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LBNL Report

Development of Bottom-up Representation of Industrial Energy Efficiency Technologies in Integrated Assessment Models for the Iron and Steel Sector

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General Acronyms

Greenhouse gas (GHG)

Carbon dioxide (CO2)

Energy-climate (EC) models

Integrated assessment models (IAM)

Cost of conserved energy (CCE)

Cost of carbon reduction (CCR)

Conservation Supply Curve (CSC)

Computational general equilibrium model (CGE)

Operation and maintenance (O&M)

Gross Domestic Product (GDP)

Environmental Protection Agency (EPA)

Bureau of Economic Analysis (BEA).

International Energy Agency (IEA)

Department of Energy (DOE)

Department of State (DOS)

International Iron and Steel Institute (IISI)

American Iron and Steel Institute (AISI)

Blast furnace (BF)

Electric arc furnace (EAF)

Energy Information Administration (EIA)

Manufacturing Energy Consumption Survey (MECS)

Model Acronyms

ADAGE - Applied Dynamic Analysis of the Global Economy Model

AIM- The Asian-Pacific Integrated Model

AMIGA - All-Modular Industry Growth Assessment Model

BEAR - Berkeley Energy and Resources

COBRA - Cost-Optimized Burden-Sharing and Regional emission Allocation

MARKAL - MARKet ALlocation

MESSAGE - Model for Energy Supply Strategy Alternatives and their General Environmental Impact

Units

Energy (in petajoules -PJ, or in gigajoules - GJ)

Cost of conserved energy (CCE, $/GJ)

Energy savings per production (GJ/Tonne)

Million metric ton, or million tonne (Mt)

Million tonne of carbon (MtC)

Cost of carbon reduction (CCR, $/MtC)

Capital cost ($)

Capital recovery factor (yr-1)

Annual change in O&M costs ($/yr)

Annual total of productivity benefits ($/yr)

Annual energy savings (GJ/yr)

Lifetime of the mitigation option (years)

Annual carbon savings (tC/yr)

Development of Bottom-up Representation of Industrial Energy Efficiency Technologies in Integrated Assessment Models for the Iron and Steel Sectors

Executive Summary

Adoption of efficient end-use technologies is one of the key measures for reducing greenhouse gas (GHG) emissions. How to effectively analyze and manage the costs associated with GHG reductions becomes extremely important for the industry and policy makers around the world.

Energy-climate (EC) models are often used for analyzing the costs of reducing GHG emissions for various emission-reduction measures, because an accurate estimation of these costs is critical for identifying and choosing optimal emission reduction measures, and for developing related policy options to accelerate market adoption and technology implementation. However, accuracies of assessing of GHG-emission reduction costs by taking into account the adoption of energy efficiency technologies will depend on how well these end-use technologies are represented in integrated assessment models (IAM) and other energy-climate models.

In this report, we first conduct a brief review of different representations of end-use technologies (mitigation measures) in various energy-climate models, followed by problem statements, and a description of the basic concepts of quantifying the cost of conserved energy including integrating no-regrets options. According to IPCC (2001), no-regrets opportunities for GHG emissions reduction are the options whose benefits such as reduced energy costs and reduced emissions of local or regional pollutants equal or exceed their costs to society, excluding the benefits of avoided climate change. In this report, a no-regrets option is defined as a GHG reduction option (i.e., via energy efficiency measure) that is cost effective over the lifetime of the technology compared with a given energy price, without considering benefits of avoided climate change. There are two types of treatments of no-regrets options: 1) options that include other benefits, e.g., reduced operational and maintenance costs and productivity benefits; and 2) options that exclude other benefits. Although existence of no-regret options is not acknowledged by some economists, a number of cost-effective measures were identified in the U.S. iron and steel sector, regardless whether or not other benefits are included. There are many factors, including market barriers and knowledge gap, which contribute to slower adoption of such measures in the markets.

Based upon reviews of literature and technologies, we develop information on costs of mitigation measures and technological change. These serve as the basis for collating the data on energy savings and costs for their future use in integrated assessment models. In addition to descriptions of the iron and steel making processes, and the mitigation measures identified in this study, the report includes tabulated databases on costs of measure implementation, energy savings, carbon-emission reduction, and lifetimes.

Through characterizing energy-efficiency technology costs and improvement potentials, we have developed and presented energy cost curves for energy efficiency measures applicable to the U.S. iron and steel industry for the years 1994 and 2002. The cost curves can change significantly under various scenarios: the baseline year, discount rate, energy intensity,

production, industry structure (e.g., integrated versus secondary steel making and number of plants), efficiency (or mitigation) measures, share of iron and steel production to which the individual measures can be applied, and inclusion of other non-energy benefits. Inclusion of other non-energy benefits from implementing mitigation measures can reduce the costs of conserved energy significantly. In addition, costs of conserved energy (CCE) for individual mitigation measures increase with the increases in discount rates, resulting in a general increase in total cost of mitigation measures for implementation and operation with a higher discount rate. As all the cost data (U.S. dollars) are obtained and presented as the currency values for the respective reference years (i.e., 1994, 2002), a direct comparison of costs (U.S. dollars), when desired, can be made by converting the existing reference-year data (i.e., 1994, 2002 in this study) to a preferred reference year (e.g., 2007). The conversions may be accomplished by multiplying the existing cost numbers represented in a reference year by an inflation index based on Gross Domestic Product (GDP) for the preferred year (BEA 2009).

The cost curve data on mitigation measures are available over time, which allows an estimation of technological change over a decade-long historical period. In this study, we compared the same set of mitigation measures for both 1994 and 2002. No additional mitigation measures for year 2002 were included due to unavailability of such data. Based upon the available data and cost curves, the rate of change in the savings potential at a given cost can be evaluated and be used to estimate future rates of change that can be the input for energy-climate models.

In 1994, integrated steel mills in the U.S. produced 55.4 Mt steel and secondary steel mills produced 35.9 Mt steel, for a total of 91.3Mt steel production in the United States (IISI 1994). Primary energy use for integrated steel making was 1,444 petajoules (PJ), over three times the energy use in secondary steel making, which was 426 PJ. The total carbon emissions from steel making related to energy use in 1994 were 34.3 MtC, with 78% of these emissions from integrated steel making (26.9 MtC) and the rest (22%) from the secondary steel making. In 2002, integrated steel mills in the U.S. produced 50.1 Mt steel and secondary steel mills produced 50.8 Mt steel, for a total of 100.9 Mt annual steel production. Primary energy use for integrated steel making was 1115 PJ, about twice of the energy use in secondary steel making, which was 519 PJ. The total carbon emissions from steel making related to energy use in 2002 was 30.6 MtC, with 71% of these emissions from integrated steel making (21.9 MtC) and the rest (29%) from the secondary steel making. We calculated that from 1994 to 2002 the steel production energy intensity has decreased by 15% and 14% for integrated steel and secondary steel, respectively – indicating efficiency technology uptakes for both sectors over the period of time. In addition, the production shift from integrated steel to much less energy intensive secondary steel, in combination with the observed technology uptakes, resulted in an overall reduction in energy intensity by 21% for the U.S. iron and steel industry from 1994 to 2002.

We estimated that the potential savings of final energy use resulting from applicable mitigations measures was 397 PJ in 1994 (287 PJ for integrated steel making, and 110 PJ for secondary steel making), and 304 PJ in 2002 (223 PJ for integrated steel making, and 81 PJ for secondary steel making). The potential annual energy savings corresponded to 25% and 24% of total annual final energy use in the U.S. iron and steel sector in 1994 and 2002, respectively.

We have identified a number of cost-effective mitigation measures in this study. Furthermore, inclusion of other benefits from implementing mitigation measures can reduce the costs of conserved energy significantly, making more measures cost-effective. Using the final energy price of US$2.59/GJ in 1994 and US$3.49/GJ in 2002, a number of measures are identified to be cost-effective in this study when including non-energy benefits. We estimated that the potential savings of final energy use resulting from the cost-effective mitigations measures was 251 PJ in 1994 (186 PJ for integrated steel making, and 65 PJ for secondary steel making), and 217 PJ in 2002 (144 PJ for integrated steel making, and 73 PJ for secondary steel making). Overall, implementing applicable cost-effective mitigation measures could result in potential final energy savings by 16% and 17% of the total annual final energy use in the U.S. iron and steel sector in 1994 and 2002, respectively.

We also estimated overall potentials in carbon-emission reductions due to mitigation measures for both years (1994 and 2002), respectively. In this study, we have developed and defined the concept of cost curves for carbon reduction associated with the mitigation measures. The potential reduction of carbon emissions resulting from the applicable mitigation measures was 6.1 million ton of carbon (MtC) in 1994 (3.9 MtC from integrated steel making, and 2.2 MtC from secondary steel making), and 5.7 MtC in 2002 (3.7 MtC from integrated steel making, and 2.0 MtC from secondary steel making), corresponding to 18% and 19% of annual energy-related carbon emissions in 1994 and 2002, respectively. Applying cost-effective measures would reduce carbon emissions by 4.7 MtC in 1994 (3.4 MtC from integrated steel making, and 1.3 MtC from secondary steel making), and 4.4 MtC in 2002 (2.7 MtC from integrated steel making, and 1.7 MtC from secondary steel making), corresponding to approximately 14% of annual energy-related carbon emissions in each year.

We have also concluded that based upon the cost curves derived from available information on mitigation measures for both years, the rate of change in the energy-savings or carbon-reduction potential at a given cost can be evaluated and be used to estimate future rates of change for input in energy-climate models. Accuracies of such estimation of the rate change may be improved as more comprehensive information on characterizing the mitigation measures becomes available. Implementing existing cost effective measures can result in significant energy savings and carbon-emission reduction for both years relative to their technical potential in energy savings and carbon-emission reduction. In addition, total costs of conserved energy increase with the increases in discount rates. The outcomes from this research provide information on initial technology database that can be accessible to integrated assessment modeling groups seeking to enhance their empirical descriptions of technologies.

While many energy efficiency technologies have become cost-effective to mitigate long-term climate change, it is important and necessary to continue to incorporate new information on technology characteristics, and their evolution and response to energy and carbon price into various integrated assessment models to enhance empirical descriptions of the technologies, e.g., econometric models, service demand models, discrete choice models, or computational general equilibrium (CGE) models.

There appears to be a need to develop and refine sectoral algorithms and produce databases that can be used to match the needs of different integrated assessment modeling of climate policies. New algorithms should allow transformation of information on behavioral responses, technology costs, energy savings, other benefits, and policy costs into meaningful and functional data forms. Developing such algorithms may require customization and automation of database functions that would account for many variables. Furthermore, the desired data-model linking effort will require close interfaces between modelers and the developers of the cost-curve databases on energy efficiency measures. Future efforts should also include additional business sectors.

1 Background

Iron and steel is used in diverse applications such as buildings, bridges, automobiles and trucks, machines, food containers, and medical devices, to name a few. The global iron and steel sector produced approximately 1.3 billion metric tons (tonnes) of crude steel in 2008 (IISI 2008), with China, Japan and the USA topping the list of leading steel-producing countries. Annual production in the USA was 91.5 million metric tons (IISI 2008), of which 42% was produced using electric arc furnaces and the remainder through basic oxygen furnaces.

According to the International Energy Agency (IEA 2007), over one-third of the world's energy consumption and 36% of carbon dioxide (CO2) emissions are attributable to manufacturing industries worldwide. Energy use in the iron and steel industry is intensive and constitutes a significant portion of the steel-production costs, up to 40% in some countries. In addition, the iron and steel industry accounts for a significant portion of carbon dioxide (CO_2) emissions worldwide. For example, producing molten iron and steel products requires a mix of carbon-intensive energy sources such as coal and electricity. Largely due to the use of coal-based resources to reduce iron ores in blast furnaces (BF) or heat metal in electric arc furnaces (EAF), iron and steel manufacturing generates significant carbon emissions. Overall, the iron and steel industry accounts for about 19% of final energy use and about one quarter of direct CO_2 emissions from all industry sectors (IEA 2007).

The U.S. iron and steel industry is made up of (1) integrated steel mills that produce pig iron from raw materials (iron ore and coke) using a blast furnace and steel using a basic oxygen furnace, and (2) secondary steel mills that produce steel from scrap, pig iron or direct reduced iron using an electric arc furnace. Integrated steel producers smelt iron ores to liquid iron in blast furnaces and use basic oxygen furnaces to refine this iron with some scrap to produce raw liquid steel. Mini-mills and specialty mills are nonintegrated steel producers that use EAF to melt low-cost raw materials (usually scrap). The efficiency of an iron and steel plant are significantly affected by several elements such as technology, plant size, and quality of raw materials. Increased recycling and higher efficiency of energy and materials use have played an important role in achieving significant efficiency improvements in the U.S. iron and steel industry within the last several decades.

2 Introduction

With ambitious energy and carbon policies being implemented globally, effectively analyzing and managing the costs associated with GHG reductions becomes extremely important for industry and policy makers. Adoption of efficient end-use technologies is one of the key measures for reducing greenhouse gas (GHG) emissions. In many cases, implementing energy efficiency measures is among one of the most cost effective investments that the industry could make in improving efficiency and productivity while reducing CO_2 emissions.

Energy-climate (EC) models are often used for analyzing the costs of reducing GHG emissions because an accurate estimate of these costs is critical for identifying optimal emission reduction measures, and for developing related policy options to accelerate market adoption. However, the accuracy of assessing costs of the adoption of energy efficiency technologies will depend on how well these end-use technologies are represented in integrated assessment models (IAM) and other energy-climate models. Integrated assessment is a method of analysis that combines results and models from the physical, biological, economic, and social sciences, and the interactions between these components, in a consistent framework, to evaluate the status and the consequences of environmental changes and policy responses to it (IPCC 2001). For example, if the models do not include end-use technologies with an appropriate level of detail in their modeling framework, it will be difficult to evaluate, with confidence, the costs and benefits of reducing GHG emissions by adopting efficient end-use technologies.

In this report, we will first conduct a brief review of different representations of end-use technologies in selected energy-climate models; then we will elaborate the statement of the problems upon which the purpose of this study will be defined. The report will then describe the basic concepts of quantifying the cost of conserved energy including integrating no-regrets options. According to IPCC (2001), no-regrets opportunities for GHG emissions reduction are the options whose benefits such as reduced energy costs and reduced emissions of local or regional pollutants equal or exceed their costs to society, excluding the benefits of avoided climate change. In this report, a no-regrets option is defined as a GHG reduction option (i.e., via energy efficiency measure) that is cost effective over the lifetime of the technology compared with a given energy price, without considering benefits of avoided climate change. Although existence of no-regret options is not entirely acknowledged by some economists, a number of cost-effective measures in the U.S. iron and steel sector were identified and studied in this report, regardless whether or not other benefits are included. There are many factors including market barriers and knowledge gap that contribute to slower adoption of such measures in the markets.

We will develop information on costs of mitigation measures and technological change. These serve as the basis for collating the data on energy savings and costs for their future use in IA models. The following section then develops energy efficiency cost curves for the iron and steel industry in the United States. The cost curve data on mitigation measures are available over time, which allows an estimation of technological change over a decade-long historical period. In particular, the report will address technological change in energy-climate modeling, e.g., assessing the changes in costs and savings potentials between two or more historical conservation supply curves. The last section summarizes the conclusions and provides recommendations for future work. In addition, the report includes tabulated databases on costs of implementation, energy savings, carbon-emission reduction, and lifetimes as exhibited in Appendix A. Finally, Appendix B of this report includes descriptions of the iron and steel making processes, and the mitigation measures noted in Appendix A.

2.1 Representation of end-use technologies in selected energy-climate models

Many existing integrated assessment models originally emerged primarily from economic and energy modeling approaches that were for the most part developed for, and applied to, industrialized economies (Sanstad and Greening, 1998). Increasingly, however, these models have been enhanced and extended over time, and in many cases created, to encompass the global economy at various levels of regional and sectoral disaggregation.

Factoring technological changes in both energy supply and end-use technologies may significantly affect the outcomes of estimated GHG emissions associated with energy systems in such energy-climate models. A majority of energy-climate models can handle, to various extents, the input of technological changes. In exogenous modeling of technological change, the rate of technological changes (improvement) is specified exogenously by the modelers, not the model itself. In endogenous modeling of technological change, various approaches exist, such as modeling technological changes via “learning by doing.” In this case, the costs of new technologies decline overtime and their technical characteristics improve with increased market adoption. Improvement in efficiency, cost, and market adoption (e.g., cumulative installed capacity) are included as input to the model. Both exogenous and endogenous modeling of technological changes can benefit from historical data. In this study, we focus particularly on two issues related to the representation of end-use technologies in energy climate models: treatment of technological change, and treatment of no-regrets options. There are two types of treatments of no-regrets options: 1) options that include other benefits, e.g., reduced operational and maintenance costs and productivity benefits; and 2) options that exclude other benefits.

To improve the representation of end-use technologies in energy-climate models, it is necessary to understand how end-use technologies are represented in common models. Table 1 summarizes an overview of how end-use technologies are represented in seven energy-climate models included for this study. End-use technologies are represented in five of the seven models. Four out of the seven models explicitly take both no-regrets options and technological change in end-use technologies into consideration.

Pending the availability of information, or body of knowledge about what is known (or even knowable), modelers commonly made one choice over another when establishing input assumptions, and methodologies for their desired models. In all of the selected models reviewed in this study, except for the *MARKet ALlocation* (MARKAL) model, the technological change is considered in an exogenous manner. Among the six models with exogenous treatment of technological changes, only four of them include end-use technology representation, as well as concurrent no-regrets options. In addition, the levels of detail in handling technological change and no-regrets options also vary across the models. For example, in All-Modular Industry Growth Assessment (AMIGA) modeling, end-use technologies in residential and commercial sectors and some industries are represented to date. In Berkeley Energy and Resources (BEAR) modeling, end-use technologies are represented only for the cement industry. Energy savings due to overall improvements in end-use energy efficiency are represented for different sectors. However, specific technologies associated with these savings are not identified. In Cost-Optimized Burden-Sharing and Regional emission Allocation (COBRA) modeling, end-use technologies and no-regrets treatment are considered for some key energy consuming industries. However, the cost of policies and programs to promote no-regrets options are not included.

Table 1. An overview on different representation of end-use technologies in common energy-climate models

Model	**Representation of End-Use Technologies**	**Treatment of No-regrets Options**	**Treatment of Technological Change**	**Treatment of Technological Change in End-Use Technologies**
ADAGE - *Applied Dynamic Analysis of the Global Economy, by Research Triangle Institute*	No	No	Exogenous	No
AIM - *The Asian-Pacific Integrated Model, by a collaborative international team led by Japan's National Institute for Environmental Studies*	Yes	Yes	Exogenous	Yes
AMIGA - *All-Modular Industry Growth Assessment, by Argonne National Laboratory (ANL)*	Some	Yes	Exogenous	Yes
BEAR - *Berkeley Energy and Resources, by UC Berkeley*	Some	Yes	Exogenous	Yes
COBRA - -*Optimized Burden-Sharing and Regional emission Allocation, by Lawrence Berkeley National Laboratory*	Some	Yes	Exogenous	Yes
MARKAL - *MARKet Allocation, by Brookhaven National Laboratory*	Some	No	Endo-genous	Yes, exogenous.
MESSAGE *Model for Energy Supply Strategy Alternatives and their General Environmental Impact, by Austria's International Institute for Applied Systems Analysis (IIASA)*	No	No	Exogenous	No

Note: CGE models are included in many IAMs, except AMIGA, COBRA, MARKAL, or MESSAGE.

Apparently, there are opportunities to improve technology representation in the selected models and many others, which can provide more accurate estimation of the costs of reducing GHG emissions due to technological changes and associated benefits.

2.2 Statement of problem

Information on costs and saving potentials of energy efficiency measures and ways that these end-use technologies are represented in energy-climate models vary greatly from model to model. Many energy-climate models are not created to represent technology-specific costs, energy savings or GHG-emission reductions; instead they are often restricted to evaluation of carbon prices or cap-and-trade programs without adequate consideration of issues on mitigation technologies. The difference in cost estimates can be attributed to various assumptions in economic growth, resource endowment, selection of policy instrument, treatments of no-regrets options (e.g., including or excluding other benefits), and cost and availability of supply- or demand-side technologies.

An often-debated issue is the integration of end-use technologies in large bottom-up energy-climate models. The extent of including representation of such technologies in large energy-climate models varies greatly: e.g., some without technological representation, some with representation if any being limited to certain sectors such as electric power generation, or some with detailed end-use technological representation. Therefore, a major challenge is to determine the appropriate interfaces for the use of bottom-up technology or sector-specific data in energy-climate models.

Often many IA models ignore policy and programmatic costs of measure implementation; on the other hand, other non-energy benefits are also often not included or accounted for in model input. Therefore, such modeling is often inadequate to accurately estimate the real costs of reducing GHG emissions. For example, exclusion of other benefits (as one way of treating no-regret options) in models is largely because modelers either lack sufficient data or because their current model structure is not suitable for representing these options. As a result, the way in which most of these models are calibrated tends to force a prediction of positive mitigation costs. In addition, although some models that represent end-use technologies model technological change over time, none of them represents technological change in end-use technologies endogenously. This approach has limited their ability to analyze the effect of policies that promote early adoption of efficient end-use technologies to reduce their future costs.

Integrated assessment modeling of climate policy uses various top-down models that describe the general economy and its interactions, and the effects of price changes. Many of these models include a sectoral representation of the economy. The existing empirical basis for modeling of sector-based technologies is often weak, and often largely arises from literature at the sectoral level rather than technology level. There is a need to investigate and improve the representation of end-use technologies in energy-climate models, in coordination with energy-climate modelers who will stand to benefit from this research.

Given the growing importance of technological improvement (e.g., energy efficiency) as an avenue to mitigate climate change, it is critical that technology characteristics, their evolution and response to energy and carbon price be understood better than has been the case to date. This is also particularly true of developing countries where obsolete technologies are likely to see a more rapid transformation as their markets integrate into the global economy, while newer technologies are likely to be adopted faster due to evolving global markets and availed policy support.

2.3 Project Purpose

The overarching goal of this research is to characterize technology costs and potentials for improvement in energy efficiency in several U.S. industrial sectors. The purpose of this project is to develop a technology database and modules that will be accessible to IAM groups seeking to enhance their empirical descriptions of technologies for modeling. In this report, we will describe concepts of cost of conserved energy (CCE) and cost of carbon reduction (CCR), and develop and present the cost curves of mitigation options based upon available historical data, with a focus on the U.S. iron and steel sector. Effect of technological change on savings potential will be analyzed, which may become useful input for estimating future savings potential in energy-climate models.

3 Concepts of Cost Curves of Conserved Energy and Carbon Reduction

3.1 Calculation of cost of conserved energy curves with and without other benefits

Conservation Supply Curves (CSCs) were developed in the 1970s as a way to rank energy conservation investment along with energy supply investment in order to identify the least cost approach. CSCs can be used to show how much energy-conservation would be supplied corresponding to a specific energy price, and have long been a primary analytical tool for evaluating the economic benefits of energy efficiency. These have been constructed for the major energy demand sectors, and the energy savings have been translated into corresponding GHG emissions reductions in many countries.

A CSC plots the marginal cost of conserved energy by a mitigation option (mitigation capital cost) against the total amount of energy conserved. Equation 1 shows the parameters used in estimating the marginal cost of conserved energy (CCE). By calculating and ranking CCE value for each efficiency measure, a CSC curve can be developed by plotting the ranked CCE values consecutively on the y-axis against cumulative energy savings along the x-axis.

$$CCE = \frac{I \cdot q}{ES} \text{, Equation (1)}$$

$$q = \frac{d}{(1-(1+d)^{-n})} \text{, Equation (2)}$$

Where:

CCE = Cost of conserved energy for an energy-efficiency measure (or mitigation option), in \$/GJ

I = Capital cost (\$)

q = Capital recovery factor (yr^{-1})

ES= Annual energy savings (GJ/yr)

d = Discount rate

n = Lifetime of the mitigation option (years)

Earlier analyses of energy efficiency options typically ignored other effects of their implementation. Modification of Equation 1 to Equation 3 includes other benefits: These effects include changes in operation and maintenance (O&M), which may lead to a reduction in “M” value; as well as reduced capital cost, which may correspond to a lowered “I” value in the equation. The effects can also include additional monetizable productivity benefits, noted as “B” in Equation 3.

The contributing factors to productivity benefits include additional labor, material, and other resource requirements that are often monetizable, and other benefits such as reduced pollution due to decreased use of electricity and other fuels that may be more difficult to quantify, and in particular more difficult to attribute to a single mitigation measure (e.g., as shown in Table 2). In principle, adding monetizable non-energy effects that are attributable to an energy efficiency option can decrease the cost of conserved energy. These may be expressed as shown in Equation 3 (Worrell et al. 2003).

$$CCE = \frac{I \cdot q + (M - B)}{ES}, \text{ Equation 3}$$

Where

CCE = Cost of conserved energy for an energy-efficiency measure (or mitigation option), in \$/GJ
I = Capital cost (\$)
q = Capital recovery factor (yr^{-1})
M = Annual change in O&M costs (\$/yr)
B = Annual total of productivity benefits (\$/yr)
ES = Annual energy savings (GJ/yr)
d = Discount rate
n = Lifetime of the mitigation option (years)

Accounting for such "hidden benefits" requires that bottom-up models look beyond the energy markets and examine the cost considerations in light of their impact on other resource markets.

Using the primary energy price of $2.14/GJ in 1994, Worrell et al. (2003) reported cost effective annual primary energy savings of 1.9 GJ/tonne for the U.S. iron and steel industry in 1994 (Figure 1). Corresponding to the implementation of an array of 47 measures, the cost of supplied energy conservation is generally reduced when productivity benefits associated with labor and material cost savings are included in the calculation during the operation of an efficient iron and steel plant. Inclusion of such productivity benefits has however, increased the savings potential due to cost-effective measures to 3.8 GJ/tonne at the same unit price of primary energy ($2.14/GJ in 1994), as is clearly shown in Figure 1.

When including productivity benefits, the CCE ranking of technologies changes dramatically. Inclusion of all resource benefits thus is crucial to understanding the full cost impacts of a technology. This may be particularly relevant to end-use energy efficiency technologies whose main goal often is not only providing energy savings but also providing some other form of services related to the production of an industrial product.

Table 2. Examples of non-energy benefits from efficiency improvements in U.S. iron and steel industry (Worrell et al. 2003)

Waste	**Emissions**	**Operation & Maintenance**
Use of waste fuels, heat, gas	Reduced dust emissions	Reduced need for engineering controls
Reduced product waste	Reduced CO, CO2, NOx, Sox emissions	Lower cooling requirements
Reduced waste water		Increased facility reliability
Reduced hazardous waste		Reduced wear and tear on equipment/machinery
Materials reduction		Reductions in labor requirements
Production	**Working Environment**	**Other**
Increased product output/yields	Reduced need for personal protective equipment	Decreased liability
Improved equipment performance	Improved lighting	Improved public image
Shorter process cycle times	Reduced noise levels	Delaying or Reducing capital expenditures
Improved product quality/purity	Improved temperature control	Additional space
Increased reliability in Production	Improved air quality	Improved worker morale

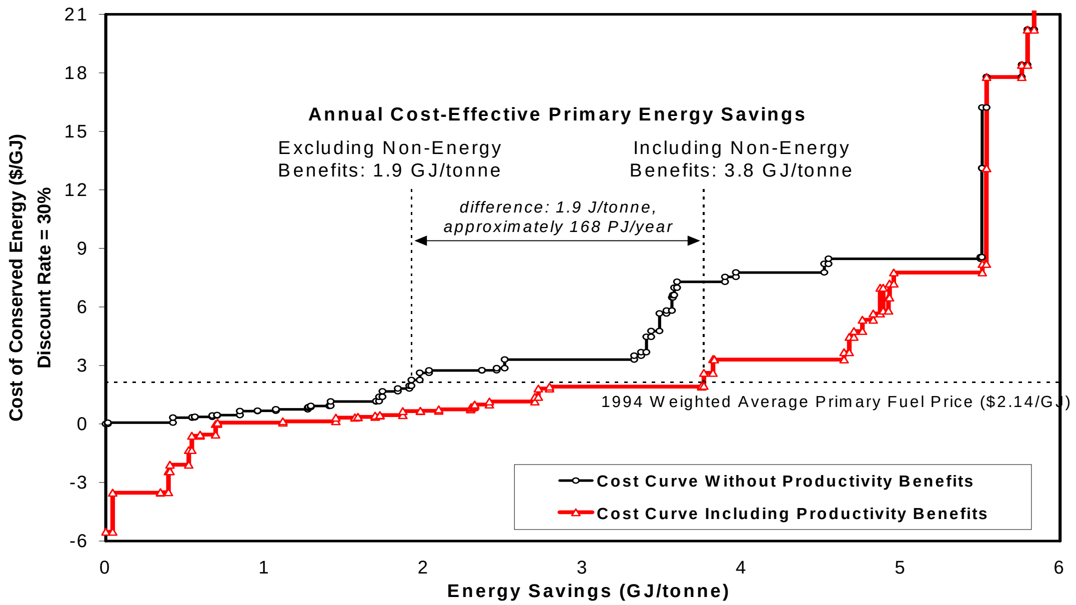

Figure 1. Conservation supply curves with and without including non-energy productivity benefits in the U.S. iron and steel industry (Worrell et al. 2003).

3.2 Calculation of cost of carbon reduction related to energy savings

Adopting energy efficiency options can reduce carbon emissions associated with energy use in the industry. In this study, we define cost of carbon reduction (CCR) associated with energy use in the iron and steel sector, which has included the other benefits monetizable for the changes in operation and maintenance. The cost of energy-related carbon reduction is treated to be the same as the cost of mitigation measures normalized by the quantity of carbon reduction corresponding to each mitigation measure.

Mitigation cost of carbon reduction (CCR) related to energy use may be expressed in Equation 4.

$$CCR = \frac{I \cdot q + (M - B)}{\Delta(C)},\ \text{Equation 4}$$

Where:

CCR = Cost of carbon reduction for an energy-efficiency measure (or mitigation option), in $/tC (carbon tonne)

I = Capital cost ($)

q = Capital recovery factor (yr^{-1}), determined by discount rate and lifetime of mitigation option, see Equation 3

M = Annual change in monetizable other benefits ($/yr)

B = Annual total of productivity benefits ($/yr)

ΔC= Annual carbon savings (tC/yr)

4 Treatments of Technological Change in Energy-Climate Modeling

An important issue related to the representation of both supply and end-use technologies is how the technological change that results in mitigation improvement is taken into account in energy-climate modeling. Assumptions about technological change may include determination of efficiency levels of energy supply and end-use technologies into the near future. Therefore, the treatment of technological change is an important factor that will influence the mitigation costs and reductions in future emissions in energy-climate models. As discussed earlier, there are two common methods of including technological change in energy-climate models: exogenous modeling and endogenous modeling.

In exogenous modeling, the rate of improvement in technology is specified exogenously by the modelers and is not determined or simulated within the exogenous model.

In endogenous modeling, various approaches are implemented to model endogenous technological change. For example, one of the popular approaches is to model technological change as learning-by-doing where the costs of technologies decline and their technical characteristics improve with increased adoption of technologies. In this case, the external input to the model includes learning rates that specify the relationship between improvements in technology characteristics (primarily technology cost and efficiency) and the technology's cumulative installed capacity.

Overall, the input parameters required for modeling technological change in exogenous or endogenous models can be based upon estimates from analyzing historical trends. For example, Nakicenovic et al. (2000) have published curves showing the decline in costs of electricity-supply technologies over time. These time trends are typically used for exogenously specifying technological change. Sathaye et al. (2006) developed a simplified global energy supply and carbon cycle model, the Cost-Optimized Burden-Sharing and Regional Emission Allocation in the energy sector (COBRA-Energy). It is driven by exogenous energy demand projections and implements a scheme for international burden sharing for the 21st century, which takes into account the regional amounts of cumulative, anthropogenic emissions. U.S. iron and steel technologies were represented in the COBRA model using the historical data and changes over time included in this report.Other studies estimated learning rates (Manne and Barreto, 2002) and used them in endogenous modeling of technological change.

To date, there has been limited representation of demand-side technological change in the energy-climate models reviewed in this report, in part because of a lack of such information. In this study, we develop a new approach of treating technological change in energy-climate modeling. The new approach is based on quantifying changes in costs and savings potentials between two or more historical conservation supply curves. In this approach, cost curves of mitigation technologies are first developed for two historic periods, respectively; followed by calculating the rate of change of the savings potential at a given cost, which can then be the basis for estimating future rates of change and the input into energy-climate models.

For example, Figure 2 shows two cost curves, one that was developed for 1994 and another for 2004 for the U.S. cement sector. Each curve shows the costs of conserved energy versus energy-savings potential in each year. We can see that the energy-savings potential in 2004 was larger than that in 1994 when given the same cost of conserved energy (i.e., exhibited by a same Y-value in the figure). In this example, we can quantify the rate of change in energy-savings potential at a given cost over this decade (2004 vs. 1994) using 1994 as the baseline. For instance at the cost of $40/GJ, the energy-savings potential increased from 1.06 GJ/tonne to 1.24 GJ/tonne (by approximately 15%) over this decade. The changes may be a reference point for estimating future rates of change.

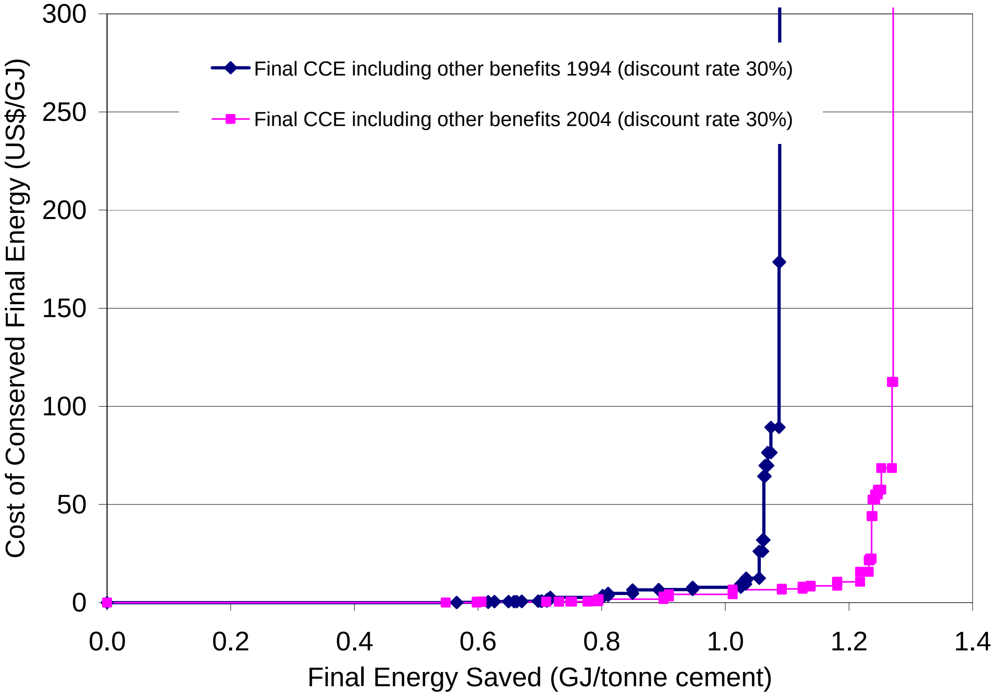

Figure 2. Example in the U.S. cement sector: Changes in energy savings potential between 1994 and 2004, 30% discount rate with other benefits.

5 Development of Cost Curves and Estimate of Technological Changes for the Iron and Steel Sector

The U.S. iron and steel industry is made up of (1) integrated steel mills that produce pig iron from raw materials (iron ore and coke) using a blast furnace and steel using a basic oxygen furnace, and (2) secondary steel mills that produce steel from scrap steel, pig iron or direct reduced iron using an electric arc furnace. Integrated steel producers smelt iron ores to liquid iron in blast furnaces and use basic oxygen furnaces to refine this iron with some scrap to produce raw liquid steel. Mini-mills and specialty mills are nonintegrated steel producers that use EAF to melt low-cost raw materials (usually scrap).

The efficiency of an iron and steel plant is significantly affected by several elements, such as products, technologies, plant size, and quality of raw materials. Increased recycling and higher efficiency of energy and materials use have played an important role in achieving significant efficiency improvements in the U.S. iron and steel industry within the last several decades.

In 1994, integrated steel mills produced 55.4 Mt steel and secondary steel mills produced 35.9 Mt steel, for a total of 91.3Mt steel production in the United States (IISI 1994). Primary energy use for integrated steel making was 1,444 PJ, over three times the energy use in secondary steel making, which was 426 PJ. The total carbon emissions from steel making related to energy use in 1994 were 34.3 MtC, with 78% of these emissions from integrated steel making (26.9 MtC) and the rest (22%) from the secondary steel making. In 2002, integrated steel mills in the U.S. produced 50.1 Mt steel and secondary steel mills produced 50.8 Mt steel, for a total of 100.9 Mt steel production in the United States. Primary energy use for integrated steel making was 1115 PJ, about twice of the energy use in secondary steel making, which was 519 PJ. The total carbon emissions from steel making related to energy use in 2002 was 30.6 MtC, with 71% of these emissions from integrated steel making (21.9 MtC) and the rest (29%) from the secondary steel making.

Table 3. Primary energy, associated carbon emissions, and production in 1994 and 2002.

		Integrated	Secondary	Total
1994	Energy Use (PJ)	1444	426	1870
2002	Energy Use (PJ)	1115	519	1634
1994	Carbon Emissions (MtC)	26.9	7.4	34.3
2002	Carbon Emissions (MtC)	21.9	8.7	30.6
1994	Production (Mt)	55.4	35.9	91.3
2002	Production (Mt)	50.1	50.8	100.9
1994	Energy Intensity (PJ/Mt)	26.1	11.9	20.5
2002	Energy Intensity (PJ/Mt)	22.3	10.2	16.2

We calculated that from 1994 to 2002 the integrated steel production energy intensity has decreased from 26.1 PJ/Mt to 22.3 PJ/Mt (by 15%), and from 11.9 PJ/Mt to 10.2 PJ/Mt (by 14%) for secondary steel production in the U.S. The changes indicate efficiency technology uptakes for both sectors over the same period of time. In addition, the production shift from integrated steel to much less energy intensive secondary steel, in combination with the observed technology uptakes, resulted in an overall reduction in energy intensity from 20.5 to 16.2 PJ/Mt (by 21%) for the U.S. iron and steel industry from 1994 to 2002.

In this paper, we analyze the potential of energy savings and carbon reduction of energy efficiency measures and their annualized costs based upon the available data for years 1994 and 2002. The analysis was accomplished by developing cost curves of energy savings and carbon reductions. The sensitivities of cost curves to their determinants are then discussed and evaluated. Based upon the cost curves, the rate of change in the savings potential at a given cost can be evaluated and be used to estimate future rates of change that can be the input for energy-climate models.

5.1 Development of Cost Curves for Mitigation Measures

In order to develop cost curves for mitigations measures, we adopted the methodology discussed in the previous section to evaluate applicable measures for 1994 and 2002. For example, cost curves for 47 measures for improving energy efficiency in the iron and steel sector were evaluated for the year 1994 using the data by Worrell et al. 2003. Then, updated cost curves of measures were developed for the year 2002 for the same set of measures. These cost curve data are included in Appendix A for 1994 and 2002. In addition, Appendix B includes descriptions of the mitigation measures noted in Appendix A. The following describe the steps to develop needed information in formulating cost curves.

First, each energy-efficiency measure was characterized individually by performing extensive literature research, including case studies or interviews. Data were collected from a variety of sources, including data from the American and International Iron and Steel Institutes, case studies and experts from around the world. Data on costs of implementation, energy savings and lifetimes were also collected.

In addition to data on energy savings and costs, some of the measures had identifiable and quantifiable additional benefits, such as reduced labor and maintenance or increased yields. Table 4 enlists a selection of the mitigation technologies and their corresponding benefits for the iron and steel industry. After each measure was characterized individually, its applicability to the U.S. iron and steel industry as a whole was assessed. In principle, in order to estimate the potential for future uptake of each energy efficiency and GHG-emission reduction measure, each measure was characterized by the degree to which implementation of the measure can still be applied in the U.S. iron and steel industry. The potential degree of implementation depends on a number of factors, of which the most important are the technical limitations on the implementation of the measure in specific processes, the degrees of application of competing technologies and the current degrees of implementation of the measure.

In general, overall data availability limits the accuracies of estimating the potential degree of implementation. For some measures, it is easier to find data than other measures. For example, the Energy Information Administration reports the uptake of some energy efficiency measures in the Manufacturing Energy Consumption Survey (MECS), such as crosscutting technologies like process controls, building controls, waste heat recovery or adjustable speed drives (EIA 1997, 2001 and 2005). For other measures specific to the iron and steel industry, additional literature sources, sector specific statistics, or expert estimates were used. The key literature sources used for iron and steel industry specific measures were the "Round-Up's" published by the journal Iron & Steelmaker on electric arc furnaces, blast furnaces and continuous casters (I&SM, 1997a; I&SM, 1997b). In addition, statistical material from the AISI and IISI were used for production rates of various processes (see, for example, AISI 1995, 1996, 1997 and 2006 and IISI 1996 and 2006). For key technologies, reference lists of manufacturers such as VAI and SMS (VAI, 1997) were also used.

In this report, we focus on years 1994 and 2002, largely because the data available for both years were more complete than other years, as exhibited by available MECS results. Even though the 1994 MECS and 2002 MECS results are only an indication, they serve as a relative gauge for the penetration of those measures. These data were used initially in 1994 and then again in 2002, using the latest MECS to compare with the degree of implementation in the 1994 MECS. All the cost data (U.S. dollars) are obtained and presented as the currency values for the respective reference years (i.e., 1994, 2002). A direct comparison of costs (U.S. dollars), when desired, can be easily made by converting the existing reference-year data (i.e., 1994, 2002 in this study) to a preferred reference year (e.g., 2007). The conversions can be accomplished by multiplying the existing cost in a reference year by an inflation index based on GDP for the preferred year (BEA 2009).

Table 4. Examples of Mitigation Technologies for the Iron and Steel Industry that Have Other Benefits as well as Energy Benefits (Worrell et al. 2003).

Secondary Steel making	
Improved process control	Average increase in productivity of 9-12% and reduced electrode consumption of 25%
Bottom Stirring / Stirring gas injection	Net cost savings of $0.9-2.3/tonne from increased yield of 0.5%
Foamy slag	Reduced tap to tap times
Oxy-fuel burners	Reduced tap-to-tap time of 6% and improved product quality from O2 injection
DC-Arc furnace	Reduced tap-to-tap time, reduced electrode use, increased refractory life and improved stability
Scrap preheating - Tunnel furnace (CONSTEEL)	Increased productivity by 33%, reduced electrode consumption by 40% and reduced dust emissions
FUCHS Shaft furnace	Reduced electrode consumption, reduced flue gas dust emissions by 25%, increased yield of 0.25-2.0% and 20%

	increased productivity
Twin Shell w/ scrap preheating	Reduced tap-to-tap time
Integrated Steel making	
Coke dry quenching	Reduced dust emissions and improved working climate
Pulverized coal injection to 130 kg/thm	Reduced coke-related emissions
Pulverized coal injection to 225 kg/thm	Reduced coke-related emissions
Injection of natural gas to 140 kg/thm	Reduced coke-related emissions
Adopt continuous casting	Reduced material losses from about 8% to 2%
Hot charging	Improved material quality, reduced material losses, improved productivity by up to 6% and potential reduction of slab stocking
Both	
Thin slab casting	Improved productivity and reduced material losses

5.2 Energy Cost Curves with and without Other Benefits—1994

Two different curves of conserved energy (in U.S. dollar per GJ energy used) of mitigation measures can be plotted against the specific final energy savings (GJ per tonne of steel) of two scenarios: with and without inclusions of other non-energy benefits for the U.S. iron and steel industry in 1994, as shown in Figure 3.

For this calculation of CCE values, we assumed that a real discount rate of 30% is applied, partly reflecting the steel industry's capital constraints and preference for short payback periods and high internal rates of return. The assumption of higher discount rates (e.g., 30%) can also indirectly account for program costs and various barriers against the adoption of cost-effective energy efficient technologies. It is also clear that such an assumption would mathematically lead to a prediction with higher (e.g., positive) annualized costs of GHG mitigation measures. An energy-climate model that assumes a high discount rate or constrains market penetration of efficient technologies may represent two likely scenarios – the first being that market failures and indirect costs are a reality for implementing efficiency measures; or the second being that cost-effective policies are not implemented while the costs of efficiency measures are positive. In the latter case, however, implementing these policies could in fact lead to negative-costs of GHG mitigation measures and improved market.

In this report, we used an industry average weighted fuel cost in our calculation based on energy data provided by the American Iron and Steel Institute (AISI, 1995, 1996, 1997) and cost data from the EIA (EIA, 1997). We included a weighted fuel cost separate for integrated and for secondary steel making measures and used the source price for electricity. We combined measures applicable to each process for integrated and secondary steel making, and then created two cost curves with and without including other benefits (Figure 3).

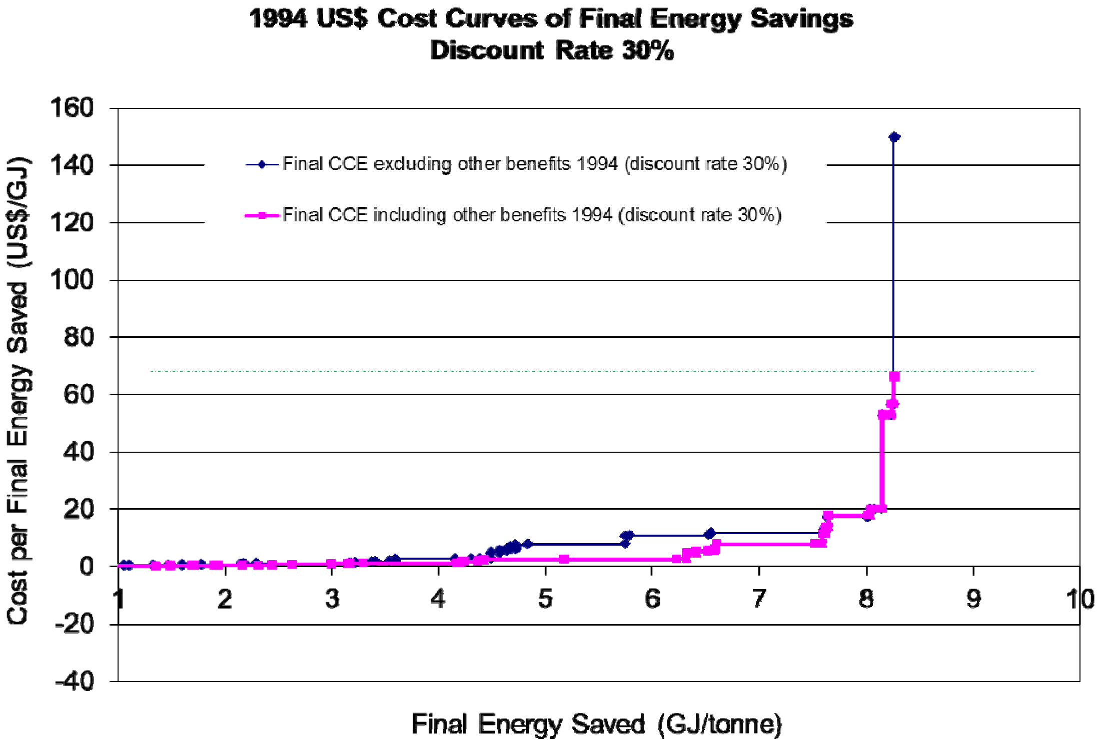

Figure 3. Cost curves for inclusion and exclusion of other benefits in the U.S. iron and steel industry

Figure 3 shows differences in the values for costs of conserved energy (in final energy terms), in 1994 U.S. dollar per GJ saved, between curves with non-energy benefits included and excluded for the iron and steel industry. Not all the measures selected in this study have obvious other benefits (non-energy); furthermore, not all other benefits of the measures could be quantitatively evaluated due to limitation or availability of relevant information or data. Therefore, other benefits that are not quantifiable are not included in the calculations or curves. For the measures that did have quantifiable non-energy benefits, each measure was evaluated individually and included in the curves.

The CCE of some measures becomes higher when other benefits are excluded from calculation. In fact, considering other benefits could significantly lower the CCE. For example, the CCE excluding non-energy benefits for implementing oxy-fuel burners is $10.8/t, whereas including the benefits of reduced tap-to-tap time (6%) and improved product quality lowers its CCE down to a negative value: -$17.0/t. Significant changes in the ranks occurred in terms of their cost of conserved energy as well as their cost effectiveness when other non-energy benefits were included in the analysis. Overall, including non-energy benefits in the cost curves for the iron and steel industry can significantly decrease the total cost of conserved energy for final marginal measures from $150/GJ to $66/GJ to achieve the same total energy savings of 8.3 GJ/tonne steel in 1994 (Figure 3).

5.3 Energy Cost Curves with and without Other Benefits – 2002

In this study, we compared the same set of mitigation measures for both 1994 and 2002. Additional mitigation measures for year 2002 are not included in this study due to unavailability of such data or information.

Figure 4 shows differences in the values for costs of conserved energy (in final energy terms), in 2002 U.S. dollar per GJ saved, between curves with other benefits included and excluded for the iron and steel industry. Similar to 1994, not all the measures selected have other benefits. In addition, not all other benefits of the measures could be quantitatively evaluated due to data limitation; therefore, these non-quantified other benefits are not included in the calculations or curves. For the measures that did have quantifiable other benefits, each measure was evaluated individually and included in the curves. Including these benefits could significantly lower the values of CCE for the selected measures. Overall, including other benefits in the cost curves for the iron and steel industry can significantly decrease the total cost of conserved energy for the final marginal measures from $150/GJ to $57/GJ to achieve the same total energy savings of 6.5 GJ/tonne steel in 2002 (Figure 4).

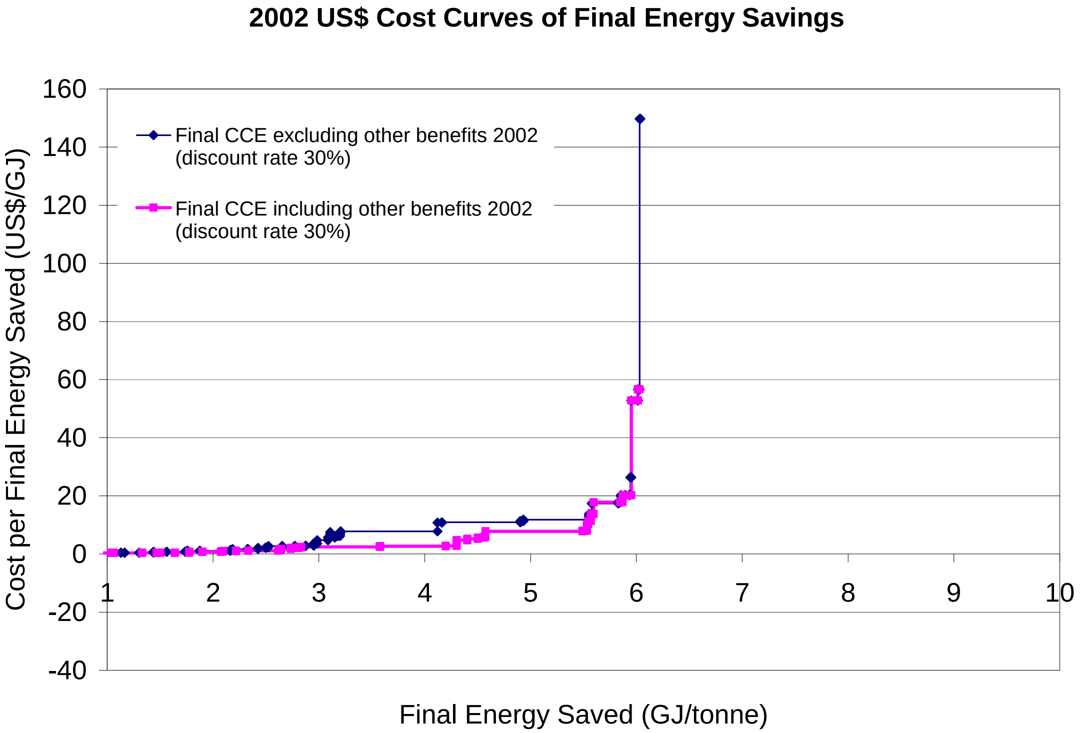

Figure 4. Cost curves for inclusion and exclusion of other benefits in the U.S. iron and steel industry (2002)

The magnitudes of energy-savings potential presented in the figure should be considered conservative because additional efficiency measures in fact were made available in 2002 while their non-energy benefits were not quantified or included due to data unavailability.

One would expect that at a lower discount rate (e.g., 10%), including other benefits for all measures in the cost curve should decrease the total cost of conserved energy for all measures. The effects of cost determinants (e.g., discount rates) on the changes in cost curves are further discussed and evaluated in the following section.

5.4 Estimate of Technological Change (Uptake) between 1994 and 2002

Many factors affect the changes seen in the curve: discount rates, energy intensity, production, industry structure changes (e.g., changing shares of integrated versus secondary steel making and number of plants), shares of the U.S. production to which the individual measures were applied. Quantifying or comparing historic changes in the magnitudes of savings potential can be useful for predicting future trends for energy climate modeling. Available cost and benefit data for the efficiency measures were included for analysis in years 1994 and 2002. Figure 5 shows the cost curves for iron and steel for the years 1994 and 2002. For the cost curves, we generally assumed that nominal capital costs were the same as in 1994 because nominal steel price had not changed much during that period and the equipment used in most of the technologies evaluated is made of steel.

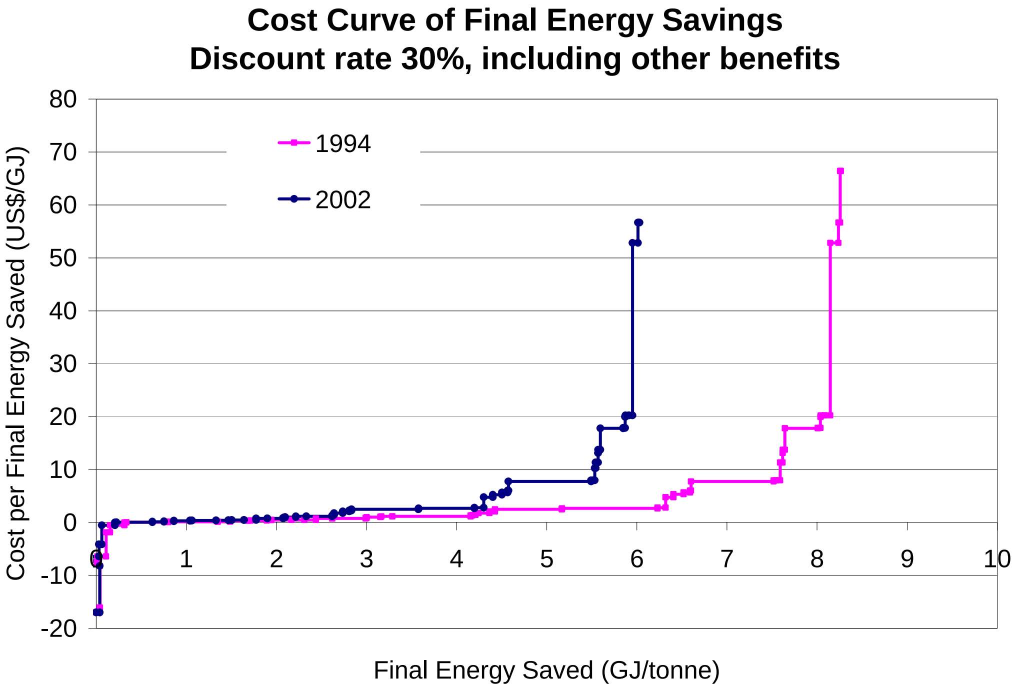

Figure 5. Cost curves of final energy for 1994 and 2002, including other benefits

Based upon the available data sets, with other benefits taken into account and 30% discount rate assumed for the mitigation measures, we estimated that for a total cost of $66.4/GJ saved (for the whole U.S. iron and steel industry), the technical potential for energy efficiency was 8.3 GJ per tonne of steel in 1994, and was 6.5 GJ per tonne of steel for the same set of measures in 2002. As discussed earlier, the estimated savings potential in 2002 was conservative because we only assessed potential gains from the same set of measures, while there were additional measures that were not included due to data unavailability.

The observed shift based upon the same measures in fact was also influenced by structural changes in the U.S. industry, i.e., the shift from integrated steel making to more secondary steel making such as electric arc furnace (EAF) steel making. Integrated steel making accounted for 61% of total steel making in 1994 and accounted for 50% in 2002. The sector's structural change affected the percentage applicability of each measure to the whole U.S. iron and steel industry, and therefore its total potential energy savings, which was represented by the shift of cost curves from right (1994) to left (2002). Because energy intensity of secondary steel is lower than that of integrated steel production. It was not surprising to observe the downward shift that indicates a smaller amount of potential total energy savings in year 2002 compared to year 1994.

In addition, final energy intensity for integrated steel making also decreased from 24 GJ/t in 1994 to 22 GJ/t in 2002, as was true for secondary steel making (i.e., 7 GJ/t in 1994 and 6 GJ/t in 2002). Apparently, technological uptake of the measures between 1994 and 2002 has happened and collectively contributed to the overall reduction in energy intensity for the industry. If more mitigation measures (existing or new) had been implemented since 1994, the industry could expect to reach higher technical potential in energy savings because of the increased measures and shares of U.S. production to which the individual measures were applied.

Considering other benefits and assuming 30% discount rate for the mitigation measures evaluated in 2002, for a total cost of up to $66.4/tonne, the technical potential for energy savings are calculated, as shown in Table 5. The potential technical savings was 218 PJ for integrated and 80 PJ for secondary in 2002, while it was 287 PJ for integrated and 110 PJ for secondary sectors in 1994. We evaluated overall integrated steel making and secondary steel making, and estimated that 1586 PJ final energy was used in 1999, and 1245 PJ final energy was used in 2002. Therefore, the technical potential of energy savings was approximately one-quarter of total final energy use in both years.

Table 5. Technical potential for energy savings in the U.S. iron and steel making in 1994 and 2002.

	Applied Final Energy Savings (PJ)			
Year	**Integrated steel making**	**Secondary steel making**	**Total**	**Energy Savings (%)**
1994	**287**	**110**	**398**	**25%**
2002	**218**	**80**	**298**	**24%**

Furthermore, based upon the unit energy prices, we can identify cost effective measures from the pool of mitigation measures. For example, using $2.59/GJ for 1994 (final energy price) and $3.49/GJ for 2002 (final energy price) to select cost-effective measures, we calculate the potential energy savings from implementing cost-effective measures, as shown in Table 6.

Table 6. Technical potential for cost-effective energy savings in the U.S. iron and steel making in 1994 and 2002.

	Cost-effective Final Energy Savings (PJ)			
Year	**Integrated steel making**	**Secondary steel making**	**Total**	**Energy Savings (%)**
1994	**186**	**65**	**251**	**16%**
2002	**144**	**73**	**217**	**17%**

We estimated that the potential savings of final energy use resulting from cost-effective mitigations measures was 251 PJ (186 PJ integrated, and 65 PJ secondary) in 1994 and 217 PJ (144 PJ integrated, and 73 PJ secondary) in 2002, corresponding to 16% and 17% of total annual final energy use in the U.S., respectively. The cost-effective energy savings would be approximately 16-17% (251 PJ out of a total of 1586 PJ final energy in 1999, and 217 PJ out of 1282 PJ final energy in 2002). This is an important finding in that implementing existing cost effective measures can result in significant energy savings for both years (and future years) relative to their technical potential in energy savings.

Based upon the cost curves derived from available information, the rate of change in the savings potential at a given cost can be evaluated and be used to estimate future rates of change that can be the input for energy-climate models. For example, from the cost curves, we can quantify the rate of change in energy-savings potential at a given cost over this decade (2002 vs. 1994) using 1994 as the baseline.

6 Estimation of Carbon Reduction and its Costs

Associated with the energy savings from implementing mitigations measures is the mitigation cost and carbon reduction. We consider that the cost of carbon reduction is the same as the cost of the mitigation measures, whether or not taking into account of other benefits (when monetized data is available).

Figure 6 and Figure 7 represent the cost of carbon reductions (in U.S. dollar per metric ton of carbon) of mitigation measures versus the carbon reduction (metric ton of carbon) with inclusions of other benefits for the U.S. iron and steel industry in 1994 and 2002, respectively.

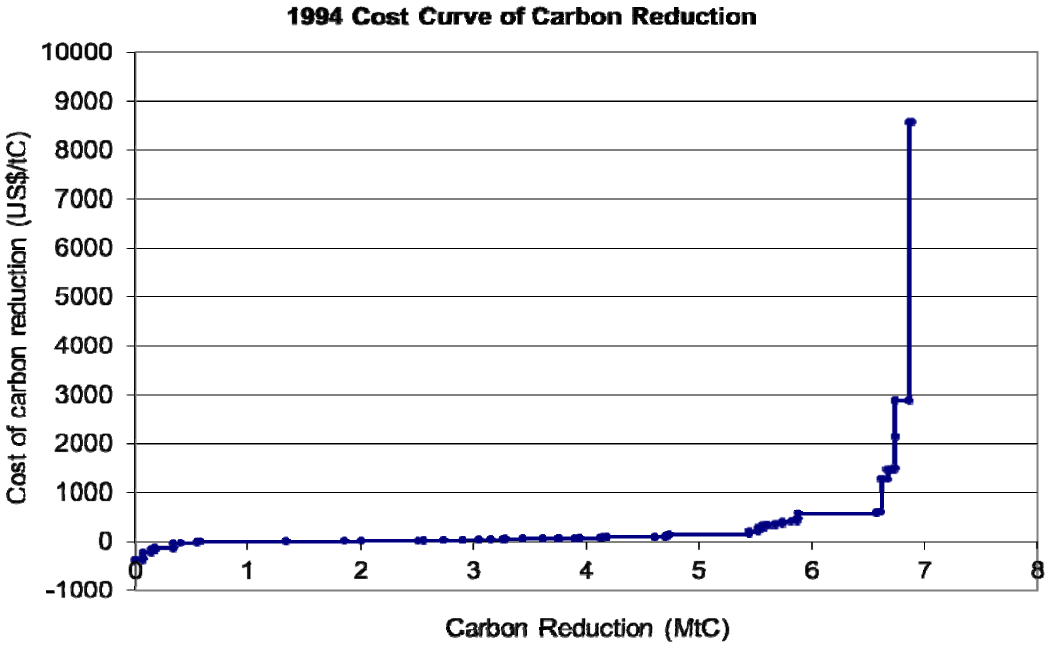

Figure 6. Cost curve for carbon reduction in the U.S. iron and steel making in 1994, discounted rate 30%.

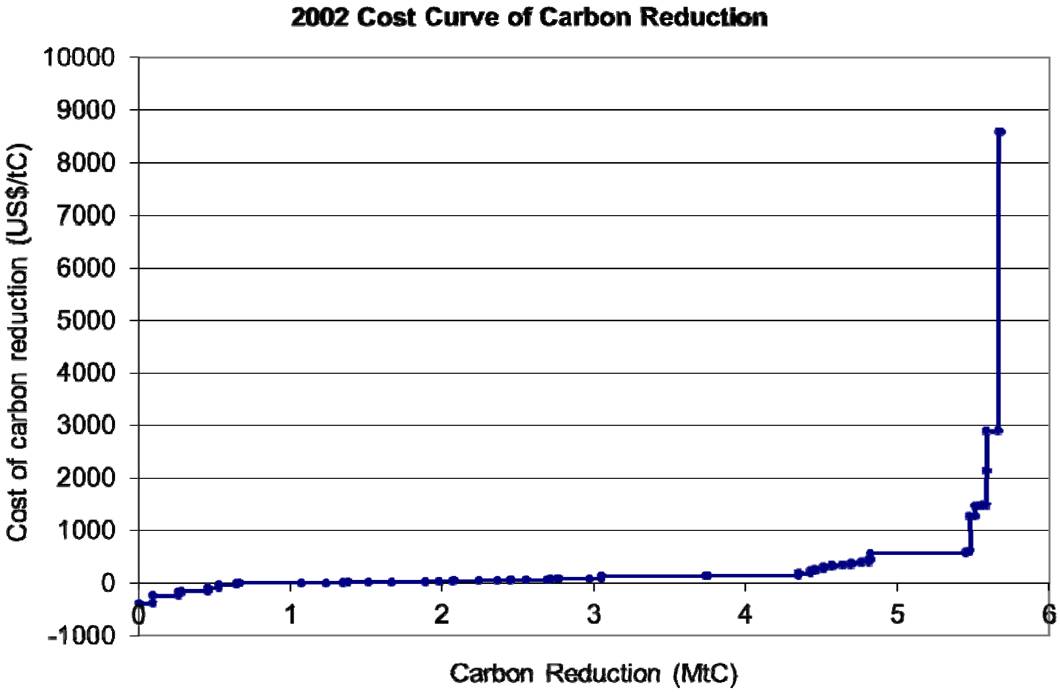

Figure 7. Cost curve for carbon reduction in the U.S. iron and steel making in 2002, discounted rate 30%.

In addition, Table 7 and Table 8 show the aggregated numbers for potential carbon reductions grouped by integrated and secondary steel making sectors. Table 7 shows the technical potential of carbon-emission reduction as it corresponded to the technical potential of energy savings associated with the mitigation measures. We estimated that the potential reduction of carbon emissions resulting from applicable mitigation measures was 6.1 MtC in 1994 (3.9 MtC integrated steel making, and 2.2 MtC secondary steel making), and 5.0 MtC in 2002 (3.3 MtC integrated steel making, and 1.8 MtC secondary steel making), corresponding to 18% and 17% of annual energy-related carbon emissions in 1994 and 2002, respectively.

Table 7. Technical potential for carbon reductions in the U.S. iron and steel making in 1994 and 2002.

	Applied Total Carbon Reduction (MtC)			
	Integrated steel making	**Secondary steel making**	**Total**	**Max Applied Carbon Reduction (%)**
1994	**3.9**	**2.2**	**6.1**	**18%**
2002	**3.3**	**1.8**	**5.0**	**17%**

Table 8 shows the potential of annual carbon reduction via cost-effective measures. Applying cost-effective measures would reduce carbon emissions of 4.7 MtC in 1994 (3.4 MtC integrated steel making, and 1.3 MtC secondary steel making), and 4.4 MtC in 2002 (2.7 MtC integrated steel making, and 1.7 MtC secondary steel making), corresponding to 14%-15% of the total annual carbon emissions related to energy use in each year. This is an important finding in that implementing existing cost effective measures can result in significant reduction in carbon emissions for both years relative to their technical potential reduction in carbon emissions.

Table 8 Technical potential for cost-effective carbon reductions in the U.S. iron and steel making in 1994 and 2002.

	Cost-effective Carbon Reduction (MtC)			
	Integrated steel making	**Secondary steel making**	**Total**	**Carbon Reduction (%)**
1994	**3.4**	**1.3**	**4.7**	**14%**
2002	**2.7**	**1.7**	**4.4**	**15%**

Finally, we performed parallel analyses to examine the effects of discount rates on the magnitudes of costs of conserved energy and savings potential for individual mitigation measures.

Figures 8 and 9 show the cost curves with various discount rates (10%, 20%, and 30%) in 1994 and 2002, respectively. For each year, we have found no changes in the magnitudes of potential savings for all rates, while the cumulative costs of conserved energy increase greatly with the increase in discount rates. In addition, the costs of conserved energy corresponding to individual measures also tend to increase with the increase in discount rates. The sensitivities of such increases to discount rates are different across specific measures, however. The higher discount rates result in an overall increase in the total cost of mitigation measures for implementation and operation.

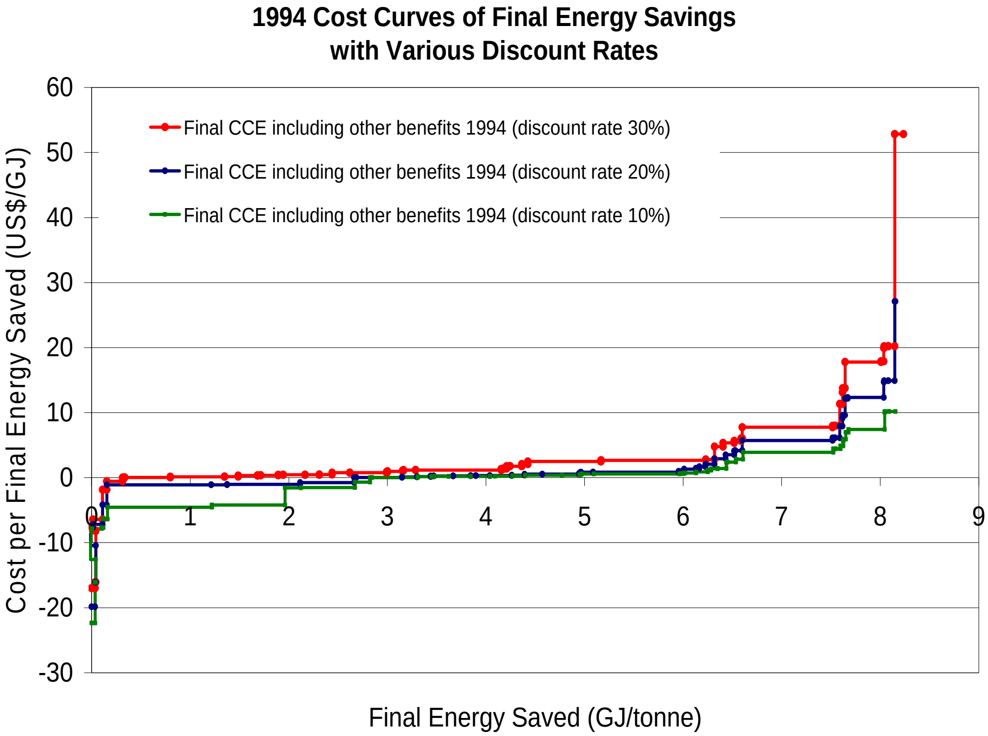

Figure 8. 1994 Cost curves of final energy savings with discounts rates 10%, 20% and 30% in the U.S. iron and steel industry

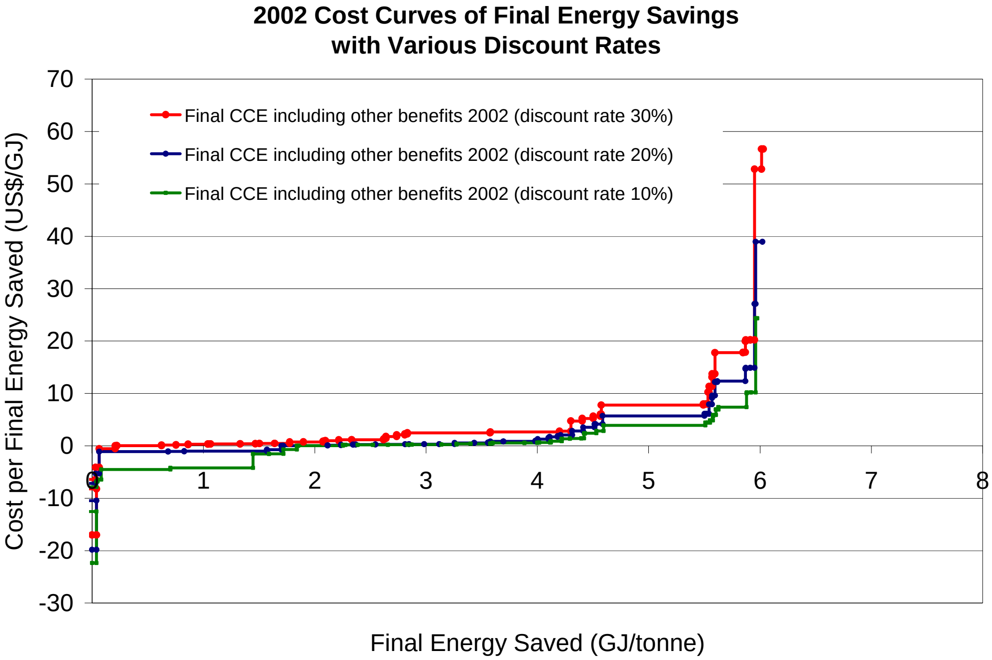

Figure 9. 2002 Cost curves of final energy savings with discounts rates 10%, 20% and 30% in the U.S. iron and steel industry.

In summary, similar to the analysis about energy saving potential, we also performed analysis about potential reduction in carbon emissions for both years. Based upon the cost curves derived from available information on mitigation measures, the rate of change in the carbon reduction potential at a given cost can be evaluated and may be used to estimate future rates of change as input for energy-climate models. For example, from the cost curves, we can quantify the rate of change in carbon reduction potential at a given cost over the studied decade (e.g., 2002 vs. 1994).

7 Conclusions

Through characterizing energy-efficiency technology costs and improvement potentials, we have developed and presented energy cost curves for energy efficiency measures applicable to the U.S. iron and steel industry for the years 1994 and 2002. The cost curves can change significantly under various scenarios: the baseline year, discount rate, energy intensity, production, industry structure (e.g., integrated versus secondary steel making and the number of operating plants), efficiency measures, share of iron and steel production to which the individual measures can be applied, and inclusion of other benefits. We have identified a number of cost-effective mitigation measures in this study. Furthermore, inclusion of other benefits from implementing mitigation measures can reduce the costs of conserved energy significantly, making more measures cost-effective. Some important findings in energy savings are included below:

1) The potential savings of final energy use resulting from applicable mitigation measures was 397 PJ in 1994 (287 PJ for integrated steel making, and 110 PJ for secondary steel making), and 304 PJ in 2002 (223 PJ for integrated steel making, and 81 PJ for secondary steel making). The potential annual energy savings corresponded to 25% (in 1994) and 24% (in 2002) of total annual final energy use in the U.S. iron and steel sector.

2) The potential savings of final energy use resulting from cost-effective mitigations measures identified in the study was 251 PJ in 1994 (186 PJ for integrated steel making, and 65 PJ for secondary steel making), and 217 PJ in 2002 (144 PJ for integrated steel making, and 73 PJ for secondary steel making). Overall, implementing applicable cost-effective mitigation measures could result in potential final energy savings by 16% and 17% of the total annual final energy use in the U.S. iron and steel sector in 1994 and 2002, respectively.

The total carbon emissions associated with the U.S. iron and steel sector consists of two categories: 1) energy use for steel production, and 2) direct emissions from steel and iron production. Annual carbon emissions related to energy use in the iron and steel sector in the U.S. was approximately 35 MtC in 1994 and 31 MtC in 2002. EPA reported annual carbon emissions of 16 MtC associated with the iron and steel production in 2002 (EPA 2008). Annual total carbon emissions from the iron and steel sector in the U.S. were approximately 47 MtC in 2002. Corresponding to the energy use in iron and steel manufacturing, we estimated the overall potentials in carbon-emission reductions due to mitigation measures for both years (1994 and 2002), respectively.

3) The potential reduction of carbon emissions resulting from applicable mitigations measures was 6.1 million ton of carbon (MtC) in 1994 (3.9 MtC from integrated steel--making, and 2.2 MtC from secondary steel making), and 5.7 MtC in 2002 (3.7 MtC from integrated steel making, and 2.0 MtC from secondary steel making), corresponding to 18% and 19% of annual energy-related carbon emissions in 1994 and 2002, respectively.

4) Applying cost-effective measures would reduce carbon emissions by 4.7 MtC in 1994 (3.4 MtC from integrated steel making, and 1.3 MtC from secondary steel making), and 4.4 MtC in 2002 (2.7 MtC from integrated steel making, and 1.7 MtC from secondary steel making), corresponding to 14% of annual energy-related carbon emissions in each year.

Implementing existing cost effective measures can result in significant energy savings and carbon-emission reduction for both years relative to their technical potential in energy savings and carbon-emission reduction. We have also concluded that based upon the cost curves derived from available information on mitigation measures, the rate of change in the energy-savings or carbon-reduction potential at a given cost can be evaluated and be used to estimate future rates of change for input in energy-climate models. Such estimation of the rate change may be improved as more comprehensive information on characterizing the mitigation measures becomes available.

In addition, total costs of conserved energy increase with the increases in discount rates. The outcomes from this research provide information on initial technology database that can be accessible to integrated assessment modeling groups seeking to enhance their empirical descriptions of technologies. The report includes tabulated databases on costs (and benefits when available) of measure implementation, energy savings, carbon-emission reduction, and lifetimes. The appendix to this report also includes descriptions of the iron and steel making processes, and the mitigation measures identified in this study.

With the available carbon-reduction cost data for various scenarios, it becomes possible to assess economics of carbon caps and efficiency potentials, which will help to understand how carbon regulation may mobilize efficiency while lowering cost of GHG-emission reduction.

8 Recommendations

The development of concepts and information on costs of conserved energy for the U.S. iron and steel sector provides a better understanding of costs and carbon impact of implementing energy efficiency measures in the sector. While many energy efficiency technologies have become cost-effective to mitigate long-term climate change, it is important and necessary to incorporate new information on technology characteristics, their evolution and response to energy and carbon price, which can be utilized by integrated assessment modelers who are seeking to enhance their empirical descriptions of technologies. There appears to be a need to develop and refine sectoral algorithms and produce databases that can be used to match the needs of different integrated assessment modeling of climate policies. New algorithms should allow transformation of information on behavioral responses, technology costs, energy savings, other benefits, and policy costs into meaningful and functional data forms. Developing such algorithms may require customization and processing of database functions. Furthermore, the desired data-model linking effort will require close interfaces between modelers and the developers of the cost-curve databases on energy efficiency measures. In this study, all the cost data (U.S. dollars) are obtained and presented as the currency values for the respective reference years (i.e., 1994, 2002). A direct comparison of costs (U.S. dollar), when desired, can be made by converting the existing reference-year data (i.e., year 1994 and year 2002 in this study, respectively) to a preferred reference year (e.g., 2007). The conversions can be accomplished by multiplying the existing cost in a reference year by a GDP-based inflation index for the preferred year (BEA 2009).

In addition to the iron and steel sector, other industrial sectors are energy-intensive. In order of their relative energy consumption, these include refinery industry, other petrochemicals industries, cement, pulp and paper, food industry, fabricated metal products, transportation equipment and aluminum. Because of the variety of petrochemicals products, the characterization of this industry is more complex than for the other sectors. It is important, however, to develop data similar to that produced in this report for additional sectors. These too will cover information on types of mitigation options that can be readily utilized to improve energy efficiency, their economic potential, and changes that have occurred in the nature of the cost curves including the non-energy benefits.

Future work will be needed for pulp and paper sector, refineries, petrochemicals and food processing industry, and will need to include other business sectors such as commercial and residential buildings and transportation. This is particularly true if comprehensive carbon policies such as carbon offset are to be addressed, given that the building sector possesses largest potential in global carbon reduction.

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Appendix A. Cost Curve Data for the U.S. Iron and Steel Sector (1994 US$ and 2002 US$ respectively)

1994 BASELINE *Secondary Steelmaking*	Applied Carbon Savings	Applied Final Energy Savings	Cost of Measure	Operation Cost Change	Measure Lifetime	Applied Carbon Savings	Final CRC	Final CCE	Capital Recovery Factor
Steelmaking Electric Arc Furnace	kgC/tonne steel	(GJ/tonne)	(US$/tonne)	(US$/tonne)	(years)	(Million kgC)	US$/tC	(US$/GJ)	Real discount rate
Improved process control (neural network)	4.3	0.10	0.86	(0.90)	10.0	155	(144.26)	(6.41)	$0.32
Fluegas Monitoring and Control	1.2	0.03	1.00	-	15.0	43	254.88	11.33	$0.31
Transformer efficiency - UHP transformers	1.1	0.02	1.10	-	15.0	39	309.23	13.75	$0.31
Bottom Stirring / Stirring gas injection	0.4	0.01	0.07	(0.22)	0.5	13	(167.40)	(7.44)	$2.44
Foamy slag	0.3	0.01	3.50	(0.63)	10.0	12	1,493.84	66.42	$0.32
Oxy-fuel burners	1.6	0.04	1.20	(1.00)	10.0	57	(382.26)	(17.00)	$0.32
Eccentric Bottom Tapping (EBT) on existing furnace	1.2	0.03	1.66	-	20.0	45	401.96	17.87	$0.30
DC-Arc furnace	0.7	0.02	-	(0.13)	30.0	26	(173.54)	(7.72)	$0.30
Scrap preheating - Tunnel furnace (CONSTEEL)	1.9	0.04	1.00	(0.38)	30.0	69	(41.59)	(1.85)	$0.30
FUCHS Shaft furnace	1.9	(0.05)	1.20	(0.80)	30.0	69	(228.75)	(8.21)	$0.30
Twin Shell w/ scrap preheating	0.3	0.01	z	(0.11)	30.0	11	(361.70)	(16.08)	$0.30
Secondary Casting									
Efficient ladle preheating	0.3	0.02	0.08	-	10.0	10	97.81	1.34	$0.32
Near net shape casting/thin slab casting	19.9	1.06	41.44	(9.67)	20.0	716	141.83	2.67	$0.30
Secondary Hot Rolling									
Process control in hot strip mill	5.1	0.37	0.87	-	10.0	183	55.07	0.75	$0.32
Recuperative burners	11.9	0.87	3.10	-	10.0	427	84.30	1.16	$0.32
Insulation of furnaces	0.9	0.06	4.04	-	10.0	32	1,475.20	20.22	$0.32
Controlling oxygen levels and VSDs on combustion air fans	3.0	0.22	0.34	-	15.0	109	33.83	0.46	$0.31
Energy-efficient drives in the rolling mill	0.3	0.01	0.13	-	20.0	11	135.66	6.03	$0.30
Waste heat recovery from cooling water	0.7	0.05	0.99	0.09	15.0	23	600.55	7.98	$0.31
General Technologies									
Preventative Maintenance	4.1	0.14	0.01	0.02	20.0	147	5.63	0.17	$0.30
Energy monitoring and management system	1.0	0.03	0.15	-	5.0	37	60.31	1.78	$0.41
	-	-	-	-	-	-	-	-	
Integrated Steelmaking									
Iron Ore Preparation (Sintering)									
Sinter plant heat recovery	3.4	0.12	0.66	-	10.0	189	62.46	1.78	$0.32
Reduction of air leakages	0.1	0.00	0.02	-	10.0	7	57.74	2.57	$0.32
Increasing bed depth	0.6	0.02	-	-	10.0	32	-	-	$0.32
Improved process control (sinter plant)	0.3	0.01	0.03	-	10.0	16	35.93	1.07	$0.32
Use of waste fuels in the sinter plant	0.9	0.03	0.03	-	10.0	48	12.20	0.35	$0.32
Coke Making									
Coal moisture control	0.6	0.09	14.69	-	10.0	31	8,589.38	52.83	$0.32
Programmed heating - coke plant	0.3	0.05	0.07	-	10.0	17	71.15	0.44	$0.32
Variable speed drive coke oven gas compressors	0.0	0.00	0.09	-	15.0	1	2,131.94	13.11	$0.31
Coke dry quenching	2.2	0.37	20.99	0.15	18.0	125	2,891.37	17.78	$0.30
Iron Making (Blast Furnace)									
Pulverized coal injection to 130 kg/thm	9.1	0.55	4.99	(1.43)	20.0	506	8.69	0.14	$0.30
Pulverized coal injection to 225 kg/thm	2.5	0.15	1.39	(0.27)	20.0	140	60.01	1.00	$0.30
Injection of natural gas to 140 kg/thm	2.7	0.16	0.89	(0.36)	20.0	148	(32.91)	(0.55)	$0.30
Top pressure recovery turbines (wet type)	0.9	0.02	3.57	-	15.0	47	1,274.51	56.66	$0.31
Recovery of blast furnace gas	0.6	0.04	0.16	-	15.0	33	83.72	1.39	$0.31
Hot blast stove automation	3.3	0.20	0.16	-	5.0	182	20.04	0.33	$0.41
Recuperator hot blast stove	1.2	0.07	1.25	-	10.0	66	340.73	5.66	$0.32
Improved blast furnace control systems	3.0	0.18	0.16	-	5.0	164	22.24	0.37	$0.41
Steelmaking									
BOF gas + sensible heat recovery	12.5	0.92	22.00	-	10.0	694	567.72	7.77	$0.32
Variable speed drive on ventilation fans	0.1	0.00	0.20	-	10.0	8	449.11	19.97	$0.32
Integrated Casting									
Efficient ladle preheating	0.1	0.01	0.03	-	10.0	8	63.38	0.87	$0.32
Thin slab casting	-	0.74	26.85	(6.27)	20.0	757	-	2.47	$0.30
Integrated Hot Rolling									
Hot charging	1.5	0.11	2.83	(0.25)	20.0	86	389.91	5.34	$0.30
Process control in hot strip mill	2.5	0.18	0.42	-	10.0	137	55.08	0.75	$0.32
Recuperative burners	1.7	0.12	0.44	-	10.0	93	84.30	1.16	$0.32
Insulation of furnaces	0.6	0.04	2.62	-	10.0	32	1,475.30	20.22	$0.32
Controlling oxygen levels and VSDs on combustion air fans	2.0	0.14	0.22	-	15.0	109	33.83	0.46	$0.31
Energy-efficient drives in the rolling mill	0.2	0.00	0.09	-	20.0	11	135.67	6.03	$0.30
Waste heat recovery from cooling water	0.3	0.02	0.48	0.04	15.0	17	600.59	7.98	$0.31
Integrated Cold Rolling and Finishing									
Heat recovery on the annealing line	1.4	0.09	0.77	-	10.0	75	183.93	2.81	$0.32
Reduced steam use in the pickling line	1.2	0.09	1.28	-	10.0	69	335.05	4.77	$0.32
Automated monitoring and targeting system	2.8	0.06	0.32	-	5.0	153	47.03	2.09	$0.41
General									
Preventative Maintenance	9.3	0.46	0.01	0.02	20.0	518	2.46	0.05	$0.30
Energy monitoring and management system	2.6	0.13	0.15	-	5.0	143	23.79	0.48	$0.41

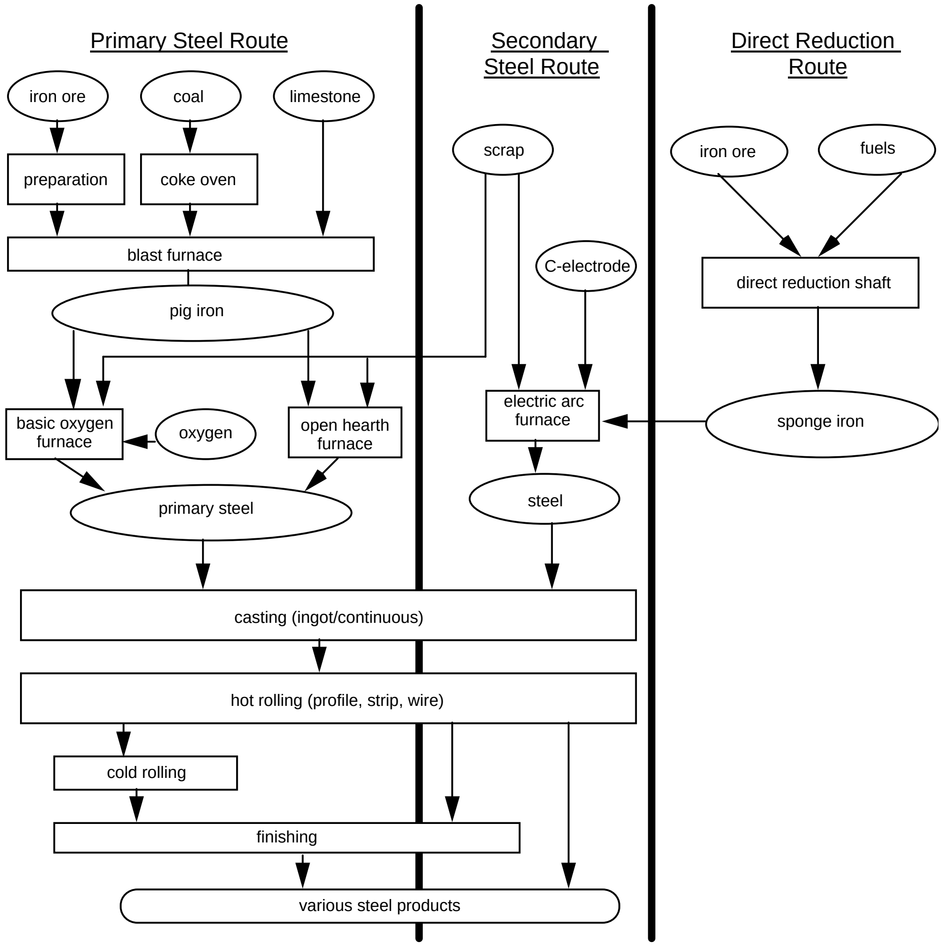
2002 BASELINE

Secondary Steelmaking	**Applied Carbon Savings**	**Applied Final Energy Savings**	**Cost of Measure**	**Operation Cost Change**	**Measure Lifetime**	**Applied Carbon Savings**	**Final CRC**	**Final CCE**	**Capital Recovery Factor**
Steelmaking Electric Arc Furnace	kgC/tonne steel	(GJ/tonne)	(US$/tonne)	(US$/tonne)	(years)	(Million kgC)	US$/tC	(US$/GJ)	Real discount rate
Improved process control (neural network)	3.1	0.08	0.67	(0.71)	10.0	157	(158.75)	(6.41)	$0.32
Fluegas Monitoring and Control	1.1	0.03	1.00	-	15.0	55	280.49	11.33	$0.31
Transformer efficiency - UHP transformers	1.0	0.02	1.10	-	15.0	50	340.30	13.75	$0.31
Bottom Stirring / Stirring gas injection	0.3	0.01	0.07	(0.22)	0.5	16	(184.22)	(7.44)	$2.44
Foamy slag	0.3	0.01	4.00	(0.72)	10.0	18	1,643.91	66.42	$0.32
Oxy-fuel burners	1.6	0.04	1.34	(1.12)	10.0	83	(420.66)	(17.00)	$0.32
Eccentric Bottom Tapping (EBT) on existing	0.9	0.02	1.31	-	20.0	45	442.34	17.87	$0.30
DC-Arc furnace	1.3	0.03	0.39	(0.25)	30.0	66	(101.57)	(4.10)	$0.30
FUCHS Shaft furnace	3.1	(0.09)	2.10	(1.40)	30.0	155	(251.73)	(8.21)	$0.30
Twin Shell w/ scrap preheating	0.4	0.01	0.90	(0.17)	30.0	21	253.55	10.24	$0.30
Secondary Casting									
Efficient ladle preheating	0.1	0.01	0.04	-	10.0	8	77.15	0.96	$0.32
Near net shape casting/thin slab casting	11.7	0.68	26.73	(6.24)	20.0	594	156.08	2.67	$0.30
Secondary Hot Rolling									
Process control in hot strip mill	2.4	0.19	0.45	-	10.0	123	60.61	0.75	$0.32
Recuperative burners	3.9	0.32	1.13	-	10.0	199	92.77	1.16	$0.32
Insulation of furnaces	0.5	0.04	2.70	-	10.0	27	1,623.40	20.22	$0.32
Controlling oxygen levels and VSDs on combustion	1.9	0.15	0.23	-	15.0	94	37.23	0.46	$0.31
Energy-efficient drives in the rolling mill	0.2	0.00	0.09	-	20.0	9	149.29	6.03	$0.30
Waste heat recovery from cooling water	0.3	0.03	0.52	0.05	15.0	16	660.88	7.98	$0.31
General Technologies									
Preventative Maintenance	3.1	0.11	0.01	0.02	20.0	156	7.51	0.20	$0.30
Energy monitoring and management system	0.7	0.03	0.14	-	5.0	35	80.36	2.15	$0.41
	-	-	-	-	-	-	-	-	
Integrated Steelmaking									
Iron Ore Preparation (Sintering)									
Sinter plant heat recovery	2.8	0.11	0.59	-	10.0	138	68.77	1.78	$0.32
Reduction of air leakages	0.1	0.00	0.02	-	10.0	5	63.58	2.57	$0.32
Increasing bed depth	0.4	0.02	-	-	10.0	21	-	-	$0.32
Improved process control (sinter plant)	0.2	0.01	0.03	-	10.0	10	44.44	1.27	$0.32
Use of waste fuels in the sinter plant	0.7	0.03	0.03	-	10.0	33	13.44	0.35	$0.32
Coke Making									
Coal moisture control	0.4	0.07	11.16	-	10.0	19	9,456.92	52.83	$0.32
Programmed heating - coke plant	0.2	0.04	0.05	-	10.0	11	78.33	0.44	$0.32
Variable speed drive coke oven gas compressors	0.0	0.00	0.07	-	15.0	0	2,347.27	13.11	$0.31
Coke dry quenching	1.6	0.28	15.94	0.11	18.0	78	3,183.40	17.78	$0.30
Iron Making (Blast Furnace)									
Pulverized coal injection to 130 kg/thm	2.2	0.14	1.30	(0.37)	20.0	108	9.56	0.14	$0.30
Pulverized coal injection to 225 kg/thm	2.0	0.13	1.20	(0.23)	20.0	99	66.07	1.00	$0.30
Injection of natural gas to 140 kg/thm	2.4	0.16	0.88	(0.35)	20.0	120	(36.23)	(0.55)	$0.30
Top pressure recovery turbines (wet type)	0.7	0.02	3.18	-	15.0	35	1,403.23	56.66	$0.31
Recovery of blast furnace gas	0.3	0.02	0.08	-	15.0	13	92.17	1.39	$0.31
Hot blast stove automation	3.0	0.20	0.16	-	5.0	148	22.06	0.33	$0.41
Recuperator hot blast stove	1.1	0.07	1.24	-	10.0	53	375.15	5.66	$0.32
Improved blast furnace control systems	4.4	0.29	0.26	-	5.0	222	24.49	0.37	$0.41
Steelmaking									
BOF gas + sensible heat recovery	11.4	0.92	22.00	-	10.0	570	625.06	7.77	$0.32
Variable speed drive on ventilation fans	0.1	0.00	0.20	-	10.0	7	494.47	19.97	$0.32
Integrated Casting									
Efficient ladle preheating	0.1	0.01	0.03	-	10.0	6	85.67	1.07	$0.32
Thin slab casting	13.7	0.82	29.67	(6.92)	20.0	687	147.75	2.47	$0.30
Integrated Hot Rolling									
Hot charging	1.4	0.11	2.74	(0.23)	20.0	68	437.31	5.44	$0.30
Process control in hot strip mill	1.7	0.14	0.32	-	10.0	85	60.64	0.75	$0.32
Recuperative burners	1.6	0.13	0.46	-	10.0	80	92.82	1.16	$0.32
Insulation of furnaces	0.5	0.04	2.74	-	10.0	27	1,624.31	20.22	$0.32
Controlling oxygen levels and VSDs on combustion	1.9	0.15	0.23	-	15.0	94	37.25	0.46	$0.31
Energy-efficient drives in the rolling mill	0.2	0.00	0.09	-	20.0	9	149.37	6.03	$0.30
Waste heat recovery from cooling water	0.2	0.02	0.40	0.04	15.0	12	661.25	7.98	$0.31
Integrated Cold Rolling and Finishing									
Heat recovery on the annealing line	1.6	0.11	0.99	-	10.0	79	202.50	2.81	$0.32
Reduced steam use in the pickling line	1.4	0.11	1.64	-	10.0	72	368.89	4.77	$0.32
Automated monitoring and targeting system	3.2	0.08	0.40	-	5.0	160	51.78	2.09	$0.41
General									
Preventative Maintenance	7.9	0.43	0.01	0.02	20.0	395	2.92	0.05	$0.30
Energy monitoring and management system	2.8	0.15	0.14	-	5.0	139	20.00	0.37	$0.41

Appendix B. Description of Iron and Steel making Process

Currently there are two main routes for the production of steel: production of primary steel using iron ores and scraps and production of secondary steel using scraps only. A wide variety of steel products are produced by the industry, ranging from slabs and ingots to thin sheets, which are used in turn by a large number of other manufacturing industries. Figure A. 1 presents a simplified scheme of the production routes.

Figure A. 1. Iron and Steel Production Routes



Pig iron is produced in a blast furnace, using coke in combination with injected coal or oil, to reduce sintered or pelletized iron ore to pig iron. Limestone is added as a fluxing agent. Coke is produced in coke ovens. Reduction of the iron ore is the largest energy-consuming process in the production of primary steel. Modern blast furnaces are operated at various scales, ranging from mini blast furnaces (capacity of 75 Ktonnes/year) to the largest with a capacity of 4 Mtonnes/year. Besides iron, the blast furnace also produces blast furnace gas (used for heating purposes), electricity (if top gas pressure recovery turbines are installed) and slags (used as building materials). Direct reduced iron (DRI) is produced by reduction of the ores below the melting point in small scale plants (< 1 Mtonnes/year) and has different properties than pig iron. DRI production is growing and nearly 4% of the iron in the world is produced by direct reduction, of which over 90% uses natural gas as a fuel (Midrex, 1996). DRI serves as a high quality alternative for scrap in secondary steel making (see below).

Primary steel is produced by two processes: open hearth furnace (OHF) and basic oxygen furnace (BOF). The OHF is still used in different configurations, mainly in Eastern Europe, China, India and other developing countries. While OHF uses more energy, this process can also use more scrap than the BOF process. However, BOF process is rapidly replacing OHF worldwide, because of its greater productivity and lower capital costs. In addition, this process needs no net input of energy and can even be a net energy exporter in the form of BOF-gas and steam. The process operates through the injection of oxygen, oxidizing the carbon dioxide in the hot metal. Several configurations exist depending on the way the oxygen is injected. The steel quality can be improved further by ladle refining processes used in the steel mill.

Secondary steel is produced in an electric arc furnace (EAF) using scrap. Scrap is melted and refined, using a strong electric current. DRI can be used to enhance product quality. Several process variations exist, using either AC or DC currents, and fuels can be injected to reduce electricity use.

Casting and shaping are the next steps in steel production. Casting can be a batch (ingots) or a continuous process (slabs, blooms, billets). Ingot casting is the classical process and is rapidly being replaced by continuous casting machines (CCM). In 1998, 83% of global crude steel production was cast continuously [IISI 1999]. Continuous casting is a significantly more energy-efficient process for casting steel than the older ingot casting process. The casted material can be sold as ingots or slabs to steel manufacturing industries. However, most of the steel is rolled by the steel industry to sheets, plates, tubes, profiles or wire. Generally the steel is first treated in a hot rolling mill. The steel is heated and passed through heavy roller sections reducing the thickness of the steel. Hot rolling produces profiles, sheets, or wire. After hot rolling the sheets may be reduced in thickness by cold rolling. Finishing is the final production step, and may include different processes such as annealing, pickling, and surface treatment. A more advanced technology, near net shape casting, reduces the need for hot rolling because products are cast closer to their final shape.

B.1. Overall Measures[1]

Preventative maintenance involves training personnel to be attentive to energy consumption and efficiency. Successful programs have been launched in many industries (Caffal, 1995; Nelson, 1994). Examples of good housekeeping in steel making include timely closing of furnace doors to reduce heat leakage and reduction of material wastes in the shaping steps. We estimate energy savings of 2% of total energy use, or fuel savings of 0.45 GJ/t of product and electricity savings of 0.04 GJ_e/t of product, based on savings experienced at an integrated steel plant in The Netherlands (Worrell et al., 1993). We assume minimal investment costs for good housekeeping options

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[1] Excerpted from Ernst Worrell, Nathan Martin, Lynn Price (1999) *Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the U.S. Iron and Steel Sector*. LBNL Report #41724

($0.01/t), although training and in-house information are needed, resulting in increased annual operating costs. Based on good housekeeping projects at Rover (a large car manufacturing plant in the UK), we estimate annual operating costs of about $11,000 per plant, or approximately $0.02/t crude steel (Caffal, 1995). We apply this measure to all integrated and secondary steel making in the U.S. in 1994.

Energy monitoring and management systems. This measure includes site energy management systems for optimal energy recovery and distribution between various processes and plants. A wide variety of such energy management systems exist (Worrell et al., 1997; Caffal, 1995). Based on experience at the Hoogovens steel mill (The Netherlands) and British Steel (Port Talbot, UK), we estimate energy savings of 0.5%, or fuel savings of 0.12 GJ/t of product and electricity savings of 0.01 GJ_e/t of product, for U.S. integrated sites (Farla et al., 1998; ETSU, 1992). We estimate the costs of such a system to be approximately $0.15/t crude steel based on the costs for the system installed at Hoogovens ($0.8M) (Farla et al., 1998). This measure is applied to 100% of U.S. steel production facilities.

B.2. Iron Ore Preparation[2]

Iron ore is prepared in sinter plants where iron ore fines, coke breeze, water treatment plant sludges, dusts, and limestone (flux) are sintered into an agglomerated material (U.S. DOE, OIT, 1996). In 1994, 12.1 Mt of sinter were produced in the U.S. (AISI, 1996). Fuel consumption for this process 26 PJ and electricity consumption was 2 PJ resulting in a primary energy intensity of 2.6 GJ/t sinter.

Sinter plant heat recovery. Heat recovery at the sinter plant is a means for improving the efficiency of sinter making. The recovered heat can be used to preheat the combustion air for the burners and to generate high pressure steam which can be run through electricity turbines. Various systems exist for new sinter plants (e.g. Lurgi EOS process) and existing plants can be retrofit (Stelco, 1993; Farla et al., 1998). In 1994, only 15% of the blast furnace feed consisted of sinter; the remainder of the feed was composed of pellets, pelletized at the mining site (AISI, 1996). We apply this measure to all existing sinter plants and estimate the fuel savings (steam and coke) associated with production of this 12.2 Mt of sinter to be 0.55 GJ/t sinter, based on a retrofitted system at Hoogovens in The Netherlands, with increased electricity use of 1.5 kWh/tonne sinter (Rengersen et al., 1995). NOx, SOx and particulate emissions are also reduced with this system. The measure has capital costs of approximately $3/t sinter (Farla et al. 1998). We do not estimate costs for new sinter plants since it is unlikely that such plants will be built in the U.S., due to the large investment required. New iron making technologies (discussed below) aim at the use or lump ore or ore fines, instead of using agglomerated ores.

Reduction of air leakage. Reduction of air leakages will reduce power losses for the fans by approximately 3-4 kWh/t sinter (Dawson, 1993), and could have a positive effect on the heat recovery equipment. These savings may need small investments for repair of the existing equipment. We estimate these costs at $0.1/t sinter capacity.

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[2] Two energy efficiency measures that we do not include are the use of higher quality iron ores in iron ore preparation and reduction of the basicity of the sinter (Aichinger, 1993). These measures are not considered due to lack of data on current implementation and future potential in the U.S.

Increasing bed depth. Increasing bed depth in the sinter plant results in lower fuel consumption, improved product quality, and a slight increase in productivity. The savings amount to 0.3 kg coke/t sinter per 10 mm bed thickness increase, and an electricity savings of 0.06 kWh/t sinter (Dawson, 1993). We assume a bed thickness of 550 mm in 1994, which can be increased to 650 mm. This will result in a fuel savings of 0.09 GJ/t sinter and an electricity savings of 0.002 GJ/t sinter. No investment costs are assumed for this measure.

Improved process control. Improved process controls in various systems have resulted in energy savings, and many different control systems have been developed. Based on general experience with industrial control and management systems, the savings may be estimated at 2-5% of energy use (Worrell et al., 1997). We conservatively use a figure of 2% savings or a primary energy savings 0.05 GJ/t sinter. Capital costs are assumed to be $0.15/t sinter (See also the measure on Energy management and monitoring systems).

Use of waste fuels in the sinter plant can reduce the energy demand in sinter making. The energy demand in sinter making is met by mixing iron ore with breeze from coke making and gas in burners. Sinter making is also used to "scavenge" byproducts such as millscale and iron-containing dusts and sludges. It is possible to use waste oils (especially from cold rolling mills) which are currently landfilled (U.S. DOE, OIT, 1996), however the use will be limited by emission limits due to incomplete combustion. A well-monitored combustion process could reduce the use of gas in the burners (Cores et al., 1996). It is difficult to estimate the savings for this measure, since it depends on the composition and quantity of lubricants and the installed gas clean-up system at the sinter plant. However, based on a survey of European mills, the average sludge production from cold rolling mills is 1 kg/t rolled material. The variation can be large, though, ranging from 0.01 to 10 kg/t steel. The oil content is less than 10% and the sludge contains around 45-55% iron. While this does not represent much energy, it is beneficial to process this sludge in the sinter plant to recover the iron losses. About 50% of the sludge is recycled in the sinter plant in Europe. Along with the oil recovery sludges, there are also oil, creases, and emulsions produced at a rate of 1.3 kg/t rolled steel (Roederer and Gourtsoyannis, 1996). Assuming that the high heating value of these oils is the same as that of heavy fuel oil, total oil production is estimated to be around 1.2 kg oil/t rolled steel (assuming 7.5% in oil recovery sludges and 90% in oils, creases, and emulsions). We assume a calorific value of 34 MJ/kg, or an energy savings of 41 MJ/t rolled steel, or 0.18 GJ/t sinter. (Cores et al., 1996). This is measure is applied to integrated plants with sinter plants on site (allowing for waste recovery), or 74% of the rolling sludges and oils (1.68 PJ). Bethlehem steel has developed a waste recovery and waste injection system, at a cost of about $25 M to recycle 200 ktons of various materials (Schriefer, 1997). We estimate the tonnage of waste fuels recycled to be 4,800 tons at an estimated production of 4 Mt rolled steel. With an estimated sinter production of 3 Mt, this results in a cost of $0.20/t sinter.

B.3. Coke Making

Currently there are 50 active coke batteries in the U.S. with a total production in 1994 of 16.6 Mt coke (Hogan and Koelble, 1996b). Coke making consumed 74 PJ of fuel and 2 PJ of electricity, resulting in a primary specific energy consumption of 4.9 GJ/t (U.S. DOE, OIT, 1996).

Coal moisture control uses the waste heat from the coke oven gas to dry the coal used for coke making. The moisture content of coal varies, but it is generally around 8-9% for good coking coal (IISI, 1982). Drying reduces the coal moisture content to a constant 3-5% (Stelco, 1993) which in turn reduces fuel consumption in the coke oven by approximately 0.3 GJ/t. The coal can be dried using the heat content of the coke oven gas or other waste heat sources. Coal moisture control costs for a plant in Japan were $21.9/t of steel (Inuoe, 1995). Based on Japanese coke use data in 1990, we assume approximately 450 kg coke/t of crude steel, resulting in coal moisture control costs of $49/t coke or $14.7/t crude steel. We apply this measure to 100% of U.S. coke production in 1994.

Programmed heating instead of conventional constant heating of the coke ovens ensures optimization of the fuel gas supply to the oven at the various stages of the coking process and reduces the heat content of the coke before charging (IISI, 1982). Use of programmed heat can lead to fuel savings of about 10% (IISI, 1982), estimated to be 0.17 GJ/t coke. Small capital costs regarding the computer control system for the coke oven are incurred. We estimate these costs to be $75K per coke battery for a large energy management system (derived from Caffal, 1995), which is equivalent to approximately $0.23/t coke for the coking capacity of the integrated steel mills (excluding merchant coke producers). This measure is also applied to 100% of U.S. coke production in 1994.

Variable speed drive coke oven gas compressors can be installed to reduce compression energy. Coke oven gas is generated at low pressures and is pressurized for transport in the internal gas grid. However, the coke oven gas flows vary over time due to the coking reactions. We assume that the compressors are driven with steam turbines, since we lack information on the coke oven gas compressors in the U.S., and that this measure can therefore be applied to all U.S. coke making facilities. Installing a variable speed drive system on a compressor at a coke plant in The Netherlands saved 6-8 MJ/t coke, at an investment of $0.3/t coke (Farla et al., 1998).

Coke dry quenching is an alternative to the traditional wet quenching of the coke, and this process reduces dust emissions, improves the working climate, and recovers the sensible heat of the coke. Dry coke quenching is typically implemented as an environmental control technology. Various systems are used in Brazil, Finland, Germany, Japan, and Taiwan (IISI, 1993), but all essentially recover the heat in a vessel where the coke is quenched with an inert gas (nitrogen). The heat is used to produce steam (approximately 400-500 kg steam/t), equivalent to 800-1200 MJ/t coke (Stelco, 1993; Dungs and Tschirner, 1994). The steam can be used on site or to generate electricity. For new coke plants the costs are estimated to be $50/t coke, based on the construction costs of a recently built plant in Germany (Nashan, 1992). However, it is very unlikely that new coke plants will be constructed in the U.S., so we use retrofit capital costs in the calculation. Retrofit capital costs depend strongly on the lay-out of the coke plant and can be very high, up to $70 to $90/GJ saved (Worrell et al., 1993). We assume $70/t coke. Operating and maintenance costs are estimated to increase by $0.5/t coke. We apply this measure to all U.S. coke making facilities.

B.4. Iron Making - Blast Furnace

Iron making is the most energy-intensive step in integrated steel making. In 1994 there were 40 blast furnaces in the U.S., producing 49.3 Mt of iron (AISI, 1995). Iron making consumed 676 PJ fuel and 4 PJ electricity, resulting in a primary specific energy consumption of 13.9 GJ/t.

One of the main energy efficiency measures in the iron making stage is the injection of fuels into the blast furnace, especially the injection of pulverized coal (PCI). Pulverized coal injection replaces the use of coke, reducing coke production and hence saving energy consumed in coke making (above) and reducing emissions of coke ovens and associated maintenance costs. Coal injection has increased in recent years due to environmental legislation combined with the high average age of U.S. coke plants. Closing of old coke plants is leading to increased coke imports. In 1994 coke was mainly imported from Japan, China, and Australia (Hogan and Koelble, 1996b).

Increased fuel injection requires energy for oxygen injection, coal, and electricity and equipment to grind the coal. The coal replaces part of the coke that is used to fuel the chemical reactions. Coke is still used as support material in the blast furnace. The maximum fuel injection depends on the geometry of the blast furnace and impact on the iron quality (e.g. sulfur). Coal injection is common practice in many European blast furnaces and is increasing in the U.S. to reduce the amount of coke required. Maximum theoretical coal injection rates are around 280-300 kg/t hot metal. In the U.S. the coal injection rate varies. A 1994 survey of seven blast furnaces in the U.S. gave fuel injection rates between 41 and 226 kg/t hot metal (Lanzer and Lungen, 1996). The highest injection rates, of 225 kg/t, have been reached at USX Gary (Schuett et al., 1997). Coke replacement rates vary between 85% and 100% (Schuett et al., 1997). We assume that 1 kg of coke will be replaced by 1.08 kg of injection fuel, a replacement rate of 92%.

The investments for coal grinding equipment are estimated to be $50-55/t coal injected (Farla et al., 1998). O&M costs show a net decrease due to reduced coke purchase costs and/or reduced maintenance costs of existing coke batteries, which is partly offset by the increased costs of oxygen injection and increased maintenance of the blast furnace and coal grinding equipment. We estimate the reduced operation costs on the basis of 1994 prices of steam coal and coking coal to be $15/t (IEA, 1995). This is a low estimate, as cost savings of up to $33/t are possible, resulting in a net reduction of 4.6% of the costs of hot metal production (Oshnock, 1995a).

Pulverized coal injection to 130 kg/t hot metal. In this measure, the average coal injection rate is increased from the current average of 2 kg/t hot metal (U.S. DOE, OIT, 1996) to 130 kg/t hot metal for all blast furnaces. This net increase of 128 kg/t hot metal leads to fuel savings of 0.77 GJ/t hot metal with capital costs of $7/t hot metal (Farla et al., 1998). Operation costs will decrease by $2/t hot metal (IEA, 1995).[3] This measure is applied to 80% of all blast furnaces; injection of natural gas (see below) is applied to the remaining 20%. Injection of pulverized coal may lead to reduced capacity utilization of the blast furnace (Hanes, 1999). Hence, the economic benefits may vary by plant.

Pulverized coal injection to 225 kg/t hot metal. In this measure, the injection rate is increased to 225 kg/t hot metal (as reached at USX Gary blast furnace 13) for the large volume blast furnaces only (defined as those with production rates of 2.3-3.6 Mt/year, which is approximately 30% of total production) (Schuett et al., 1997). This leads to fuel savings of 0.57 GJ/t hot metal, with an extra investment of $5.2/t hot metal and reduced operating costs of $1/t hot metal.

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[3] Costs are calculated as follows: 128kg coal/t hot metal = 0.128t coal/t hot metal * $55 capital costs = $7/t hot metal.

Injection of natural gas.[4] This measure is only applied to a portion of medium sized furnaces, defined as those with production rates of 1.3-2.3 Mt/year, represent 20% of total furnaces. Currently, coal is seen as the favorable injection fuel because of its low price. Injection of natural gas is an alternative. Maximum injection rates are lower than for coal (Oshnock, 1995b). Replacement rates for natural gas vary between 0.9 and 1.15 kg natural gas/kg coke (Oshnock, 1995b). Natural gas injection tests by the Gas Research Institute show a maximum injection rate of 130-150 kg/t hot metal, with estimated costs savings of $4-5/t hot metal (Anonymous, 1995). Assuming a replacement rate of 1kg natural gas/kg coke, savings from replacing 140 kg of coke are estimated to be 0.9 GJ/t hot metal. We assume that operating costs will decrease similar to that seen in the lower PCI injection measure ($2/t hot metal).

Top pressure recovery turbines (wet type) are used to recover the pressure in the furnace.[5] Although the pressure difference is low, the large gas volumes make the recovery economically feasible. The pressure difference is used to produce 15-40 kWh/t hot metal (Stelco, 1993). Turbines are installed at blast furnaces worldwide, especially in areas where electricity prices are relatively high (e.g. Western Europe, Japan). The standard turbine has a wet gas cleanup system. The top gas pressure in the U.S. is generally too low for economic power recovery (I&SM, 1997a&b). A few large blast furnaces (representing 20% of production) have sufficiently high pressure. Future upgrades of blast furnaces might lead to increasing top pressures to improve productivity. We assume a power recovery of 30 kWh/t hot metal in the U.S., with typical investments of about $20/t hot metal (Inoue, 1995) for 20% of the 1994 U.S. blast furnace capacity.

Recovery of blast furnace gas during charging of the blast furnace is designed to recover the 1.5% of gas that is lost during charging. A recovery system has been developed and installed by Hoogovens in The Netherlands. The savings are estimated to be 66 MJ/t hot metal at a cost of $0.3/t hot metal (Farla et al., 1998). We assume that such systems can be installed in 60% of U.S. blast furnace capacity based on an estimate of the number of bell-type charging mechanisms in the U.S.

Hot blast stove automation can help to reduce the energy consumption of the stoves, increase the reliability of the operation, increase stove life-time, and optimize gas mix (Beentjes et al., 1989; Derycke et al., 1990; Kowalski et al., 1990). The energy savings of such systems are estimated to be between 5% (Beentjes et al., 1989) and 12 to 17% (Derycke et al., 1990). Based on the high fuel consumption of hot blast stoves in the U.S. (U.S. DOE, OIT, 1996) we assume savings of 370 MJ/t

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[4] The implementation level of this measure will interact with the level of pulverized coal injection. Following further research, we may revise both this and the pulverized coal injection measure to reflect an increased emphasis on the use of natural gas over coal due to CO2 concerns. At this time, we do not have adequate data on actual levels of natural gas injection. Other fuels can also be injected, but we have not included any due to lack of data. Injection of plastic wastes has been tested at Stahlwerke Bremen in Germany at rates of 30 kg/t hot metal (Janz and Weiss, 1996). Chlorine content (due to PVC) may lead to dioxin formation, making efficient flue gas control equipment necessary.

[5] Top pressure recovery turbines (dry type) use a dry gas clean up system which raises the turbine inlet temperature, increasing the power recovery by about 25-30% (Stelco, 1993). However, the system is more expensive, estimated at 28 US$/t hot metal (Inoue, 1995). Due to the high costs, we assume that this system will not be implemented on existing blast furnaces in the U.S. in the near term.

hot metal (Derycke et al., 1990). The installation of a hot blast stove automation system at Sidmar, Gent (Belgium) had a payback of two months (Derycke et al., 1990). We assume an investment cost of \$0.3/t hot metal, to be implemented in all small blast furnaces, or 60% of the total U.S. blast furnace capacity (equivalent to 30.3 Mt in 1994). We assume that all blast furnaces with capacities over 4500t hot metal/day have already installed automatic control systems.

Recuperator hot blast stove. Hot blast stoves are used to heat the combustion air of the blast furnace. The exit temperature of the hot blast stove flue gases is approximately 250°C. The heat can be recovered to preheat the combustion air of the stoves. Various recovery systems have been developed and implemented (Stelco, 1993). Fuel savings vary between 80 and 85 MJ/t hot metal (Farla et al., 1998; Stelco, 1993). We assume savings of 80 MJ/t hot metal. The costs of recuperation systems are high and depend strongly on the size of the stoves (i.e. the blast furnace). We estimate the costs to be \$18-20/GJ saved (Farla et al., 1998), equivalent to \$1.4/t hot metal. An efficient hot blast stove can run without the need for natural gas. We apply this measure to 100% of 1994 U.S. blast furnaces.

Improved blast furnace control systems have been developed in Japan and Europe that provide improved control over systems currently used in Canada (Stelco, 1993) and presumably in the U.S. A successful control system has been installed at Rautaruukki Steel Works in Raahe, Finland, reducing total fuel use to 440-450 kg/t hot metal (Stelco, 1993), and increasing productivity and flexibility (Pisila et al., 1995). British Steel has developed an expert system for blast furnace control (Fitzgerald, 1992). We estimate the savings of improved blast furnace control strategies at half of the savings reached at Rautaruukki, i.e. 0.4 GJ/t hot metal (Pisila et al., 1995), with the other half attributed to charge material upgrading. Capital costs are estimated to be \$0.5M per blast furnace. With 40 blast furnaces and a combined capacity of 55.5 Mt this is equivalent to \$0.36/t hot metal (Hogan and Koelble, 1996a). No large changes in operating costs are expected. We apply this measure to 50% of 1994 U.S. blast furnaces.

B.5. Iron Making - Alternatives

Direct reduced iron (DRI), hot briquetted iron (HBI,) and iron carbide are all alternative iron making processes (McAloon, 1994). Because of the small production quantities (in the reference year 1994) we do not discuss energy efficiency measures in the alternative iron making processes separately. In 1994 only one producer (Georgetown Steel) produced 480 kt DRI (Midrex, 1995), using a gas-based Midrex process built in 1971. The energy consumption of a state-of-the-art Midrex-unit is 10 to 11 GJ/t iron and 110 kWh/t (Midrex, 1993). DRI is produced through the reduction of iron ore pellets below the melting point of the iron. DRI is mainly used as a high quality iron input in electric arc furnace (EAF) plants. The U.S. steel industry also imports DRI from countries in Latin America. New DRI plants are being constructed in Alabama (a mothballed plant built originally in 1975 in Scotland) and in Louisiana (a new Midrex Megamod module) and other plants have been announced. A new alternative iron production process, the iron carbide process, has been pioneered by Nucor which has one plant operating in Trinidad and another plant scheduled to be built in Texas. The growing production by EAF plants in the U.S., high scrap prices, and the need for high quality inputs due to the expansion of EAF producers in the flat steel market will increase the future demand for alternative iron inputs.

Steel making - Basic Oxygen Furnace (BOF)

In basic oxygen furnace (BOF) steel making a charge of molten iron and scrap steel along with some other additives (manganese and fluxes) is heated and refined to produce crude steel. BOF crude steel production in 1994 was 55.3 Mt with fuel and electricity consumption of 19 PJ and 6 PJ, respectively. Primary energy intensity for this process step in our base year (1994) was 0.7 GJ/t.

BOF gas and sensible heat recovery (suppressed combustion) is the single most energy-saving process improvement in this process step, making the BOF process a net energy producer. By reducing the amount of air entering over the convertor, the CO is not converted to CO_2. The sensible heat of the off-gas is first recovered in a waste heat boiler, generating high pressure steam. The gas is cleaned and recovered. The total savings vary between 535 and 916 MJ/t steel, depending on the way the steam is recovered (Stelco, 1993). Suppressed combustion reduces dust emissions and since the metal content of the dust is high, about 50% of the dust can be recycled in the sinter plant (Stelco, 1993). The costs will depend on the need for extra gas holders. Suppressed combustion is very common in integrated steel plants in Europe and Japan. In the U.S. no BOF gas seems to be recovered (U.S. DOE, OIT, 1996; Hanes, 1999), so we apply this measure to 100% of U.S. BOF steel making. We assume an energy recovery rate of 916 MJ/t crude steel (Stelco, 1993), with estimated capital costs of 22$/t crude steel, based on plants in Japan (Inoue, 1995) and The Netherlands (Worrell et al., 1993).

Variable speed drive on ventilation fans. The BOF process is basically a batch process. The volumes of flue gases vary widely over time, making variable speed drives an option. Large fans are used in the BOF plant to control air quality. At Hoogovens the use of variable speed drives has been shown to save power (Worrell et al., 1993) in the BOF, reducing the power demand by approximately 20%, or 0.9 kWh/t crude steel (Farla et al., 1998). With total costs of $1M (1988) the investment costs are $0.2/t crude steel (Farla et al., 1998). We assume that such variable speed drives could be used in all U.S. BOF steel making facilities.

B.6. Secondary Steel making - Electric Arc Furnace (EAF)

Electric arc furnace or secondary steel making involves the production of steel from scrap metal which is melted and refined using electricity in an electric arc furnace (U.S. DOE, OIT, 1996). Electric arc furnaces are on average smaller capacity compared to blast furnace/BOF capacity and use less energy. In 1994 there were 122 secondary steel mills with 226 electric arc furnaces. EAF steel production in 1994 was 35.9 Mt and energy consumption for the furnaces was 6 PJ fuel and 62 PJ of electricity, reflecting a primary energy intensity of 5.5 GJ/t.

Improved process control (neural networks) can help to reduce electricity consumption beyond that achieved through classical control systems. For example, neural networks or “fuzzy logic” systems analyze data and emulate the best controller. For EAFs, the first “fuzzy logic” control systems have been developed using current, power factor and power use to control the electrodes in the bath (Staib and Bliss, 1995). The average power savings are estimated to be up to 8% (or 38 kWh/t), with an average increase in productivity of 9-12% and reduced electrode consumption of 25% (Staib and Bliss, 1995). The actual savings depend on the scrap used and the furnace operation. Furnace maintenance costs are reduced as well. We assume an average efficiency improvement of 30 kWh/t (or 0.1 GJ/t). In 1994, advanced control systems were installed at 16 furnaces in the U.S. (Kimmerling, 1997), with a total capacity of 5.8 Mt (equivalent to 9% of the

U.S. EAF capacity in 1994). The capital and commissioning costs are estimated to be $250,000 per furnace, with annual costs savings at roughly $1/t (Kimmerling, 1997). Since the average capacity of EAF plants was 260 kt/year in 1994, we estimate the capital costs to be $0.95/t. The measure is assumed to be applicable for 90% of the U.S. EAF capacity.

Flue gas monitoring and control using variable speed drives can reduce the energy use for the flue gas fans, reducing the heat losses in the flue gas (Stockmeyer et al., 1990; Walli, 1991; Worrell et al., 1997). The flue gas flow varies over time, which makes the use of variable speed drives possible. Flue gas VSDs have been installed in various countries (e.g. Germany, UK). The electricity savings are estimated to be 15 kWh/t (Stockmeyer et al., 1990), with a payback period of 2 to 3 years (Walli, 1991; Worrell et al., 1997). We estimate the capital investments to be $2/t, and apply this measure to all furnaces with a size of 100 t or larger, equivalent to 50% of the U.S. EAF capacity.

Ultra high power transformers. Transformer losses can be as high as 7% of the electrical inputs (CMP, 1992). The losses will depend mainly on the sizing and age of the transformer. When replacing the transformer it is possible to convert furnace operation to ultra high power, increasing productivity, as well as reducing energy losses. Ultra high power furnaces are those with a transformer capacity of over 700 kVA/t heat size. The savings are estimated at 1 kWh/t per MW power increase. The weighted 1994 average transformer capacity is estimated to be 480 kVA/t heat size for all non-ultra high power (UHP) furnaces. In 1994 38% of EAF capacity can be classified as UHP furnaces. Many EAF operators have installed new transformers and electric systems to increase the power of the furnaces, e.g. Co-Steel (Raritan, NJ), SMI (Sequin, TX), Bayou Steel (Laplace, LA) (Ninneman, 1997). UHP operation might lead to heat fluxes, and increased refractory wear, making cooling of the furnace panels necessary. This results in heat losses partially offsetting the power savings. The increased power can be reached by installing new transformers or paralleling existing transformers. The replacement of a 93 MVA transformer at Co-Steel (Raritan, NJ) with one rated at 120-144 MVA in 1997 was included in a project totally costing $6.2M (Ninneman, 1997). This is equivalent to approximately 8.3$/t steel produced. This is a high cost estimate as the total project costs included other equipment as well. We assume that all transformers for medium to large furnaces over 15 years old can be replaced by more efficient equipment. This is equivalent to approximately 115 furnaces with a capacity of 32.2 Mts (40% of the total EAF capacity). We assume that the losses can be reduced to 4%, saving approximately 14 kWh/t. Transformers are assumed to have a lifetime of 15 years. The total energy savings are estimated to be 17 kWh/t, (14 kWh due to transformer replacement and 3 kWh for upgrading to UHP).

Bottom stirring/stirring gas injection is done by injecting an inert gas (e.g. argon) in the bottom of the EAF, which increases the heat transfer in the melt and the interaction between slag and metal (leading to an increased liquid metal yield of 0.5%) (Schade, 1991). This increased stirring in the bath can lead to electricity savings of 11 to 22 kWh/t, with annual net production cost reduction of $0.5 to 1.0/t accounting for increased labor and argon costs, based on tests at Lukens Steel Co. in 1990 (Schade, 1991). Increased liquid steel yield increases the net cost savings to $0.9-2.3/t (Jones, 1993). Furnaces with oxygen injection are sufficiently turbulent, reducing the need for inert gas stirring (see below). We assume power savings of 20 kWh/t and cost savings of $1.5/t. No data are available on the current application rate in U.S. EAFs. We assume potential application in 11% of the 1994 EAF capacity (i.e. small AC furnaces without oxygen injection). The capital costs for retrofitting existing furnaces are estimated to be $0.6/t (1987) (Riley and Sharma, 1987) for increased refractory costs and installing tuyeres. The annual costs for inert gas purchases are estimated to be $1.1/t (Riley and Sharma, 1987). The productivity increase (excluding saved energy costs, including saved electrode costs, labor and alloys) is estimated to be $3.1/t (Riley and Sharma, 1987). The lifetime of the tuyeres is limited to 100-200 heats (Riley and Sharma, 1987), or approximately 6 months.

Foamy slag practice helps to reduce the heat losses through radiation from the melt by covering the arc and melt surface with foamy slag. Foamy slag can be obtained by injecting carbon (granular coal) and oxygen, or lancing of oxygen only. Foamy slag practice seems to be common with a large number of operators in the U.S., so the potential savings are limited. However, not all operators have implemented the practice well. We will assume that all medium to large furnaces without oxygen injection can still implement this technology. Approximately 30-40% of the 1994 capacity (Jones, 1998) could still implement foamy slag practice, or improve the application. The net energy savings (accounting for energy use for oxygen production) are estimated at 5-7 kWh/tonne steel (derived from Adolph et al., 1990). Based on the costs of installing oxygen lances the investments are estimated at approximately 10$/tonne capacity (Jones, 1997b). Foamy slag practice may also increase productivity through reduced tap-to-tap times, which is equivalent to an n estimated cost saving of 1.8$/tonne steel (derived from Adolph et al., 1990).

Oxy-fuel burners/lancing can be installed in EAFs to reduce electricity consumption by substituting electricity with fuels, increase heat transfer and reduce heat losses (foamy slag, see above). Typical savings range from 2.5 to 4.4 kWh per Nm3 oxygen injected (IISI, 1982; CMP, 1987; Haissig, 1994; Stockmeyer et al., 1990), with common injection rates of 18 Nm3/t (IISI, 1982). The injection rate can be increased to 26 m3/t with increased fuel injection. Natural gas injection is 10 scf/kWh, or 0.3 m3/kWh, (CMP, 1992), with typical savings of 20-40 kWh/t (Jones, 1996). Approximately 29% of the 1994 capacity (or 16 Mt in medium to large furnaces) has no oxy-fuel burners installed (I&SM, 1997b). These furnaces have an average power consumption of 502 kWh/t. We assume implementation of oxy-fuel burners in 25% of the existing EAF capacity, with net energy savings of approximately 40 kWh/t. Modification investment costs depend on the furnace size. With an average EAF size of 110 tons, the investments are estimated to be approximately $4.8/t (Jones, 1997a). The improved heat distribution leads to reduced tap-to-tap times of about 6% (CMP, 1995), leading to estimated annual cost savings of $4.0/t (CMP, 1987). Oxygen injection also reduces the nitrogen content of the steel, leading to improved product quality (Douglas, 1993). We estimate a lifetime of 10 years for this measure.

Eccentric bottom tapping (EBT). Eccentric bottom tapping is applied in most modern furnaces, leading to slag-free tapping, shorter tap-to-tap times (increased productivity), reduced refractory consumption, reduced electrode consumption (0.1 to 0.3 kg/t) and improved ladle life. EBT helps to reduce energy losses and to improved emissions control. The energy savings are estimated to be 15 kWh/t (0.05 GJ/t) (CMP, 1992). Reconstructing an existing EAF furnace at Ipsco, Regina (Saskatchewan, Canada) cost $2.2 M (Ninneman, 1997). The furnace has an annual production capacity of 688 kt, estimating the retrofit costs at $3.2/t capacity. It is assumed that all new furnaces have EBT**.** We assume that EBT can be installed in all medium to large capacity EAF built before 1986 (29.5 Mts), as the technology was introduced commercially around 1983 (Teoh, 1989), or equivalent to 52% of the production.

DC arc furnaces use direct current (DC) instead of conventional alternating current (AC). In a DC furnace one single electrode is used, and the bottom of the vessel serves as the anode, resulting in improved heat distribution in the furnace. This reduces the power consumption. Another major advantage of DC furnaces is the reduced tap-to-tap time and electrode consumption (down to 1.2-1.6 kg/t steel) (Macauley and Smailer, 1997; Mueller, 1997), increased refractory life, and improved stability (Jones,1997b; Stelco,1993). DC technology is applicable to large furnaces (80 - 130 t heat size), and small furnaces are expected to remain AC systems. Larger DC-furnaces (using two electrodes) are being investigated. The disadvantage of DC-systems is the up to 10-35% higher capital costs (Jones, 1997b). Currently, the maximum current is restricted due to the use of one electrode, but UHP DC systems are under development (Palasios and Arana, 1995). In the US, Charter Steel, Florida Steel, Gallatin Steel, North Star, and Nucor (Hickman, Berkeley, Norfolk) are using DC furnaces. The 1994 average power consumption of furnaces over 100 ton heat size is estimated at 473 kWh/t (430 kWh/ton). The Nucor-plant (Hickman) achieves a consumption of 368 kWh/t, 36 Nm3 oxygen and 0.5-1.8 kg electrode (Mueller, 1997). The net energy savings are estimated at 90 kWh/t (accounting for oxygen production at 0.4 kWh/Nm3 (Hendriks, 1994)). Compared to new AC furnaces the savings are limited to 10-20 kWh/tonne (Jones, 1998). Based on a cost-estimate for a 100 ton furnace the net extra investments compared to an AC furnace are estimated to be $2.7M, or $3.9/t capacity (1991) (CMP, 1991). Whereas the cost savings are estimated at $2 to $6/ton (CMP, 1991). This includes electrode cost savings, that are approximately $2/ton steel (CMP, 1992). We assume annual cost savings (excluding energy costs) of $2.5/t. Introducing DC furnaces competes with oxygen lancing, fuel injection, post combustion, and eccentric bottom tapping,. We assume a market penetration of 15% of capacity in the US, of which two-thirds is assumed to use as a twin shell to preheat scrap (see below).

Scrap preheating is a technology that can reduce the power consumption of EAFs through using the waste heat of the furnace to preheat the scrap charge. Old (bucket) preheating systems had various problems, e.g. emissions, high handling costs, and a relatively low heat recovery rate. Modern systems have reduced these problems, and are highly efficient. The energy savings depend on the preheat temperature of the scrap. Various systems have been developed and are in use at various sites in the U.S. and Europe, i.e. Consteel tunnel-type preheater, Fuchs Finger Shaft, and Fuchs Twin Shaft. Twin shell furnaces (see below) can also be used as scrap preheating systems. All systems can be applied to new constructions, and also to retrofit existing plants.

The **Consteel process** consists of a conveyor belt with the scrap going through a tunnel, down to the EAF through a “hot heel”. Various U.S. plants have installed a Consteel process, i.e. Florida Steel (now AmeriSteel, Charlotte, NC) New Jersey Steel (Sayreville, NJ) and Nucor (Darlington, SC), and one plant in Japan. The installation at New Jersey Steel is a retrofit of an existing furnace (Lahita, 1995). Besides energy savings, the Consteel-process results in a productivity increase of 33% (Jones, 1997a), reduced electrode consumption of 40% (Jones, 1997a) and reduced dust emissions (Herin and Busbee, 1996). Electricity use can be decreased to approximately 370-390 kWh/t (Herin and Busbee, 1996) without supplementary fuel injection in retrofit situation, while consumption as low as 340-360 kWh/t have been achieved (Jones, 1997c) in new plants. We estimate the electricity savings to be 60 kWh/t for retrofit. The extra investments are estimated to be $2M (1989) for a capacity of 400-500,000 ton per year (Bosley and Klesser, 1991), resulting in specific investments of approximately $4.4 to $5.5/t. The annual costs savings due increased productivity, reduced electrode costs and increased yield are estimated to be $1.9/t (Bosley and Klesser, 1991).

The **FUCHS shaft furnace** consists of a vertical shaft that channels the offgases to preheat the scrap. The scrap can be fed continuously (4 plants installed world wide) or through a so-called system of 'fingers' (15 plants installed worldwide) (VAI, 1997). The optimal recovery system is the 'double shaft' furnace (3 plants installed worldwide), which can only be applied for new construction. The Fuchs-systems make almost 100% scrap preheating possible, leading to potential energy savings of 100-120 kWh/t (Hofer, 1997). The energy savings depend on the scrap used, and the degree of post-combustion (oxygen levels). In the U.S. Fuchs systems have been installed at North Star (single shaft (1996), Kingman, AZ), North Star-BHP (double shaft (1996), Delta, OH), Birmingham Steel (finger shaft (1997), Memphis, TN). Two other Finger shaft processes have been ordered by Chapparel (TX) and North Star (Youngstown, OH). Carbon monoxide and oxygen concentrations should be well controlled to reduce the danger of explosions, as happened at North Star-BHP. The scrap preheating systems lead to reduced electrode consumption, yield improvement of 0.25-2% (CMP, 1997; VAI, 1997), up to 20% productivity increase (VAI, 1997) and 25% reduced flue gas dust emissions (reducing hazardous waste handling costs) (CMP, 1997). A special system has been developed for retrofitting existing furnaces called the Fuchs Optimized Retrofit Shaft, with a relatively short shaft. Retrofit costs are estimated at $6/t (Hofer, 1997) for an existing 100 t furnace. Using post-combustion the energy consumption is estimated at 340-350 kWh/t (Jones, 1997d) and 0.7 GJ fuel injection (Hofer, 1996). The production costs savings amount up to $4.5/t (excluding saved electricity costs) (Hofer, 1997).

Scrap preheating competes with oxy-fuel injection and post combustion, as these options are basically integrated in most scrap preheating systems. All furnaces over 70 t capacity could be retrofitted cost-effectively (Hofer, 1996), or 74% of the 1994 U.S. capacity (using on average 470 kWh/t in 1994), leading to net power savings of approximately 120 kWh/t and increased fuel consumption of 0.7 GJ/t.

Twin shell furnace. The Twin shell concept comprises two EAF-vessels with a common arc and power supply system. The system increases the productivity by reducing the tap-to-tap time to approximately 45 to 50 minutes (Heinrich, 1995, Ninneman, 1997), and reducing energy costs through reduced heat losses. Also, the hot flue gases of one shell can be used to preheat the second shell. A twin shell AC plant is estimated to use 393 kWh/t compared to 412 kWh/t, saving 19 kWh/t (Macauley and Smailer, 1997) compared to current state-of-the-art single vessel plants for a 100% scrap feed. The twin shell DC plant can save even more, 80 kWh/t compared to the 1994 average large scale AC furnace. The twin-shell concept can only be applied in the construction of a new plant. New plants in the U.S. using the Twin Shell concept are Gallatin Steel, Nucor, Steel Dynamics, and Tuscaloosa Steel, and the resulting energy use varies for each of these plants. The EAF at Gallatin steel has two AC furnaces, and consumes approximately 450 kWh/t (Jones, 1997b). DC furnaces can be used as well, reducing the power consumption further (see above). The Twin Shell concept competes with the scrap preheating processes discussed above. Twin shells seem to be an appropriate process for mini mills with capacities over 1 Mt per year. Very little cost data exists on the Twin Shell (Jones, 1997b). The capital cost lay-out is expected to be a little more (with estimated payback in the U.S. of 2 years), while the production costs are expected to be 6% lower than that of a single shell (Jones, 1997b). We will assume extra investments of $4-6/t (over those of a new single shell furnace, based on the investments at Nucor, Berkeley County, SC), and production cost reduction of $1.1/t (derived from (CMP, 1987), excluding energy cost savings). We assume application of the DC twin shell concept to 10% of the 1994 production capacity.

B.7. Casting

Once crude steel is produced it is cast into different shapes (billets, blooms, slabs, or ingots). Molten steel is poured into a tundish and then released into a mold of one or more strands. A majority of steel in the U.S. is continuously cast which reduces the need for several intermediate process steps. In 1994 we estimate that casting energy use was 17 PJ fuel and 15 PJ of electricity resulting in a primary energy intensity of 0.7 GJ/t (U.S. DOE, OIT, 1996).

Efficient ladle preheating. The ladle of the caster (and the BOF vessel) is preheated with gas burners. Heat losses can occur through lack of lids and through radiation. The losses can be reduced by installing temperature controls (Caddet, 1989), installing hoods, by using recuperative burners (Caddet, 1987), use of oxygen burners (Gitman, 1998), or by efficient ladle management (reducing the need for preheating). Oxygen burners for ladle preheating are used by many steel companies in the U.S. already (Gitman, 1998), but use can be expanded considerably. No data are available on the actual energy use for preheating ladles in the U.S. steel industry. Therefore, we assume typical fuel use of approximately 0.04 GJ/t crude steel (Worrell et al., 1993). Efficient preheating will reduce energy use by 50% or 0.02 GJ/t crude steel, with an estimated payback time of 1.1 year (taking into account savings on ladle handling), or $0.06/t product**,** assuming a gas price of $2.8/GJ (IEA, 1995).

Thin slab casting is a new technology integrating casting and hot rolling in one process. Pioneered in the U.S. by Nucor at the Crawfordsville and Hickmann plants, various plants are operating, under construction, or ordered worldwide. Originally designed for small scale process-lines, the first integrated plants constructed (Acme, U.S.; Posco, Korea) or announced the construction of thin slab casters (Germany, Netherlands, Spain) with capacities up to 1.5 Mt/year (Worrell and Moore, 1997). Currently, four suppliers (Germany (2), Austria and Italy) supply this technology. We base our description on the CSP-process developed by SMS (Germany) as it represents most of the capacity installed worldwide. Energy savings are estimated to be 4.9 GJ/t crude steel (primary energy). The energy consumption of a CSP-plant is 94 MJ fuel per ton for the reheating furnace and electricity use of 43 kWh/t (Flemming, 1995). The investments for a large scale plant are estimated to vary between $110/t and $180/t product (Anon, 1997a; Anon., 1997b, Schorsch, 1996). We assume therefore an investment cost of $134/t crude steel, with estimated operation cost savings of between $25/t and $46/t product (derived from Ritt, 1997 and Hogan, 1992, Schorsch, 1996). We therefore assume an operation cost savings of $31/t crude steel. The potential capacity of thin slab casting is estimated to be 20% of U.S. integrated production and 64% of secondary steel.[6]

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[6] Estimate for the potential of thin slab casting in integrated mills is estimated to be 60% of integrated hot strip and sheet production in 1994 or 11 Mt (AISI, 1996). Estimated potential for secondary mills is based on implementation in slabs in minimills not currently continuously cast. These estimates will need to be refined in the future.

B.8. Hot Rolling[7]

After casting, the shaped products are further rolled to produce sheet, strip, plate, and other structural products (U.S. DOE, OIT, 1996). In 1994, 79.6 Mt of steel was hot rolled with an estimated energy requirement of 259 PJ fuel and 56 PJ of electricity, resulting in a primary energy intensity of 5.4 GJ/t. This energy intensity is relatively high compared to other countries and additional data is required to improve this estimate (U.S. DOE, OIT, 1996).

Hot charging is used to charge slabs at an elevated temperature into the reheating furnace of the hot rolling mill. The slabs can be charged at various temperatures. Higher charging temperatures will save more energy. The implementation of the technique depends on the lay-out of the plant, and the distance between the caster and the hot rolling mill. In some plants the caster and reheating furnace are "next door" making hot charging less costly (e.g. LTV in Cleveland and Usines Gustav Boel, Belgium). Handling and transport of the slabs (i.e. a so-called 'hot connection') is required if there is more distance between the caster and the rolling mill (Worrell et al., 1993). Hot charging not only saves energy, but also improves material quality, reduces material losses, improves productivity (by up to 6%), and may reduce slab stocking (Ritt,1996). Care should be taken to descale the slab before charging in the reheating furnace (Caddet, 1990a). The measure competes with thin slab casting (because in thin slab casting the slab is coupled through a reheating furnace to the rolling stands) and direct rolling. A few plants in the U.S. now hot charge a portion of the production, e.g. LTV (Cleveland), USS (Fairfield), Bethlehem (Burns Harbor), and Geneva Steel, although generally only a small percentage of the slab production (10-15%) is hot charged (Ritt, 1996). We assume that 60% of cold rolled products (36% of the slabs) can ultimately be "hot charged", depending on the lay-out of the plants. A plant-by-plant analysis is required to determine the actual potential. Assuming a charging temperature of 700°C, the savings may be up to 0.6 GJ/t "hot charged" steel based on experiences at Bethlehem Steel at Burns Harbor (Ritt, 1996). Additional annual costs savings amount up to $1.15/t "hot charged". Investment costs will strongly depend on lay-out and are estimated to be $15/t hot rolled steel based on experience at LTV (Wakelin, 1997).

Process control in hot strip mill saves energy and increases productivity and quality of the rolled steel products (Heesen and Burggraaf, 1991; Schriefer, 1996; Vergote, 1996). Although direct energy savings may be limited, the indirect energy savings may be substantial due to reduced rejection of product, improved productivity, and reduced down-time. Based on a system installed at Sidmar (Belgium) the share of rejects was reduced from 1.5% to 0.2% and down-time was reduced from more than 50% of the time to 6%. The costs of rolling were reduced from $7/t to $4.7/t (Vergote, 1996). Similar systems have been installed in mills in many countries. We estimate the energy savings based on the reduced rejection rate and improved productivity to be 9% of fuel use. We assume this to be equivalent to 0.3 GJ/t product. The investment costs for the

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[7] An additional measure is efficient power use in the rolling mill, which can reduce the power demand of the hot rolling mill. Current hot strip mill power use in U.S. is estimated to be 220 kWh/t (0.8 GJ/t) (U.S. DOE, OIT, 1996). A modern hot strip mill has a power consumption of about 105 kWh/t (0.4 GJ/t) (Worrell et al., 1993). Thus, installation of a modern hot strip mill could represent a savings of up to 115 kWh/t (0.4 GJ/t). One component in these mills is motors which are used for the rolling as well as in quench pumps. The quench pumps in a hot rolling mill are estimated to use 2.5 kWh/t (Anon., 1994), on which savings of 42-76% are feasible through the application of variable speed drives and installing control equipment. This system required an investment equivalent to 0.24$/t product saving 1.9 kWh/t hot rolled steel (7 MJe/t). Reduced maintenance costs amount to 0.02$/t product (Anon., 1994). This measure needs further quantification before it can be included in the analysis.

Sidmar plant were estimated to be $2M for a hot strip mill with a capacity of 2.8 Mt (Serjeantson, 1987), equivalent to $0.7/t product. This measure will be applicable to all slabs that are not cast in a thin-slab caster or sold, i.e. 69% of the total steel production. The lifetime of process control equipment is estimated at 10 years.

Recuperative burners in the reheating furnace can reduce energy consumption. Industry-wide average savings for the metals industry are estimated to be up to 30% (Worrell et al., 1997). Energy use in a reheating furnace will depend on production factors (e.g. stock, steel type), operational factors (e.g. scheduling), and design features. Therefore, in practice energy consumption can vary widely between 0.6 and 3.0 GJ/t (Flanagan, 1993), with the low figures due to hot charging (see above). Based on a survey of 151 furnaces (representing 20% of Western world steel production) in Japan, Australia, UK and Canada, it was found that 18% of the furnaces had no heat recovery and 75% had separate heat recovery (Flanagan, 1993). As no specific U.S. data were available, we assume a similar distribution for the U.S. Installing recuperative or regenerative burners may require substantial changes in the furnace construction and may have high investment costs. New designs have typically low NOx emissions, despite higher flame temperatures. We assume installing regenerative burners in 20% of the furnaces used in hot rolling mills, saving approximately 25% on fuel in these (mostly small) furnaces, based on experiences in the UK (Flanagan, 1993), or roughly estimated at 0.7 GJ/t product. The investments for a 12t/hour furnace were approximately $2-3/t. We assume $2.5/t product. The burners are expected to have a lifetime of approximately 10 years.

Insulation of furnaces using ceramic low-thermal mass insulation materials (LTM) can reduce the heat losses through the walls further than conventional insulation materials. A survey of steel reheating furnaces in the steel industry in four countries (not including the U.S.) showed that approximately 30% of the furnaces had ceramic fiber linings (Flanagan, 1993). We assume a similar figure for the U.S. steel industry. For a continuous furnace, the savings of implementing ceramic fiber lining are estimated to be 2-5% (Flanagan, 1993). We assume savings of 0.16 GJ/t product. We assume that 30% of the furnace capacity can be equipped with ceramic lining during maintenance and reconstruction (assuming an approximate life-time of 30 years) in the period until 2005. Although we did not find recent cost data, we assume relative large investments of approximately $10/t product, derived from de Beer et al. (1994). The lifetime is estimated at 10 years.

Controlling oxygen levels and variable speed drives on combustion air fans on the reheating furnace helps to control the oxygen level, and hence optimize the combustion in the furnace, especially as the load of the furnace may vary over time. The savings depend on the load factor of the furnace and control strategies applied. Two cases from the UK steel industry demonstrate the variety. Implementing a variable speed drive combustion fan on a walking beam furnace at Cardiff Rod Mill (UK) reduced the fuel consumption by 48% with a payback period of 16 months (1985 UK conditions) (Caddet, 1994). Another example (without installing variable speed drives) is a walking beam furnace for reheating billets, saving approximately 2% on fuel use, with a payback of one year (1990 UK conditions) (Flanagan, 1993). We conservatively assume savings of 10% (after previous measures have been introduced), equivalent to 0.33 GJ/t product, at an investment of 0.5$/t product. As no data is available on the current penetration of VSDs in reheating furnaces, we assume that this measure can be implemented in half of the furnaces, with a lifetime of approximately 10 years.

Energy efficient drives in the hot rolling mill can replace the currently used conventional AC drives. The efficiency of large AC drives (> 200 kWe) is estimated to be 91-97% (Worrell and Moore, 1997). High efficiency motors can save approximately 1-2% of the electricity consumption (de Almeida and Fonsesca, 1997). Assuming an electricity demand of 200 kWh/t rolled steel, the electricity savings are estimated to be 4 kWh/t, or 0.01 GJ/t product. Replacement costs are estimated to be $5/kW (the extra costs compared to that of an ordinary drive) (de Almeida and Fonsesca, 1997), equivalent to $0.05/kWh-saved, or $0.2/t rolled steel. Large motors have generally a lifetime of 20 years (de Almeida and Fonsesca, 1997). According to Rosenberg (1997) the average penetration of efficient motors in all industrial applications is between 6 and 8%. We assume that 50% of the motors will be replaced at the above mentioned costs.

Waste heat recovery from cooling water. Waste heat can be recovered from the cooling water of the hot strip mill. When ejected, the rolled steel is cooled by spraying water at a temperature of 80 ^{o}C. An absorption heat pump (or heat transformer) has been installed at Hoogovens (The Netherlands) to generate low pressure steam (1.7-3.5 bar, 130 ^{o}C), which is delivered to the grid on the site. Fuel savings are estimated to be 0.04 GJ/t product, with an increased electricity consumption of 0.15 kWh/t (Farla et al., 1998). Investment costs are 42 Dfl/GJ-saved equivalent to $0.8/t product (Worrell et al., 1993)**,** with increased O&M costs estimated at $0.07/t product. The heat transformer could be applied with all quench water in the hot rolling mills, e.g. 69% of the total production. The life time is estimated to be 15 years.

B.9. Cold Rolling and Finishing[8]

Steel that has been hot rolled may be cold rolled and further finished to make a product thinner and smoother. In 1994, 31.7 Mt (35%) of product was cold rolled, all in integrated mills. Based on fuel consumption of 43 PJ and electricity consumption of 15 PJ, the primary energy intensity was 2.8 GJ/t.

Heat recovery on the annealing line can be done through steam generation using the waste heat, or by installing regenerative or recuperative burners in the annealing furnace (Meunier and Cambier, 1993). We aggregate the various energy saving opportunities in one measure, as the total energy consumption in the annealing stage is limited. Energy use for batch annealing is estimated at 1.0 GJ/t fuel and 25 kWh/t, and for continuous annealing 0.8 GJ/t and 45 kWh/t (IISI, 1982). Energy use can be reduced by up to 40% (Meunier and Cambier, 1993), by implementing heat recovery (using regenerative burners), improved insulation, process management equipment, as well as variable speed drives. We estimate the savings at 0.3 GJ fuel/t and 3 kWh/t. All cold rolled steel is assumed to be treated in the annealing furnace, i.e. 30.9 Mt (1994). The total potential energy savings are estimated at 9 PJ. The investment costs are estimated at $2.7/t, based on practices at Hoogovens (The Netherlands).

Reduced steam use in the pickling line. In the pickling line heat escapes through evaporation from the hydrochloric acid bath. The bath is normally heated to temperatures of 95°C (IISI, 1982).

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[8] One measure in cold rolling is continuous annealing, which will reduce the heat losses of the batch furnaces but demands relative high investment costs. We do not assume implementation of this measure as an energy efficiency measure.

The IISI (1982) reports that steam use can be reduced by 5kg/t, with an assumed steam use of 30 kg/t, by installing a system of lids and floating balls on top of the bath. This is equivalent to savings of 17%. For the U.S. steel industry we estimate the savings (including boiler losses) to be 0.19 GJ/t. At a production of 32 Mt cold rolled product, the total fuel savings are estimated to be 6 PJ. No investment cost data were available for this study. We estimate the costs on the basis of a conservative estimate by de Beer et al. (1994) at $2.8/t.

Automated monitoring and targeting system. Installing an automated monitoring and targeting system at a cold strip mill can reduce the power demand of the mill, as well as reducing effluents. A system installed at British Steel at Brinsworth Strip Mills, reduced the energy demand of the cold rolling mill by approximately 15-20%, depending on the load factor (Caddet, 1990b). The savings are estimated to be 60 kWh/t assuming an average electricity consumption of 360 kWh/t (U.S. DOE, OIT, 1996). We assume the implementation of a similar system, at installation costs of $1.1/t product ($0.63/t crude steel) (Caddet, 1990b), for half of the cold strip mills in the U.S. steel industry, or 17% of the total steel production.

B.10. References

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