capital- intensive, high fixed-cost industries—and not just steel!

MARKET FAILURES, MARKET BARRIERS, AND PUBLIC POLICY

The existence of technologies that seem to offer greenhouse gas reductions and that also appear to pay for themselves, but have not been adopted widely, raises questions for policy makers. Why are some apparently economically efficient technologies not in more widespread use? Can changes in public policy cause more of them to be adopted, and at what cost? Other questions may also interest policy makers. For example, are there changes to policy that can bring about the more widespread adoption of currently efficient technologies? Are there policy initiatives that can help create new economically efficient technologies?

We have previously discussed hidden costs as one important factor that may explain the non-adoption of technologies that at first might appear to pay for themselves. Such hidden costs should be viewed as market barriers—real costs preventing the adoption of new technologies that cannot be eliminated by public policy. (Of course, public policy can be used to transfer these costs to other parties—for example, by using taxpayer subsidies to overcome them—but it cannot truly eliminate them.) Technology discovery and adoption decisions, however, may be impeded by market failures as well as by market barriers. Market failures arise when private decision makers realize costs or benefits from their actions that do not correspond to the full costs or benefits their actions impose or confer upon society. The existence of market failures offers, at least in theory, the potential for "free lunch"—reductions in energy use and greenhouse gas emissions that can occur at zero or negative costs to society.[18]

In the discussion that follows, we distinguish between two types of market failures. The first are potential failures that could work to distort energy efficiency investment decisions in general, regardless of the price of energy. Remedying such failures offers the chance for no-regrets improvements in energy efficiency that would provide net social benefits, even if greenhouse gas emissions were of no concern. If such failures exist, remedying them might bring about greater adoption of economically efficient technologies at negative social costs, or encourage the development of new, economically efficient technologies.

The second source of potential market failure arises only if greenhouse gas emissions are a cause for environmental concern. In this case, the fundamental market failure is that emissions of carbon dioxide and other greenhouse gases are not being priced. Pricing carbon emissions is probably a necessary policy in order to bring about adoption of most technologies that are not currently economically efficient.

If reducing carbon emissions is a policy goal, we can ask what cost per ton of reduction is deemed worth paying. At a zero cost per ton, we are looking at the current policy environment in which only economically efficient technologies may make economic sense. We can then think of carbon permit prices, like sulfur permit prices, that would have to be paid by industry for permits, or that would be paid to industry as an incentive for each ton of carbon dioxide emission reductions achieved. We can then ask which technologies/options move from economically inefficient into the economically efficient category for each of these price levels, until we have raised prices high enough to exhaust all options.

---

[18] For a fuller discussion of market barriers and market failures, see Adam B. Jaffe and Robert N. Stavins, "The Energy-Efficiency Gap: What Does it Mean?" *Energy Policy* 22, no. 10 (1994): 804–11. An important conclusion that can be drawn from the framework presented in this paper is that the existence of market failures is a necessary, but not a sufficient, condition for the case that public policy can produce energy savings at negative costs. Some market failures may be so costly to identify and rectify that the costs of removing them exceed any benefits that might be obtained.

Market Failures and No-Regrets Market Barriers Identified in the Literature

The literature on energy efficiency often fails to distinguish clearly between market barriers, the cost of which cannot be avoided, and true no-regrets market failures, which potentially can be eliminated at negative cost.[19] Moreover, while the literature contains extensive discussions of potential barriers and market failures in transportation, final consumer, and commercial uses of energy, relatively little of relevance has been said about major industrial energy users, such as the iron and steel industry.[20] So far as we are aware, nothing at all has been published identifying barriers or market failures specific to this industry. We have, however, found discussions about general barriers standing in the way of energy efficiency investments in industry in one frequently cited study: the "Five Labs" study of the potential for energy-efficient and low-carbon technologies to reduce CO_2 emissions.[21]

The Five Labs study notes that "many aspects of business decision making may slow the adoption of energy-efficient technology" in industry. It identifies four specific factors:

- The high capital intensity of process industries, leading to slow capital stock turnover.
- The perceived riskiness of new technology.
- The lack of internal funding, resulting in less capital for energy projects.
- Lack of information.

The first two of these factors are clearly not indicative of any form of market failure. High capital intensity is characteristic of many basic industries, including the iron and steel industry. When capital equipment is replaced prematurely, there is an added cost, and these costs cannot be avoided by government policy. Although policies that reduce the after-tax cost of capital investment to the investor, such as accelerated depreciation allowances or other reductions in the tax rate on capital investment, could lead to faster capital stock turnover, implementing such

[19] See Lisa J. Cameron, W. David Montgomery and Harry L. Foster, "Economics of Greenhouse Gas Strategies," *Energy Studies Review* 9, no. 1 (1999), and its references.

[20] For example, see Union of Concerned Scientists et al., *America's Energy Choices: Investing in a Strong Economy and a Clean Environment,* 1991; Office of Technology Assessment, *Changing by Degrees: Steps to Reduce Greenhouse Gases,* OTA-O-482, 1991; Alliance to Save Energy et al., *An Alternative Energy Future,* 1992.

[21] Interlaboratory Working Group on Energy-Efficient and Low-Carbon Technologies, *Scenarios of U. S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond,* LBNL-40533 or ORNL/CON-444, September 1997. The Five Labs study is discussed further, and its results compared with by some prior studies by several of its principal authors, in a subsequent paper: Marilyn A. Brown, Mark D. Levine, Joseph P. Romm, Arthur H. Rosenfeld, and Jonathan G. Koomey, "Engineering-Economic Studies of Energy Technologies to Reduce Greenhouse Gas Emissions: Opportunities and Challenges," *Annual Review of Energy and the Environment* 23 (1998): 287–385.

policies would effectively require other taxpayers to foot the bill for premature capital retirement.

Likewise, the perceived risk of new technology does not suggest the presence of extensive market failure—in capital-intensive industries, it is no surprise that a rational firm is reluctant to "bet the company" on an unproven technology, and as we have noted, the lack of engineering resources in the steel industry makes technological risk an especially important factor in decision making. This often leads to the rational desire to be the second or third entity to adopt a new technology—not the first entity—because the first-mover advantage may not be realizable. First-mover risks may create small market failures, since early adopters are not properly compensated for the benefits they provide to later adopters by proving the viability of new technologies. This failure is unlikely to have extensive consequences, however, since it can often be overcome by comparatively modest subsidies to the first adopter, often provided by the entrepreneur that is selling the new technology.

The third of these factors, lack of internal funding for energy projects, is also likelier to result from hidden costs than from market failures. Claims that an industry does not have internal funds for available projects is a fallacy, because, within any company, all projects compete for all sources of funding Energy projects can be funded internally or externally if their economics are favorable, and capital markets are quite willing to provide financing to growing and healthy industries. Project or vendor financing is also possible, if the basic economics—including the expected survival of the company and plant in question—are sound. The question for the steel industry is whether any form of external financing is possible, given bankruptcy and plant-closing risks. As we have already noted, scarce availability of internal and external capital for energy efficiency investments in the steel industry may largely reflect the precarious financial position of most firms and a general trend toward contraction of the industry.

Only the last of the factors cited in the Five Labs study—lack of information—represents a potential market failure. It is our impression that this potential market failure,—created because there may be insufficient incentives for firms to create information that others may later obtain for free, or to share information that has already been created— is unlikely to be of significance in the steel industry. Information exchange is rapid in the industry, aided by a host of partnerships among firms, trade associations, universities, and the government.

OTHER POTENTIAL NO-REGRETS MARKET FAILURES

While the factors identified in the Five Labs study that retard the adoption of energy efficiency technologies in industrial settings are either instances of market barriers not remediable by policy or inapplicable to the steel industry, we consider two possible additional examples of market failure that have been identified in other contexts: market failures in research and development, and principal/agent issues.

Market Failures in Research and Development

The most important disincentive for private R&D is the inability to appropriate the rewards of innovation, owing to the public goods character of technical advances. Either the diffusion of the innovation is restricted by patents and licensing fees, or the incentive to innovate is reduced.[22] The result is under-investment in R&D.

The pure public-goods problem with R&D appears largely to have been solved in this industry. The AISI funds a large portfolio of cooperative R&D projects, many with environmental objectives, and EPRI and GRI also fund R&D in collaboration with their steel customers (to improve the efficiency of steel making with their fuel and thereby take the other's business). R&D consortia have readily been formed in the industry. If carbon emissions are believed to create social costs, however, there is a role for public policy in directing these consortia into research that would reduce carbon emissions.

Principal/Agent Issues

Principal/agent issues arise in the economics of energy use when the party making investment choices, and the party making energy consumption decisions and paying energy bills are not identical. The most commonly identified principal/agent problems in the context of energy efficiency investments are alleged to occur in landlord/tenant situations. It is alleged that landlords do not invest adequately in providing energy-efficient heating, lighting, or appliances for consumers who pay their own energy bills, and that consumers do not make adequate efforts to conserve energy when the landlord pays the bill.

Bankruptcy risk creates a potential principal/agent problem in the steel industry. In an earlier section, we showed how a firm might rationally choose not to invest in a seemingly attractive technology if there were a significant risk that the plant at which it was to be deployed would be shut down. Such a decision is optimal from the firm's perspective. It is also socially optimal, since an energy efficiency investment in a facility that is due to be closed down will not produce energy savings that are commensurate with the costs of the investment for any and all parties that may own the facility. What if the risk facing the potential investor is not one of plant shutdown, but of firm bankruptcy that will merely result in a transfer of productive assets? If a particular company is in a precarious financial condition, but its plants would be economically viable if owned by a stronger company, then bankruptcy risk is an example of agency problems in which private and social interests do not coincide. A company in precarious condition may

[22] See Kenneth J. Arrow, *Essays in the Theory of Riskbearing*, Amsterdam: North-Holland, 1971.

rationally choose not to invest in an energy efficiency technology that has a positive present value over the life of the investment, if there is a high probability that many of the cost savings will be realized by the new owners—savings on which it cannot recognize any return.

This is an example of a market failure that is, in theory, remediable. It might be possible, for example, through non-recourse guaranteed loans, to provide the wherewithal for investments in energy efficiency that managers facing bankruptcy risk are not motivated to make. If the plant in which the investments are made survives beyond bankruptcy of its current owners, the energy payback from the investment will be achieved.

If, on the other hand, managers face a probability of having to close the plant in question, then bankruptcy risk does impose hidden costs—or more precisely, bankruptcy truly reduces the future benefits of investments in energy efficiency. If a plant might be closed, that possibility should be taken into account in evaluating any investments whose scrap value is considerably less than their initial cost. In the steel industry, the viability of steel plants is at risk, so that attempting to counter the influence of bankruptcy risk on investment decisions may well lead to wasteful investments that are scrapped before they provide their expected returns.

The difficulty of distinguishing between these cases is one of the problems in designing policies to bring about investments that will reduce carbon emissions. Making loan guarantees available to all could entail expenditures at plants whose short expected life does not justify the investment, leaving the federal government to pay the cost without gaining the expected reductions in emissions. Screening applicants to identify those whose plants would continue to be viable after a financial restructuring would entail significant program costs, and a probability of including some plants that will not continue to be viable, and excluding others that will.

PRICING CARBON EMISSIONS TO CORRECT MARKET FAILURE

As we have previously noted, if rising atmospheric concentrations of carbon dioxide and other greenhouse gases are a problem, then the failure to price emissions of such gases is an example of a market failure. In theory, pricing emissions of gases per unit at a level set equal to the environmental damage they create on the margin would improve economic efficiency. Such a policy would discourage some greenhouse gas emissions, while others would still occur. Those emissions that would be avoided would be those that produced less in other economic benefits than the cost imposed on society by the emissions; those emissions that remained would have higher benefits than costs.

In practice, however, it is very difficult, if not impossible, to assess the correct social costs associated with greenhouse gas emissions. Nonetheless, pricing greenhouse gas emissions represents the lowest total cost strategy to the economy of reducing such emissions by any given amount, since only such schemes can identify and assure that all relatively low-cost options are used before higher-cost emissions reductions are pursued.

As a practical matter, making all greenhouse gas emitters face an equivalent cost of carbon emissions on the margin can be achieved through carbon taxation, in which the government imposes taxes on carbon-containing fossil fuels that are not used as feedstock or otherwise sequestered. Alternatively, the same goal can be achieved by a carbon permit trading system, in which a cap on total carbon emissions is established and potential emitters (or, alternatively, fuel sellers) are required to hold a permit for each unit of carbon in the fuel they use (or sell). Finally, as an alternative to taxation, equivalent incentives on the margin can be provided by subsidizing avoided emissions—paying potential emitters a per unit amount for whatever reductions in emissions they are able to achieve.

Depending on exactly how high the explicit or implicit carbon price established by any of these policies turns out to be, some currently economically inefficient technologies would, all else equal, become more economically viable.

However, were the United States to pursue policies to price carbon emissions unilaterally, or only in conjunction with other industrialized nations (the Annex B countries subject to emissions limits under the Kyoto protocol), the results would almost certainly be disastrous for the U.S. Steel industry. Competition from non-Annex B countries in the developing world will prevent those costs from being passed through into the price of iron and steel. Thus, except to the extend that no-regrets strategies can be found, the effect of policies to limit emissions from domestic manufacture of iron and steel will be the export of carbon emissions, probably to regions where emissions are larger per ton of steel than in the plants closing in the United States.

POLICIES APPLICABLE TO THE STEEL INDUSTRY

The policy measures recommended by participants in the industry are all consistent with the diagnosis that there are a limited set of true market failures at work, and that providing significant incentives to greater energy efficiency and lower carbon dioxide emissions requires measures that can overcome the high costs of making these investments in an industry with an uncertain economic future.

What Prevents Apparently Cost-Effective Investments in Energy Efficiency?

The first step in policy design is to determine what factors are responsible for the lack of investment in apparently cost-effective opportunities to improve energy efficiency and reduce carbon dioxide emissions. In this context "cost-effective" is understood to mean "estimated by means of engineering calculations found in the literature to have a reasonable return on investment at current prices for relevant inputs and products and current policies." As stated earlier in this study, there is good reason to be skeptical of these calculations, because of their frequent failure to include all relevant costs or set the analysis in the proper context. Thus, some of the factors identified in this study are in fact based on the observation that additional investments to reduce energy use or carbon emissions would reduce the profitability of the companies involved under current conditions.

Based on interviews, and CRA's independent analysis, five factors emerged as primary reasons for the lack of investment in "apparently cost-effective" measures in existing facilities:

- The poor financial condition of the industry
- Site-specific costs associated with retrofits that preclude economic adoption of the associated technologies
- Loss of revenue when retrofitting
- Environmental regulations and permitting processes that block energy-saving investments
- Risk avoidance

Of these, the poor financial condition of the industry, site-specific costs and loss of revenue due to retrofitting, and, to some extent, risk avoidance represent real but hidden costs—not market failures. Policies addressing these obstacles, however well designed, will entail some net cost before they are to be effective. Some aspects of risk avoidance, and the impact of regulatory programs that unnecessarily discourage investment, are examples of market (or regulatory) failures whose remedy could lower greenhouse gas emissions and energy use and lower cost at the same time.

In the case of new facilities, the primary issues are the availability of technologies that will significantly reduce greenhouse gas emissions and energy use, and the overall lack of new investment in the industry to create new facilities.

Poor Financial Condition

The poor financial condition of the industry has two implications. First, poor financial conditions limit the amount of capital companies have available for investments, and raises the cost of obtaining additional capital. Under these conditions, investments that would increase energy efficiency or reduce carbon dioxide emissions compete against relatively high return investments for other purposes. With limited capital, a company must choose between one or the other, and the true cost of the investment in increasing energy efficiency or reducing carbon dioxide emissions is the foregone return on the displaced investment.

Second, the poor financial condition of the industry creates a continued risk of bankruptcy for particular companies, or shutdown of particular facilities. Engineering studies of energy efficiency and carbon reduction investments do not take this risk into account, but calculate energy savings over an extended future period of time, as if the continued existence of the facility were certain. The scrap value of retrofit projects, in particular, is likely to be very small in relation to the cost of the project. Therefore, a significant probability of failure of the firm or facility implies 1) that assumed energy savings may not occur, since there can be no savings in a facility that would have stopped operating and 2) the "cost-effectiveness" calculation exaggerates the expected monetary benefit to the company involved. Since the likelihood of plant closure or bankruptcy reduces the energy savings from a retrofit investment, it constitutes a hidden cost that can only be eliminated by policy measures that reduce risk of closure, such as trade measures that improve the overall financial condition of the industry.

Many of the apparently profitable projects for reducing greenhouse gas emissions and improving energy efficiency provide increases in capacity or productivity, and the value of the resulting potential increase in output is included in the calculation of the return on such investment. However, increased capacity is only valuable if it actually supports increased sales and revenues. In an industry with serious overcapacity, the value of increased capacity may be negligible, because of the expectation that increases in output will not be achievable.

Site-Specific Costs and Loss of Revenue

Site-specific costs and loss of revenue when retrofitting are examples of inadequacies incurred when the calculation of costs and benefits are based on generic engineering analysis. These hidden costs cannot be eliminated by policy measures, and must be covered by any incentives designed to bring about actions that are not economic under current market prices and regulatory regimes.

Environmental Regulations

Any inefficiently administered regulatory regime can create obstacles to desirable investment. The removal of these obstacles can improve the environment and reduce costs. In the case of steel, the examples given suggest that the permitting process discourages investments that would reduce greenhouse gas emissions and improve energy efficiency. Procedures and regulations implementing New Source Review and Prevention of Significant Degradation appear to be responsible for the most part. New Source Review rules do provide an exemption for investments designed to reduce emissions. However, it does not appear that investments to reduce greenhouse gas emissions (which are not regulated under the Clean Air Act, or improve energy efficiency) are considered to be eligible for these exemptions.

There also appear to be cases in which projects that produce large reductions in greenhouse gas emissions and improvements in energy efficiency, also lead to small increases in emissions of some other pollutant. Under the PSD rules, there appears to be no mechanism for trading off these large improvements for small increases in emissions, or for providing some form of offsets for the emissions involved.

Changing the relevant regulations to allow such exemptions, tradeoffs and offsets should be possible in a way that preserves the goals of the Clean Air Act and opens the door for reducing greenhouse gas and carbon emissions. These policy changes would provide for both reducing emissions and reducing costs.

Risk Avoidance

Willingness to undertake retrofit projects is an important influence of risk avoidance. This is because even a brief interruption of ongoing operations can impose costs higher than the expected benefits of a retrofit project. This is a well-documented issue in general, because of the generally small magnitude of energy costs relative to the operating margins earned in ongoing operations. The same appears to be true of steel-making, despite the importance of energy costs, because of the capital intensive nature of the process. Since any change does have a finite, perceived probability of causing serious problems, there is a true cost from interruption of operations, and it should be included in any calculation of the expected returns from a retrofit project. Since the loss may be a low probability event of large magnitude, risk aversion also is relevant—especially the possibility that such an event would be enough to tip a marginal operation into insolvency.

The interviews revealed that risk avoidance is, to some extent, an information issue—being second provides free information from the experience of the first mover—including the likelihood of interruption of ongoing operations. The appropriateness of this issue does qualify as a true market failure whose remedy can, in principle, produce overall economic gains.

Development and Introduction of New Technologies

When firms innovate and adopt new technologies, the first mover confers an external benefit on all other firms, by confronting and solving the problems that inevitably accompany the use of a new technology, and by demonstrating its feasibility and economics; thereby reducing the uncertainty faced by latecomers in using the same technology. In economic terms, these external benefits are not appropriable by the first mover—the first mover cannot protect and sell this information to others. As a result, adoption of a new technology may never happen, if its benefits are not sufficient to outweigh the first mover's unique costs, without some credit for the benefits of the technology to subsequent users.

In the interviews, factors discouraging the adoption of new technologies were largely associated with the following factors:

- Overcapacity that prevents new facilities from being built,
- Risk avoidance, and
- Availability of technologies developed specifically for the purpose of reducing greenhouse gas emissions and energy use.

Policies to improve the overall profitability of the industry; provide information, technical assistance, and "first mover" incentives; and redirect cooperative R&D toward development of technologies with energy efficiency or greenhouse gas benefits, would serve to address these problems.

WHAT MEASURES ARE FEASIBLE, BUT NOT COST-EFFECTIVE AT CURRENT PRICES AND UNDER CURRENT POLICIES?

Going beyond the search for "no-regrets" actions that are cost-effective at current prices and under current policies entails identifying a much wider range of measures that are feasible, but are not cost-effective at current energy prices considering the current lack of any limit or cost associated with carbon dioxide emissions. A comprehensive approach to this question would trace a supply curve that showed how much reduction is feasible, and how much each incremental reduction would cost.

In the case of existing facilities, constructing this curve requires understanding the most important of the most subtle hidden costs of reducing carbon dioxide emissions and reducing energy use. In the case of new facilities, the incentives for development and adoption of new technologies also come into play in a big way.

New facilities generally are built to the current, state-of-the-art technology in the United States and abroad; therefore, issues about improving the energy efficiency of new facilities are about the direction of advances in technology—not the cost-effectiveness of adopting technologies available today that reduce carbon emissions or increase energy efficiency. When a new facility is built, it does generally incorporate all design features that are cost-effective at current prices. In some cases, as the earlier technology discussion revealed, improving the economics of steelmaking involves increasing carbon dioxide emissions, since there is no penalty for those emissions under current law. This is a case where reduction of carbon dioxide emissions is feasible, but not cost-effective.

Differences Between Integrated and EAF Operations

There are likely to be significant differences in opportunities and costs for reducing greenhouse gas emission and energy use between integrated and EAF operations. For the most part, EAF plants are considerably newer than integrated operations, and included the most modern technologies when built, so the opportunities for improvement through retrofit are much more limited. This suggests that market-based programs that provide uniform incentives to reduce emissions and energy use are much more likely to be taken up by the integrated sector, and the targeted incentives, such as tax credit or loan guarantees, are likely to produce less cost-effective energy and emission savings when taken up by the minimill sector than when taken up by the integrated sector.

Literature references suggest that one of the options considered for reducing emission from steel-making would be to accelerate the replacement of integrated blast furnace operations by EAF processes, because of the inherently lower emissions of EAF. This option runs into the limits described above of a practical minimum below which ore-based feeds cannot be reduced, but certainly is a feasible method of producing some reduction in emissions. Such a policy would be immensely divisive politically within the steel industry, and would require substantial capital investments.

CRA ANALYSIS OF POLICY OPTIONS

REFORM ENVIRONMENTAL REGULATORY PROCESS

There is a clear winner in the policy recommendations universally supported by the industry—which is to remove obstacles to investment created by environmental regulations. Without embarking on a comprehensive critique of the Clean Air Act Amendments, a number of questions have been raised about how the PSD and NSR rules issued under these amendments are less cost effective than alternative, more flexible approaches to environmental policy.[23]

Economists have long advocated approaches to environmental regulations that put incentives directly on the emissions that cause harm, and place no other constraints on decisions about how to manage these emissions. The rules cited as interfering with investments in energy efficiency and greenhouse gas reduction place such restrictions on choices. NSR specifically discriminates against investments to upgrade or expand existing facilities, and perpetuates the high costs of technology-based regulations that market-oriented programs like Title V of the Clean Air Act are intended to avoid. Compared to setting an overall cap on emissions, and allowing emission trading between all sources, or establishing economic incentives the are applied universally and uniformly, NSR and PSD rules provide no benefits, and serve only to constrain choices and raise costs.

Regulations that allow no tradeoffs likewise impose arbitrarily high costs to mitigate specific pollutants when profitable investments that would reduce other pollutants are prevented, and provide no incentives to reduce those emissions below baseline levels in facilities where this could be accomplished at relatively low cost.

Regulations that require New Source Review for recommendations that increase the capacity of a facility, even if they reduce emissions, can be particularly discriminatory against projects whose economics depend on combining some increases in productivity with reductions in energy use.

In the winter of 2001–2002, the Bush Administration reviewed the New Source Review procedures of the Clean Air Act and identified a number of industries in which NSR created obstacles to desirable investments. This review, and closer coordination between EPA and DOE on a program to encourage projects that would reduce energy use and greenhouse gas emissions, might remove some obstacles that develop in the permitting process. It is unclear how much these reforms can accomplish, given the strictures in the Clean Air Act Amendments on New Source Review and Prevention of Significant Degradation. Going further to create a level playing field for large-scale projects to reduce greenhouse gas emissions, and reduce energy use at existing facilities, could require reopening these sections of the Clean Air Act to provide greater flexibility and replace prescriptive standards with a market-based approach, such as emission trading. These changes might be part of the comprehensive Three Pollutant and Four Pollutant legislation, including S. 588, which would place caps on emissions of sulfur, nitrogen oxides, mercury (three pollutants) or add carbon dioxide (four pollutants). However, to the

[23] Op. cit.

extent that PSD obstacles occur because of increases in other species of pollutants, an even broader set of changes might be required.

IMPROVE THE FINANCIAL CONDITION OF THE INDUSTRY THROUGH TRADE POLICY

If managing steel imports is desirable on other grounds, it is likely to have beneficial effects on investments in energy efficiency that will reduce carbon emissions. It would be hard to justify policies to improve the overall profitability of the U.S. steel industry on the basis of their effect on greenhouse gas emissions and energy use, since the connection is indirect, and not even guaranteed. Some of the new investments that a healthy industry might make could increase carbon dioxide emissions. Nevertheless, a healthy financial condition appears to be necessary for significant increases in investment and willingness to bear some of the risks of introducing new technologies. Therefore, if action to raise domestic steel prices are justified on other grounds, they can contribute to reductions in greenhouse gas emissions and energy use. This would be particularly true if, at the same time, policies such as emission trading programs were adopted to provide a positive incentive to adopt new technologies that provide such reductions, rather than the reverse.

The connection between steel prices and performance on greenhouse gas emissions and energy use exists because a healthy industry was seen as having more financial resources to invest in improving energy efficiency. Moreover, if the industry were more healthy financially, and less constrained in its ability to invest, the opportunity cost of displacing highly profitable investments (the only ones currently adopted) and the risk of plant closure or bankruptcy that limits benefits would be reduced. In addition, a healthy industry would not face the current, highly asymmetric returns from risky investments, If an investment in reducing greenhouse gas emissions or energy use is successful, it can be expected to provide relatively small cost savings. If such a project were to cause any significant disruption to operations, it could push cash-short companies over the edge. A financially stronger industry would also have greater capability to provide matching funds in cooperative research, and therefore be more capable of funding research with real breakthrough potential through cooperative ventures where industry can provide guidance and expertise.

Although this is the likely directional effect of an improvement in the financial health of the industry, it is not guaranteed, or necessarily large. First, not all new investments that would be attractive to a financially healthy industry reduce greenhouse gas or carbon emissions. Some could well increase carbon dioxide emissions, as discussed earlier. Second, the reduction in emissions possible by moving from the technologies used in new plants in the U.S. to the best in the world is about 10 percent.

The universal perception is that the steel industry's largest problem is excess capacity domestically, but especially worldwide. General loan guarantees (Byrd bill) are available only to those turned down for ordinary financing, and are therefore the weakest in the industry. Preventing their exit from the industry serves to continue excess capacity and other conditions that make investment in the industry unlikely. Thus, general loan guarantees are unlikely to direct any money into energy efficiency or greenhouse gas reductions, and generally work against restoring industry to financial health, and the concomitant improvement in the likelihood of energy efficiency and greenhouse gas reducing investments.

ADDRESSING MARKET FAILURES ASSOCIATED WITH INFORMATION AND INNOVATION

Two programs have sound economics, and could have net economic benefits, but possibly only small overall effects:

R&D Support

Some changes in the focus of cooperative R&D programs would also be necessary to shift attention toward technologies that reduce greenhouse gas emissions or improve energy efficiency. These changes could take place within the framework of established programs. Information provision and risk reduction, including technical advisory programs and "first mover" incentives, are potentially effective responses to obstacles to adoption of new technologies identified by industry participants. Also, if the problems have been misdiagnosed, these incentives are unlikely to be taken advantage of and "do no harm," save for fixed costs of setting up the programs.

Cooperative R&D

Generally, mechanisms for cooperative R&D, in which government and industry resources are combined, are perceived to be in place and effective. The major limitation, according to some, is the inability of industry to come up with matching funds on a large scale. The primary focus now is on technology to improve competitiveness and profitability—not to reduce carbon emissions or improve energy efficiency—because these are not seen as being among the most promising opportunities for improving profitability. It would take additional financial incentives to push R&D further into that direction. This might be done by increasing the government cost share for R&D. However, there are limits on how large a cost share the government can take without undermining some of the basic principles of cooperative research. The industry cost share serves, in part, to provide an incentive for private sector participants to give the research cooperative the same management attention and internal resources that would be given to private R&D. This attention is important in a candidate screening process, sharing of information and innovations developed within companies, and the actual management of projects. Without this commitment and sharing of information, there is a danger that research cooperatives will be limited to working on the less promising technology advances, while approaches that companies perceive as having great profit potential are addressed internally.

It is also unclear how far it is possible to push R&D in a climate-friendly direction through a greater government share in the up-front research direction. R&D is normally directed in the private sector through a profit motive based on perceptions of markets and prices in the future, when the technology will be applied. It may be difficult to create a substantial shift in the direction of research without the expectation of a policy/regulatory regime that limits carbon emissions, or provides economic incentives for lower emissions. A demand pull, from a commitment to future policies that will improve the economics of low energy and low carbon ways of producing steel, may be required in addition to the supply push of greater contributions of government funds to research on such technologies.

First Mover Incentives

Once a technology is available and ready for commercial adoption, there is a reluctance in the industry to be the first to adopt. Part of the cooperative R&D process could include cost-sharing by the government and other industry participants as part of the first commercial application of a technology. All steel companies benefit from the risks the first mover bears in solving the problems involved in the commercial application of a technology and providing information about its performance on a commercial scale; thus, it makes economic sense for the industry (as well as government agencies) to share the cost of that first application.

Given perceived risks to process integrity and operations, sharing the out-of-pocket costs of the first commercial application of a technology may not be sufficient. Some form of insurance against all adverse consequences may also be required. If technology is well developed and reliable at the time it is commercialized, this insurance will not need to be called on, but it may be important to spread the risk faced by the first mover.

Technical Advisory Programs

The current state of engineering staffing and expertise in steel companies suggests that complementing these resources with technical advisory programs could be beneficial. These programs are already available, to some extent, through utility energy audits and energy service companies. Vendors were also identified as carrying out R&D and offering technical expertise to the companies. One option is for DOE to work with state governments so that incentives for electricity providers and others to offer these services would be built into development plans for restructuring electricity markets. This approach could overcome some of the disdain expressed in the steel industry for a form of "energy extension service" by having the advisory services provided by companies that have a record of experience in working with the industry and demonstrated technical competence.

All of the programs described for providing information, supporting R&D, or reducing risks associated with adoption of new technologies will require some expenditure of resources. Given the nature of the market failures that they are addressing, there is a reasonable expectation that well-designed programs will provide benefits greater than their costs, even if resulting changes in energy use are valued at current market prices without including the benefits of reducing greenhouse gas emissions.

Policies that Require Incurring Net Costs

None of the industry's other recommendations suggest serious market imperfections that could be removed to produce costless reductions in emissions. Rather, the programs favored in interviews involve expenditures (in one form or another) to cover real costs incurred in reducing energy use or emissions

Targeted Tax Incentives

Tax incentives were the form of incentive most favored by the respondents. Support for tax incentives insisted, however, that tax credits should not specify particular technologies. Respondents were also insistent that tax credits had to be certain, and not subject to IRS negotiation and interpretation.

It is not entirely clear how a tax credit satisfying all the conditions discussed above could be constructed. There is a basic tradeoff in all tax incentives: making a tax incentive broad and simple creates conditions under which the incentive will provide a windfall to firms who claim it for projects they would have been undertaken anyway. Making a tax incentive very narrow creates conditions under which incentives for useful projects will not be undertaken (because they clearly do not fit under the narrow construction, or because it depends on whether the IRS will approve the credit). Under these circumstances, as industry respondents point out, the costs of compliance go up considerably.

These problems are inherent in constructing tax incentives, because such incentives normally work on inputs—that is, expenditures on particular types of products—rather than on outputs, which might be measured as reductions in greenhouse gas emissions or energy use relative to a baseline. Therefore, it is very difficult to construct a tax incentive that provides a performance goal tied directly to emissions and energy use.

Finally, tax credits only help profitable firms, which does not include all steel companies or those steel companies that have opportunities to reduce energy use and greenhouse gas emissions.

It needs to be recognized that tax incentives entail a clear national cost—paid in this case by other taxpayers—to meet revenue targets. Under our current Congressional budget process, decisions about levels of government spending and tax revenues are made under a budget resolution. Then changes in tax policy are considered, and any changes that reduce revenues—such as tax credits—must be offset by increases in tax revenues elsewhere.

Taking all these factors into account on a national scale, tax incentives are not the most cost-effective approach to reducing greenhouse gas emissions or energy use. However, well-designed tax incentives can indeed cause companies to make investments they would not otherwise make. There may be alternatives identified in the implementing regulations that might result in a more cost-effective investment for the steel industry in the most cost-effective manner.

Targeted Loan Guarantees

Loan guarantees share many of the characteristics of tax incentives, except that they are seen as more applicable to firms with less attractive balance sheets and prospects for survival. Guaranteeing a loan is of little benefit to a firm that is in good financial condition, because it still has to pay back the loan, and the interest rate and financing benefits of using a loan guarantee to take a project off the balance sheet are not large in the long run. Indeed, using loan guarantees to support project financing is itself a concealed subsidy, as several CBO studies have shown, because such action shifts risks to the government in a way likely to increase net costs. Also, loan guarantees are most likely to be taken up by projects that are most subject to bankruptcy or closure risk, so that their energy and greenhouse gas benefits will not last long. Overall, the general consensus of policy analysts agrees with that of the industry, that even targeted loan guarantees are not the most effective, nor economic, policies for encouraging investments to lower carbon emissions and energy use.

Broader, Cost-Effective Approaches

Once it is recognized that there are limited possibilities for reducing greenhouse gas emissions and energy use without incurring additional net costs, the next logical step is to identify programs that provide the most reduction per dollar, and decide how much a unit reduction in emissions or energy use is worth.

It is encouraging that the focus of respondents to our interviews was on incentives, not on command and control. No source has recommended a one-size-fits-all approach of technology or efficiency standards for the industry. This may be because it is recognized that such an approach would not be cost effective, or that such programs usually rely on turnover of the capital stock, and are easily seen to be unproductive in an industry that is making no investment.

There are other means for providing incentives, means that would be more broadly cost-effective than tax incentives or loan guarantees, but that were not appreciated by the respondents to the interviews. These incentives largely take the form of changing the prices paid for energy, by including potential damages from greenhouse gas emissions in the cost of energy.

Higher Energy Prices

The universal perception among industry executives interviewed is that increases in energy prices will only cause the steel industry to shut down, and further reduce the funds available for investment. The position of the U.S. steel industry in the international market makes this perception close to reality if the U.S. unilaterally raised energy prices faced by U.S. steel companies. If, on the other hand, increases in energy prices occurred worldwide on a uniform basis, the competitive position of the U.S. industry would not change greatly. Such a worldwide change would shift the entire steel supply curve, and raise market prices as well as costs.

Exactly how this shift would affect the U.S. industry is an unanswered question at this stage. In our work on global agreements to reduce carbon emissions, we find that energy-intensive industries in the United States are sufficiently energy efficient, especially relative to the competitors in developing countries. Therefore, a uniform, worldwide increase in energy costs would benefit energy-intensive industries in the U.S. Because of their somewhat greater efficiency, the energy-intensive industries in Japan and Europe might benefit more, but profitability, output, and investment in U.S. energy-intensive industries would likely increase.[24]

More specific and detailed research would be required to ascertain how such global approaches would affect the U.S. steel industry. Such research would need to examine comparative energy costs and efficiencies in different countries and identify the marginal sources of steel supply worldwide. If blast furnace operations are the marginal sources, higher worldwide energy costs will cause prices to rise sufficiently to perpetuate current industry conditions. If other countries' blast furnaces are significantly less efficient, but required as marginal sources to meet demand, U.S. industry will benefit.

[24] Christoph Böhringer and Thomas F. Rutherford. "Carbon Taxes with Exemptions in an Open Economy: A General Equilibrium Analysis of the German Tax Initiative." *Journal of Environmental Economics and Management*, pages 189-203, 1996. Thomas F. Rutherford, "Carbon Abatement versus Industrial Competitiveness: Rhetoric or Reality" Crest Workshop on the Kypoto Mechanism, (Osaka University, Japan, September 21, 2001).

Another possibility is that policies that raise energy costs, or impose carbon taxes on greenhouse gas emissions, would cause a shift in production technology from blast furnace to EAF operations. The inherently lower energy use and carbon emissions from EAF operations give them a cost advantage that increases as the cost of energy or carbon taxes increase. This shift could occur within the United States, or between the United States and other countries where electricity is even cheaper, or produced from fuels with lower carbon content.

Kyoto Protocol

Interviews revealed a correct perception that adherence by the United States to the Kyoto Protocol, which does not include any commitments by developing countries to limit emissions, would shift production to facilities in those countries that produce more emissions. It is not surprising that the industry understood and emphasized the leakage and industry effects of either unilateral U.S. action, or action that leaves out limits on carbon emissions from developing countries.

Another option that could be pursued in the U.S. is to use emission caps and trading programs to limit emissions from U.S. steelmakers, and impose countervailing duties on steel imports from any countries that do not undertake similar limits on emissions. This option is controversial, and there are conflicting interpretations of whether it is allowable under current trade agreements. It is a mechanism for preventing the leakage and damage to the U.S. industry that is likely under the Kyoto Protocol, although it has some danger in undoing the progress made in recent years, in trade negotiations, to reduce trade barriers and create greater opportunities for free trade.[25]

Universal industry opposition to the measures that are globally cost-effective, such as emission trading and energy taxes, suggests that constructing a comprehensive, least-cost policy toward energy efficiency and carbon emission reduction will be very difficult. The difficulty of obtaining an industry consensus on such policies is also heightened by the clear differences between minimills and integrated operations in the cost and opportunities for reducing emissions, and their relative economics in a world of uniformly higher energy prices or uniform taxes on carbon emissions.

[25] W. David Montgomery and James L. Sweeney, *Trade and Industry Impacts of the Kyoto Protocol*, Business Roundtable, Washington, DC, October 1999.

6. Bibliography

[1] Energy Use in the U.S. Steel Industry: An Historical Perspective and Future Opportunities, U.S. Department of Energy, Office of Industrial Technologies, September 2000.

[2] Theoretical Minimum Energies to Produce Steel for Selected Conditions, U.S. Department of Energy, Office of Industrial Technologies, March 2000.

[3] Op cit.

[4] Op cit.

[5] Op cit.

[6] Op cit.

[7] Op cit.

[8] Interlaboratory Working Group on Energy-Efficient and Low-Carbon Technologies, *Scenarios of U. S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond,* LBNL-40533 or ORNL/CON-444, September 1997 (http://www.ornl.gov/ORNL/Energy_Eff/labweb.htm); EMF 13 issue of Energy Journal.

[9] Energy Policy Alternatives, CRA, 1991, for the MVMA; No Free Lunch, a review of a series of studies released through 1993, Jaccard and Montgomery; Energy Policy, Cameron, Foster and Montgomery, in Reviews of Energy; W.D. Montgomery, "The Economics of Conservation." In M. Kuliasha, A. Zucker, and K. Ballew (eds.), Technologies for a Greenhouse-Constrained Society. Chelsea, MI: Lewis Publishers, 1992.

[10] "Framework for Short and Long-Term Decisions." In critical issues in The Economics of Climate Change, ed. B. Flannery and D. Kennedy, IPIECA, London, 1997 and "Developing a Framework for Short- and Long-Run Decisions on Climate Change Policies." In C. Walker, M. Bromfield, and M. Thorndike (eds.), *An Economic Perspective on Climate Change Policies,* Washington, D.C.: American Council for Capital Formation, 1996.

[11] Op cit.

[12] *Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the US Iron and Steel Sectors,* LBNL-41724, July 1999.

[13] *Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the US Iron and Steel Sectors*, LBNL–41724, July 1999.

[14] *Scenarios for a Clean Energy Future* (Oak Ridge, TN: Oak Ridge National Laboratory and Berkeley, CA: Berkeley National Laboratory), ORNL/CON-476 and LBNL-44029, November 2000.

[15] Op cit.

[16] P. Portney and J. Weyant, eds., *Discounting and Intergenerational Equality*, Washington, DC: RFF, 1999. See also R.C. Lind, *Discounting for Time and Risk in Energy Policy*, Baltimore: Johns Hopkins University Press, 1982.

[17] The need to account for engineering costs as a factor in explaining decisions about whether or not to adopt technology has been stressed most recently in a study of the potential for greenhouse gas reductions in the Canadian auto parts sector. Transportation Equipment Manufacturing Sector Working Group, National Climate Change Industry Table, *Greenhouse Gas Options, Policy and Measures for the Canadian Transportation Equipment Manufacturing Industry*, February 2000.

[18] For a fuller discussion of market barriers and market failures, see Adam B. Jaffe and Robert N. Stavins, "The Energy-Efficiency Gap: What Does it Mean?" *Energy Policy* 22, no. 10 (1994): 804–11. An important conclusion that can be drawn from the framework presented in this paper is that the existence of market failures is a necessary, but not a sufficient, condition for the case that public policy can produce energy savings at negative costs. Some market failures may be so costly to identify and rectify that the costs of removing them exceed any benefits that might be obtained.

[19] See Lisa J. Cameron, W. David Montgomery and Harry L. Foster, "Economics of Greenhouse Gas Strategies," *Energy Studies Review* 9, no. 1 (1999), and its references.

[20] For example, see Union of Concerned Scientists et al., *America's Energy Choices: Investing in a Strong Economy and a Clean Environment,* 1991; Office of Technology Assessment, *Changing by Degrees: Steps to Reduce Greenhouse Gases,* OTA-O-482, 1991; Alliance to Save Energy et al., *An Alternative Energy Future*, 1992.

[21] Interlaboratory Working Group on Energy-Efficient and Low-Carbon Technologies, *Scenarios of U. S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond*, LBNL-40533 or ORNL/CON-444, September 1997. The Five Labs study is discussed further, and its results compared with by some prior studies by several of its principal authors, in a subsequent paper: Marilyn A. Brown, Mark D. Levine, Joseph P. Romm, Arthur H. Rosenfeld, and Jonathan G. Koomey, "Engineering-Economic Studies of Energy Technologies to Reduce Greenhouse Gas Emissions: Opportunities and Challenges," *Annual Review of Energy and the Environment* 23 (1998): 287–385.

[22] See Kenneth J. Arrow, *Essays in the Theory of Riskbearing,* Amsterdam: North-Holland, 1971.

[23] Op. cit.

[24] Christoph Böhringer and Thomas F. Rutherford. "Carbon Taxes with Exemptions in an Open Economy: A General Equilibrium Analysis of the German Tax Initiative." *Journal of Environmental Economics and Management*, pages 189-203, 1996. Thomas F. Rutherford, "Carbon Abatement versus Industrial Competitiveness: Rhetoric or Reality" Crest Workshop on the Kypoto Mechanism, (Osaka University, Japan, September 21, 2001).

[25] W. David Montgomery and James L. Sweeney, *Trade and Industry Impacts of the Kyoto Protocol*, Business Roundtable, Washington, DC, October 1999.

APPENDIX A

CRA ESTIMATES OF CARBON DIOXIDE

REDUCTION POTENTIAL OF VARIOUS TECHNOLOGIES

Table 5. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Pelletizing

1. Agglomerating I	Units	Notes	Pelletizing: Current Avg.	Pelletizing: Best Practice U.S.	Pelletizing: Best Practice in World	Potential Improvements: Grinding	Potential Improvements: Separation	Potential Improvements: Heat recovery and induration	Potential Improvements: Lower air infiltration
Classification of Potential Improvement:						1	1	1	1
Status of Potential Improvement:						4	4	3	3
Unit Consumption (per Ton Pellets)									
Electricity	kWh/Ton		125	125	50	100	100	125	115
Coal	lbs/Ton								
Natural Gas	SCF/Ton		1,400	1,000	900	1,400	1,400	1,300	1,300
Oil	Gal/Ton								
Grinding Balls/Rods	lbs/Ton		8	8	8	6	6	8	8
Flux Agent	lbs/Ton		75	150	150	75	75	75	75
Refractory	lbs/Ton								
Equivalent Carbon Dioxide, lbs CO2/Ton									
Electricity			302	302	121	242	242	302	278
Steam Coal			0	0	0	0	0	0	0
Natural Gas			171	122	110	171	171	159	159
Oil			0	0	0	0	0	0	0
Grinding Balls/Rods			8	8	8	6	6	8	8
Flux Agent			55	109	109	55	55	55	55
Refractory			0	0	0	0	0	0	0
Total			535	541	347	473	473	523	499
Economic Screening									
CRA Economic Estimate						1	1	2	2
Other Economic Estimate									
Comments						Depends on ore	Depends on ore	High retrofit costs	High retrofit cost

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 6. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Sintering

	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice In World	Lower air infiltration	Heat recovery from sinter cooling	Increased bed depth	Waste fuel additions
2. Agglomerating II				Sintering	Japan				
Classification of Potential Improvement:						1	1	1	1
Status of Potential Improvement:						3	3, 4	4	4
Unit Consumption (per Ton Sinter)									
Electricity	kWh/Ton		27	27	15	20	27	20	27
Steam Coal	lbs/Ton								
Natural Gas	SCF/Ton		50	50	50	50	40	50	0
Oil	lbs/Ton								
COG	SCF/Ton								
BFG	SCF/Ton								
Coke	lbs/Ton								
Coke Breeze	lbs/Ton		85	85	77	85	85	85	77
Flux Agent	lbs/Ton		230	230	230	230	230	230	230
Refractory	lbs/Ton								
Equivalent Carbon Dioxide, lbs CO2/Ton									
Electricity			65	65	36	49	65	49	65
Steam Coal			0	0	0	0	0	0	0
Natural Gas			6	6	6	6	5	6	0
Oil			0	0	0	0	0	0	0
COG									
BFG									
Coke			0	0	0	0	0	0	0
Coke Breeze			287	287	260	287	287	287	260
Flux Agent			167	167	167	167	167	167	167
Refractory			0	0	0	0	0	0	0
Total			525	525	469	509	524	509	492
Economic Screening									
CRA Economic Estimate						2	3	2	3
Other Economic Estimate						2	2	1	1
Comments							Higher retrofit costs	Operational issues, higher capital	Equipment de-rating, increase costs

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 7. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Scrap Processing

3. Obsolete Scrap Production	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Improved handling	Potential Improvements: Residual reduction technologies development
			Sorting and shredding				
Classification of Potential Improvement:						4	1, 4
Status of Potential Improvement:						4	1
Unit Consumption (per Ton Scrap)							
Electricity	kWh/Ton		10	10	10	9	500
Coal	lbs/Ton						
Natural Gas	SCF/Ton						
Oil	Gal/Ton		1.3	1.3	1.3	1.3	1.3
Refractory	lbs/Ton						2
Equivalent Carbon Dioxide, lbs CO2/Ton							
Electricity			24	24	24	22	1,209
Coal							
Natural Gas							
Oil			34	34	34	34	34
Refractory							1
Total			58	58	58	55	1,243
Economic Screening							
CRA Economic Estimate						2	3
Other Economic Estimate							
Comments						Depends on raw scrap grade, mix, etc.	High capital, complexity. RIF preferred.

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 8. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Cokemaking

			Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements			
4. Cokemaking			Conventional Byproduct recovery coke ovens			Advanced conventional ovens/program heating	Formcoke	Nonrecovery cokemaking	Dry quenching
Classification of Potential Improvement:						2	2	2	1
Status of Potential Improvement:						4	2	4	4
Unit Consumption (per Ton Coke)	Units	Notes							
Electricity	kWh/Ton		35	35	35	30	60	30	50
Coking Coal	lbs/Ton		2,588	2,588	2,588	2,588	2,700	2,588	2,500
Natural Gas	SCF/Ton		18	18	18	18	18	18	18
COG	SCF/Ton		5,669	5,669	5,669	5,669			5,669
BFG	SCF/Ton		1,483	1,483	1,483				1,483
Coke	lbs/Ton								
Coke Breeze	lbs/Ton								
Refractory	lbs/Ton		2	2	2	2	2		
Equivalent Carbon Dioxide, lbs CO2/Ton									
Electricity		1							
Coking Coal			7,591	7,591	7,591	7,591	7,920	7,591	7,333
Natural Gas			2	2	2	2	2	2	2
COG		2							
BFG		2							
Coke			0	0	0	0	0	0	0
Coke Breeze			0	0	0	0	0	0	0
Refractory			1	1	1	1	1	0	0
Credit for COG/Power Generation			(458)	(458)	(458)	(458)			(458)
Total			7,137	7,137	7,137	7,136	7,923	7,593	6,878
Economic Screening									
					CRA Economic Estimate	2	3	1	3
					Other Economic Estimate	1			3
					Comments	Control retrofit may pay.	Lower quality, high capital cost	Lower capital cost	Justified for environmental reasons

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

Notes
1 Self generated by recovered energy.
2 Emitted carbon dioxide content included in coking coal.

Current average consumption rates for fuels in underfiring and for coking coal are based on AISI 1998 Annual Statistical Report.
See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 8. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Cokemaking (continued)

4. Cokemaking	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Coal moisture control	Potential Improvements: Recover Flared COG
			Conventional Byproduct recovery coke ovens				
Classification of Potential Improvement:						1	
Status of Potential Improvement:						4	
Unit Consumption (per Ton Coke)							
Electricity	kWh/Ton		35	35	35	50	35
Coking Coal	lbs/Ton		2,588	2,588	2,588	2,500	2,588
Natural Gas	SCF/Ton		18	18	18	18	18
COG	SCF/Ton		5,669	5,669	5,669	6,200	5,669
BFG	SCF/Ton		1,483	1,483	1,483	0	1,483
Coke	lbs/Ton						
Coke Breeze	lbs/Ton						
Refractory	lbs/Ton		2	2	2		2
Equivalent Carbon Dioxide, lbs CO2/Ton							
Electricity		1	-				(92)
Coking Coal			7,591	7,591	7,591	7,333	7,591
Natural Gas			2	2	2	2	2
COG		2					
BFG		2					
Coke			0	0	0	0	0
Coke Breeze			0	0	0	0	0
Refractory			1	1	1	0	1
Credit for COG/Power Generation			(458)	(458)	(458)	(458)	(458)
Total			7,137	7,137	7,137	6,878	7,045
Economic Screening							
CRA Economic Estimate						3	
Other Economic Estimate						3	
Comments							

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

Notes
1 Self generated by recovered energy.
2 Emitted carbon dioxide content included in coking coal.

Current average consumption rates for fuels in underfiring and for coking coal are based on AISI 1998 Annual Statistical Report.
See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 9. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Ironmaking

	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements[1]: High-rate natural gas injection	High-rate coal injection	Plasma-enhanced blast	Higher blast temperature	Ore fines injection @ 200 lbs/THM
5. Unit Iron Production I			Iron production from blast furnace							
Classification of Potential Improvement:						1	1	2	1	1
Status of Potential Improvement:						4	3, 4	1	3, 4	1
Unit Consumption (per Ton HM)										
Electricity	kWh/Ton		50	50	50	50	50	250	45	50
Steam Coal	lbs/Ton		103	360	346	103	150	103	103	103
Natural Gas	SCF/Ton		1,792	440	500	3,000	1,792	1,792	1,792	1,792
Oil	Gal/Ton		3	6		3	3	3	3	3
COG	SCF/Ton		2,176							
BFG	SCF/Ton		37,132							
Coke	lbs/Ton		823	620	624	758	781	700	778	873
Oxygen	SCF/Ton		1,852	2,800	1,820	2,500	2,100	1,852	1,852	1,852
Acid Pellets	lbs/Ton		1,256		1,606	1,256	1,256	1,256	1,256	1,256
Self Flux Pellets	lbs/Ton		1,296	2,300		1,296	1,296	1,296	1,296	1,296
Sinter	lbs/Ton		408	750	1,466	408	408	408	408	208
RIF	lbs/Ton		19			19	19	19	19	19
Flux Agent	lbs/Ton		150		200	110	150	90	120	190
Refractory	lbs/Ton		6	6	6	6	6	6	6	6
Equivalent Carbon Dioxide, lbs CO2/Ton										
Electricity		1						338		
Steam Coal			303	1,056	1,015	303	440	303	303	303
Natural Gas			219	54	61	366	219	219	219	219
Oil			70	155	0	70	70	70	70	70
COG		2								
BFG		2								
Coke			2,936	2,212	2,227	2,704	2,786	2,498	2,776	3,115
Oxygen			74	113	73	100	84	74	74	74
Acid Pellets			336	0	279	336	336	336	336	336
Self Flux Pellets			347	622	0	347	347	347	347	347
Sinter			107	197	344	107	107	107	107	55
RIF			20	0	0	20	20	20	20	20
Flux Agent			109	0	145	80	109	65	87	138
Refractory			3	3	3	3	3	3	3	3
Total			4,525	4,412	4,147	4,438	4,523	4,382	4,343	4,680
Economic Screening										
CRA Economic Estimate						1	1	3	1	3
Other Economic Estimate						1	1			
Comments						Only where natural gas is available	Large furnaces only or multiple medium furnaces.	High capital, poor reliability	Retrofit costs site speicific	High capital cost

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

Notes
1 Self generated by recovered energy. Plasma enhanced blast requires about 140 kWh/ton of externally purchased electricity.
2 Emitted carbon dioxide content included in coking coal.

[1] Changes on furnace with current average mix of operating practices (e.g., fuel injections, burdening practices, etc.)

Current average consumption rates for natural gas, oil, COG, BFG, oxygen and coke are based on AISI 1998 Annual Statistical Report; coal consumption rate and metallic burdening are based on 1998 and 1999 ISS Blast Furnace Surveys.
See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 9. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Ironmaking (continued)

5. Unit Iron Production I	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	HBI charge	Top gas pressure recovery	Increased refractory life	Improved I&C	Hot blast stove automation[2]
			Iron production from blast furnace			Potential Improvements[1]				
Classification of Potential Improvement:						1	1	1	1	1
Status of Potential Improvement:						4	3	4	4	4
Unit Consumption (per Ton HM)										
Electricity	kWh/Ton		50	50	50	50	60	50	50	50
Steam Coal	lbs/Ton		103	360	346	103	103	103	103	103
Natural Gas	SCF/Ton		1,792	440	500	1,792	1,792	1,792	1,792	1,792
Oil	Gal/Ton		3	6		3	3	3	3	3
COG	SCF/Ton		2,176							2,176
BFG	SCF/Ton		37,132							37,132
Coke	lbs/Ton		823	620	624	693	813	823	741	823
Oxygen	SCF/Ton		1,852	2,800	1,820	1,852	1,852	1,852	1,852	1,852
Acid Pellets	lbs/Ton		1,256		1,606	1,056	1,256	1,256	1,256	1,256
Self Flux Pellets	lbs/Ton		1,296	2,300		1,296	1,296	1,296	1,296	1,296
Sinter	lbs/Ton		408	750	1,466	0	408	408	408	408
RIF	lbs/Ton		19			400	19	19	19	19
Flux Agent	lbs/Ton		150		200	100	150	150	110	150
Refractory	lbs/Ton		6	6	6	6	6	3	6	6
Equivalent Carbon Dioxide, lbs CO2/Ton										
Electricity		1								
Steam Coal			303	1,056	1,015	303	303	303	303	303
Natural Gas			219	54	61	219	219	219	219	219
Oil			70	155	0	70	70	70	70	70
COG		2								
BFG		2								
Coke			2,936	2,212	2,227	2,472	2,901	2,936	2,843	2,936
Oxygen			74	113	73	74	74	74	74	74
Acid Pellets			336	0	279	282	336	336	336	336
Self Flux Pellets			347	622	0	347	347	347	347	347
Sinter			107	197	344	0	107	107	107	107
RIF			20	0	0	423	20	20	20	20
Flux Agent			109	0	145	73	109	109	80	109
Refractory			3	3	3	3	3	2	3	3
Total			4,525	4,412	4,147	4,267	4,490	4,524	4,203	4,525
Economic Screening										
CRA Economic Estimate						2	2	1	2	1
Other Economic Estimate							3		1	1
Comments						Only where productivity required	For larger, high pressure furnaces	Delays reline capex	Small furnaces cannot justify	Mostly implemented already

Classification
1 = Process Improvement
2 = Process Replacement
3 = Energy Source Replacement
4 = Recycling

Status
1 = R&D
2 = First Mover
3 = Layout Constraint
4 = Demonstrated

Economic Criteria
1 = Likely to be justified by energy cost savings.
2 = Energy cost savings justification unclear.
3 = Unlikely to be justified by energy cost savings.

Notes
1 Self generated by recovered energy.
2 Emitted carbon dioxide content included in coking coal.

[1] Changes on furnace with current average mix of operating practices (e.g., fuel injections, burdening practices, etc.)
[2] Carbon dioxide emission savings are site specific.

Current average consumption rates for natural gas, oil, COG, BFG, oxygen and coke are based on AISI 1998 Annual Statistical Report; coal consumption rate and metallic burdening are based on 1998 and 1999 ISS Blast Furnace Surveys.
See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 9. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Ironmaking (continued)

	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements[1]: Top gas leakage recovery[2]	Potential Improvements[1]: Recover Flared Top Gas	Potential Improvements[1]: Stove recuperation[2]	Potential Improvements[1]: Pebble stoves[2]
5. Unit Iron Production I			Iron production from blast furnace						
Classification of Potential Improvement:						1		1	1
Status of Potential Improvement:						2		4	2
Unit Consumption (per Ton HM)									
Electricity	kWh/Ton		50	50	50	50	50	50	50
Steam Coal	lbs/Ton		103	360	348	103	103	103	103
Natural Gas	SCF/Ton		1,792	440	500	1,792	1,792	1,792	1,792
Oil	Gal/Ton		3	6		3	3	3	3
COG	SCF/Ton		2,176			2,176	2,176	2,176	2,176
BFG	SCF/Ton		37,132			37,132	37,132	37,132	37,132
Coke	lbs/Ton		823	620	624	823	823	823	823
Oxygen	SCF/Ton		1,852	2,800	1,820	1,852	1,852	1,852	1,852
Acid Pellets	lbs/Ton		1,256		1,606	1,256	1,256	1,256	1,256
Self Flux Pellets	lbs/Ton		1,296	2,300		1,296	1,296	1,296	1,296
Sinter	lbs/Ton		408	750	1,466	408	408	408	408
RIF	lbs/Ton		19			19	19	19	19
Flux Agent	lbs/Ton		150		200	150	150	150	150
Refractory	lbs/Ton		6	6	6	6	6	6	6
Equivalent Carbon Dioxide, lbs CO2/Ton									
Electricity		1					(67)		
Steam Coal			303	1,056	1,015	303	303	303	303
Natural Gas			219	54	61	219	219	219	219
Oil			70	155	0	70	70	70	70
COG		2							
BFG		2							
Coke			2,936	2,212	2,227	2,936	2,936	2,936	2,936
Oxygen			74	113	73	74	74	74	74
Acid Pellets			336	0	279	336	336	336	336
Self Flux Pellets			347	622	0	347	347	347	347
Sinter			107	197	344	107	107	107	107
RIF			20	0	0	20	20	20	20
Flux Agent			109	0	145	109	109	109	109
Refractory			3	3	3	3	3	3	3
Total			4,525	4,412	4,147	4,525	4,458	4,525	4,525
Economic Screening									
CRA Economic Estimate						3		3	1
Other Economic Estimate						2		3	
Comments						Capex underestimated		High capex, low energy recovery	Requires new capex

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

Notes
1 Self generated by recovered energy.
2 Emitted carbon dioxide content included in coking coal.

[1] Changes on furnace with current average mix of operating practices (e.g., fuel injections, burdening practices, etc.)
[2] Carbon dioxide emission savings are site specific.

Current average consumption rates for natural gas, oil, COG, BFG, oxygen and coke are based on AISI 1998 Annual Statistical Report; coal consumption rate and metallic burdening are based on 1998 and 1999 ISS Blast Furnace Surveys.
See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 10. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Smelting

6. Unit Iron Production II-Smelting	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Corex process	Hismelt process	DIOS process	AISI-DOE process	Technored process
			Iron production from blast furnace			Potential Improvements				
Classification of Potential Improvement:						2	2	2	2	2
Status of Potential Improvement:						3, 4	2	2	1	2
Unit Consumption (per Ton HM)										
Electricity	kWh/Ton		50	50	50	54	200	125	30	140
Steam Coal	lbs/Ton		103	360	346	1,900	1,700	1,600	1,120	700
Natural Gas	SCF/Ton		1,792	440	500		2,500			
Oil	Gal/Ton		3	6						
COG	SCF/Ton		2,176							
BFG	SCF/Ton		37,132							
Coke	lbs/Ton		823	620	824					700
Oxygen	SCF/Ton		1,852	2,800	1,820	16,400	7,600	18,100	19,400	
Acid Pellets	lbs/Ton		1,256		1,806					
Self Fluxing Pellets	lbs/Ton		1,296	2,300		3,200			3,200	
Sinter	lbs/Ton		408	750	1,466					
Lump Ore	lbs/Ton									
Ore Fines	lbs/Ton						3,000	3,000		3,100
RIF	lbs/Ton		19							
Flux Agent	lbs/Ton		150		200	500	440	400	400	320
Refractory	lbs/Ton		6	6	6					
Electrodes	lbs/Ton									
Equivalent Carbon Dioxide, lbs CO2/Ton										
Electricity		1				131	483	302	73	338
Steam Coal			303	1,056	1,015	5,573	4,987	4,693	3,285	2,053
Natural Gas			219	54	61	0	305	0	0	0
Oil			70	155	0	0	0	0	0	0
COG		2								
BFG		2								
Coke			2,936	2,212	2,227	0	0	0	0	2,361
Oxygen			74	113	73	659	305	728	780	0
Acid Pellets			336	0	279	0	0	0	0	0
Self Fluxing Pellets			347	622	0	856	0	0	856	0
Sinter			107	197	344	0	0	0	0	0
Lump Ore			0	0	0	0	0	0	0	0
Ore Fines			0	0	0	0	36	36	0	38
RIF			20	0	0	0	0	0	0	0
Flux Agent			109	0	145	364	320	291	291	233
Refractory			3	3	3	0	0	0	0	0
Electrodes										
Total			4,525	4,412	4,147	7,583	6,437	6,050	5,285	5,023
Economic Screening										
					CRA Economic Estimate	2	2	2	3	2
					Other Economic Estimate					
					Comments	Justified at high power costs	High capex, justify environmentally	High capex, justify environmentally	High capex, justify environmentally	Low productivity, justify environmentally

Classification
1 = Process Improvement
2 = Process Replacement
3 = Energy Source Replacement
4 = Recycling

Status
1 = R&D
2 = First Mover
3 = Layout Constraint
4 = Demonstrated

Economic Criteria
1 = Likely to be justified by energy cost savings.
2 = Energy cost savings justification unclear.
3 = Unlikely to be justified by energy cost savings.

Notes
1 Self generated by recovered energy in integrated plants. Purchased for all else.
2 Emitted carbon dioxide content included in coking coal.

Current average consumption rates for natural gas, oil, COG, BFG, oxygen and coke are based on AISI 1998 Annual Statistical Report; coal consumption rate and metallic burdening are based on 1998 and 1999 ISS Blast Furnace Surveys.
See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 10. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Smelting (continued)

6. Unit Iron Production II-Smelting	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Rotary hearth reduction/electric furnace melting	Potential Improvements: Romelt
			Iron production from blast furnace				
Classification of Potential Improvement:						2	2
Status of Potential Improvement:						1, 2	2
Unit Consumption (per Ton HM)							
Electricity	kWh/Ton		50			540	100
Steam Coal	lbs/Ton		103	360	346	1,070	1,400
Natural Gas	SCF/Ton		1,792	440	500	2,000	0
Oil	Gal/Ton		3	6			
COG	SCF/Ton		2,176				
BFG	SCF/Ton		37,132				
Coke	lbs/Ton		823	620	624		
Oxygen	SCF/Ton		1,852	2,800	1,820		22,400
Acid Pellets	lbs/Ton		1,256		1,606		
Self Fluxing Pellets	lbs/Ton		1,296	2,300			
Sinter	lbs/Ton		408	750	1,466		
Lump Ore	lbs/Ton						
Ore Fines	lbs/Ton					3,000	
RIF	lbs/Ton		19				
Flux Agent	lbs/Ton		150		200	150	
Refractory	lbs/Ton		8	6	6		
Electrodes	lbs/Ton					10	
Equivalent Carbon Dioxide, lbs CO2/Ton							
Electricity		1				1,305	242
Steam Coal			303	1,056	1,015	3,139	4,107
Natural Gas			219	54	61	244	0
Oil			70	155	0	0	0
COG		2					
BFG		2					
Coke			2,936	2,212	2,227	0	0
Oxygen			74	113	73	0	900
Acid Pellets			336	0	279	0	0
Self Fluxing Pellets			347	622	0	0	0
Sinter			107	197	344	0	0
Lump Ore			0	0	0	0	0
Ore Fines			0	0	0	36	0
RIF			20	0	0	0	0
Flux Agent			109	0	145	109	0
Refractory			3	3	3	0	0
Electrodes							
Total			4,525	4,412	4,147	4,834	5,249
Economic Screening							
CRA Economic Estimate							2
Other Economic Estimate							
Comments						High capital, low productivity	High capital, low productivity

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

Notes
1 Self generated by recovered energy in integrated plants. Purchased for all else.
2 Emitted carbon dioxide content included in coking coal.

Current average consumption rates for natural gas, oil, COG, BFG, oxygen and coke are based on AISI 1998 Annual Statistical Report; coal consumption rate and metallic burdening are based on 1998 and 1999 ISS Blast Furnace Surveys.
See Table 4 in text for carbon dioxide equivalents.

Table 11. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Direct Reduction

7. Unit Iron Production III-Direct Reduction	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Iron carbide process	Fluidized bed reduction (e.g., Finmet, Circored)	Rotary hearth bed reduction (e.g., Fastmet, Iron Dynamics)
			Conventional gas-based process (e.g., Midrex or HYL)					
Classification of Potential Improvement:						2	2	2
Status of Potential Improvement:						1	2	2
Unit Consumption (per Ton RIF)								
Electricity	kWh/Ton		110	110	110	150	160	60
Steam Coal	lbs/Ton							850
Natural Gas	SCF/Ton		9,000	9,000	7,900	15,000	12,200	2,500
Oxygen	SCF/Ton				3,600			
Pellets	lbs/Ton		2,800	2,800	2,800			
Lump Ore	lbs/Ton							
Ore Fines	lbs/Ton					3,000	3,300	2,600
RIF	lbs/Ton							
Flux Agent	lbs/Ton							200
Refractory	lbs/Ton							
Equivalent Carbon Dioxide, lbs CO2/Ton								
Electricity			266	266	266	363	387	145
Steam Coal			0	0	0	0	0	2,493
Natural Gas			1,099	1,099	965	1,832	1,490	305
Oxygen			0	0	145	0	0	0
Pellets			749	749	749			
Lump Ore								
Ore Fines								
RIF								
Flux Agent			0	0	0	0	0	145
Refractory			0	0	0	0	0	0
Total			2,114	2,114	2,124	2,194	1,876	3,089
Economic Screening								
CRA Economic Estimate						3	2	2
Other Economic Estimate							1	
Comments						High capex, severe technical problems	High capex, require low cost natural gas	High capex, low quality product

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 12. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: BOP Steelmaking

8. Steelmaking I	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements[1]: Combination BOF and EAF, high scrap charge	Offgas energy recovery	Lower slag volume	Increased refractory life	Lower air infiltration, variable speed fans
			Conventional hot metal/cold scrap charge BOF/Q-BOP							
Classification of Potential Improvement:						1	1	1, 3	1	1
Status of Potential Improvement:						2	3, 4	4	4	3, 4
Unit Consumption (per Ton LS)										
Electricity	kWh/Ton		23	23	23	200	0	23	23	16
Steam Coal	lbs/Ton									
Oil	Gal/Ton									
Natural Gas	SCF/Ton									
COG	SCF/Ton		14	14	14	7	14	14	14	14
Oxygen	SCF/Ton		1,937	1,800	1,640	1,000	1,937	1,700	1,937	1,937
Hot Metal	lbs/Ton		1,709	1,709	1,700	854	1,709	1,709	1,709	1,709
Prompt Scrap	lbs/Ton		503	503	700	251	503	503	503	503
Obsolete Scrap	lbs/Ton					937				
RIF	lbs/Ton		4	4	4	22	4	4	4	4
Flux Agent	lbs/Ton		150	150	150	135	150	150	150	150
Desulfurizing Agent	lbs/Ton		4	4	4	2	4	4	4	4
Refractory	lbs/Ton		17	17	17	19	17	17	8	17
Ferroalloy Agent	lbs/Ton		15	15	15	13	15	15	15	15
Equivalent Carbon Dioxide, lbs CO2/Ton										
Electricity			56	56	56	483	0	56	56	39
Steam Coal			0	0	0	0	0	0	0	0
Oil										
Natural Gas			0	0	0	0	0	0	0	0
COG		1								
Oxygen			78	72	66	40	78	68	78	78
Hot Metal			3,867	3,770	3,525	1,933	3,867	3,867	3,867	3,867
Prompt Scrap			9	9	12	4	9	9	9	9
Obsolete Scrap			0	0	0	28	0	0	0	0
RIF			4	4	4	24	4	4	4	4
Flux Agent			109	109	109	98	109	109	109	109
Desulfurizing Agent			20	20	20	10	20	20	20	20
Refractory			8	8	8	10	8	8	4	8
Ferroalloy Agent			70	70	70	59	70	70	70	70
Recovery of Offgas Energy							(121)			
Total			4,221	4,118	3,871	2,689	4,045	4,211	4,217	4,204
Economic Screening										
CRA Economic Estimate						1	3	1	1	3
Other Economic Estimate							3			3
Comments						Site specific, retrofit require high quality, low cost scrap	High capital cost	Blast furnace must reduce hot metal Si content		High retrofit cost

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

Notes
1 Emitted carbon dioxide content included in coking coal.

[1] Improvements by computer control are not included because they are unlikely to change carbon dioxide emissions; however, they will improve productivity.

Current average consumption rates for hot metal, scrap, RIF, oxygen and COG are based on AISI 1998 Annual Statistical Report.
See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001

Table 13. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: EAF Steelmaking

9. Steelmaking II	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	DC furnace	Scrap preheating (e.g. Consteel and Fuch shaft process)	Hot metal charging	RIF charging[2]	RIF charging[3]
			Conventional cold-charged AC EAF with oxyfuel boost			Potential Improvements[1]				
Classification of Potential Improvement:						2	2	1, 3	3	3
Status of Potential Improvement:						3, 4	3, 4	3, 4	4	4
Unit Consumption (per Ton LS)										
Electricity	kWh/Ton		420	410	360	400	310	230	450	450
Steam Coal	lbs/Ton									
Natural Gas	SCF/Ton		587	587	587	587	587	300	587	587
Charge Carbon	lbs/Ton		25	25	25	25	25	0	20	25
Oxygen	SCF/Ton		1,264	1,264	1,264	1,264	1,264	600	1,264	1,264
Hot Metal	lbs/Ton		151	151	151	151	151	1,000	151	0
Obsolete Scrap	lbs/Ton		1,875	1,875	1,875	1,875	1,875	1,020	1,430	500
RIF	lbs/Ton		41	41	41	41	41	41	530	1780
Cold Pig Iron	lbs/Ton									
Flux Agent	lbs/Ton		120	120	120	120	120	70	120	120
Refractory	lbs/Ton		22	22	22	22	22	22	22	22
Ferroalloy Agent	lbs/Ton		10	10	10	10	10	10	10	10
Electrodes	lbs/Ton		4	4	4	2	2	2	4	4
Equivalent Carbon Dioxide, lbs CO2/Ton										
Electricity			1,015	991	870	967	749	556	1,088	1,088
Steam Coal			0	0	0	0	0	0	0	0
Natural Gas			72	72	72	72	72	37	72	72
Charge Carbon			73	73	73	73	73	0	59	73
Oxygen			51	51	51	51	51	24	51	51
Hot Metal			341	333	313	341	341	2,263	341	0
Obsolete Scrap			55	55	55	55	55	30	42	15
RIF			43	43	43	43	43	43	560	1,882
Cold Pig Iron						0	0	0	0	0
Flux Agent			87	87	87	87	87	51	87	87
Refractory			11	11	11	11	11	11	11	11
Ferroalloy Agent			47	47	47	47	47	47	47	47
Electrodes			36	36	36	18	22	18	36	36
Total			1,832	1,799	1,658	1,765	1,551	3,079	2,394	3,361
Economic Screening										
					CRA Economic Estimate	2	2	1	1	1
					Other Economic Estimate	1	1			
					Comments	Not for in-kind replacement	Maybe retrofit constrained	Layout constraint	Quality control	

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

[1] Plasma and induction furnaces are used for special applications only. EOF is similar to hot metal charging. Better quality scrap, UHP transformers, bottom stirring, twin-shell furnaces, etc., are directed to improving quality and productivity.

[2] 25% RIF charge.

[3] 75% RIF charge and no hot metal.

Current average consumption rates for hot metal, scrap, RIF, oxygen and natural gas are based on AISI 1998 Annual Statistical Report.
See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 13. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: EAF Steelmaking (continued)

9. Steelmaking II	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice In World	CPI charging[2]	Oxyfuel burners	Foamy slag	UHP transformers	Bottom stirring/eccentric bottom tapping
			Conventional cold-charged AC EAF with oxyfuel boost			Potential Improvements[1]				
Classification of Potential Improvement:						3	1	1	1	1
Status of Potential Improvement:						4	4	4	4	3
Unit Consumption (per Ton LS)										
Electricity	kWh/Ton		420	410	360	420	384	415	405	388
Steam Coal	lbs/Ton									
Natural Gas	SCF/Ton		587	587	587	587	587	587	587	587
Charge Carbon	lbs/Ton		25	25	25	1	25	25	25	25
Oxygen	SCF/Ton		1,264	1,264	1,264	1,264	1,264	1,264	1,264	1,264
Hot Metal	lbs/Ton		151	151	151	151	151	151	151	151
Obsolete Scrap	lbs/Ton		1,875	1,875	1,875	1,390	1,875	1,875	1,875	1,875
RIF	lbs/Ton		41	41	41	41	41	41	41	41
Cold Pig Iron	lbs/Ton					530	0	0	0	0
Flux Agent	lbs/Ton		120	120	120	120	120	120	120	120
Refractory	lbs/Ton		22	22	22	22	22	22	22	22
Ferroalloy Agent	lbs/Ton		10	10	10	10	10	10	10	10
Electrodes	lbs/Ton		4	4	4	4	4	4	4	4
Equivalent Carbon Dioxide, lbs CO2/Ton										
Electricity			1,015	991	870	1,015	928	1,003	979	938
Steam Coal			0	0	0	0	0	0	0	0
Natural Gas			72	72	72	72	72	72	72	72
Charge Carbon			73	73	73	3	73	73	73	73
Oxygen			51	51	51	51	51	51	51	51
Hot Metal			341	333	313	341	341	341	341	341
Obsolete Scrap			55	55	55	41	55	55	55	55
RIF			43	43	43	43	43	43	43	43
Cold Pig Iron						1,199	0	0	0	0
Flux Agent			87	87	87	87	87	87	87	87
Refractory			11	11	11	11	11	11	11	11
Ferroalloy Agent			47	47	47	47	47	47	47	47
Electrodes			36	36	36	36	36	36	36	32
Total			1,832	1,799	1,658	2,946	1,745	1,820	1,795	1,750
Economic Screening										
CRA Economic Estimate						1	1	1	2	1
Other Economic Estimate							1	3	3	1, 3
Comments						Quality control	Adopted already	Justify by refractory savings	Not for retrofit, will pay for new installation	Retrofit constrained

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

[1] Plasma and induction furnaces are used for special applications only. EOF is similar to hot metal charging. Better quality scrap, UHP transformers, bottom stirring, twin-shell furnaces, etc., are directed to improving quality and productivity.

[2] 25% CPI charge.

Current average consumption rates for hot metal, scrap, RIF, oxygen and natural gas are based on AISI 1998 Annual Statistical Report.
See Table 4 in text for carbon dioxide equivalents.

Charles River Associates, 2001.

Table 13. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: EAF Steelmaking (continued)

	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements[1]
			Conventional cold-charged AC EAF with oxyfuel boost			Neural controls
9. Steelmaking II						
Classification of Potential Improvement:						1
Status of Potential Improvement:						4
Unit Consumption (per Ton LS)						
Electricity	kWh/Ton		420	410	360	393
Steam Coal	lbs/Ton					
Natural Gas	SCF/Ton		587	587	587	587
Charge Carbon	lbs/Ton		25	25	25	25
Oxygen	SCF/Ton		1,264	1,264	1,264	1,264
Hot Metal	lbs/Ton		151	151	151	151
Obsolete Scrap	lbs/Ton		1,875	1,875	1,875	1,875
RIF	lbs/Ton		41	41	41	41
Cold Pig Iron	lbs/Ton					0
Flux Agent	lbs/Ton		120	120	120	120
Refractory	lbs/Ton		22	22	22	22
Ferroalloy Agent	lbs/Ton		10	10	10	10
Electrodes	lbs/Ton		4	4	4	3
Equivalent Carbon Dioxide, lbs CO2/Ton						
Electricity			1,015	991	870	950
Steam Coal			0	0	0	0
Natural Gas			72	72	72	72
Charge Carbon			73	73	73	73
Oxygen			51	51	51	51
Hot Metal			341	333	313	341
Obsolete Scrap			55	55	55	55
RIF			43	43	43	43
Cold Pig Iron						0
Flux Agent			87	87	87	87
Refractory			11	11	11	11
Ferroalloy Agent			47	47	47	47
Electrodes			36	36	36	27
Total			1,832	1,799	1,658	1,757
Economic Screening						
					CRA Economic Estimate	1
					Other Economic Estimate	1
					Comments	

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

[1] Plasma and induction furnaces are used for special applications only. EOF is similar to hot metal charging. Better quality scrap, UHP transformers, botto stirring, twin-shell furnaces, etc., are directed to improving quality and productivity.

Current average consumption rates for hot metal, scrap, RIF, oxygen and natural gas are based on AISI 1998 Annual Statistical Report.
See Table 4 in text for carbon dioxide equivalents.

Charles River Associates, 2001.

Table 14. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Casting & Hot Rolling-BOP Source

10. Solidification and Hot Gauge Reduction	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Thin slab casting	Direct-strip casting	Spray forming	Improved reheat furnaces, insulate, and burner controls	Efficient ladle preheat
			Conventional slab/billet casting, reheat furnaces, and hot rolling mill							
Classification of Potential Improvement:						2	2	2	1	1
Status of Potential Improvement:						4	1	1	3	4
Unit Consumption (per Ton HR Coil)										
Electricity	kWh/Ton		100	90	90	50	50	50	100	100
Natural Gas	SCF/Ton		750	600	600	850	850	850	1,400	730
Oil	Gal/Ton									
COG	SCF/Ton		1,899	1,800	1,800	1,899	1,899	1,899	1,899	1,899
BFG	SCF/Ton									
Oxygen	SCF/Ton									
Liquid Steel-BOP	lbs/Ton		2,122	2,122	2,122	2,000	2,000	2,000	2,122	2,122
Refractory	lbs/Ton		7	7	7	5	5	5	7	7
Equivalent Carbon Dioxide, lbs CO2/Ton										
Electricity			242	218	218	121	121	121	242	242
Natural Gas			92	73	73	104	104	104	171	89
Oil			0	0	0	0	0	0	0	0
COG		1								
BFG			0	0	0	0	0	0	0	0
Oxygen			0	0	0	0	0	0	0	0
Liquid Steel-BOP			4,478	4,369	4,107	4,221	4,221	4,221	4,478	4,478
Refractory			4	4	4	3	3	3	4	4
Total			4,815	4,664	4,401	4,448	4,448	4,448	4,894	4,813
Economic Screening										
CRA Estimate						3			2	1
Other Estimates						2			3	1
Comments						Can't retrofit	Not scale for continuous casting	Not scale for continuous casting	Requires retrofit capital	

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 14. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Casting & Hot Rolling-BOP Source (continued)

10. Solidification and Hot Gauge Reduction	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Hot charging	Energy efficient mill drives	Recuperative burners
			Conventional slab/billet casting, reheat furnaces, and hot rolling mill					
Classification of Potential Improvement:						1	1	1
Status of Potential Improvement:						3	4	3, 4
Unit Consumption (per Ton HR Coil)								
Electricity	kWh/Ton		100	90	90	100	96	100
Natural Gas	SCF/Ton		750	600	600	220	750	563
Oil	Gal/Ton							
COG	SCF/Ton		1,899	1,800	1,800	1,899	1,899	1,899
BFG	SCF/Ton							
Oxygen	SCF/Ton							
Liquid Steel-BOP	lbs/Ton		2,122	2,122	2,122	2,122	2,122	2,122
Refractory	lbs/Ton		7	7	7	7	7	7
Equivalent Carbon Dioxide, lbs CO2/Ton								
Electricity			242	218	218	242	232	242
Natural Gas			92	73	73	27	92	69
Oil			0	0	0	0	0	0
COG		1						
BFG			0	0	0	0	0	0
Oxygen			0	0	0	0	0	0
Liquid Steel-BOP			4,478	4,369	4,107	4,478	4,478	4,478
Refractory			4	4	4	4	4	4
Total			**4,815**	**4,664**	**4,401**	**4,750**	**4,805**	**4,792**
Economic Screening								
					CRA Estimate	3	3	2
					Other Estimates	3	2	1
					Comments	Layout constrained	Only as part of general upgrade	Retrofit costs

Classification
1 = Process Improvement
2 = Process Replacement
3 = Energy Source Replacement
4 = Recycling

Status
1 = R&D
2 = First Mover
3 = Layout Constraint
4 = Demonstrated

Economic Criteria
1 = Likely to be justified by energy cost savings.
2 = Energy cost savings justification unclear.
3 = Unlikely to be justified by energy cost savings.

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 14. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Casting & Hot Rolling-EAF Source (continued)

10. Solidification and Hot Gauge Reduction	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Thin slab casting	Direct-strip casting/NNS	Spray forming	Improved reheat furnaces, insulate, and burner controls	Efficent ladle preheat
			Conventional slab/billet casting, reheat furnaces, and hot rolling mill							
Classification of Potential Improvement:						2	2	2	1	1
Status of Potential Improvement:						4	1	1	3	4
Unit Consumption (per Ton HR Coil)										
Electricity	kWh/Ton		100	90	90	50	50	50	100	100
Natural Gas	SCF/Ton		1,700	1,500	1,500	850	850	850	1,400	1,660
Oil	Gal/Ton									
COG	SCF/Ton									
BFG	SCF/Ton									
Oxygen	SCF/Ton									
Liquid Steel-EAF	lbs/Ton		2,122	2,122	2,122	2,000	2,000	2,000	2,122	2,122
Refractory	lbs/Ton		7	7	7	5	5	5	7	7
Equivalent Carbon Dioxide, lbs CO2/Ton										
Electricity			242	218	218	121	121	121	242	242
Natural Gas			208	183	183	104	104	104	171	205
Oil			0	0	0	0	0	0	0	0
COG			0	0	0	0	0	0	0	0
BFG			0	0	0	0	0	0	0	0
Oxygen			0	0	0	0	0	0	0	0
Liquid Steel-EAF			1,943	1,908	1,759	1,832	1,832	1,832	1,943	1,943
Refractory			4	4	4	3	3	3	4	4
Total			2,398	2,313	2,164	2,059	2,059	2,059	2,359	2,394
Economic Screening										
CRA Estimate						1	2	2	1	1
Other Estimates						2	2			1
Comments						For flat rolled products	Unresolved technical problems	Unresolved technical problems	Site specific capital	

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 14. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Casting & Hot Rolling-EAF Source (continued)

10. Solidification and Hot Gauge Reduction	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Hot charging	Potential Improvements: Energy efficient mill drives	Potential Improvements: Recuperative burners
			Conventional slab/billet casting, reheat furnaces, and hot rolling mill					
Classification of Potential Improvement:						1	1	1
Status of Potential Improvement:						3	4	3, 4
Unit Consumption (per Ton HR Coil)								
Electricity	kWh/Ton		100	90	90	100	96	100
Natural Gas	SCF/Ton		1,700	1,500	1,500	1,170	1,700	1,275
Oil	Gal/Ton							
COG	SCF/Ton							
BFG	SCF/Ton							
Oxygen	SCF/Ton							
Liquid Steel-EAF	lbs/Ton		2,122	2,122	2,122	2,122	2,122	2,122
Refractory	lbs/Ton		7	7	7	7	7	7
Equivalent Carbon Dioxide, lbs CO2/Ton								
Electricity			242	218	218	242	232	242
Natural Gas			208	183	183	143	208	156
Oil			0	0	0	0	0	0
COG			0	0	0	0	0	0
BFG			0	0	0	0	0	0
Oxygen			0	0	0	0	0	0
Liquid Steel-EAF			1,943	1,908	1,759	1,943	1,943	1,943
Refractory			4	4	4	4	4	4
Total			2,396	2,313	2,164	2,331	2,386	2,344
Economic Screening								
					CRA Estimate	3	3	2
					Other Estimates	3	2	1
					Comments	Layout constrained	Only as part of general upgrade	Retrofit costs

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 15. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Pickling-BOP Source

11. Surface Preparation	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Pickle liquor recovery	Potential Improvements: Elimination of pickling	Potential Improvements: Pickle liquor steam reduction
			Continuous pickling line					
CRA Classification of Potential Improvement:						1	1	1
Status:						4	1	4
Unit Consumption (per Ton Pickled Coil)								
Electricity	kWh/Ton		20	20	20	15	0	20
Natural Gas	SCF/Ton		450	450	450	400	0	374
Oil	Gal/Ton							
COG	SCF/Ton							
BFG	SCF/Ton							
HR Coil-BOP	lbs/Ton		2,100	2,100	2,100	2,100	2,100	2,100
Equivalent Carbon Dioxide, lbs CO2/Ton								
Electricity			48	48	48	36	0	48
Natural Gas			55	55	55	49	0	46
Oil								
COG								
BFG								
HR Coil-BOP			5,056	4,897	4,621	5,056	5,056	5,056
Total			5,159	5,000	4,724	5,141	5,056	5,150
Economic Screening								
CRA Estimate						1	1	2
Other Estimates								3
Comments						Not where direct disposal allowed	Not retrofittable	Site specific

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 15. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Pickling-EAF Source (continued)

11. Surface Preparation	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Pickle liquor recovery	Potential Improvements: Elimination of pickling	Potential Improvements: Pickle liquor steam reduction
			Continuous pickling line					
CRA Classification of Potential Improvement:						1	1	1
Status:						4	1	4
Unit Consumption (per Ton Pickled Coil)								
Electricity	kWh/Ton		20	20	20	15	0	20
Natural Gas	SCF/Ton		450	450	450	400	0	374
Oil	Gal/Ton							
COG	SCF/Ton							
BFG	SCF/Ton							
HR Coil-EAF	lbs/Ton		2,100	2,100	2,100	2,100	2,100	2,100
Equivalent Carbon Dioxide, lbs CO2/Ton								
Electricity			48	48	48	36	0	48
Natural Gas			55	55	55	49	0	46
Oil								
COG								
BFG								
HR Coil-EAF			2,516	2,428	2,272	2,516	2,516	2,516
Total			**2,619**	**2,532**	**2,375**	**2,601**	**2,516**	**2,610**
Economic Screening								
					CRA Estimate	1	1	2
					Other Estimates			3
					Comments	Not where direct disposal allowed	Not retrofittable	Site specific

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Charles River Associates, 2001.

Table 16. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Cold Rolling-BOP Source

12. Cold Gauge Reduction	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Improved lubrication	Improved on-stream time	Computer controlled operation
			Conventional cold rolling mill					
CRA Classification of Potential Improvement:						1	1	1
Status:						1	1	2
Unit Consumption (per Ton CR Coil)								
Electricity	kWh/Ton		90	75	75	70	75	70
Natural Gas	SCF/Ton							
Oil	Gal/Ton							
COG	SCF/Ton							
BFG	SCF/Ton							
Pickled Coil-BOP	lbs/Ton		2,020	2,020	2,020	2,020	2,020	2,020
Equivalent Carbon Dioxide, lbs CO2/Ton								
Electricity			218	181	181	169	181	169
Natural Gas								
Oil								
COG								
BFG								
Pickled Coil-BOP			5,211	5,050	4,772	5,211	5,211	5,211
Total			5,428	5,231	4,953	5,380	5,392	5,380
Economic Screening								
CRA Estimate						1	1	1
Other Estimates								
Comments								

Classification
1 = Process Improvement
2 = Process Replacement
3 = Energy Source Replacement
4 = Recycling

Status
1 = R&D
2 = First Mover
3 = Layout Constraint
4 = Demonstrated

Economic Criteria
1 = Likely to be justified by energy cost savings.
2 = Energy cost savings justification unclear.
3 = Unlikely to be justified by energy cost savings.

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 16. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Cold Rolling-EAF Source (continued)

12. Cold Gauge Reduction	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Improved lubrication	Potential Improvements: Improved on-stream time	Potential Improvements: Computer controlled operation
			Conventional cold rolling mill					
CRA Classification of Potential Improvement:						1	1	1
Status:						1	1	2
Unit Consumption (per Ton CR Coil)								
Electricity	kWh/Ton		90	75	75	70	75	70
Natural Gas	SCF/Ton							
Oil	Gal/Ton							
COG	SCF/Ton							
BFG	SCF/Ton							
Pickled Coil-EAF	lbs/Ton		2,020	2,020	2,020	2,020	2,020	2,020
Equivalent Carbon Dioxide, lbs CO2/Ton								
Electricity			218	181	181	169	181	169
Natural Gas								
Oil								
COG								
BFG								
Pickled Coil-EAF			2,645	2,557	2,399	2,645	2,645	2,645
Total			2,863	2,738	2,580	2,815	2,827	2,815
Economic Screening								
					CRA Estimate	1	1	1
					Other Estimates			
					Comments			

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 17. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Hot Dip Galvanizing-BOP Source

	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Optimize operation
13. Coating-Hot-Dip Galvanizing			Continuous HD galvanizing line			
CRA Classification of Potential Improvement:						1
Status:						3, 4
Unit Consumption (per Ton HD Coil)						
Electricity	kWh/Ton		20	20	20	18
Natural Gas	SCF/Ton		700	700	700	600
Oil	Gal/Ton					
COG	SCF/Ton					
BFG	SCF/Ton					
HR Coil-BOP	lbs/Ton		2,240	2,240	2,240	2,240
Zinc	lbs/Ton					
Equivalent Carbon Dioxide, lbs CO2/Ton						
Electricity			48	48	48	44
Natural Gas			85	85	85	73
Oil						
COG						
BFG						
HR Coil-BOP			5,393	5,223	4,929	5,393
Zinc						
Total			5,527	5,357	5,063	5,510
Economic Screening						
CRA Estimate						1
Other Estimates						
Comments						Evolutionary improvements and improved quality

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 17. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Hot Dip Galvanizing-EAF Source (continued)

	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements
13. Coating-Hot-Dip Galvanizing			Continuous HD galvanizing line			Optimize operation
CRA Classification of Potential Improvement:						1
Status:						3, 4
Unit Consumption (per Ton HD Coil)						
Electricity	kWh/Ton		20	20	20	18
Natural Gas	SCF/Ton		700	700	700	600
Oil	Gal/Ton					
COG	SCF/Ton					
BFG	SCF/Ton					
HR Coil-EAF	lbs/Ton		2,240	2,240	2,240	2,240
Zinc	lbs/Ton					
Equivalent Carbon Dioxide, lbs CO2/Ton						
Electricity			48	48	48	44
Natural Gas			85	85	85	73
Oil						
COG						
BFG						
HR Coil-EAF			2,684	2,590	2,423	2,684
Zinc						
Total			2,817	2,724	2,557	2,800
Economic Screening						
					CRA Estimate	1
					Other Estimates	
					Comments	Evolutionary improvements and improved quality

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 18. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Electrogalvanizing-BOP Source

14. Coating-Electogalvanizing	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements
			Continous electrogalvanizing line			Optimize operation
CRA Classification of Potential Improvement:						1
Status:						3, 4
Unit Consumption (per Ton EG Coil)						
Electricity	kWh/Ton		100	100	100	90
Natural Gas	SCF/Ton		50	50	50	50
Oil	Gal/Ton					
COG	SCF/Ton					
BFG	SCF/Ton					
HR Coil-BOP	lbs/Ton		2,440	2,440	2,440	2,440
Zinc	lbs/Ton					
Equivalent Carbon Dioxide, lbs CO2/Ton						
Electricity			242	242	242	218
Natural Gas			6	6	6	6
Oil						
COG						
BFG						
HR Coil-BOP			5,874	5,690	5,369	5,874
Zinc						
Total			6,122	5,937	5,617	6,098

Economic Screening

CRA Estimate	1
Other Estimates	
Comments	Evolutionary improvements and improved quality

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 18. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Electrogalvanizing-EAF Source (continued)

14. Coating-Electogalvanizing	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements
			Continous electrogalvanizing line			Optimize operation
CRA Classification of Potential Improvement:						1
Status:						3, 4
Unit Consumption (per Ton EG Coil)						
Electricity	kWh/Ton		100	100	100	90
Natural Gas	SCF/Ton		50	50	50	50
Oil	Gal/Ton					
COG	SCF/Ton					
BFG	SCF/Ton					
HR Coil-EAF	lbs/Ton		2,440	2,440	2,440	2,440
Zinc	lbs/Ton					
Equivalent Carbon Dioxide, lbs CO2/Ton						
Electricity			242	242	242	218
Natural Gas			6	6	6	6
Oil						
COG						
BFG						
HR Coil-EAF			2,923	2,822	2,640	2,923
Zinc						
Total			3,171	3,069	2,887	3,147
Economic Screening						
					CRA Estimate	1
					Other Estimates	
					Comments	Evolutionary improvements and improved quality

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 19. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Tin Mill Products-BOP Source

	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Optimize operation
15. Coating-Tin Mill Products				Tin Mill		
CRA Classification of Potential Improvement:						1
Status:						3, 4
Unit Consumption (per Ton TMP)						
Electricity	kWh/Ton		45	45	45	40
Natural Gas	SCF/Ton		1,800	1,800	1,800	1,700
Oil	Gal/Ton					
COG	SCF/Ton					
BFG	SCF/Ton					
HR Coil-BOP	lbs/Ton		2,460	2,460	2,460	2,460
Tin	lbs/Ton					
Equivalent Carbon Dioxide, lbs CO2/Ton						
Electricity			109	109	109	97
Natural Gas			220	220	220	208
Oil						
COG						
BFG						
HR Coil-BOP			5,922	5,736	5,413	5,922
Tin						
Total			6,251	6,065	5,742	6,227
Economic Screening						
					CRA Estimate	1
					Other Estimates	
					Comments	Evolutionary improvements and improved quality

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 20. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Annealing & Tempering-BOP Source

16. Aging and Conditioning	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Optimize operation	Potential Improvements: Annealing line heat recovery
			Annealing and tempering				
CRA Classification of Potential Improvement:						1	1
Status:						3, 4	4
Unit Consumption (per Ton A&T Coil)							
Electricity	kWh/Ton		75	75	75	70	72
Natural Gas	SCF/Ton		1,400	1,400	1,400	1,300	1,140
Oil	Gal/Ton						
COG	SCF/Ton						
BFG	SCF/Ton						
CR Coil-BOP	lbs/Ton		2,080	2,080	2,080	2,080	2,080
Hydrogen	SCF/Ton						
Equivalent Carbon Dioxide, lbs CO2/Ton							
Electricity			181	181	181	169	174
Natural Gas			171	171	171	159	139
Oil							
COG							
BFG							
CR Coil-BOP			5,645	5,441	5,151	5,645	5,645
Hydrogen							
Total			5,997	5,793	5,503	5,973	5,958
Economic Screening							
CRA Estimate						1	3
Other Estimates							3
Comments						Evolutionary improvements and improved quality	

Classification
1 = Process Improvement
2 = Process Replacement
3 = Energy Source Replacement
4 = Recycling

Status
1 = R&D
2 = First Mover
3 = Layout Constraint
4 = Demonstrated

Economic Criteria
1 = Likely to be justified by energy cost savings.
2 = Energy cost savings justification unclear.
3 = Unlikely to be justified by energy cost savings.

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 20. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: Annealing & Tempering-EAF Source (continued)

16. Aging and Conditioning	Units	Notes	Current Avg.	Best Practice U.S.	Best Practice in World	Potential Improvements: Optimize operation	Potential Improvements: Annealing line heat recovery
			Annealing and tempering				
CRA Classification of Potential Improvement:						1	1
Status:						3, 4	4
Unit Consumption (per Ton A&T Coil)							
Electricity	kWh/Ton		75	75	75	70	72
Natural Gas	SCF/Ton		1,400	1,400	1,400	1,300	1,140
Oil	Gal/Ton						
COG	SCF/Ton						
BFG	SCF/Ton						
CR Coil-EAF	lbs/Ton		2,080	2,080	2,080	2,080	2,080
Hydrogen	SCF/Ton						
Equivalent Carbon Dioxide, lbs CO2/Ton							
Electricity			181	181	181	169	174
Natural Gas			171	171	171	159	139
Oil							
COG							
BFG							
CR Coil-EAF			2,977	2,848	2,683	2,977	2,977
Hydrogen							
Total			3,330	3,200	3,035	3,305	3,291
Economic Screening							
CRA Estimate						1	3
Other Estimates							3
Comments						Evolutionary improvements and improved quality	

Classification	Status	Economic Criteria
1 = Process Improvement	1 = R&D	1 = Likely to be justified by energy cost savings.
2 = Process Replacement	2 = First Mover	2 = Energy cost savings justification unclear.
3 = Energy Source Replacement	3 = Layout Constraint	3 = Unlikely to be justified by energy cost savings.
4 = Recycling	4 = Demonstrated	

See Table 4 in text for carbon dioxide equivalents.

Source: Charles River Associates, 2001.

Table 21. Equivalent CO_2 Generation for Conventional and Potential Process Improvements: General Improvements

	Current Avg.	Best Practice U.S.	Best Practice in World	Improved process control[1]	Preventive maintenance program[2]	Employees' skill upgrading[2]	Cogeneration[3]
	Conventional Practice			Potential Improvements			
17. General Improvements							
CRA Classification of Potential Improvement:				1	1	1	1
Status:				4	4	4	4
Equivalent Carbon Dioxide, lbs CO2/Ton HR Coil							
Steelmaking-Coke, Blast Furnace, and BOP Route	5,438	5,252	4,990	5,166	5,438	5,438	5,166
Steelmaking-Conventional Charge EAF Route	3,019	2,901	2,752	2,868	3,019	3,019	2,868
Economic Screening							
CRA Estimate				1	1	1	1
Other Estimates							3
Comments				More productivity and better quality	Already practiced		From flared gases, but retrofit

Classification
1 = Process Improvement
2 = Process Replacement
3 = Energy Source Replacement
4 = Recycling

Status
1 = R&D
2 = First Mover
3 = Layout Constraint
4 = Demonstrated

Economic Criteria
1 = Likely to be justified by energy cost savings.
2 = Energy cost savings justification unclear.
3 = Unlikely to be justified by energy cost savings.

[1] Approximately 5% decrease.
[2] Impact on carbon dioxide emissions minor.
[3] Potential minimum. Estimated reduction is less than 5%.

Source: Charles River Associates, 2001.

Table 22. Summary of Carbon Dioxide Emissions by Steelmaking Route and Process

Process	Product	Carbon Dixoide Emission by Conventional Process lbs per Ton Product			Carbon Dixoide Emission by Conventional Process lbs per Ton Hot-Rolled Coil		
		Current Avg.	Best Practice-U.S.	Best Practice-ROW	Current Avg.	Best Practice-U.S.	Best Practice-ROW
Coke, Blast Furnace, and BOP							
Steelmaking							
Pelletizing	Pellets	535	541	347	619	564	252
Sintering	Sinter	525	525	469	97	179	310
Cokmaking	Coke	7,137	7,137	7,137	2,662	2,006	2,008
Ironmaking-Blast Furnace	Hot Metal	4,525	4,412	4,147	4,102	3,999	3,740
Steelmaking-BOP	Steel	4,221	4,118	3,871	4,478	4,369	4,107
Casting-Hot Strip Mill	Hot Rolled Coil	4,815	4,664	4,401	4,815	4,664	4,401
Finishing							
Pickling	Pickled Coil	5,159	5,000	4,724	4,913	4,762	4,499
Cold Rolling	Cold Rolled Coil	5,428	5,231	4,953	5,118	4,933	4,670
Annealing-Tempering	Annealed & Temp. Coil	5,997	5,793	5,503	5,438	5,252	4,990
Total					**5,438**	**5,252**	**4,990**
EAF-Conventional Charge Practice							
Steelmaking							
Steelmaking-EAF	Steel	1,832	1,799	1,658	1,943	1,908	1,759
Casting-Hot Strip Mill	Hot Rolled Coil	2,396	2,313	2,164	2,396	2,313	2,164
Finishing							
Pickling	Pickled Coil	2,619	2,532	2,375	2,494	2,411	2,262
Cold Rolling	Cold Rolled Coil	2,863	2,738	2,580	2,700	2,582	2,433
Annealing-Tempering	Annealed & Temp. Coil	3,330	3,200	3,035	3,019	2,901	2,752
Total					**3,019**	**2,901**	**2,752**

Source: Charles River Associates, 2001.

APPENDIX B

PRESENTATION DOCUMENTS

FOR INDUSTRY INTERVIEWS

Assessment of Steel Industry Options for Improving Energy Efficiency and Reducing CO_2 Emissions

Presentation by:

Charles River Associates
CRA Reference: D02559-00

How Can the Steel Industry Improve Energy Efficiency and Reduce Carbon Dioxide Emissions?

- **CRA has been retained by the DOE to evaluate policy options that might be implemented to assist the steel industry in improving its energy efficiency and reducing CO_2 emissions**
  - Our evaluation includes a review of current industry practices — where we are — and possibilities for reduced energy use in steelmaking — where we are going

- **We are seeking your input to improve our analyses of any policy options that could move the steel industry along that path from where we are to where we want to go**
  - Our evaluation will also include a review of the steel industry's past achievements, current issues, and the successes and failures of past policies

CRA

Your Inputs Will Help CRA Understand Constraints and Requirements for Energy Saving and CO_2 Reducing Investments

- **We recognize that limited capital availability forces decision makers to set priorities in such a way that opportunity costs for energy savings can be high**
  - We are seeking to understand the significance of these costs for both existing and new technologies
  - We are also seeking your opinion on the types of policy options that might be helpful or that should be avoided

- **The scope of options that are of interest are:**
  - Those that improve the general health of the industry
  - Those that are targeted at increasing energy efficiency and CO_2 emissions

CRA

The Industry Faces Serious Economic Challenges

- **The past 20 years have been difficult for the industry for a number of reasons:**
  - Slowly growing domestic demand
  - Import pressures on prices and markets
  - More stringent environmental requirements
  - Higher quality requirements
  - Inability to restructure effectively

- **Financial performance has suffered accordingly:**
  - Low levels of returns on assets
  - Increasing debt-to-equity ratios
  - Loss of investment-grade status
  - Decreasing market capitalization
  - Bankruptcies

CRA

The Industry Has Continued to Innovate

- **Energy efficiencies of the key production step have improved significantly over the past 20 years**
  - ▲ Coke rates and fuel rates in blast furnaces have decreased
  - ▲ Power consumption in electric arc furnaces has decreased

- **Many of these improvements have been associated with increased productivity**

- **However, there remain significant gaps between the "best practice" performance levels achieved in some mills and "industry average" values**
  - ▲ Some apparently cost-effective technologies are not being utilized fully — why?

What kind of policy options, if any, can address obstacles to adopting cost-effective technologies for reducing energy use and CO_2 emissions?

- **Raise all boats**
  - Import restrictions
  - Non-targeted loan guarantees
- **Capital subsidies**
  - Accelerated depreciation or other tax preferences
  - Loan guarantees
- **Higher energy costs**
  - How much more would energy have to cost to raise these projects above the bar?

What kind of policy options, if any, can address obstacles to adopting cost-effective technologies for reducing energy use and CO_2 emissions?

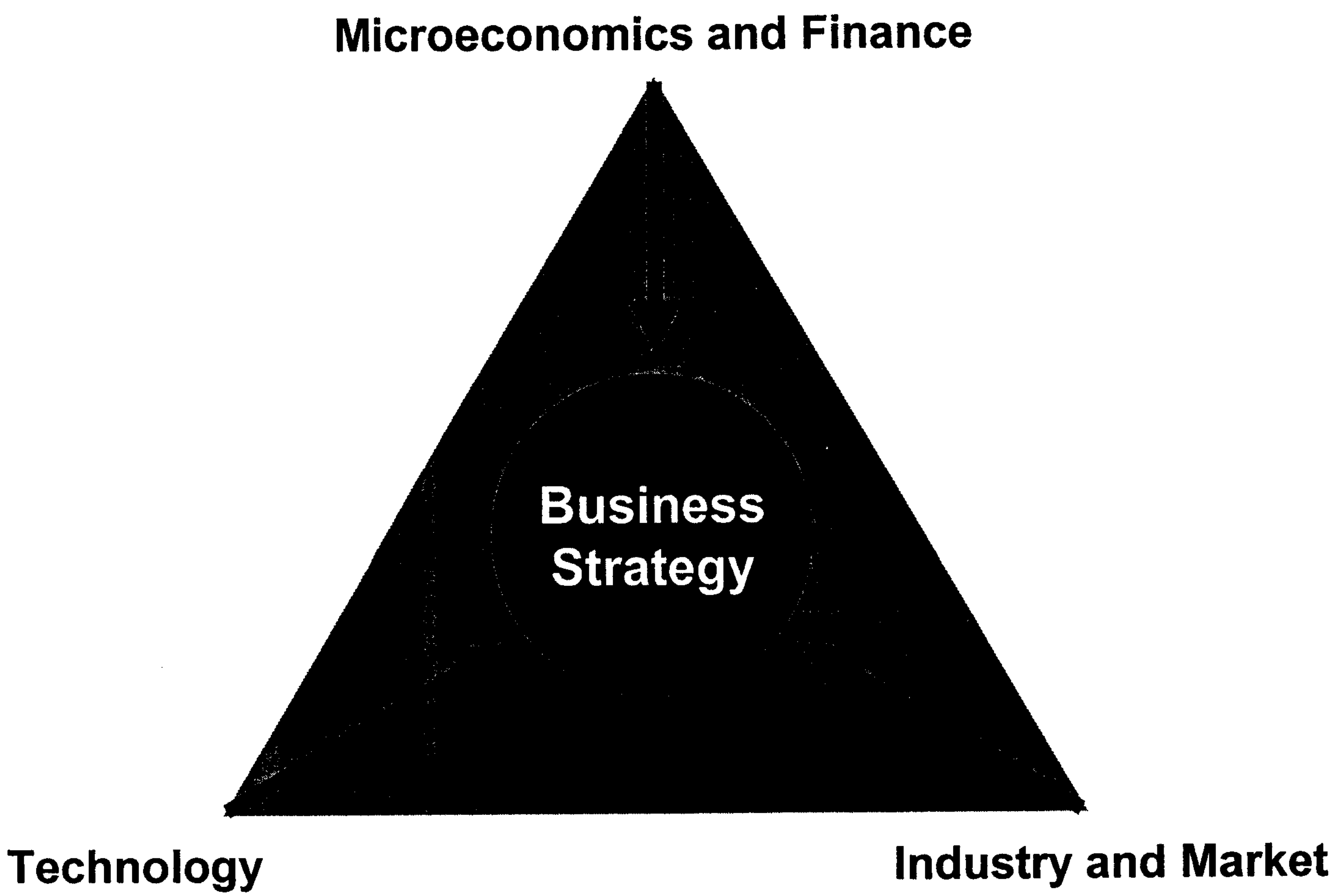
- **Targeted spending**
  - Loan guarantees earmarked for projects that reduce energy use
  - Cost-sharing with R&D consortia
- **Technical assistance programs**
  - First mover assistance to decrease technical risks
  - Dedicated project management teams
- **Resolution of antitrust issues**
- **Labor issues**
  - Fostering improved labor relations
  - Assistance with legacy labor costs
  - Composition of labor force

Your experience and recommendations will help us develop analyses that will support effective policy making

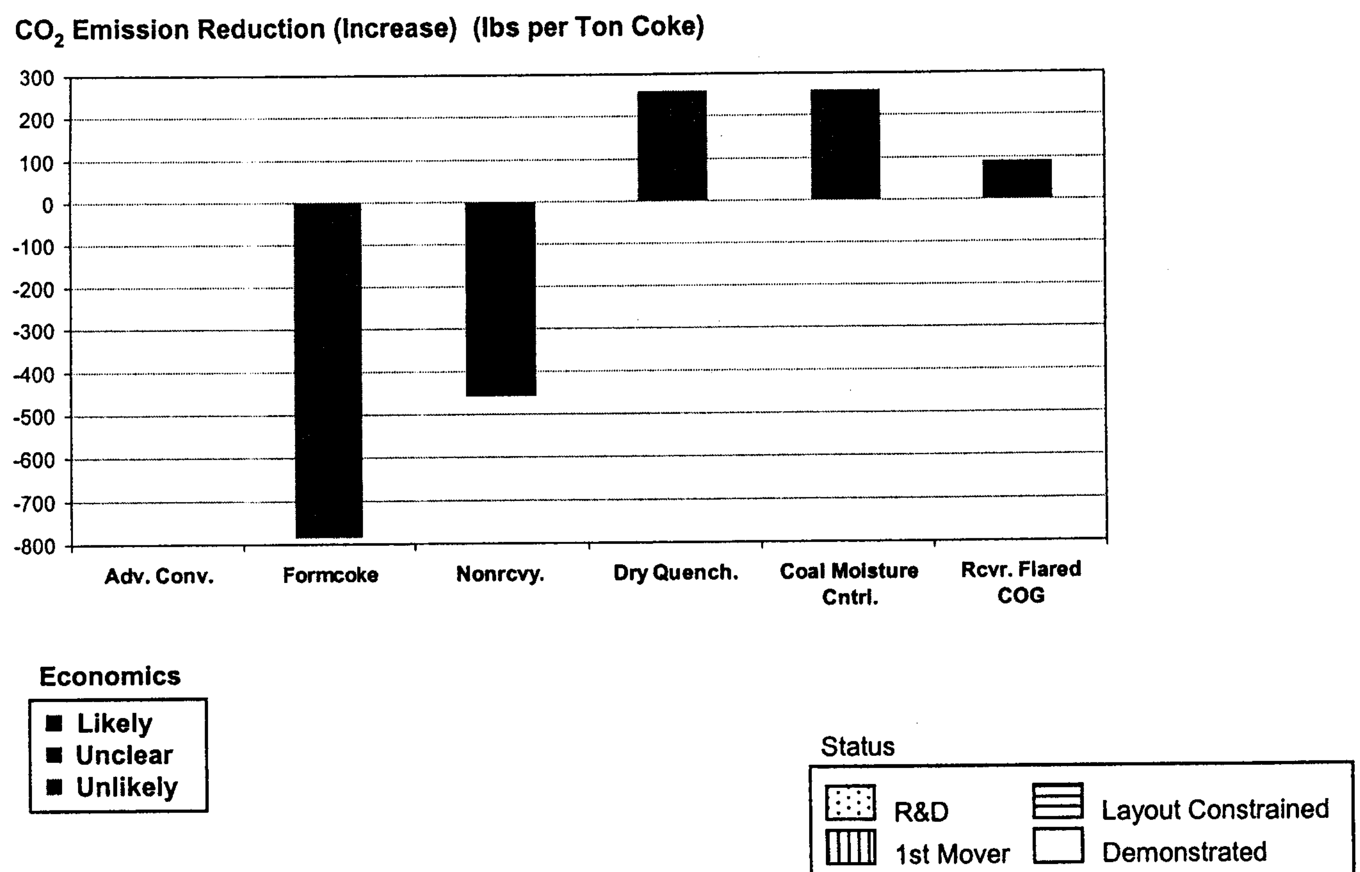
About Charles River Associates

- Founded in 1965
- Offices in Boston, Washington DC, Palo Alto, Los Angeles, Oakland, Salt Lake City, College Station TX, Canada, Mexico, the United Kingdom, Australia, and New Zealand
- Staff of nearly 300
- Corporate philosophy: Provide top-quality microeconomic analysis combined with expertise in business, engineering, and technology management to our clients

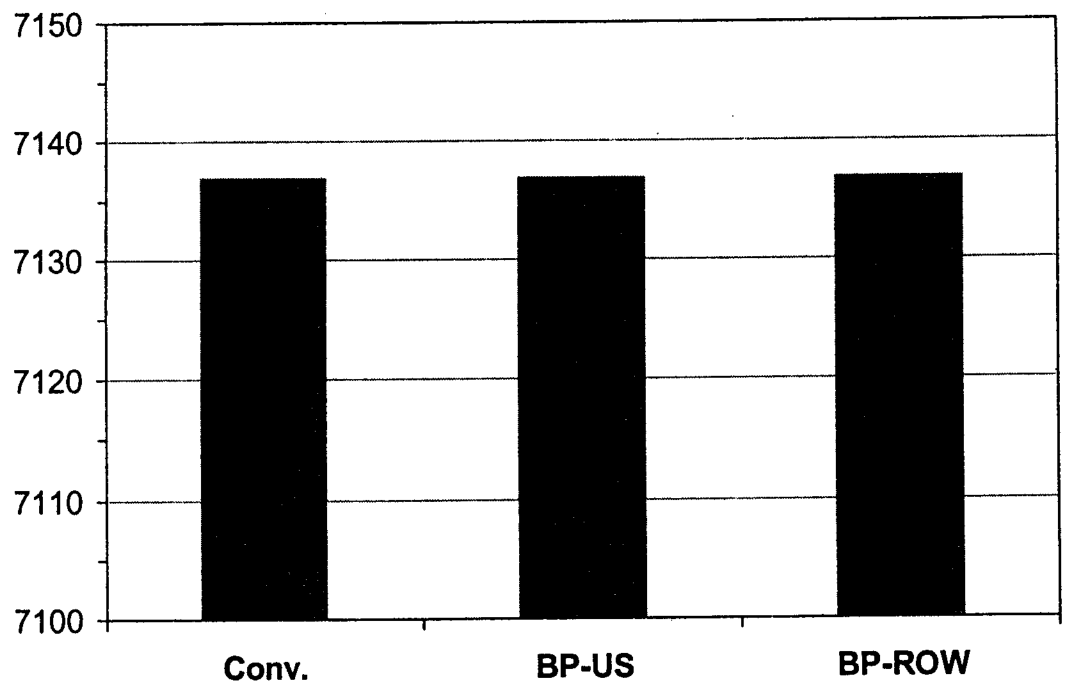
Our Background and Approach: CRA Is an Expertise-Oriented Consulting Company



Carbon Dioxide Emission Level: Cokemaking



CO_2 Emission Level (Pounds per Ton Coke)



Note: Pounds CO_2 emitted are a surrogate for energy efficiency.