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Greenhouse Gas Mitigation Options in ISEEM Global Energy Model: 2010-2050 Scenario Analysis for Least-Cost Carbon Reduction in Iron and Steel Sector

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General Acronyms & Units

AIR	Annual Improvement Rate
BOF	Basic Oxygen Furnace
BUEM	Bottom-Up Energy Model
CISRI	China Iron & Steel Research Institute
CO_2	Carbon Dioxide
COBRA	Cost-Optimized Burden-Sharing and Regional Emissions Allocation
GAMS	General Algebraic Modeling System
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GOI	Government of India
DOE	The U.S. Department of Energy
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EC	Emission Reduction without Trading Scenario Set
EFOM	Energy Flow Optimization Model
EIA	Energy Information Administration
EPA	The U.S. Environmental Protection Agency
EPPA	Economic Prediction and Policy Analysis
ER	Emission Reduction with Carbon Trading Scenario Set
ET	Emission Reduction with Commodity Trading Scenario Set
IBM	India Bureau of Mine
IEA	International Energy Agency
IREA	International Renewable Energy Agency
ISEEM	Industrial Sector Energy Efficiency Modeling
ISEEM-IS	Application of the ISEEM Framework in Iron and Steel Sector
LBNL	Lawrence Berkeley National Laboratory
MARKAL	Market Allocation Model
MESSAGE	Model for Energy Supply Systems and Their General Environment
MIDAS	Multinational Integrated Demand and Supply Model
MIT	Massachusetts Institute of Technology
SEC	Specific Energy Consumption
U.S.	The United States
USGS	The United States Geological Survey
WSA	World Steel Association

EJ	Exajoule
GJ	Gigajoule
Mton	Million ton
Mtonnes	Million tonne
PJ	Petajoule
Tonne	Metric ton

Contents

Greenhouse Gas Mitigation Options in ISEEM Global Energy Model: 2010-2050 Scenario Analysis for Least-Cost Carbon Reduction in Iron and Steel Sector 1
1. Introduction 1
1.1. Project Objective and Scope 2
1.2. Report Organization 3
2. Overview of the ISEEM Framework 3
3. Application of the ISEEM Modeling Framework in Iron and Steel Sector (ISEEM-IS) 7
3.1. ISEEM-IS Generic Structure and Assumptions 7
3.1.1. Supply Module 9
3.1.1.1. Supply Module Generic Structure 9
3.1.1.2. Supply Module Assumptions 9
3.1.2. Process Module 15
3.1.2.1. Process Module Generic Structure 15
3.1.2.2. Process Module Assumptions 15
3.1.3. Trading Module 17
3.1.4. Environmental Module 18
3.1.5. National Steel Demand 18
3.2. Current Production Profiles of the U.S, China, and India's Iron and Steel Sectors 19
4. Carbon Emission Reduction Scenario Analysis 22
4.1. Base Scenario 23
4.1.1. Base Scenario Definition 24
4.1.2. Base Scenario Results 24
4.1.2.1. The U.S. Iron and Steel Sector 24
4.1.2.1.1. Annual Production and Imports 24
4.1.2.1.2. Annual Production Costs 26
4.1.2.1.3. Annual Energy Consumption 28
4.1.2.1.4. Annual CO_2 Emissions 30
4.1.2.2. China's iron and steel Sector 30
4.1.2.2.1. Annual Production and Imports 31
4.1.2.2.2. Annual Production Costs 32
4.1.2.2.3. Annual Energy Consumption 34
4.1.2.2.4. Annual CO_2 Emissions 36
4.1.2.3. The India's iron and steel Sector 37
4.1.2.3.1. Annual Production and Imports 37

4.1.2.3.2. Annual Production Costs 39
4.1.2.3.3. Annual Energy Consumption 40
4.1.2.3.4. Annual CO_2 Emissions 43
4.1.3. Base Scenario Summary 43
4.2. Base with Efficient Technologies (Base-E) Scenario 47
4.2.1. Base-E Scenario Definition 47
4.2.2. Base-E Scenario Results 48
4.2.2.1. Annual Production and Imports 48
4.2.2.2. Annual Production Costs 50
4.2.2.3. Annual Energy Consumption 53
4.2.2.4. Annual CO_2 Emissions 63
4.2.3. Base-E Scenario Summary 65
4.3. Emission Reduction without Trading Scenarios (ER) 69
4.3.1. ER Scenario Definitions 69
4.3.2. ER Scenario Results 71
4.3.2.1. Annual Production and Imports 71
4.3.2.2. Annual Energy Consumption 76
4.3.2.3. Annual CO_2 Emissions 87
4.3.2.4. Annual Production Costs 88
4.3.3. ER Scenario Summary 91
4.4. Emission Reduction with Commodity Trading Scenarios (ET) 94
4.4.1. ET Scenario Definitions 95
4.4.2. ET Scenario Results 95
4.4.2.1. Annual Production and Imports 96
4.4.2.2. Annual Energy Consumption 104
4.4.2.3. Annual CO_2 Emissions 108
4.4.2.4. Annual Production Costs 111
4.4.3. ET Scenario Summary 113
4.5. Emission Reduction with Carbon Trading Scenarios (EC) 115
4.5.1. EC Scenario Definitions 115
4.5.2. EC Scenario Results 116
4.5.2.1. Annual Production and Imports 116
4.5.2.2. Annual Energy Consumption 125
4.5.2.3. Annual CO_2 Emissions 129
4.5.2.4. Annual Production Costs 131

4.5.3. EC Scenario Summary 133
5. Comparison and Discussion of Scenarios 136
6. Summary of Modeling Outcomes 153
6.1. Base and Base-E Scenarios 154
6.2. Scenarios for Emission Reduction Strategies 156
7. Recommendations 161
ACKNOWLEDGEMENTS 163
REFERENCES 164
APPENDIX A 170
APPENDIX B 172
APPENDIX C 191

1. Introduction

In pursuing reduction of Greenhouse Gas (GHG) emissions in the energy intensive manufacturing sectors (e.g., iron and steel and cement sectors) and other building sectors, there are needs and challenges for policy makers and researchers to advance the understanding of energy reduction and GHGs abatement solutions and their implications in setting reasonable prices. Energy-environment models are often used for analyzing the costs of reducing energy consumption and GHG emissions under various emission reduction alternatives. In today's changing and energy-sensitive environment, it is essential to improve energy-climate models and analyze the system dynamics under alternative emission reduction scenarios.

The iron and steel industry is one of the largest global industrial energy consumers and carbon dioxide (CO_2) emitters. According to IEA (2007), it accounts for about 3–5% of the global CO_2-emissions. China is the largest steelmaking country with a production of 638.7 Million tonnes (Mtonnes) in 2010 (WSA, 2011; China Statistical Yearbook, 2011). The United States (U.S.) and India take the 3rd and 4th places with annual production of 80.5 Mtonnes and 67.3 Mtonnes in 2010, respectively (WSA, 2011; IBM, 2011).

The overarching goals of our study are to investigate and improve the representation of end use technologies as the GHG mitigation options in iron and steel sector of the U.S., to enhance analytical capability that can assist decision makers in designing or implementation of potential mitigation policies and programs for iron and steel sector in the U.S., and to advance understanding of technological and economic implications of implementing energy efficiency measures in mitigating GHG emissions on the regional or global scales.

In recent years, studies at Lawrence Berkeley National Laboratory (LBNL) have focused on developing bottom-up representation of energy efficiency measures and cost curves of the mitigation technologies in major industrial sectors that are energy intensive, including iron and steel, pulp and paper, and cement in the U.S. and other countries (Xu et al. 2010, 2012, 2013a, 2013b; Sathaye et al. 2010a&b; Morrow et al. 2013; Hasanbeigi et al. 2012). We have found that significant potentials exist in cost effective energy savings and carbon-emission reduction in these industrial sectors, and that estimated costs of conserved energy and carbon reduction varied significantly across measures, sectors, and countries. These studies have advanced the understanding of country specific potentials in energy savings and carbon reductions in various years, while providing valuable bottom-up representation of energy efficiency measures for energy-climate modeling. Using this new information in an energy climate modeling will allow us to further address the global and regional economic consequences of various emission reduction options.

It is expected that implementing emission reduction options will normally increase the production costs, while any production cost changes would affect the dynamics of industrial competitiveness as well as structural changes. In the past, energy-environment optimization models are often applied for analyzing the costs associated with production, measures, and emission reduction. However, many of those models are based on the theoretical representation of an ideal closed market, for example EFOM (Energy Flow Optimization Model) model of Van der Voort et al. (1984), the MARKAL (Market Allocation Model) model of Fishbone and Abilock (1981), the MESSAGE (Model for Energy Supply Systems and Their General Environment) model of Schrattenholzer (1981), the MIDAS (Multinational Integrated Demand and Supply Model) model of Capros and Karadeloglu (1992), and the BUEM (Bottom-Up Energy Model) model of Karali (2012). Accurate estimation of these costs is especially critical for identifying and choosing optimal emission reduction strategies. In order to advance understanding of technological and economic implications of energy efficiency measures in emission reduction in regional and global contexts, comprehensive analysis of the costs associated with production, measures, and reduced emissions on the global or regional scale is needed.

In reality, few economies can be described adequately or accurately by closed market assumptions in a model without any the interference of trade policies, while alternative emission reduction policies can be deployed using applicable trading strategies. Therefore, in addition to direct adoption of energy efficient end-use technologies in the U.S. iron and steel industry, international commodity trading (e.g., with China and India) can be considered as an alternative for national GHG mitigation options. For example, U.S. steel production and the related carbon emissions may be projected to decrease by increasing the share of imports from China and India, whereas decreasing the emissions from the U.S. industry by increasing commodity imports from the emerging economies or developing world alone would not necessarily result in reducing net global emissions or global risks in climate change. Such a commodity trading strategy for The U.S. may result in simply transferring actual production burdens to China and India where actual intensities of energy use and emissions are likely to be higher. As another alternative strategy to achieve carbon reduction (e.g., by a specific carbon caps on total amount of carbon emissions), we also consider carbon trading of the U.S. via carbon offset from China and India while seeking the lowest cost.

1.1. Project Objective and Scope

The goal of the modeling work carried out in this project was to quantify long-term scenarios for the future emission reduction potentials in the iron and steel sector. The main focus of the project is to examine the impacts of carbon reduction options in the U.S. iron and steel sector under a set of selected scenarios. In order to advance the understanding of carbon emission reduction potential on the national and global scales, and to evaluate the regional impacts of potential U.S. mitigation strategies (e.g., commodity and carbon trading), we also included and examined the carbon reduction scenarios in China's and India's iron and steel sectors in this project. For this purpose, a new bottom-up energy modeling framework, the Industrial Sector Energy Efficiency Modeling (ISEEM), (Karali et al. 2012) was used to provide detailed annual projections starting from 2010 through 2050. We used the ISEEM modeling framework to carry out detailed analysis, on a country-by-country basis, for the U.S., China's, and India's iron and steel sectors. The ISEEM model applicable to iron and steel section, called ISEEM-IS, is developed to estimate and evaluate carbon emissions scenarios under several alternative mitigation options - including policies (e.g., carbon caps), commodity trading, and carbon trading. The projections will help us to better understand emission reduction potentials with technological and economic implications.

The database for input of ISEEM-IS model consists of data and information compiled from various resources such as World Steel Association (WSA), the U.S. Geological Survey (USGS), China Steel Year Books, India Bureau of Mines (IBM), Energy Information Administration (EIA), and recent LBNL studies on bottom-up techno-economic analysis of energy efficiency measures in the iron and steel sector of the U.S., China, and India, including long-term steel production in China (Sathaye et al. 2010a; Xu et al. 2010; Morrow et al. 2012; Hasanbeigi et al. 2012; Zhou et al. 2011). In the ISEEM-IS model, production technology and manufacturing details are represented, in addition to the extensive data compiled from recent studies on bottom-up representation of efficiency measures for the sector. We also defined various mitigation scenarios including long-term production trends to project country-specific production, energy use, trading, carbon emissions, and costs of mitigation. Such analyses can provide useful information to assist policy-makers when considering and shaping future emissions mitigation strategies and policies.

The ISEEM modeling framework is specifically designed for industrial sectors, with its mechanisms and relationships emulating the selected industry sector as realistically as possible. The model allows analysis of changes in energy consumption and carbon emissions as they correspond to variations in supplies (e.g., material, energy), processes (e.g., production, measures), trading, and environmental constraints over time. One of the most important attributes is the model's unique capability to project future commodity and carbon trading across regions and countries as an alternative strategy for emission reduction. Performing scenario analyses using ISEEM-IS model can assist decision makers to assess potential impacts from future energy strategies and emission reduction planning (including international commodity and carbon trading) for the iron and steel sector.

The technical objective is to analyze the costs of production and CO_2 emission reduction in the U.S, China, and India's iron and steel sectors under different emission reduction scenarios, using the ISEEM-IS as a cost optimization model. The scenarios included in this project correspond to various CO_2 emission reduction targets for the iron and steel sector under different strategies such as simple CO_2emission caps (e.g., specific reduction goals), emission reduction via commodity trading, and emission reduction via carbon trading. Specifically, the main CO_2 emission reduction scenarios are defined as follows:

- Emission Reduction without Trading Scenarios: Annual CO_2 emissions are restricted to be 10%, 20%, and 30% below those of the ISEEM-IS Base scenario for each country (U.S., China, and India).
- Emission Reduction with Commodity (Steel) Trading Scenario: Annual CO_2 emissions in U.S. iron and steel sector are restricted to be 10%, 20%, and 30% below those of the ISEEM-IS Base scenario with commodity trading opportunities from India and China.
- Emission Reduction with Carbon Trading Scenario: Annual CO_2 emissions are restricted to be 10%, 20%, and 30% below those of the ISEEM-IS Base scenario for each country (U.S., China, and India) with carbon trading opportunities of the U.S. from India and China.

1.2. Report Organization

Section 2 provides an overview of the ISEEM modeling framework and its application in this study. Section 3 presents insight into the comprehensive data compilation and assumptions, including processes to establish the database and the base representation in the ISEEM-IS model. Section 4 presents detailed scenario definitions and modeling results, and comparisons of efficiency improvements, carbon emissions, and changes in different cost structures. Results for each scenario are presented sequentially by annual production and import, production costs, energy consumption, emissions, and country. Section 5 presents a summary of findings and comparisons among the scenarios, including discussion of the results. Section 6 highlights the main conclusions and Section 7 provides a list of recommendations for future work.

2. Overview of the ISEEM Framework

The ISEEM modeling framework is a bottom-up linear programming model that minimizes the total system cost of industrial production over a set of pre-defined constraints. The framework is developed using GAMS (General Algebraic Modeling System) optimization modeling interface. For each optimization modeling, a set of constraints are specified and used to seek for the least cost solution. Those constraints are of various kinds including the relationships that must be satisfied for proper representation of the associated industrial systems. The main groups of constraints predefined for the modeling include 1) the balance constraints, which require that total usage of any material remains less than or equal to its total supply; 2) the periodic capacity constraints, which compute the available capacity of a production technology for a period of time; 3) the activity-capacity constraints, which determine the level of available capacity of a production technology that is used in the period; 4) the demand constraints, which ensure that demands are satisfied in each period of time; 5) the trade constraints, which match up the trading volumes among countries or regions; and 6) the carbon emissions constraints, which may be used to set national or global emission targets or caps.

Parameters for an ISEEM model indicate the input requirements and output generation for each technology. They describe the operation and limitations of the individual technologies (e.g., availability factors, cumulative or periodic raw material and energy source supply bounds, production bounds, and trading bounds), and represent the demands for industry products. The demand projections are placed into the model for the entire planning time-horizon, and are developed exogenously (i.e., defined outside of the ISEEM model). Cost parameters, on the other hand, define the objective functions of the system and are essential for the least-cost solution. Raw material and energy source supply costs, subsidies, technology investment costs, process operation costs, tariffs and transport costs of trading materials, environmental taxes and costs are listed as the main items in total cost objective functions of ISEEM models.

Figure 1 shows the basic ISEEM modeling framework structure, including input data, main output (including commodity production, energy consumption, carbon emission), and major relationships. With the goal to achieve the least cost from a mix of technologies in this framework, the ISEEM model structure is composed of four modules: Supply Module, Process Module, Trading Module, and Environmental Module.

Supply module: Supply module includes the supply technologies that are responsible for supplying raw materials and energy sources to the system. Supply technologies can be defined for any type of supplies (e.g., aggregated supply, domestic production, or import of any input source) with a unit cost and limitations on supply levels. In the module, supply technologies do not need any input source to operate. In other words, supply technologies are the starting point of the process.

Process module: Process module defines the production system of the industrial sector in each region. Process technologies in this module produce intermediate or final products of the system. For example, the module includes the process technologies that generate a product by using another product as input. In addition, sector production facilities and onsite electricity generation facilities are other examples of process technologies defined within the process module. After the process technologies process intermediate products to produce the final products, the output of the module (i.e., final product) is then expected to satisfy the demand requirements.

Trading module: Final products produced by process technologies are used to satisfy either the demand from a region (in which the final product is produced), or demand from other regions via trading relationships. Product demand of regions is determined outside of the model and is exogenously placed to the system. Product export and import levels, on the other hand, are endogenously determined in the trading module of the system. In other words, trading module allows import and export of the final products between regions. The trading module also includes costs of transportation and tariff. According to optimization process, if it is cost effective for a region to satisfy its demand via imports from another region or other regions, production in the region may be reduced while shares of import from other regions can be increased. However, in this case, production and export levels of the other regions are expected to increase simultaneously. In trading module, import and export levels between the regions are balanced within each period of time.

Environmental module: Environmental module represents the GHG emissions and other pollutions due to process and other industry activities. The objective function considers environmental costs such as penalties, taxes, and applicable expenses to comply with environmental regulations. Environmental costs can be characterized as a normalized cost per unit of global, regional, national, or sectoral emissions or a cost per unit of excess emissions. Emissions released into the environment that go beyond the limit of predetermined or regulated levels are considered as excess emissions. Policy measures dedicated to regulate environmental impacts can affect the scales of environmental cost, therefore are expected to influence model's optimization process and outcomes. For example, model input using different environmental policies and costs may lead to the least cost solutions that suggest fuel and structural changes (e.g., process technologies and production shift from Basic Oxygen Furnace to Electric Arc Furnace in steel sector).

More detailed information about the ISEEM modeling framework structure, parameters, variables, and formula can be found in Karali et al. (2012).

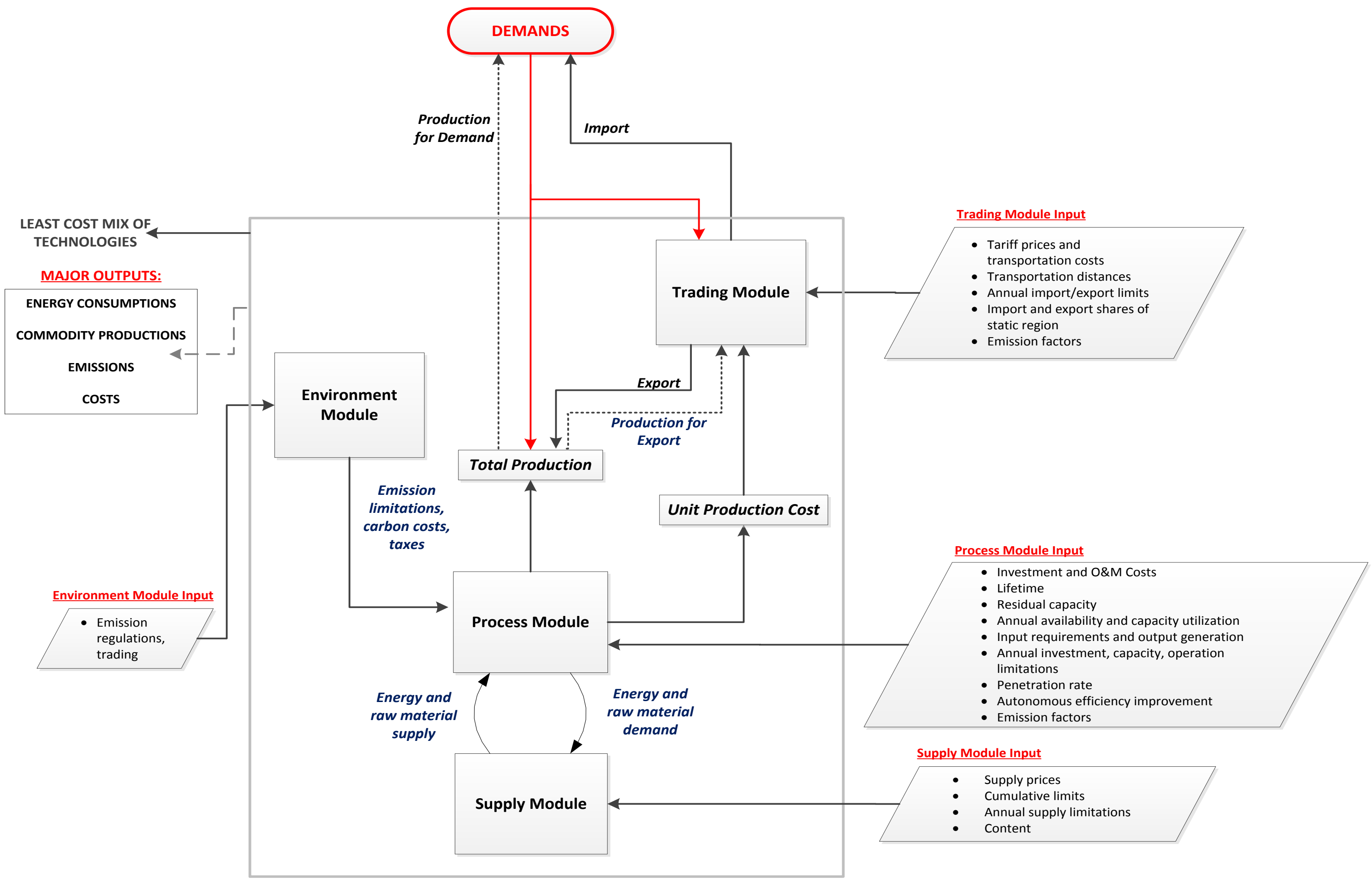

Figure 1. Basic ISEEM Modeling Framework Structure

3. Application of the ISEEM Modeling Framework in Iron and Steel Sector (ISEEM-IS)

For the ISEEM-IS model, we selected year 2010 as the base year because it was the most recent year for which the majority of relevant data was available for iron and steel industries in countries (the U.S., China, and India) included in this study. In addition, there have been no extraordinary political, economic, or social events in 2010 that would have been compromising the statistical data integrity. The planning horizon for future projections is set with consecutive five-year intervals between 2010 and 2050.

The generic structure, parameters, and assumptions of the ISEEM-IS model are defined in the following sub sections in detail.

3.1. ISEEM-IS Generic Structure and Assumptions

Figure 2 shows the production flow of the iron and steel production in the ISEEM-IS model. In this diagram, three modules of the ISEEM-IS model are included in detail: Supply Module, Process Module, and Trading Module. The production flow combines the supply module and the process module, with the trading module showing circulation of the final product (steel). The production flow structure exhibited by the module combinations can be considered as a network, in which technologies represent the nodes of the network, while energy sources, raw materials, intermediate products, and final product represent the arcs flowing in to or out from the nodes (i.e., technologies).

Energy sources and raw materials needed for the iron and steel production are supplied to the system by supply technologies included in the supply module of the ISEEM-IS model. From this perspective, coking coal, non-coking coal, miscellaneous oil (all types of oil), natural gas, coke, and electricity are defined as the energy sources; while iron ores (both domestic and import), scraps (both domestic and import), and oxygen are defined as the raw materials in the ISEEM-IS' supply module.

Process technologies defined in the ISEEM-IS' process module represents the processes of the iron and steel production. Process technologies use the energy sources and raw materials (from the supply module) to produce the intermediate and final products of the iron and steel production. From this perspective, pellet, sinter, coke, pig iron, DRI (coal or gas based), and raw steel are the intermediate products of the system that are produced in the steps of the steel production (final product).

Final steel production from each country is used to satisfy national steel demand and trading needs. In the trading module, iron and steel production system of the each country communicates with each other via the trading module. Import and export decisions are made in the trading module; and according to those decisions total steel production of the country is separated into the national steel requirements and steel export.

The following sub sections describe the technologies, energy sources, and raw materials used in the process flow diagram and discuss the associated parameters and assumptions made for those technologies, energy sources, and raw materials of the system.

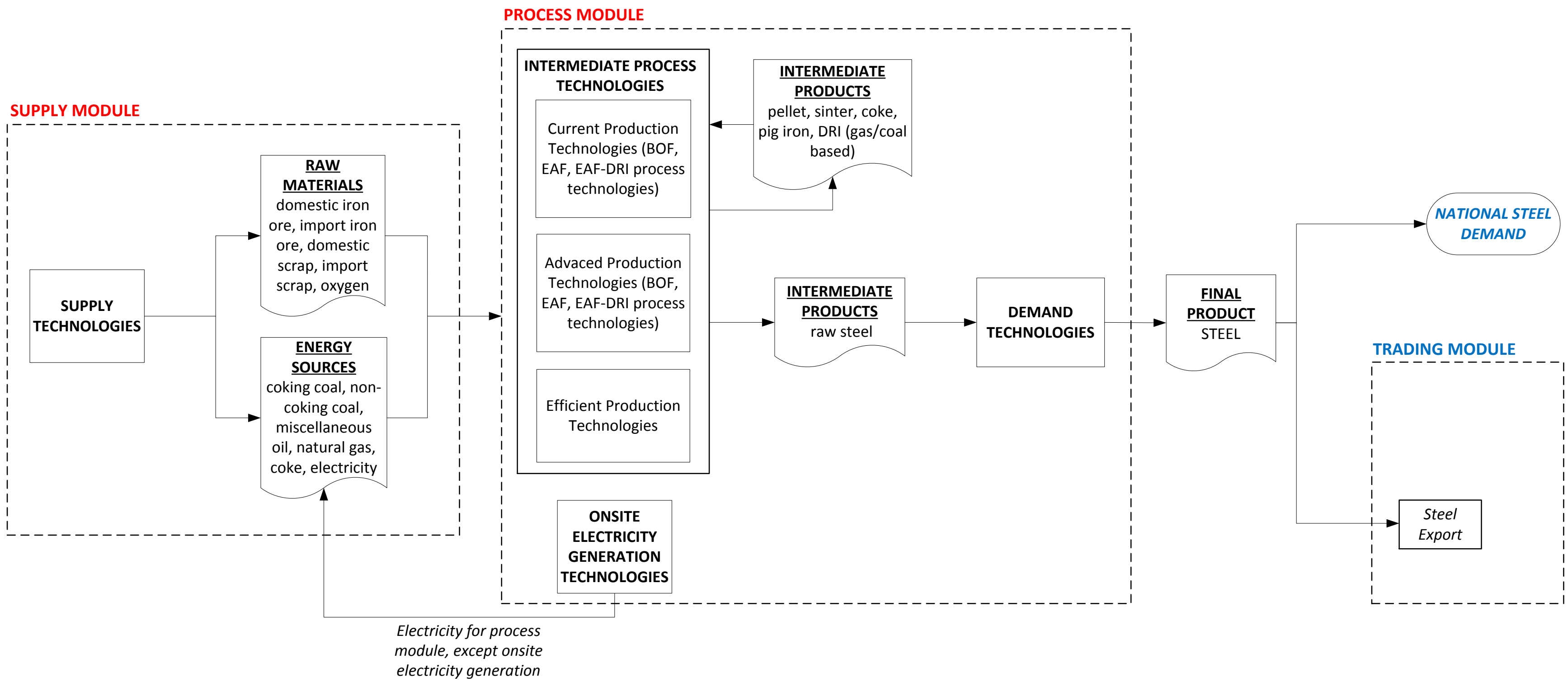

Figure 2. Production Flow Diagram of the Iron and Steel Sector in the ISEEM-IS Model

3.1.1. Supply Module

3.1.1.1. Supply Module Generic Structure

In the ISEEM-IS model, supply technologies are defined for each energy source and raw material that is necessary for the iron and steel production, e.g., coking coal supply and iron ore supply. Each supply technology is responsible for supplying a resource (e.g., energy source or raw material) to the system.

Specifically, the ISEEM-IS model incorporates six energy sources and five types of raw materials. The six energy sources used in the ISEEM-IS model are steam coal, coking coal, coke, electricity, miscellaneous oil, and natural gas. It is assumed that there is no distinction between domestic and imported energy sources. Thus, a single supply technology is defined for each type of energy source. However, because the coke price in domestic market of China is much lower than that of the international market, China's domestic and import coke supplies are treated separately in the model. On the other hand, the five types of raw materials used in the ISEEM-IS model are domestic iron ore, import iron ore, domestic scrap, import scrap, and oxygen. The prices of iron ores and scraps differ in domestic and international markets, mostly depending on the domestic availabilities. Since price and availability impacts of those resources are important elements in the model's least cost objective function, domestic and import resources are treated separately in the ISEEM-IS model. Because domestic iron ore reserves are limited in each country, including separate domestic iron ore resources would enable analysis of reserve capacity effects (e.g., switches to import resources when domestic resources are not available anymore). In addition, current domestic scrap availability is not enough in China and India thus scrap prices are higher in both countries compared to the international markets.

Appendix A enlists the supply technologies in this model.

3.1.1.2. Supply Module Assumptions

Levels of reserve capacities, annual availabilities, and supply prices associated with supply module technologies influence the modeling optimization and results. In the ISEEM-IS model, reserve capacities are only defined for domestic iron ore reserves; and annual availabilities are only defined for domestic scrap. It is assumed that there is no restriction on the availability of any other energy sources or raw materials. Supply prices, on the other hand, are defined for all energy sources and raw materials. Content parameter is also used in the ISEEM-IS model to define the iron content per tonne iron ore produced in China.

The information gathered, assumptions made, and methodologies applied to finalize those parameters are discussed in the following subsections.

Iron Ore Reserve Capacities

Iron ore reserve capacities are based on current USGS statistical data. Specifically, according to USGS (2012), annual iron ore reserve capacities in the U.S., China, and India are 6.9 billion tonnes, 23.0 billion tonnes, and 7.0 billion tonnes, respectively.

The reserve capacity is a particularly important issue for China and India's iron and steel sectors. Current reserve capacities of both countries are considered to be insufficient after 2020 to satisfy the projected steel production (in der Heiden, 2011; IBM, 2010). In the last decade, China has been investing abroad in iron ore mining as a strategy of gaining access to affordable and sustainable iron ore resources (in der Heiden, 2011).

Annual Domestic Scrap Availabilities

According to Steel Recycling Institute (2012), annual scrap availability in the U.S. did not change drastically in the past 25 years. Therefore, it is assumed that annual domestic scrap availability in the U.S. will grow 1% per year from 2010 to 2050. On the other hand, there is no historical information on scrap availability of China and India. However, domestic scrap availabilities depend on the phases of the country's social and economic development. In developing countries such as China and India, scraps are not self-sufficient today, but enough scrap may be produced in the future to satisfy their future demand requirements. Therefore, we consider that China and India will become net scrap exporters in future years, once they complete initial development and expansions. The David J. Joseph Company (2012) projected that China will be a net scrap exporter after 2020 with a recovery rate of 28%. When taking the expert estimation that India follows China steel sector growth with roughly 20 years delay (Ernst & Young, 2012), we assume that India will be a net scrap exporter starting in 2040. Under these assumptions, Table 1 presents our projections for annual domestic scrap availabilities in the U.S., China, and India between 2010 and 2050.

Table 1. Annual Availabilities of Domestic Scrap Considered in the ISEEM-IS Model (in million tonnes per year, Mt/year)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
The U.S.	76.0	80.0	84.0	88.0	93.0	98.0	103.0	108.0	113.0
China	100.0	125.0	168.0	244.0	299.0	333.0	352.0	362.0	367.0
India	16.0	18.0	23.0	31.0	45.0	69.0	114.0	151.0	176.0

Iron Content of Crude Iron Ore

Iron content of crude iron ore varies depending on the location from which the crude iron ores are extracted. Because iron contents of a tonne of crude iron ore from China is approximately 50% of that of the crude iron ores from the U.S. and India, we assumed that domestic crude iron ore resource in China supplies 0.5 tonne iron product per tonne of crude iron ore, while a tonne of crude iron ore mined in the U.S. or India or imported from international market supplies 1.0 tonne iron product.

Raw Material Supply Costs

Future prices of the raw materials used in this analysis are estimated through linear regression forecasts. International and domestic market prices of major raw materials for iron and steel production were found to be strongly associated with China steel production in the last decade (in der Heiden, 2011, Tang, 2010). We first performed correlation analyses to understand the strength of the correlation between each raw material price and China's annual production volumes in historical years. The correlation analyses show that all raw material prices were highly correlated with the China production volumes (see Appendix B). Second, we performed regression analyses using historical data to model raw material market prices with China's annual steel production volumes as the independent parameter. Third, we used China's steel production projection data toward 2050 from a recent study (Zhou et al. 2011) and applied them to the regression model to forecast and estimate future prices. The steel production projected in their research is displayed in

Figure 3. As can be seen, the production peaks around 2025, drops through 2040, and has another peak.

In this report, all the raw material prices projected in the regression analysis are assumed to follow the same pattern as the regression lines generated from China production projections shown in **Figure 4** and Figure 5. All the regression lines to forecast raw material prices in our study are included in Appendix B.

We further calibrated scrap prices in China and India by applying multipliers to the prices so that they would approach the U.S. prices in 2025 and 2040, respectively. The purpose of calibrating prices is to reflect the effect of changing domestic scrap availability in China and India. Starting in 2025, scrap prices in China and India would continue to decline, with decreasing rates of price reduction. Table 2 lists the projected raw material prices obtained through those calculations, which are used in the ISEEM-IS model.

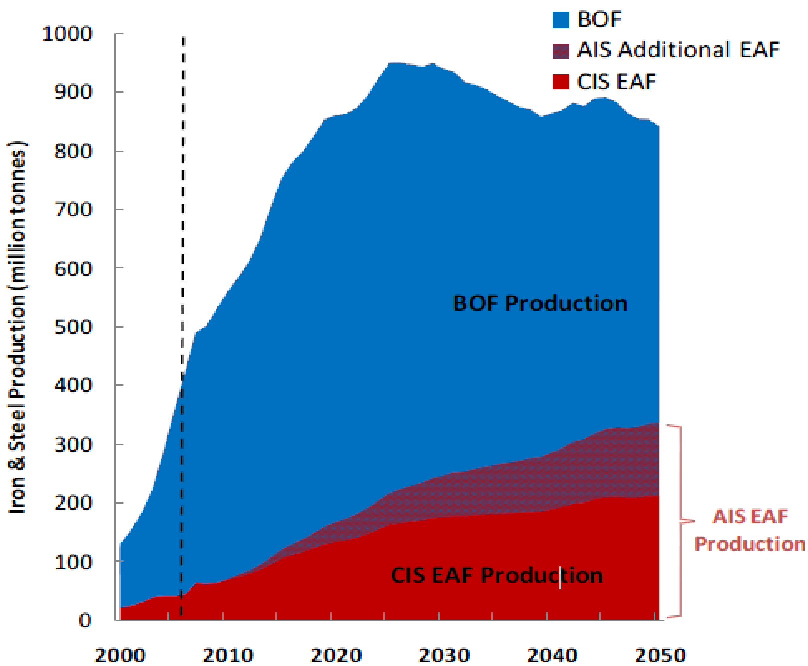

Figure 3. Annual Iron and Steel Production in China (Mtonnes)

(Source: Zhou, N., Fridley, D., McNeil, M., Zheng, N., Ke, J., and Levine, M., 2011, "China's Energy and Carbon Emissions Outlook to 2050." Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL Report 4472E.)

Table 2. Iron ore and Scrap Prices Used in the ISEEM-IS Model (2005 $/tonne material)

		2010	2015	2020	2025	2030	2035	2040	2045	2050
The U.S.	**Domestic Iron Ore**	88.0	115.0	128.0	140.0	139.0	133.0	129.0	132.0	126.0
The U.S.	**Import Iron Ore**	97.0	118.0	136.0	150.0	149.0	141.0	136.0	141.0	133.0
China	**Domestic Iron Ore***	130.0	182.0	207.0	228.0	225.0	215.0	208.0	214.0	203.0
China	**Import Iron Ore**	114.0	132.0	149.0	163.0	161.0	154.0	149.0	153.0	146.0
India	**Domestic Iron Ore**	120.0	128.0	147.0	163.0	162.0	153.0	148.0	153.0	144.0
India	**Import Iron Ore**	124.0	133.0	151.0	166.0	165.0	157.0	152.0	156.0	148.0

The U.S.	**Domestic Scrap**	284.0	373.0	423.0	466.0	461.0	439.0	425.0	416.0	404.0
The U.S.	**Import Scrap**	334.0	434.0	489.0	535.0	530.0	506.0	490.0	505.0	479.0
China	**Domestic Scrap**	337.0	413.0	443.0	473.0	430.0	381.0	374.0	373.0	366.0
China	**Import Scrap**	443.0	504.0	540.0	576.0	546.0	495.0	485.0	523.0	493.0
India	**Domestic Scrap**	337.0	413.0	466.0	511.0	506.0	459.0	426.0	412.0	400.0
India	**Import Scrap**	443.0	504.0	540.0	576.0	546.0	495.0	485.0	523.0	493.0

** The historic time series used for China domestic iron ore prices include the extra cost of agglomeration processes (i.e., sintering and pelletization). Therefore, they seem to be higher than the U.S. and India domestic iron ore prices. In the ISEEM-IS model, agglomeration processes of China are adjusted according to this price structure.*

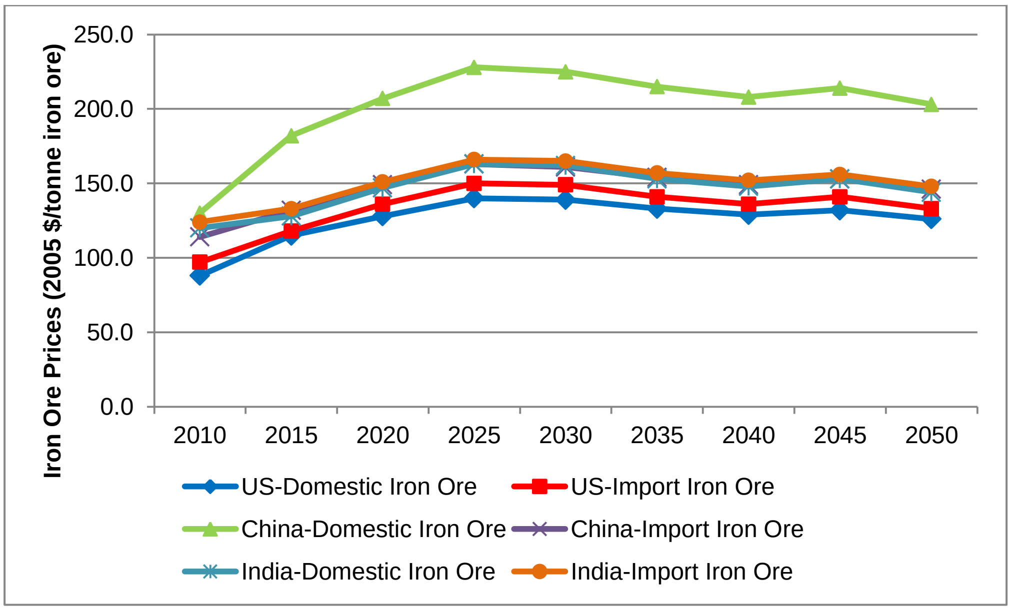

Figure 4. Iron Ore Prices Used in the ISEEM-IS Model (2005 $/tonne iron ore)

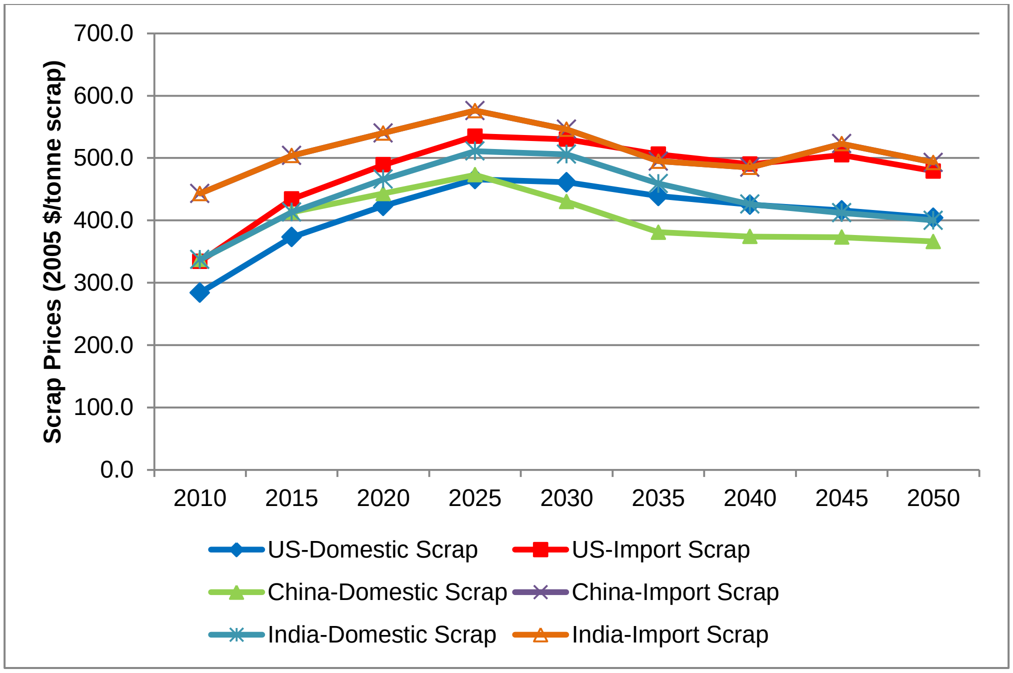

Figure 5. Scrap Prices Used in the ISEEM-IS Model (2005 $/tonne scrap)

Energy Sources Supply Costs

Forecasting future energy prices is challenging as they are influenced by numerous factors. Despite a large body of empirical work, there is no consensus as to the best way to capture the true dynamics of energy price changes (Ghoshray and Johnson, 2010).

In this study, we assume future prices of the energy sources using EIA forecast, coupled with additional forecast method to extend the forecasted time horizon to 2050. First, EIA (2012) energy price forecasts for the period 2010-2035 are used to project future prices of the energy sources other than coking coal and coke. Second, the average growth rates in the period of 2010-2035 are calculated and then used to estimate the energy prices in the years from 2036 to 2050. Normally, the EIA price projections are for the U.S. industry sector.

Third, we used the price trends projected by the EIA for the U.S. industry sector as a guide to estimate energy prices in China and India. In particular, we consider that natural gas in China and India are under the impact of international oil prices. Therefore, we used international oil prices to project natural gas prices in China and India.

Prices of coking coal and coke are the exceptions. They are the primary energy sources of the Basic Oxygen Furnace (BOF) Steel Production, which accounts for approximately 70% of the total steel production of the world in 2010 (WSA, 2011) and consumption of coking coal and coke forms more than 60% of the total energy consumption in BOF steel production (Sathaye et al. 2010a). Similar to the prices of iron ore and scrap, prices of coking coal and coke were mainly driven by China steel production in the last decade (in der Heiden, 2011). Therefore, we applied linear regression analyses to project the prices of coking coal and coke using China's production as input in the forecast models. On the other hand, we assume that the U.S. iron and steel sector produces its own coke from coking coal (i.e., no domestic purchase or import of coke), since the share of offsite purchase is negligibly small. Appendix B presents the regression forecast equations.

For the major fuel categories, the average price assumed in this study is presented in Table 3 and Table 4. These energy prices are exogenous input into the model, together with other technology costs (e.g., investment costs) and technical characteristics (e.g., energy savings, conversion efficiencies).

Table 3. Steam Coal, Electricity, Miscellaneous Oil, and Natural Gas Prices Considered in the ISEEM-IS Model (2005 $/GJ fuel)

		2010	2015	2020	2025	2030	2035	2040	2045	2050
The U.S.	**Steam Coal**	2.3	2.7	2.8	2.8	2.9	3.1	3.2	3.4	3.6
China	**Steam Coal**	4.1	4.8	4.9	5.0	5.2	5.4	5.7	6.0	6.4
India	**Steam Coal**	1.5	2.9	3.4	4.0	4.1	4.3	4.5	4.8	5.1
The U.S.	**Electricity**	16.7	15.5	15.5	15.9	15.9	16.9	16.9	16.9	17.0
China	**Electricity**	14.8	16.4	16.5	16.8	16.9	17.9	17.9	17.9	18.0
India	**Electricity**	24.0	26.5	26.6	27.2	27.2	28.9	28.9	29.0	29.1
The U.S.	**Miscellaneous Oil**	11.0	14.4	18.3	21.7	25.0	27.9	31.6	35.8	40.5
China	**Miscellaneous Oil**	11.9	15.6	19.8	23.5	27.0	30.2	34.2	38.7	43.9
India	**Miscellaneous Oil**	11.9	15.6	19.8	23.5	27.0	30.2	34.2	38.7	43.9
The U.S.	**Natural Gas**	4.5	5.0	5.4	6.3	6.7	7.3	8.1	8.9	9.8
China	**Natural Gas**	4.4	6.5	7.7	9.0	10.5	12.3	14.4	16.8	19.7
India	**Natural Gas**	3.7	6.5	7.7	9.0	10.5	12.3	14.4	16.8	19.7

The gray shaded cells represent the prices taken from other sources: The U.S. prices for steam coal, electricity, miscellaneous oil, and natural gas from EIA, Annual Energy Outlook, 2011; China price for steam coal from IEA, 2011; China price for electricity from http://sporthats.over-blog.com/article-china-s-electricity-price-really-high-or-low-99947827.html, 2012; China price for miscellaneous oil from IEA, 2011; China price for natural gas from http://www.istockanalyst.com/article/viewiStockNews/articleid/4165286, 2010; India price for steam coal from IEA, 2011; India price for electricity from GOI, 2012; India price for miscellaneous oil from IEA, 2011; India price for natural gas from IEA, 2011.

Table 4. Coking Coal and Coke Prices Considered in the ISEEM-IS Model (2005 $/tonne fuel)

		2010	2015	2020	2025	2030	2035	2040	2045	2050
The U.S.	**Coking Coal**	163.0	178.0	201.0	220.0	218.0	208.0	202.0	208.0	197.0
China	**Coking Coal**	109.0	134.0	150.0	164.0	163.0	156.0	151.0	155.0	147.0
India	**Coking Coal**	178.0	203.0	233.0	259.0	256.0	243.0	234.0	242.0	228.0
China	**Coke**	224.0	302.0	340.0	371.0	368.0	351.0	341.0	351.0	333.0
India	**Coke**	369.0	420.0	472.0	516.0	511.0	488.0	474.0	487.0	463.0

Raw material and energy supply prices are among the major determinants of the cost minimization objective. In addition, optimization process also consider other costs into the modeling calculations, such as efficiency technology investment costs and operational costs, transportation costs, tariffs, and environmental related costs associated with steel production. A list of energy efficiency investment and operational costs is given in Appendix C, while transportation costs and tariffs are discussed in the following section.

3.1.2. Process Module

Process technologies defined in the process module of the ISEEM-IS model are responsible for producing the necessary amount of intermediate and the final products that will satisfy the user-defined steel demands. Process technologies rely on energy sources and raw materials supplied by supply technologies to operate.

Specifically, there are three types of intermediate process technologies used for iron and steel production in the ISEEM-IS model: *current* production technologies, *advanced* production technologies, and *efficient* production technologies. Demand technologies are directly linked to the steel demand and are used to serve final product (i.e., steel). Onsite electricity generation technologies represent the electricity generated in the iron and steel sector.

3.1.2.1. Process Module Generic Structure

In the ISEEM-IS model, we include 260 intermediate process technologies, which are composed of current production technologies (18 technologies), advanced production technologies (108 technologies), and efficient production technologies (134 technologies). More details of the technologies are further discussed in this section and Appendix A.

Current production technologies represent the process technologies that are currently used for iron and steel production, such as Basic Oxygen Furnace (BOF) production route technologies, Electric Arc Furnace (EAF) production route technologies, and Electric Arc Furnace - Direct Reduced Iron (EAF-DRI) production route technologies (Gas based as well as Coal based). Advanced production technologies (e.g., new generations of current production technologies) are assumed to represent the autonomously improved versions of current iron and steel production technologies. Efficient production technologies represent the group of technologies that improve the energy efficiency of the current production technologies often with extra costs.

In addition, there are four onsite generation technologies included in the process module. The entire list of process technologies is given in Appendix A.

3.1.2.2. Process Module Assumptions

For simplicity in the ISEEM-IS model, we assume that each of current and advanced production technologies have 30-year lifetime, while individual efficient production technologies selected in the study may have different lifetime. Advanced production technologies have the same parameter values (e.g., costs, energy/raw material requirements, etc.) as those of the current production technologies, except for the specific energy consumption (SEC, i.e., energy consumption per unit of production). It is assumed that specific energy consumption of advanced technologies is reduced by an annual improvement rate in all regions compared to that of current production technologies. Eq. 1 is used to quantify energy requirements of each advanced production technology with respect to the year in which the production technology becomes available.

$$SEC\ of\ Advanced\ Production\ Technology = SEC\ of\ Current\ Production\ Technology * (1 - AIR)^{nyrs} \quad \text{Eq. 1}$$

where SEC, AIR, and $nyrs$ represent 'Specific Energy Consumption', 'Annual Improvement Rate', and number of years in a period. For ISEEM-IS, we adopted an annual improvement rate of 0.75%, which was used in the Economic Prediction and Policy Analysis (EPPA) model of Massachusetts Institute of Technology (MIT) (Webster, 1997). For example, if the current pig iron production technology (all current technologies defined according to 2010 parameter structures) needs 9.96 GJ coke to produce one tonne of pig iron in 2010; then an advanced pig iron production technology that is available in 2015 is projected to use 9.59 GJ coke/tonne pig iron (i.e., $9.96x(1-0.75/100)^5 = 9.59$); furthermore, an advanced pig iron production technology available for installation in 2025 would need 8.89 GJ coke/tonne pig iron to operate in 2025 (i.e., $9.96x(1-0.75/100)^{15} = 8.89$). All parameters for advanced production technologies other than specific energy requirements are kept the same as those of the current technologies. Thus, if the advanced production technology can bring cost-effectiveness compared to the current production technologies, the ISEEM model optimization process will identify and favor selection of such technologies.

Energy efficient production technologies improve energy efficiencies of the current production technologies, usually with additional costs. While energy efficient production technologies may provide higher degrees of efficiency improvements compared to the advanced or current production technologies, they may often come with extra investment and operation costs. Therefore, efficient measures are often not favored in the optimization process of ISEEM modeling. This is particularly true in the base case scenario when there is no pre-determined constraint for emission cap or reduction. However, it is possible that some efficient technologies can bring cost-effectiveness to the optimization process. In this case, ISEEM optimization process would select efficient technologies providing cost reduction based on the least cost objective. The information on specific efficient technologies included in this modeling analysis and assumptions related to them are mainly based upon LBNL's recent studies (Xu et al. 2013, Morrow et al. 2013, and Hasanbeigi et al. 2012), with the descriptions included in Appendix C.

On the other hand, some of those efficient production technologies are already in the current iron and steel production profile of the three countries (i.e., the U.S., China, and India). The ISEEM-IS model is calibrated to represent current adoption of those technologies in the base year, 2010. To determine the future adoption and implementation, we assumed that 90% of the remaining potential of each efficient production technology will be realized by the end of 2050, with a constant step-wise increase rate between the 5-year intervals during the period 2010-2050.

In the ISEEM modeling framework, technology capacity in the current period is the sum of the residual capacity plus the new capacity additions from the previous periods. Residual capacity is the capacity installed before the start of base year (but still operational in the current period). Residual capacity is exogenously determined and placed into the model. Because actual remaining lifetime of a residual capacity in the base year (2010) is normally unknown, we assumed that residual capacity of any current production technology has 30-year lifetime starting from 2010, with the capacity linearly depreciated throughout its lifetime (30 years) starting from the base year. Linear depreciation means residual capacity is decreased by the inverse of its lifetime. For example, if the lifetime of a technology is 30 years, it loses '1/30' of its original capacity each year. In the meanwhile, new capacity additions of the model preserve their initial levels until the end of their lifetimes (i.e., 30 years in the ISEEM-IS model).

In addition to the generic assumptions, specific limitations are pre-defined for certain production technology activities. Because costs of unit final steel production via BOF production route are higher than those via other production technology routes represented in each country, the model's optimization process would tend to reduce the share of BOF production while seeking for alternative processes with the least costs. However, in reality, it would be inappropriate to totally abandon BOF production route because BOF is necessary for producing high-quality steel that other processes just would not be able to achieve (Grobler and Minnit, 1999). For example, during the normal EAF production, there is a good chance that the melted scrap would contain impurities with other materials attached (e.g., leather parts or paintings that might come from vehicle scraps). Considering the need for high quality steel to be expected from the more expensive BOF production, we define a lower bound for annual production from the BOF production route in each country. The lower bound simply means we set a limit on the lowest BOF production shares as a fraction of total steel production. The limits on lowest BOF production shares are provided in Table 5. Basically, we do not allow BOF production to drop below 10% in any country. However, the lower bounds defined for the U.S. and India decrease in a step wise fashion, starting at 25% in 2015, dropping to 10% in 2030, and staying at the level (i.e., 10%) throughout the remaining of the planning horizon. Such limitation is predefined to avoid sudden and dramatic decreases of BOF production within a period.

Table 5. Lower Bounds of Annual BOF Production Shares in the ISEEM-IS Model

	2015	2020	2025	2030	2035	2040	2045	2050
US	25%	20%	15%	10%	10%	10%	10%	10%
China	10%	10%	10%	10%	10%	10%	10%	10%
India	25%	20%	15%	10%	10%	10%	10%	10%

In addition, in India case, final steel production costs from EAF-DRI (Gas based) and EAF production are more expensive when compared to that of EAF-DRI (Coal based) production. Therefore it is necessary to define lower bounds for EAF-DRI (Gas based) and EAF production in India to avoid diminishing shares of production due to model's optimization process that favors lowest cost production. For this purpose, the current production shares (which is 14.5% for EAF-DRI (Gas based) process and 13.6% for EAF process) are trending down gradually to 5% as the lower bounds. This is to ensure that none of the production processes defined in the ISEEM-IS model can be abandoned completely, e.g., lower bound of 5% share is reached for both processes starting in 2040.

Table 6. Lower Bounds Considered for Annual EAF-DRI (Gas based) and EAF production in India in the ISEEM-IS Model

	2015	2020	2025	2030	2035	2040	2045	2050
EAF-DRI (Gas based)	13%	12%	10%	8%	6%	5%	5%	5%
EAF	13%	12%	10%	8%	6%	5%	5%	5%

3.1.3. Trading Module

Trading module of the ISEEM-IS model is used to represent the product flows among the U.S., China, and India. The countries are allowed to import from and export to each other.

Transportation costs and tariffs are the key parameters of the ISEEM-IS trading module. Transportation cost ($/tonne steel) is defined as the cost of transporting one tonne of steel from one country to another one. Tariffs ($/tonne steel) are the rate of import tax applied on one tonne of steel imported by each country.

Table 7 shows the transportation costs predefined in the ISEEM-IS modeling. Transportation costs are assumed to increase through the planning horizon (i.e., 2010-2050) according to oil price projections provided by the EIA (see Table 3). For the tariff rates, current average border taxes (1.5% for US, 20% for China, and 12% for India) applied on imports are used and are kept constant for the period 2010-2050. However, variations in tariff rates for future import can be an interesting topic to analyze using the model.

Table 7. Transportation Costs Considered in the ISEEM-IS Model (2005 $/tonne steel)

	2010*	2015	2020	2025	2030	2035	2040	2045	2050
The U.S. - China	23.0	24.5	25.9	27.4	31.4	35.1	39.8	45.0	51.0
The U.S. - India	46.0	49.0	51.8	54.8	62.8	70.2	79.6	90.0	102.0
China to India	11.0	11.7	12.4	13.1	15.0	16.8	19.0	21.5	24.4

Data Source for 2010: Brown, H., 2010.

3.1.4. Environmental Module

Environmental module of the ISEEM-IS model is used to represent the GHG emissions and other pollutions due to process and other industry and trading activities in the U.S., China, and India iron and steel sectors. The module is also used to apply environmental limitations in emission reduction scenarios (without trading, with commodity trading, and carbon trading).

3.1.5. National Steel Demand

Projection of annual steel demand for the period 2010 – 2050 is established through reviewing and compiling various available sources including previous LBNL studies (Wagner and Sathaye, 2006; Zhou et al. 2011). Figure 6 presents country-specific annual demand assumed in the ISEEM-IS model.

First, the U.S. annual demand projection is based on results from COBRA (Cost-Optimized Burden-Sharing and Regional Emissions Allocation) energy modeling analysis (Wagner and Sathaye, 2006). Second, China's annual demand projection is obtained from the report titled 'China's Energy and Carbon Emissions Outlook to 2050' (Zhou et al. 2011). Essentially, the projection by Zhou et al 2011 is used as model input and constraint exogenously. Third, because there is no sufficient information or direct data source for Indian steel demand projection for the period 2010-2050, we developed an approach to create the steel demand projection for India. We first correlated the India GDP projection of the period 2015-2025 (Bhushan, 2010) with the steel demand; then assume that annual growth rates for steel demand in the period 2025 - 2045 are the same as that of China's annual growth rates for the period 2010-2025 (Zhou et al. 2011) – reflecting the expert estimation that India follows China steel sector growth with a 20-year delay (Ernst & Young, 2012). Based on this calculation, annual steel demand of India approaches 491 Mtonnes by 2045. We assumed that India's annual steel demand stabilizes at 491 Mtonnes after 2045. This projection is slightly lower than IEA projections of steel production under "strong growth case" scenario, which would be 550

Mtonnes in 2050 (Trudeau et al. 2011) and Tata Steel forecasts in a strong economy, which is 500 Mtonnes around 2050 (Sulekha.com Magazine, 2011)[1]

In the ISEEM-IS model's optimization process, supply module technologies are selected from each of the energy sources, raw materials, and intermediate production technologies to produce the least-cost solution to satisfying the projected annual steel demand. The annual demand levels used in this application are price insensitive (i.e., demand remains unchanged if the supply prices change and vice versa) and are exogenous to the model. In fact, the price insensitiveness is a necessary assumption for this bottom-up representation study as there is no information on price elasticity.

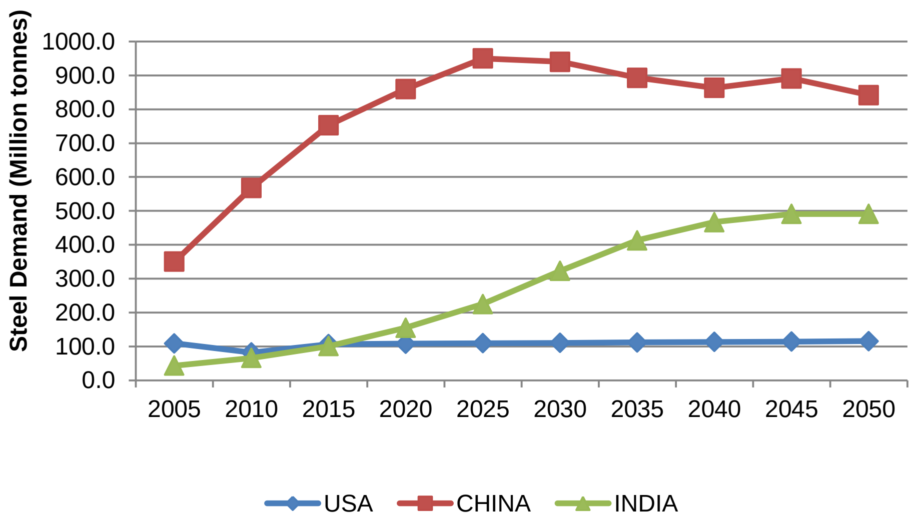

Figure 6. Annual National Steel Demands Considered in the ISEEM-IS Model (Mtonnes)

Table 8. Annual National Steel Demands Considered in the ISEEM-IS Model (Mtonnes)

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
The U.S.	82.0	106.7	107.9	109.2	110.4	111.7	113.0	114.2	115.5
China	568.0	753.0	860.0	950.0	940.0	893.0	863.0	891.0	842.0
India	66.0	101.0	155.0	225.0	323.0	413.0	467.0	491.0	491.0

Finally, a cost and utility discount rate of 10% was assumed to account for the opportunity cost and shadow price of capital in each country. In addition, the model excludes extra production that would be stored in the warehouses to use in the future years.

3.2. Current Production Profiles of the U.S, China, and India's Iron and Steel Sectors

[1] *For India's iron and steel sector analysis, IEA uses three different demand profiles; (1) low demand case: steel production is 266 Mtonnes in 2050, (2) high demand case: steel production is 355 Mtonnes in 2050, and (3) strong growth case: steel production is 550 Mtonnes in 2050 (Trudeau et al. 2011).*

The base year of the ISEEM-IS model is 2010. Since it was the most recent year for which the majority of relevant data is available for iron and steel industries of the U.S., China, and India, and represented a good starting point for the future projection. This section aims to describe the statistical results of production, trading, energy consumption, and emissions of the U.S., China, and India's iron and steel sectors in the base year.

According to WSA (2011), China Statistical Yearbook (2011), and IBM (2011), annual total steel production of the U.S., China, and India was 80.5, 638.7, and 67.3 Mtonnes in 2010, respectively. These production statistics included extra production that was not used or sold but was stored for the future years. We calibrate the base year of the ISEEM-IS model using the statistics. Thus, the extra production of 2010 is included in the analysis. However, for the rest of the planning horizon, there is no extra production. The model brings the annual production and annual demands into the equilibrium. The shares of import in total availability are different: 21.5% in the U.S., 2.5% in China, and 11.9% in India in 2010 (Figure 7). In addition, Table 9 includes more details in steel import and export in the U.S., China, and India in the base year, 2010.

Figure 7. Total Steel Production and Imports in the U.S., China, and India in 2010 (Mtonnes)
(Data Source: WSA, 2011, USGS, 2011, China Statistical Yearbook, 2011, IBM, 2011)

Table 9. Steel Imports and Exports in the U.S., China, and India in 2010
(Data Source: USGS, 2011, China Statistical Yearbook, 2011, IBM, 2011)

		Import (Mtonnes)	Import Share in Total Steel Availability (%)	Export (Mtonnes)	Export Share in Total Steel Production (%)
The U.S.	**Total**	22.0	21.5%	11.0	13.7%
	From/To China	0.8		2.2	
	From/To India	0.8		0.1	
	*From/To Others**	20.4		8.7	
China	**Total**	16.4	2.5%	42.6	6.7%
	From/To the U.S.	0.1		0.8	
	From/To India	0.1		2.7	
	*From/To Others**	16.2		39.0	

India	**Total**	9.1	11.9%	5.8	8.7%
	From/To the U.S.	2.2		0.8	
	From/To China	2.7		0.1	
	*From/To Others**	4.2		4.9	

** Import/Export from/to rest of the world.*

Table 10 presents steel production in the U.S., China, and India by process types. EAF and EAF-DRI (Gas based) production had the largest share of annual steel production in the U.S. in 2010, accounting for 61.3% (see Table 10). 60.4% is from EAF production and the rest is from EAF-DRI (Gas based) production. The share of BOF process decreased to 38.7% in 2010 from 45% in 2005. This shift from BOF to EAF represented structural changes and technology uptakes, largely driven by reducing production costs in the U.S.

In contrast, BOF production is the dominant process in China with almost 90% shares in both 2005 and 2010. Scarcity of domestic scrap and dependence on highly priced import scrap disfavors EAF production process in China.

In India, on the other hand, there are two dominant production processes in 2010. BOF production has the largest share with 38.1% and EAF-DRI (Coal based) production has the second largest share with 32.7%. EAF-DRI (Gas based) and EAF production follow them with 14.3%, and 13.4%, respectively. However, steel production departs from BOF process over the years. The share of BOF production decreased to 38.6% in 2010 from 44.7% in 2005. This shift is mainly because of the higher costs in BOF processes and shortage of coking coal in India (a large part of the coking coal is imported over high prices). International prices of coking coal have gone from $125/ton to above $200/ton between 2005 and 2010 (as average of the year). Moreover, the coking coal prices peak in 2009 to above $300/ton, but fall around $220 in the first quarter of 2010 (CRISIL Research, 2011; Steel Mint, 2012)

Table 10. Steel Production in the U.S., China, and India by Process (Mtonnes)
(Data Source: USGS, 2011, China Statistical Yearbook, 2011, IBM, 2011, Sathaye et al. 2010a)

		2005	**2010**	**2005**	**2010**
		(Mtonnes)	**(Mtonnes)**	**(%)**	**(%)**
US	BOF	42.7	31.2	45.0%	38.7%
	EAF-DRI (Gas based)	1.0	0.7	54.0%	60.4%
	EAF	51.2	48.6	1.0%	0.9%
China	BOF	313.5	572.4	88.2%	89.6%
	EAF	41.8	66.3	11.8%	10.4%
India	BOF	20.0	26.0	44.7%	38.6%
	EAF-DRI (Coal based)	16.1	22.3	35.9%	33.2%
	EAF-DRI (Gas based)	5.4	9.8	12.1%	14.5%
	EAF	3.3	9.2	7.3%	13.6%

Average final energy intensity of the U.S. iron and steel sector is assumed to be 11 GJ/tonne steel in 2010 (Xu et al. 2010). Coal and coke, natural gas, and electricity are the main energy sources consumed in the U.S. iron and steel sector, with coal and coke accounting for approximately half of total final energy use in between 2005 and 2010.

Average final energy intensity in China was 20.8 GJ/tonne steel in 2005 (Zhou et al. 2011). Since the share of EAF process in steel production is around 10%, the average energy intensity of China steel production is close to that of BOF process intensity. Coal was the main energy source consumed in China's iron and steel sector, accounting for more than 90% of total energy use in 2006 (Hasanbeigi et al. 2011).

Average final energy intensity of the India's iron and steel sector was 28.2 GJ/ton in 2006 (Sathaye et al. 2010a). Since BOF and EAF-DRI (Coal based) production dominates the steel production in India, coal was also the main energy source consumed in India's iron and steel sector, accounting for 77% of total energy use in 2006 (Sathaye et al. 2010a).

4. Carbon Emission Reduction Scenario Analysis

A scenario is composed of a set of assumptions and the consequent modeling results from those assumptions. The ISEEM modeling framework is used to establish a base scenario, with which additional alternative policy-oriented scenarios can be compared. The base scenario serves as a reference with which alternative CO_2 emission reduction scenarios are assessed and compared. Scenario analyses aim at evaluating the impacts and the cost-effectiveness of efficiency measures and emission reduction strategies defined in the alternative carbon emission reduction scenarios.

In this study, we established two types of base scenarios: Base Scenario and Base-E Scenario. Both scenarios project future annual production, energy use, carbon emission, and costs of the U.S., China, and India's iron and steel sectors, reflecting business-as-usual trends from 2010 to 2050, with and without accounting for implementing energy efficient production technologies, respectively. Both scenarios take into account of autonomous efficiency improvement of the current iron and production technologies (i.e., via replacing retiring production technologies with advanced production technologies).

Base Scenario itself does not include the adoption of efficient production technologies; while Base-E scenario accounts for progress on energy efficiency, i.e., penetration of new energy efficiency technologies throughout the planning horizons. In essence, Base-E scenario is a projection of future annual production, energy use, carbon emissions, and costs of the U.S., China, and India's iron and steel sectors, reflecting business-as-usual trends (including autonomous improvement via implementation of advanced production technologies) as well as the implementation of cost-effective energy efficient production technologies. The purpose of establishing Base-E scenario is to evaluate the impacts and the cost-effectiveness of the policies and measures that are reflected in the assumptions for the alternative carbon emission reduction scenarios, while accounting for the availability of efficient production technologies. Similar to Base scenario, Base-E scenario can be used as a reference with which the alternative carbon emission reduction scenarios can be compared.

In this study, we predefined carbon reduction targets as alternative scenarios, using Base scenario as the reference base. Specifically, in each alternative scenario, annual carbon emissions for the country of concern would be lower than that of Base scenario by 10%, 20%, and 30%, respectively. The alternative scenarios studied represent various strategies for meeting the emission-reduction goals by incorporating different assumptions and tools. Each of the three scenarios is established and defined in the following:

1. The 'Emission Reduction without Trading (ER)' scenario: In this scenario, the mitigation strategy may be to apply energy efficiency on the national scale. The purpose of this

scenario is to analyze the emission reduction potentials in iron and steel sector of each country by means of investing in advanced production technologies and energy efficient production technologies, and switching to more efficient production processes, without any trading instrument (e.g., trading of commodities or carbon). Specifically, the annual CO_2 emissions in this ER scenario are reduced by 5% when compared to that of the Base scenario in 2015; and then the magnitude of annual reduction (starting in year 2020 throughout 2050 in each country's iron and steel sector) is predefined at three levels (i.e., 10%, 20%, and 30%, respectively) compared to that of the Base scenario.

2. The 'Emission Reduction with Commodity (Steel) Trading (ET)' scenario: In this scenario, the mitigation strategy may be to use commodity trading as a way to meet the emission reduction goals that are predetermined for the U.S. steel sector. In this case, emission restrictions are only applicable to the U.S. iron and steel sector. The primary purpose is to analyze the emission reduction potential of the U.S. iron and steel sector, while commodity trading from China and India is considered to be an instrument to decrease emissions that will affect emission reduction through changes in production and efficiency investments. In this case, changes in production processes, energy consumption and emissions of the China and India's iron and steel sectors due to increasing exports to the U.S. are also examined. Specifically, the annual CO_2 emissions in this scenario are reduced by 5% when compared to that of the Base scenario in 2015; and then the magnitude of annual reduction (starting in year 2020 throughout 2050 in U.S. iron and steel sector) is predefined at three levels (i.e., 10%, 20%, and 30%, respectively). As the ET scenarios (commodity trading strategies) aim to decrease emissions in the U.S. iron and steel sector alone (via increasing steel imports), they may not necessarily result in reducing net global emissions or global risks in climate change, but may simply transfer actual production burdens to China and India, where production costs are lower and actual intensities of energy use and emissions are higher.
3. The 'Emission Reductions with Carbon Trading (EC)' scenario: In this scenario, the mitigation strategy may be to use carbon trading of the U.S. with China and India, as a way to meet the emission reduction goals that are predetermined for the U.S., China, and India's steel sector collectively. The EC scenarios aim to understand global emission reduction potentials via carbon trading (i.e., U.S. investments in efficiency improvements in China and India, before imports). Specifically, the annual CO_2 emissions in this scenario are reduced by 5% when compared to that of the Base scenario in 2015 for each of country; and then the magnitude of annual reduction (starting in year 2020 throughout 2050 in each country, i.e., the U.S., China, and India) is predefined at three levels (i.e., 10%, 20%, and 30%, respectively).

4.1. Base Scenario

The Base scenario is a projection of future trends of the U.S., China, and India's iron and steel sectors (including production, energy consumption, emissions, and costs), reflecting business-as-usual assumptions. It also reflects trends and changes in structure and technologies, e.g., production process shifts, changes in fuel consumption, autonomous replacement with more advanced production technologies over time under cost minimization objective. The purpose of establishing the Base scenario is to

1. Examine the country-specific annual production, trading, and structure changes over time

2. Quantify the magnitudes and intensity of country-specific annual energy consumption and CO_2 emissions
3. Estimate country-specific costs of steel production and cost of emission reduction.

The Base scenario result is used as a baseline for comparisons with those of alternative mitigation scenarios.

4.1.1. Base Scenario Definition

The Base scenario is defined to characterize the iron and steel sector's development trends from 2010 to 2050, including production, trading, and effects of Chinese economic development on global markets, e.g., changes of raw material prices driven by the growing steel production in China. The approach to model and forecast price changes in primary raw materials of iron and steel production were discussed earlier in Section 3.1.1.2.

The Base scenario takes into account of autonomous efficiency improvement, i.e., autonomous upgrade or replacement of current iron and production technologies (e.g., replacement with more advanced production technologies described in Section 3.1.2.1). However, in Base scenario, penetration of new energy efficient production technologies is excluded. As presented earlier, in order to account for impacts from adopting cost effective energy efficient production technologies, we establish a second base scenario including efficient production technologies (term "Base-E"), which will be described in more details in Section 4.2. Base and Base-E scenarios have the same model assumptions (e.g., iron ore reserve capacities, annual scrap availabilities, energy source and raw material prices, and so on), except that there is no input for including energy efficient production technologies in Base scenario.

In addition to the Base scenario assumptions described in Section 3.1, statistical numbers derived from the WSA, USGS, China Statistical Year Book, and IBM are the base for model calibration (i.e., future projections spanning from 2010 to 2050 with a 5-year interval). In addition, trading levels in Base scenario are constrained through the planning horizon so that they do not exceed their current shares in total steel availability, as discussed in Section 3.2. If this constraint was not activated, the country that had the lowest production cost would become, by default, the main producer of the production from the model's optimization process (i.e., other countries would be exporting from it due to the cost minimization objective).

4.1.2. Base Scenario Results

4.1.2.1. The U.S. Iron and Steel Sector

In this section, we discuss the projection of annual production and trading, production costs, energy consumption, and CO_2 emissions in the U.S. iron and steel sector for the period 2010-2050 under the Base scenario.

4.1.2.1.1. Annual Production and Imports

Annual steel availabilities (i.e., domestic production plus import) in the U.S. are driven by the annual steel demand levels and projection as exogenous input of the ISEEM-IS model and represented earlier in Figure 6. Figure 8 shows that growth patterns of steel production and steel import are similar to that of annual steel demand in the U.S. On the other hand, relative shares of import in the total steel availability stays close to initial levels according to the Base scenario definitions. Table 11 shows that U.S. trading countries other than China and India account for approximately 90% of the total import throughout the planning horizon, which reflects the current statistics discussed earlier in Section 3.2.

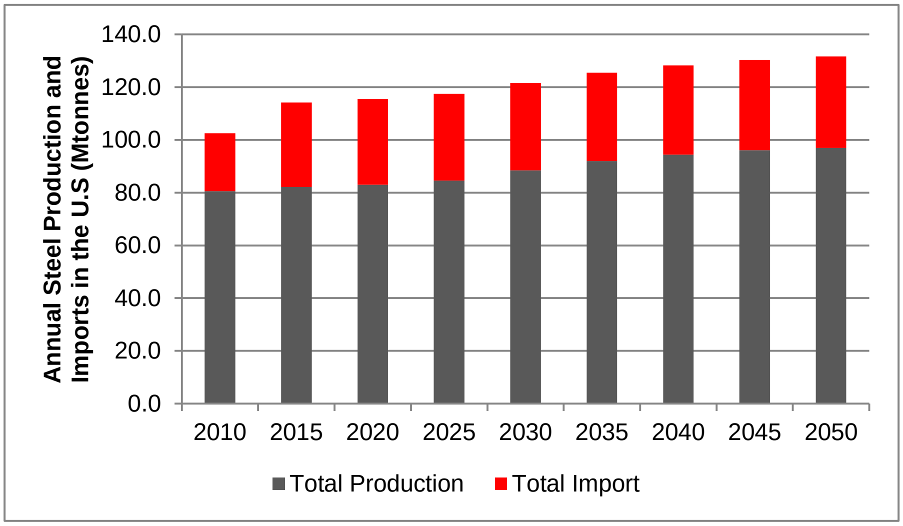

Figure 8. Annual Steel Production and Imports of the U.S. Projected in the Base Scenario (Mtonnes)

Table 11. Projected Annual Steel Production and Imports of the U.S. in Base Scenario (Mtonnes)

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total Production	80.5	82.1	83.0	84.6	88.4	91.9	94.4	96.0	96.9
BOF	31.2	24.6	20.8	16.9	13.3	10.8	9.4	9.6	9.7
EAF	48.6	56.0	59.5	64.9	72.4	79.0	83.6	85.1	87.2
EAF-DRI (Gas based)	0.7	1.5	2.8	2.8	2.7	2.1	1.3	1.3	0.0
Total Import	22.0	32.0	32.4	32.8	33.1	33.5	33.9	34.3	34.7
From China	0.8	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4
From India	0.8	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4
*From Others**	20.4	29.5	29.8	30.1	30.5	30.8	31.2	31.5	31.9

** The U.S. total import from countries other than China and India*

Figure 9 shows that BOF production in the U.S. accounted for 39% of the total production in the base year (WSA, 2011), and its share gradually decreases in the long term in the Base scenario, due to structural changes and higher unit production cost associated with BOF process. Since BOF production is relatively more expensive compared to EAF production through the planning horizon, the optimization process tends to favor EAF production. BOF production levels drop toward the lower production boundary predefined in the model assumptions (see Section 3.1.2.2). For example, the projected BOF production is 12% of the total production in 2035, slightly higher than the predefined lower bound for BOF production (i.e., 10% in 2035). Conversely, share of EAF production rises to 82% in 2030 and 90% in 2050 (from only 60% in 2010). EAF-DRI (Gas based) production remains stabled and is diminishing starting in 2045, after which no additional production or investment is favored in the model.

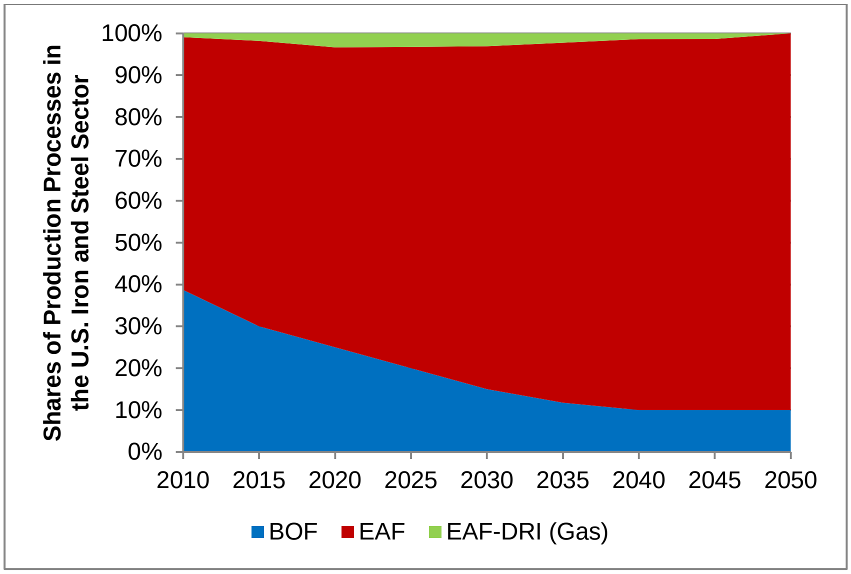

Figure 9. Shares of Production Processes of the U.S. Iron and Steel Sector Projected in the Base Scenario (%)

4.1.2.1.2. Annual Production Costs

Figure 10 illustrates the annual total cost of the U.S. iron and steel sector in the Base scenario through the planning horizon. Annual total cost of the U.S. iron and steel sector tends to stabilize after 2045. Figure 11 shows the unit production costs of three products, which are the cost of one tonne of steel. BOF and EFA unit cost lines show similar trends of increases between 2010 and 2030, after which EAF unit production cost seems to be stabilizing while there is a significant drop in BOF unit production cost between 2030 and 2040.

In addition to the assumptions for raw material costs described in Section 3.1.1.2, Table 12 shows that costs of raw materials (i.e., iron ore and scrap) account for the highest share of the annual total cost, which continues to increase over time. Therefore, it is expected that annual total cost would imitate the raw material cost projections. On the other hand, the sudden decrease of BOF unit production cost from 2030 to 2040 can be explained by the model's optimization process, which stops seeking for investments in BOF production after 2030. Then, the unit production costs stabilize around $650/tonne beginning in 2040.

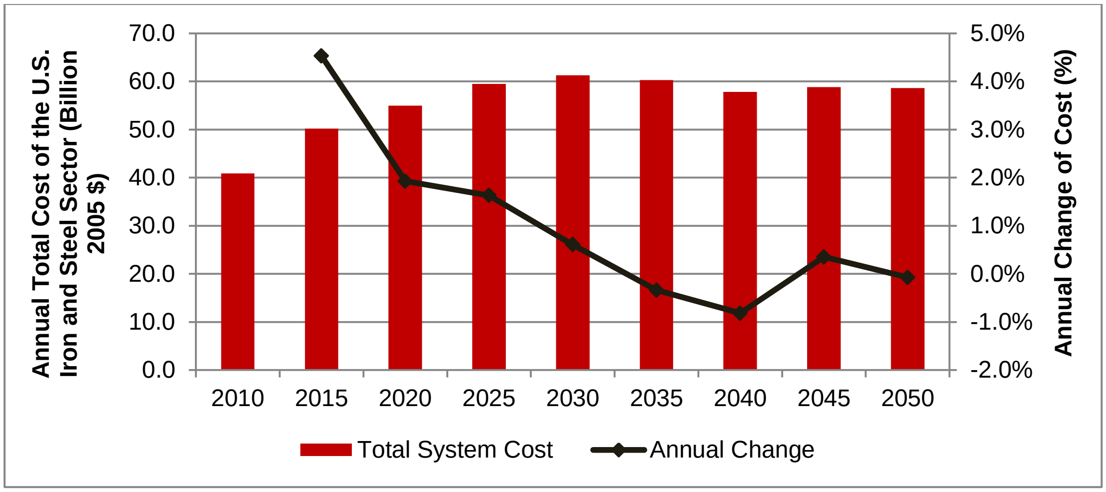

Figure 10. Projected Annual Total Cost of the U.S. Iron and Steel Sector in the Base Scenario (Billion 2005 $)

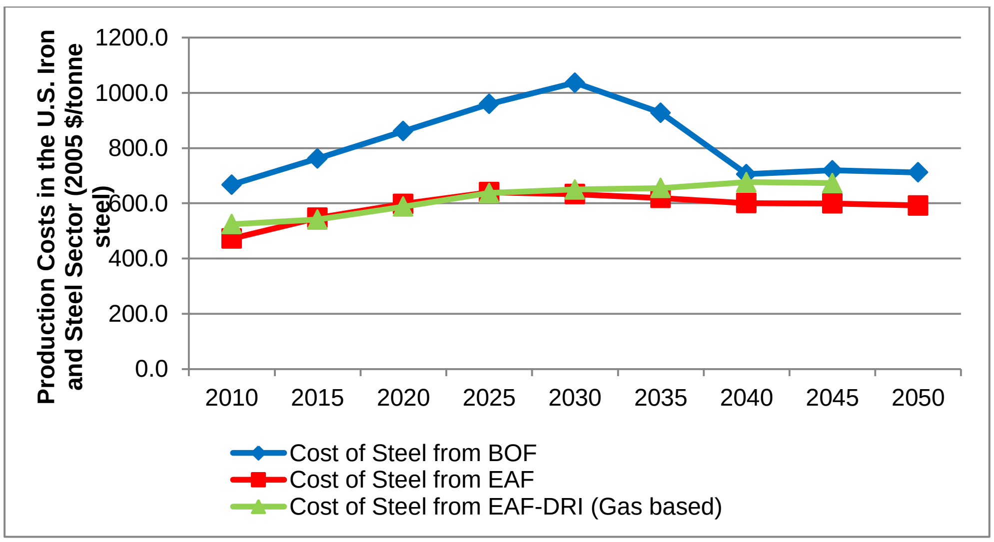

Figure 11. Process Based Production Costs of the U.S. Iron and Steel Sector Projected in the Base Scenario (2005 $/tonne steel)

Table 12. Share of Cost Items in Annual Total Cost of the U.S. Iron and Steel Sector Projected in the Base Scenario (%)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Investment Cost	13.1%	11.7%	10.9%	10.2%	10.0%	8.1%	6.7%	6.7%	6.7%
Total O&M Cost	26.6%	23.6%	22.2%	20.9%	20.8%	20.6%	20.5%	20.9%	21.5%
Energy Cost	15.9%	13.7%	13.2%	12.4%	12.1%	12.4%	11.2%	11.7%	11.9%
Raw Material Cost	44.4%	51.0%	53.7%	56.5%	57.1%	58.9%	61.6%	60.8%	59.9%
Annual Total Cost of the U.S. Iron and Steel Sector (Billion $)	44.1	50.2	55.1	59.6	61.4	60.3	57.8	58.8	58.6

4.1.2.1.3. Annual Energy Consumption

Figure 12 shows the annual total energy consumption of the U.S. iron and steel sector in the Base scenario throughout the planning horizon. The total energy consumption of the U.S. iron and steel sector decreases throughout the periods, while annual production increases slightly. The reduction in total energy use can be attributed to the shifts from BOF production to EAF production process that is more energy efficient. In addition, investments in advanced production technologies to replace current production technologies also bring about autonomous efficiency improvements to the sector.

In the model, we assumed that all the current production technologies were invested in the base year (2010) and would have 30-year lifetime. The current production technologies, if not otherwise selected by the model's optimization process to be replaced by advanced production technologies in any given year before 2040, will nevertheless reach the end of their lifetimes around 2040. In that case, we expect a higher level of investments in that particular year for replacing current production technologies, and the model's optimization process favors (among the available advanced production technologies) those providing the highest efficiency improvements. There is no other investment in production technologies needed for additional capacities because the steel demand is relatively stable. Therefore, total energy use tends to be stabilized between 2040 and 2050.

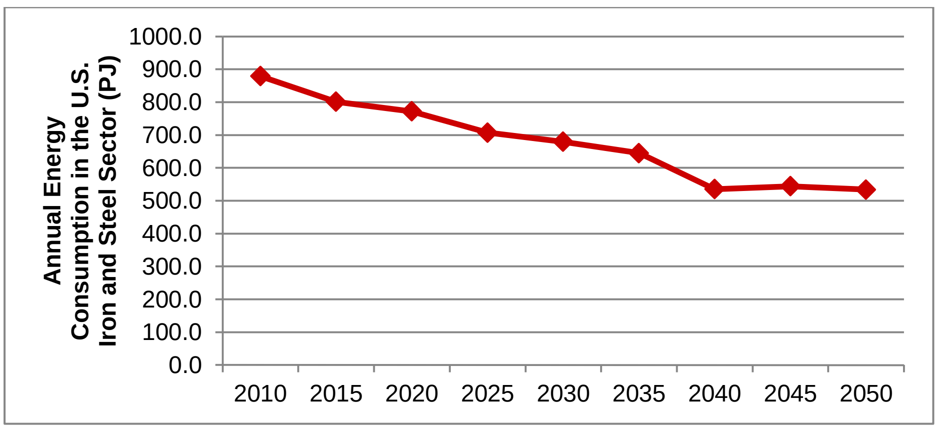

Figure 12. Annual Total Energy Consumption of the U.S. Iron and Steel Sector Projected in the Base Scenario (PJ)

Table 13 and Table 14 show the process- and fuel-based annual energy consumption of the U.S. iron and steel sector under the Base scenario. Table 13 shows that energy consumption of the EAF production increases in accordance with the increasing EAF production volumes. However, the annual total energy consumption decreases through the periods, largely attributed to the decreasing BOF production which has higher energy intensity than EAF production. Table 13 indicates that the total energy consumption of the BOF processes was more than twice as much as that of EAF processes in 2010, although BOF only accounted for 39% of total annual production.

In addition, coking coal consumption, which is one of the greatest contributors of the CO_2 emissions, declines by 70% over the planning horizon (from 347 PJ in 2010 to 96 PJ in 2050), due to the reduction in BOF production (Table 14). Table 14 also includes the energy consumed for onsite electricity generation (thus, summations of Table 13 and Table 14 do not match).

Table 13. Process Based Annual Energy Consumption of the U.S. Iron and Steel Sector Projected in the Base Scenario (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
BOF	572.4	444.7	375.1	287.3	222.8	181.6	117.9	120.1	120.4
EAF	272.2	311.7	330.5	354.4	391.7	408.7	376.3	380.4	387.3
EAF-DRI (Gas based)	14.1	27.9	50.8	48.8	47.6	35.7	20.5	20.5	0.0

Table 14. Fuel Based Annual Energy Consumption of the U.S. Iron and Steel Sector Projected in the Base Scenario (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Non-Coking Coal	13.1	11.0	9.6	8.2	7.0	6.2	4.6	4.7	4.8
Coking Coal	347.4	279.0	243.1	189.8	158.6	140.8	93.7	95.6	96.4
Coke Gas	23.3	18.7	16.3	12.7	10.7	9.5	6.3	6.4	6.5
Electricity	173.1	178.8	184.2	190.7	201.7	203.1	185.7	190.3	192.8
Natural Gas	271.0	263.8	268.1	256.6	253.3	240.3	205.3	207.1	196.6
Miscellaneous Oil	51.0	49.8	50.9	49.1	48.1	45.0	39.7	39.8	36.9
TOTAL Energy Consumption of the U.S. Iron and Steel Sector	878.9	801.1	772.2	707.2	679.4	644.9	535.3	544.0	534.0

Figure 13 and Table 15 present energy intensity trends in the Base scenario. Declining average energy intensity indicates efficiency improvements associated with structural changes as well as autonomous replacements with more advanced production technologies over time. The energy intensity starts to level out in 2040.

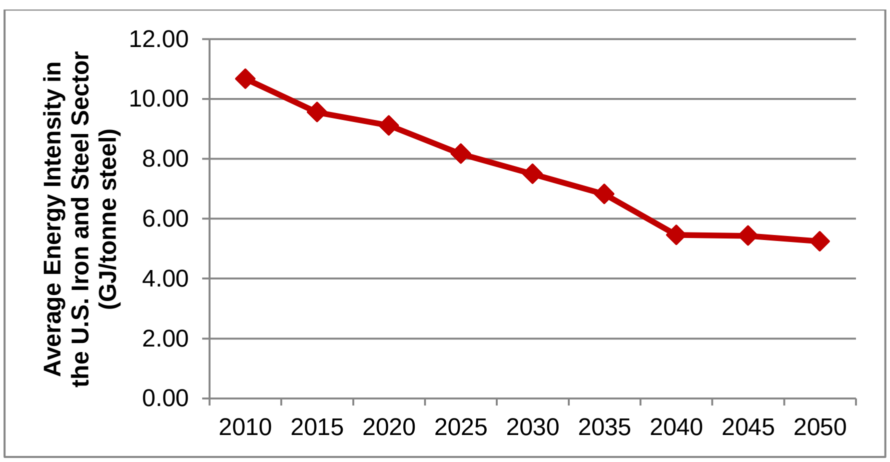

Figure 13. Average Energy Intensity of the U.S. Iron and Steel Sector Projected in the Base Scenario (GJ/tonne steel)

Table 15. Process Based Energy Intensities of the U.S. Iron and Steel Sector Projected in the Base Scenario (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
BOF	18.38	18.06	18.07	16.98	16.81	16.81	12.49	12.50	12.43
EAF	5.60	5.57	5.55	5.46	5.41	5.17	4.50	4.47	4.44
EAF-DRI (Gas based)	19.02	18.76	18.25	17.73	17.44	17.27	15.71	15.71	N.A.
Average Energy Intensity of the U.S. Iron and Steel Sector	10.67	9.55	9.11	8.16	7.49	6.82	5.45	5.43	5.24

4.1.2.1.4. Annual CO_2 Emissions

Figure 14 shows that corresponding to the trend of annual energy consumption, annual CO_2 emissions and CO_2 emission intensity of the U.S. iron and steel sector decrease in the Base scenario throughout the planning horizon. Contrary to the annual steel production increases between 2010 and 2050 (20% higher than those in 2010), annual CO_2 emissions show a continuously decreasing trend over the years. The results also indicate that corresponding to improved energy efficiency of the U.S. iron and steel sector, annual CO_2 emission intensity shows a continuously decreasing trend (Figure 14), largely due to the major production shifts from BOF production to EAF production and autonomous production technology replacement (and improvement) by investing in more advanced production technologies.

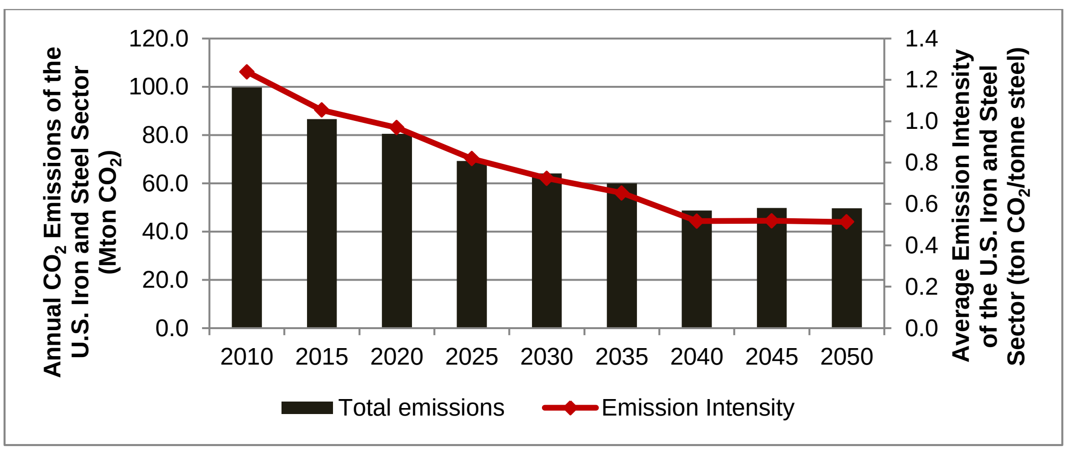

Figure 14. Annual CO_2 Emissions (Million ton (Mton) CO_2) and CO_2 Emissions Intensity (CO_2/tonne steel) of the U.S. Iron and Steel Sector Projected in the Base Scenario

4.1.2.2. China's iron and steel Sector

The following section discusses the annual production and trading, production costs, energy consumption, and CO_2 emissions projection of the China's iron and steel sector for the period 2010-2050 under the Base scenario.

4.1.2.2.1. Annual Production and Imports

Annual steel availabilities (i.e., sum of annual production and annual import) in China are driven by the annual steel demand levels and the projection as exogenous input to the ISEEM-IS model presented earlier in Figure 6. With the pre-defined annual demand projection, Figure 15 and Table 16 show that China's annual steel production and import follow the same growth patterns with the annual steel demand of China. On the other hand, steel import of China is relatively low compared to the China steel production. Chinese steel production costs are the lowest compared to other steel-producing countries included in the model. Thus, the model's optimization process would minimize steel import to China. However, there is no decrease on import levels in the Base scenario because the import shares are restricted. Table 16 shows that trading countries other than the U.S. and India supply more than 98% of the total steel import to China through the planning horizon.

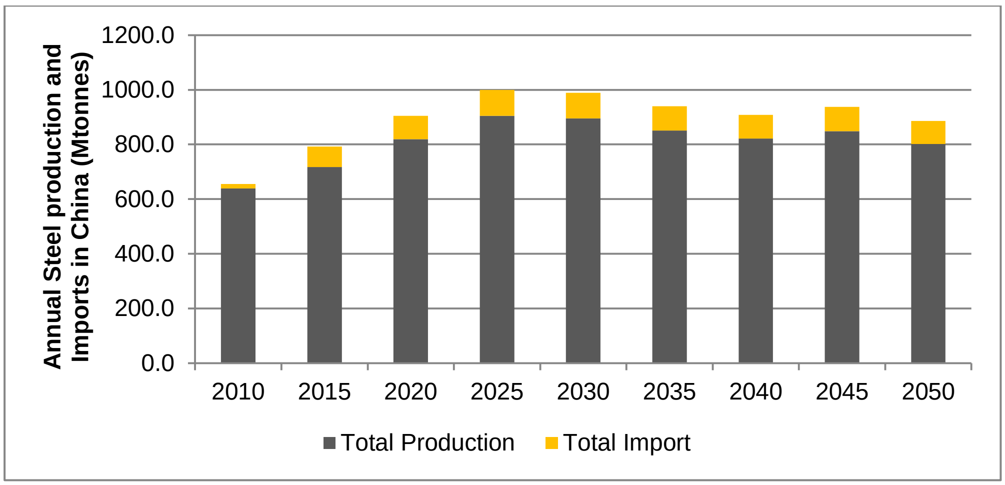

Figure 15. Annual Steel Production and Imports of China Projected in the Base Scenario (Mtonnes)

Table 16. Annual Steel Production and Imports of China Projected in the Base Scenario (Mtonnes)

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total Production	638.7	717.1	819.0	904.8	895.2	850.5	821.9	848.6	801.9
BOF	572.4	645.4	716.7	777.9	761.0	722.9	657.6	657.6	640.8
EAF	66.3	71.7	102.4	126.9	134.3	127.6	164.3	190.9	161.1
Total Import	16.4	75.3	86.0	95.0	94.0	89.3	86.3	89.1	84.2
From the U.S.	0.1	1.1	1.3	1.4	1.4	1.3	1.3	1.3	1.3
From India	0.1	0.4	0.4	0.5	0.5	0.5	0.4	0.5	0.4
*From Others**	16.2	73.8	84.3	93.1	92.1	87.5	84.6	87.3	82.5

** China total import from countries other than the U.S. and India*

Steel production in China is dominated by BOF production, which accounted for 90% of the total steel production in 2010 (Figure 16). This domination continues throughout the planning horizon, while EAF production rises from 10.4% in 2010 to 15% in 2030 and 20% in 2050, along with the increasing availabilities of domestic scrap after 2025.

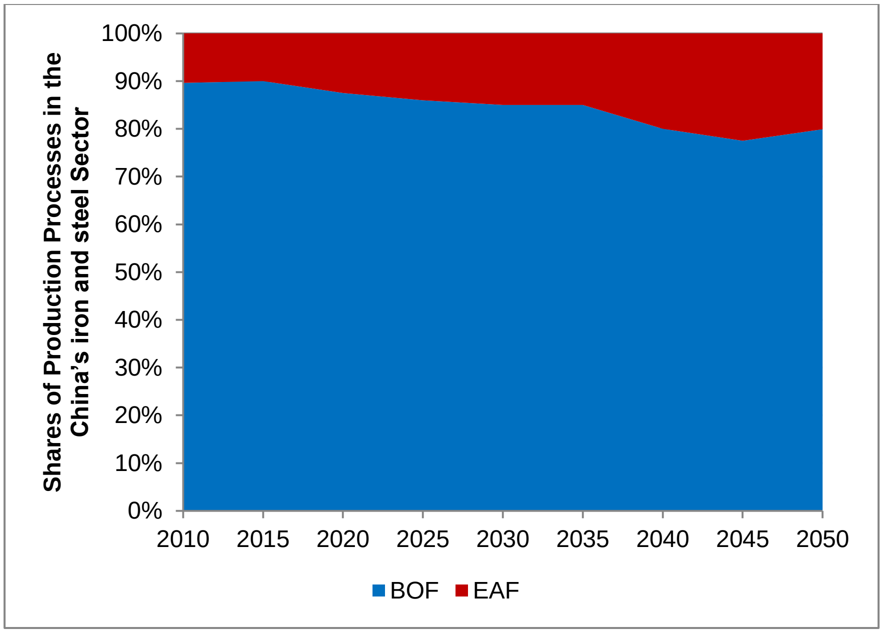

Figure 16. Shares of Production Processes of the China's iron and steel sector Projected in the Base Scenario (%)

4.1.2.2.2. Annual Production Costs

Figure 17 exhibits the total cost of the China's iron and steel sector in the Base scenario annually. Table 17 shows that raw materials, coking coal, and coke together account for more than 60% of the total sector cost each year. Since their price projections are generated from China steel demand, total annual production cost also follow a similar trend to that of China's annual steel demand.

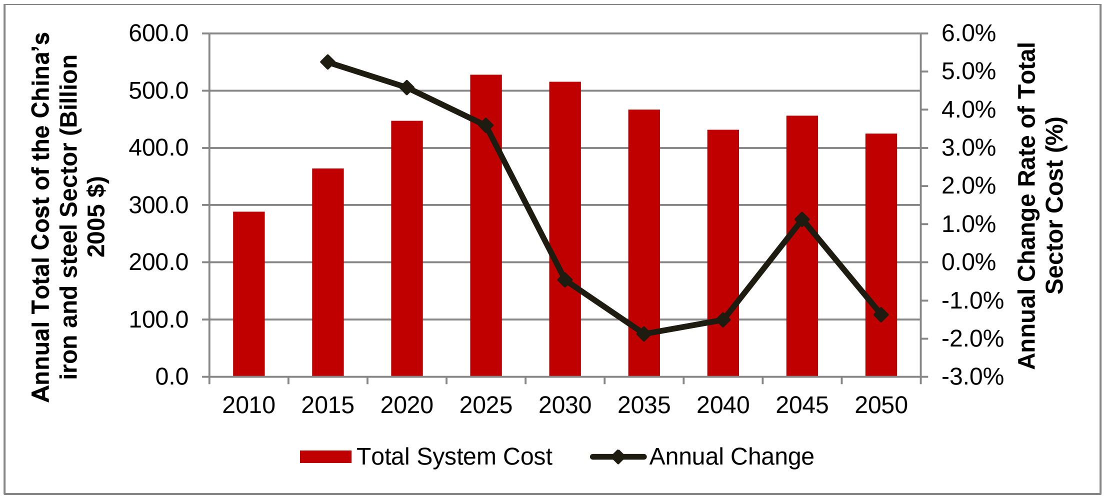

Figure 17. Annual Total Cost of the China's iron and steel sector Projected in the Base Scenario (Billion 2005 $)

Table 17. Share of Cost Items in Annual Total Cost of the China's iron and steel sector Projected in the Base Scenario (%)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Investment Cost	10.4%	8.8%	7.8%	9.5%	9.7%	9.5%	11.0%	10.6%	11.1%
Total O&M Cost	8.2%	7.5%	6.9%	7.1%	7.3%	7.5%	8.1%	7.9%	8.3%
Energy Cost (*other than Coking Coal and Coke)*	19.0%	19.4%	18.5%	17.3%	18.0%	19.8%	18.8%	19.0%	20.3%
Coking Coal and Coke Cost	19.1%	19.8%	19.6%	17.2%	16.9%	16.6%	14.0%	13.9%	13.5%
Raw Material Cost	43.3%	44.5%	47.2%	48.9%	48.1%	46.6%	48.1%	48.6%	46.8%
Annual Total Cost of the China's iron and steel sector (Billion $)	293.5	362.8	446.1	527.9	518.2	476.9	441.6	464.0	430.9

Figure 18 shows unit production costs of BOF and EAF production processes in China are very close to each other from 2010 to 2025, both exhibiting an increasing trend similar to that of annual steel demand during the period. Unit production costs of BOF and EAF production start to decline starting in 2025, with the unit cost of EAF production becoming lower than that of BOF (thus more economically viable) even though the scrap prices remain high.

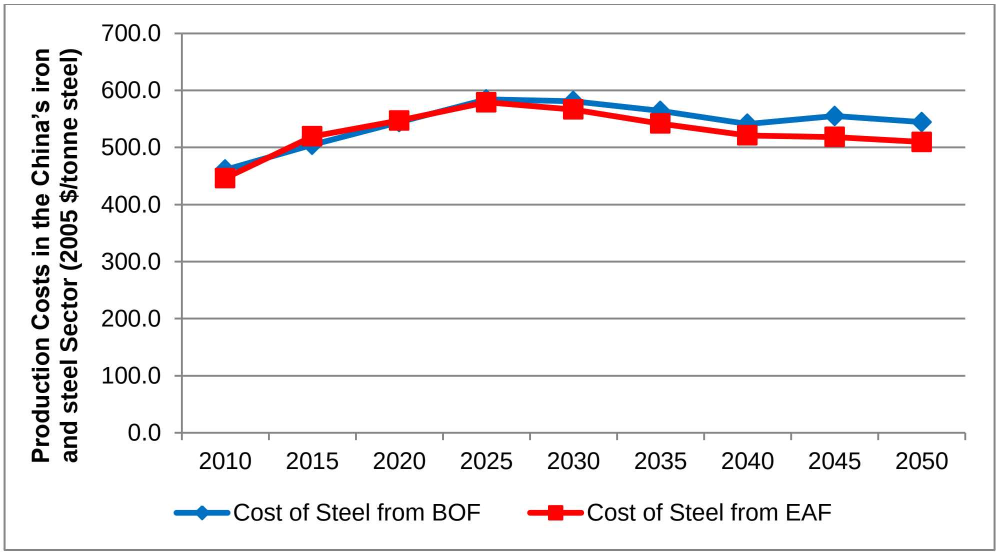

Figure 18. Process Based Production Costs of the China's iron and steel sector Projected in the Base Scenario (2005 $/tonne steel)

4.1.2.2.3. Annual Energy Consumption

Annual energy consumption of the China's iron and steel sector in the Base scenario through the planning horizon is shown in Figure 19. Annual energy consumption trend is also similar to China steel demand. Since the production structure does not change that much (BOF share was 90% in 2010 and will be 80% in 2050), China steel demand is dominantly satisfied by its BOF production. The increased share of EAF production shows its effect on reduced total energy use especially after 2025, however.

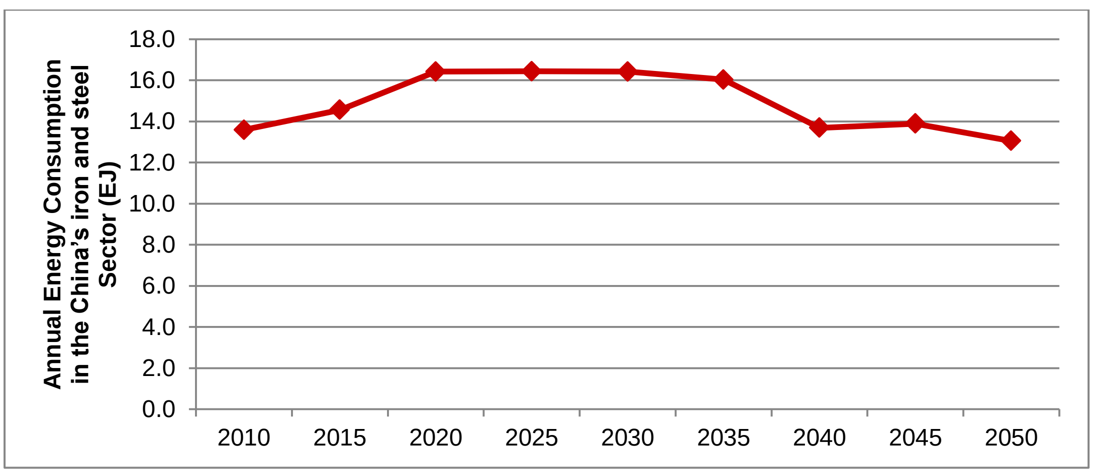

Figure 19. Annual Total Energy Consumption of the China's iron and steel sector Projected in the Base Scenario (PJ)

Table 18 and Table 19 provide the process and fuel based energy consumption of the China's iron and steel sector. Energy consumption in EAF process increases with the EAF production increases. In addition, coking coal and coke usage in the China's iron and steel sector decreases through the planning horizon due to the decrease in BOF production. Table 19 also includes the energy consumed for onsite electricity generation (thus, summations of Table 18 and Table 19 do not match).

Table 18. Process Based Annual Energy Consumption of the China's iron and steel sector Projected in the Base Scenario (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
BOF	11.25	11.98	13.33	12.92	12.52	11.83	9.35	9.33	8.92
EAF	0.56	0.58	0.83	0.95	1.00	0.94	1.07	1.23	1.02

Table 19. Fuel Based Annual Energy Consumption of the China's iron and steel sector Projected in the Base Scenario (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Non-Coking Coal	0.32	0.33	0.37	0.36	0.35	0.34	0.28	0.28	0.27
Coking Coal	3.17	3.70	4.54	4.10	3.92	3.72	2.84	2.87	2.64
Coke (Purchased & Imported)	3.63	3.42	3.47	3.40	3.33	3.16	2.61	2.64	2.55
Coke Gas	0.05	0.06	0.08	0.07	0.07	0.06	0.05	0.05	0.05
Electricity	4.90	5.44	6.17	6.72	7.00	7.10	6.53	6.66	6.21
Natural Gas	1.34	1.40	1.57	1.54	1.51	1.43	1.19	1.20	1.15
Miscellaneous Oil	0.18	0.20	0.23	0.24	0.24	0.22	0.19	0.18	0.17
TOTAL Energy Consumption of the China's iron and steel Sector	13.58	14.56	16.42	16.43	16.42	16.03	13.69	13.89	13.05

Figure 20 and Table 20 show the average energy intensity of the China's iron and steel sector per period. The trend clearly indicates continuous reduction in average energy intensity throughout the planning horizon, with the intensity dropping from 18.5 GJ/tonne steel in 2010 to 15.1 GJ/tonne steel in 2030, and 12.4 GJ/tonne steel in 2050. The sudden decreases in energy intensity from year 2025 to year 2040 can be attributed to the increased investments and the need for replacing existing production technologies. First, in 2025, China steel demand approaches the peak and the investments become necessary to implement advanced production technologies that are expected to have lower energy intensity. This will contribute to lowering average energy intensity level. Second, in 2040, the current production technologies adopted in the base year (2010) are expected to reach end of their lifetime (30-year) and replacement of the existing production technologies with more efficient production technologies are expected. Overall, the trend of decreasing energy intensity is largely attributed to structural shifts along with autonomous improvement of production technologies over time.

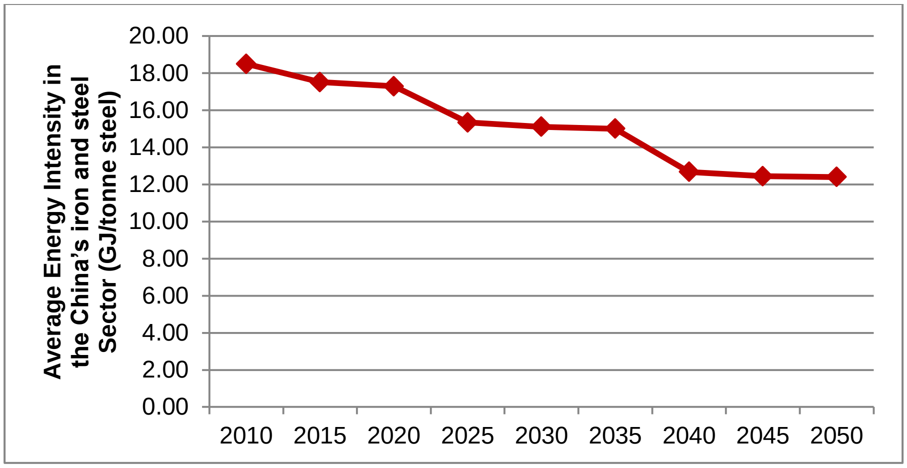

Figure 20. Average Energy Intensity of the China's iron and steel sector Projected in the Base Scenario (GJ/tonne steel)

Table 20. Process Based Energy Intensities of the China's iron and steel sector Projected in the Base Scenario (GJ/tonne steel)

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
BOF	19.66	18.56	18.60	16.61	16.46	16.36	14.22	14.18	13.92
EAF	8.43	8.14	8.09	7.51	7.43	7.33	6.49	6.46	6.34
Average Energy Intensity of the China's iron and steel Sector	18.49	17.51	17.29	15.34	15.10	15.00	12.68	12.44	12.40

4.1.2.2.4. Annual CO_2 Emissions

Figure 21 shows that annual CO_2 emissions of the China's iron and steel sector decreases through the planning horizon, coupled with decreasing energy use. Overall, the energy intensity and CO_2 emission intensity decreases by 34% and 26% from 2010 to 2050, respectively. It is clear that CO_2 emission intensity of the China's iron and steel sector are reduced without any mitigation interventions in the Base scenario, exhibiting a similar trend of energy intensity. The mitigation of carbon emission intensity can be mainly attributed to observed production shifts from BOF production to EAF production, and in particular, autonomous production technology replacement (and improvement) by investing in more advanced production technologies.

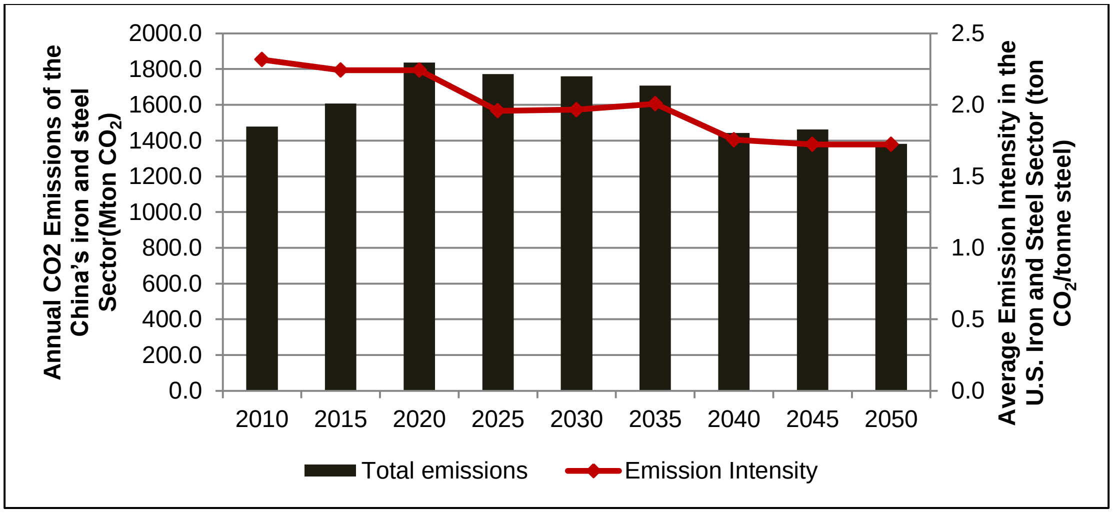

Figure 21. Annual CO_2 Emissions (Mton CO_2) and CO_2 Emission Intensity (ton CO_2/tonne steel) of the China's iron and steel sector Projected in the Base Scenario

4.1.2.3. The India's iron and steel Sector

This section discusses the projection of annual production and trading, production costs, energy consumption, and CO_2 emissions in India's iron and steel sector for the period 2010-2050 under the Base scenario assumptions.

4.1.2.3.1. Annual Production and Imports

Annual steel availabilities (i.e., sum of annual production and annual import) in India are driven by the annual steel demand levels and projection as exogenous input to the ISEEM-IS model presented earlier in Figure 6. Annual growth patterns of steel production and steel import are similar to that of annual steel demand of India. On the other hand, share of import in the total steel availability stays at current shares due to the Base scenario definitions (Figure 22). As can be seen from Table 21, annual imports from the U.S. and China account for almost half of the total annual import to India throughout the planning horizon.

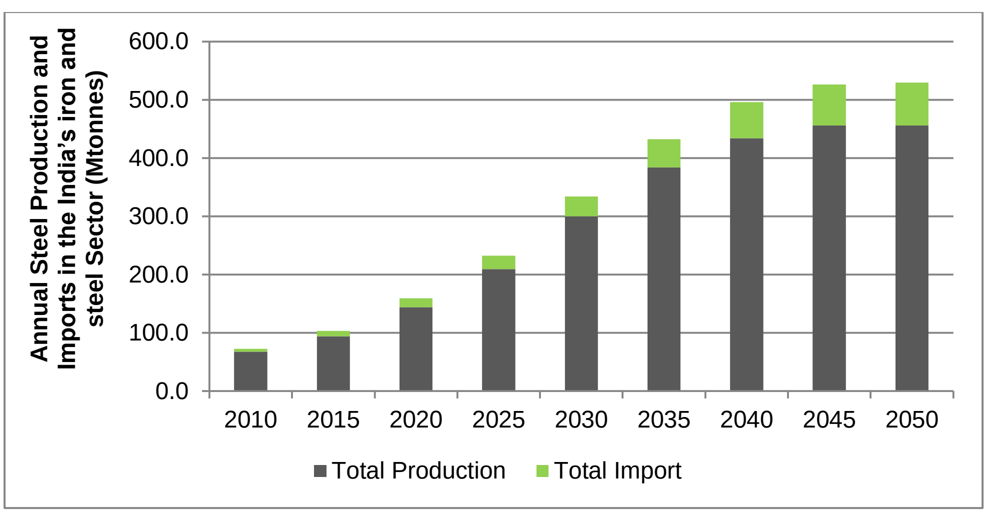

Figure 22. Annual Steel Production and Imports of India Projected in the Base Scenario (Mtonnes)

Table 21. Annual Steel Production and Imports of India Projected in the Base Scenario (Mtonnes)

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total Production	67.3	93.8	144.0	209.0	300.1	383.7	433.8	456.1	456.1
BOF	26.0	28.1	36.0	41.8	45.0	38.4	43.4	45.6	45.6
EAF	9.2	12.2	17.3	20.9	24.0	23.0	74.5	68.7	130.4
EAF-DRI (Gas based)	9.8	12.2	17.3	20.9	24.0	23.0	21.7	22.8	22.8
EAF-DRI (Coal based)	22.3	41.3	73.4	125.4	207.0	299.3	294.3	319.0	257.3
Total Import	9.1	15.2	23.3	33.8	48.4	62.0	70.0	73.6	73.6
From the U.S.	2.2	3.0	4.7	6.8	9.7	12.4	14.0	14.7	14.7
From China	2.7	4.6	7.0	10.1	14.5	18.6	21.0	22.1	22.1
*From Others**	4.2	7.6	11.6	16.9	24.2	31.0	35.0	36.8	36.8

** India total import from countries other than the U.S. and China*

Steel production in India is mostly dominated by EAF-DRI (Coal based) process, which is the least expensive production alternative of the India's iron and steel sector. ISEEM-IS modeling's optimization process favors increasing shares of such a production mode as illustrated in Figure 23. However, especially after 2035, scarcity in domestic iron ore availability leads to increased usage of imported iron ores that are more expensive. Due to the increasing domestic scrap availability, EAF production cost becomes lower in the second half of the planning horizon. Therefore, share of EAF production starts to increase after 2040 (Table 21 and Figure 23). A small decline in EAF production in 2045 can be attributed to the response to peaking of import iron ore prices.

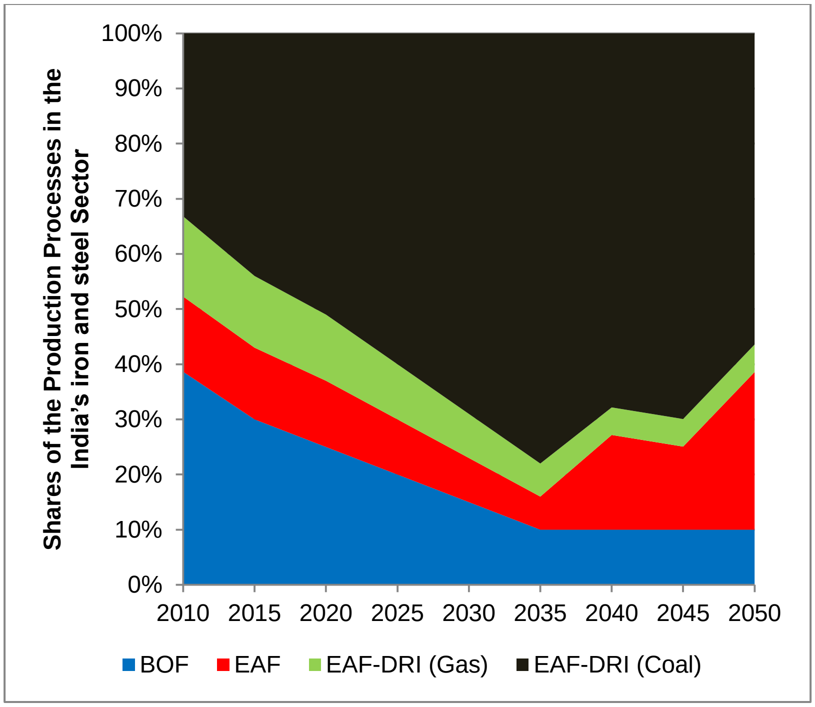

Figure 23. Shares of Production Processes of the India's iron and steel sector Projected in the Base Scenario (%)

4.1.2.3.2. Annual Production Costs

Figure 24 shows annual total costs of India's iron and steel sector in the Base scenario from 2010 to 2050, which exhibited similar trend of annual steel production. Annual total cost of the India's iron and steel sector tends to stabilize after 2045.

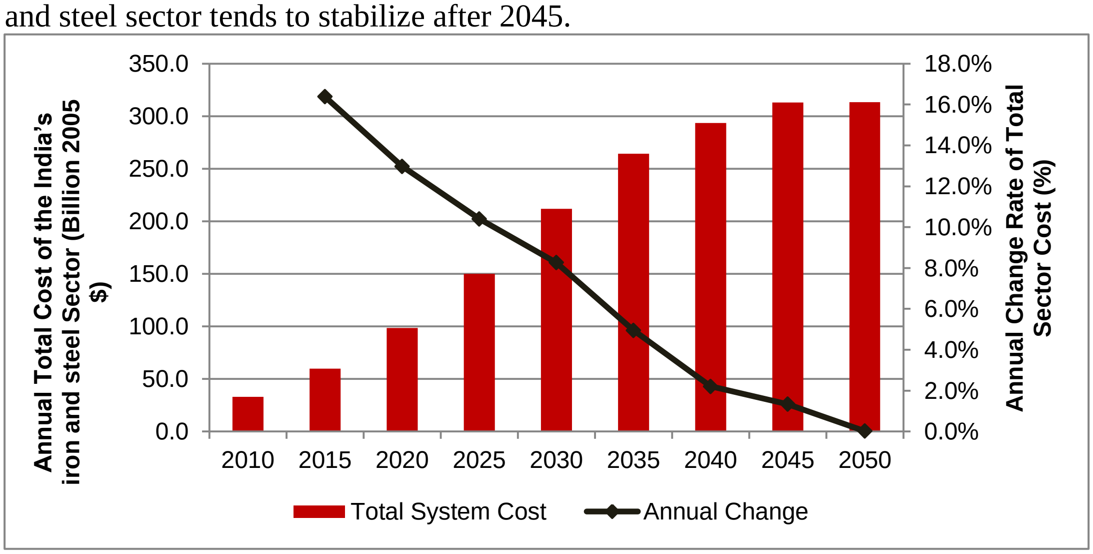

Figure 24. Annual Total Cost of the India's iron and steel sector Projected in the Base Scenario (Billion 2005 $)

Figure 25 shows the unit production costs of four products, which are the cost of one tonne of steel. BOF and EFA unit cost lines show similar trends of increases between 2010 and 2030, after which both unit production costs decreased and exhibited a dip in 2040 followed by stabilization between 2040 and 2050. BOF production cost in India is the highest through the planning horizon Costs of other three EAF production processes are very close to each other at the beginning of the planning horizon. Then, with the increasing natural gas and scrap prices, the price difference between EAF-DRI (Coal based) and other processes grows. EAF-DRI (Gas based) production cost continues to increase since the natural gas price continues to increase. EAF unit production cost is the higher than EAF-DRI between 2010 and 2035, after which it becomes lower, approaching to the unit production cost of EAF-DRI (coal-based) that is the lowest among all process. This is largely due to the decreasing scrap prices starting in 2035.

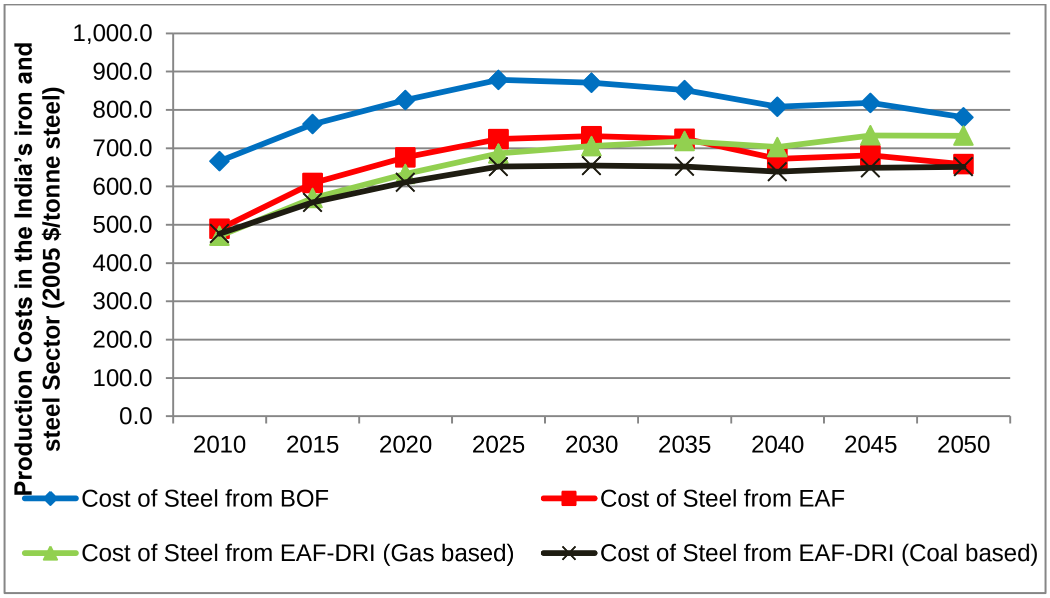

Figure 25. Process Based Production Costs of the India's iron and steel sector Projected in the Base Scenario (2005 $/tonne steel)

Table 22. Share of Cost Items in Annual Total Cost of the India's iron and steel sector Projected in the Base Scenario (%)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Investment Cost	7.4%	6.0%	5.5%	5.4%	5.2%	4.9%	5.5%	5.3%	5.7%
Total O&M Cost	12.9%	11.5%	10.9%	10.6%	10.8%	11.0%	11.1%	11.1%	10.9%
Energy Cost	38.3%	40.3%	38.8%	37.8%	37.8%	39.8%	39.0%	40.4%	40.7%
Raw Material Cost	41.3%	42.2%	44.9%	46.2%	46.2%	44.4%	44.5%	43.2%	42.7%
Annual Total Cost of the India's iron and steel sector (Billion $)	37.1	58.9	97.2	147.9	209.2	261.1	288.2	307.6	305.7

4.1.2.3.3. Annual Energy Consumption

Figure 26 shows the annual energy consumption of India's iron and steel sector in the Base Scenario, which exhibits a similar trend to the annual steel production. The total energy consumption stabilizes between 2040 and 2050, largely due to the increased production share of EAF process that is less energy intensive in those years, along with autonomous efficiency improvement due to replacement with advanced production technologies in the period. Numbers in Table 23 confirm such a trend: Energy consumption of EAF process increases in 2040 and 2050, while the energy consumption of other processes reduces. The small increase in 2045 corresponds to the tentative reduction of EAF production in 2045 due to changes in domestic and import iron ore prices for that particular year.

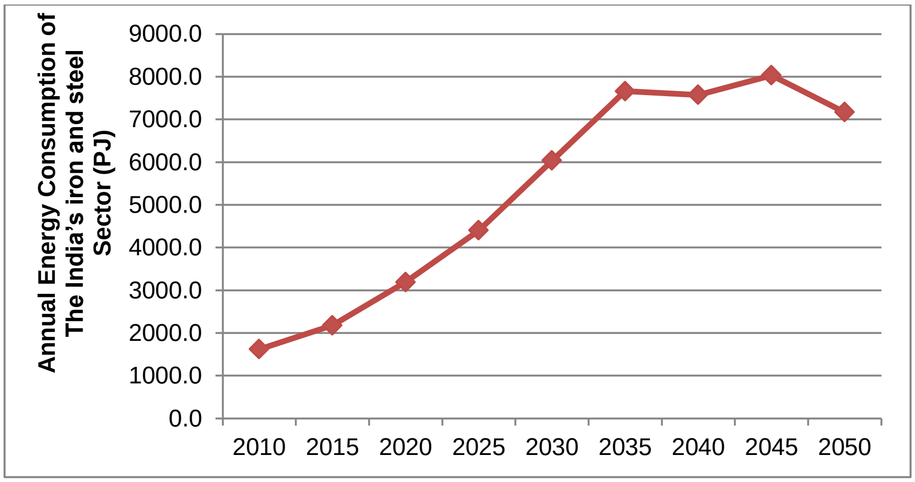

Figure 26. Annual Total Energy Consumption of the India's iron and steel sector Projected in the Base Scenario (PJ)

Table 23. Process Based Annual Energy Consumption of the India's iron and steel sector Projected in the Base Scenario (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
BOF	824.5	893.6	1094.7	1192.5	1238.0	1043.2	1034.0	1088.9	1024.9
EAF	109.0	143.6	195.8	233.1	259.2	247.7	717.4	657.2	1174.2
EAF-DRI (Gas based)	192.4	237.7	320.3	381.1	419.2	400.4	349.1	364.4	340.4
EAF-DRI (Coal based)	503.8	915.3	1587.8	2598.5	4118.1	5964.6	5466.9	5912.8	4623.5

Table 24 shows that non-coking coal is the major energy source of the India's iron and steel sector, because it is the primary energy source of EAF-DRI (Coal based) production route that has the highest share in total steel production.

Table 24. Fuel Based Annual Energy Consumption of the India's iron and steel sector Projected in the Base Scenario (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Non-Coking Coal	568.8	859.1	1366.8	2060.2	3055.3	4220.9	3820.3	4144.1	3311.5
Coking Coal	253.0	284.9	352.0	385.2	390.0	329.7	313.5	333.2	299.7
Coke (Purchased &Import)	200.0	203.5	243.6	250.5	264.3	223.0	227.6	240.2	233.6

Coke Gas	41.0	46.1	57.0	62.4	63.2	53.4	50.8	54.0	48.5
Electricity	274.7	393.4	600.8	873.2	1252.0	1620.3	1729.7	1801.8	1689.8
Natural Gas	166.2	209.1	278.6	331.3	360.4	345.2	501.3	490.3	673.7
Miscellaneous Oil	117.1	182.4	292.3	440.3	651.4	866.8	931.5	967.7	914.2
TOTAL Energy Consumption of the India's iron and steel Sector	1620.8	2178.5	3191.1	4402.9	6036.6	7659.3	7574.5	8031.2	7171.0

Figure 27 shows the average energy intensity trend of the India's iron and steel sector, which is reduced by 35% from 2010 to 2050 (i.e., a drop from 24.2 GJ/tonne steel in 2010 to 15.7 GJ/tonne steel in 2050). The sudden drops in 2040 and 2050, on the other hand, are again due to the EAF production increases and autonomous efficiency improvement due to replacement with advanced production technologies (i.e., replacing the retired capacities of the base year, which has 30-year lifetime) in 2040. Table 25 shows more details of the process-based energy intensities from 2010 to 2050.

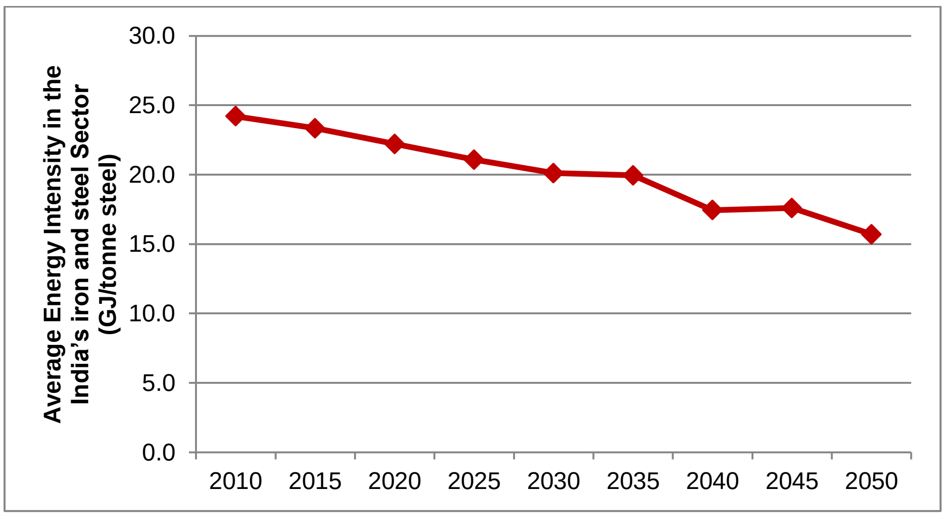

Figure 27. Average Energy Intensity of the India's iron and steel sector Projected in the Base Scenario (GJ/tonne steel)

Table 25. Process Based Energy Intensities of the India's iron and steel sector Projected in the Base Scenario (GJ/tonne steel)

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
BOF	31.71	31.75	30.41	28.53	27.51	27.19	23.83	23.87	22.47
EAF	11.88	11.78	11.33	11.15	10.80	10.76	9.63	9.56	9.01
EAF-DRI (Gas based)	19.65	19.49	18.54	18.23	17.46	17.39	16.10	15.98	14.93
EAF-DRI (Coal based)	22.56	22.17	21.62	20.72	19.89	19.93	18.58	18.54	17.97
Average Energy Intensity of the India's iron and steel Sector	24.20	23.34	22.21	21.08	20.11	19.95	17.44	17.59	15.70

4.1.2.3.4. Annual CO_2 Emissions

Figure 28 shows the annual CO_2 emissions of the India's iron and steel sector in the Base scenario. Compared to Figure 26 and Figure 27, CO2 emissions and emission intensity exhibit very similar trends to energy consumption and energy intensity, respectively. Similar to the cases for the U.S. and China cases, the intensity levels of annual energy consumption and annual CO2 emissions of the India's iron and steel sector are reduced over the period of 2010 to 2050 in the Base scenario.

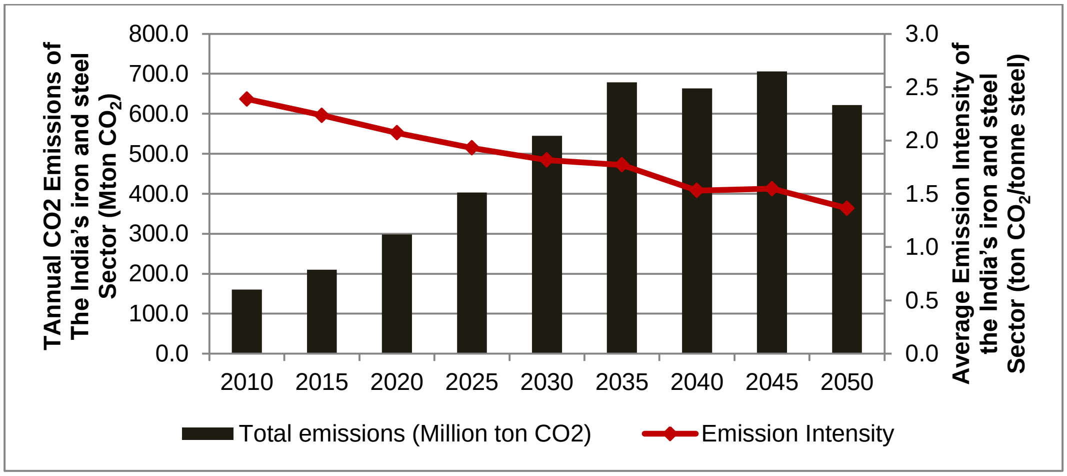

Figure 28. Annual CO_2 Emissions (Mton CO_2) and CO_2 Emissions Intensity (ton CO_2/tonne steel) in India's iron and steel Sector

4.1.3. Base Scenario Summary

The Base scenario for 2010-2050 projection reflects business-as-usual practice, with the goal of achieving the least-cost iron and steel sector production in each period, by using ISEEM-IS model's optimization process. The model projects what would happen given the assumptions predefined for the ISEEM-IS model with the cost-minimization objective. In the Base scenario, there is no additional constraint such as environmental regulation constraint or policy measure to affect the costs or optimization process. However, the Base scenario allows autonomous energy efficiency improvement associated with adoption of advanced production technologies in any given time between 2010 and 2050 that is attributed to cost optimization process and/or replacement requirements for retiring production equipment.

- ***Base scenario projection reflects production structure shifts guided by production cost minimization in each country.*** The share of BOF production in the U.S. gradually decreases in the medium- and long-term in the Base scenario: down from 39% in 2010 to 15% in 2030 and 10% in 2050, mainly due to the fact that BOF is more expensive production (technological, energy, and raw material costs) compared to EAF production in the U.S. Steel production in China is dominated by BOF production throughout the planning horizon, while the share of EAF production rises modestly over time, from 10% in 2010 to 15% in 2030 and 20% in 2050 with the increasing availabilities of domestic scrap and decreasing prices of domestic scrap starting in 2025. Steel production in India is mostly dominated by EAF-based production, especially EAF-DRI (Coal based) process, throughout the planning horizon, given that EAF-DRI (Coal based) production is the cheapest production compared to other processes in India's iron and steel sector. Specifically, the following highlight the production projection in the Base scenario:

- *Share of EAF production in the U.S. increases to 82% in 2030 and 90% in 2050 (up from 60% in 2010), while share of BOF production declines to 15% in 2030 and 10% 2050 (up from 39% in 2010). Share of EAF-DRI (Gas based) production is negligibly small through the planning horizon.*
- *Share of EAF production in China increases to 15% in 2030 and 20% in 2050 (up from 10% in 2010), while share of BOF production declines from 90% in 2010 to 85% in 2030 and 80% 2050. This narrow range is largely due to the production constraints applied exogenously in the model. A free-run cost optimization process could result in higher EAF shares over time.*
- *Share of EAF based production (i.e., sum of EAF and EAF-DRI production) in India increases to 85% in 2030 and 90% in 2050 (up from 61% in 2010), while share of BOF production declines from 39% in 2010 to 15% in 2030 and 10% 2050.*
- *The increase in scrap availability in India make the EAF production more attractive in 2040 - EAF share increases to 29% in 2050 while EAF-DRI (Coal based) production share first increases from 33% in 2010 to 78% in 2035, then drops to 56% in 2050.*

➢ ***The Base scenario projection is highly influenced by raw material prices, especially in China and India.*** Because scrap availabilities in both China and India are insufficient to satisfy domestic market requirements, both countries depend on imported scrap from international market to reduce the otherwise more expensive scrap prices that would increase the EAF production costs. Lowered scrap prices could make model favor increasing investments in EAF production that is more less energy intensive. Modeling results show that once China and India are self-sufficient for scrap (e.g., scrap prices drop to reasonable levels in 2020 in China and 2040 in India), shares of EAF production will increase and intensity levels of energy use and CO_2 emissions from the iron and steel sector will be reduced. It is clear that scrap price has an indirect effect on overall energy intensity of the iron and steel sector. On the other hand, iron ore prices are one of the major determinants of the EAF-DRI (Coal based) production in India. Any increase in iron ore prices makes this process unattractive compared to other EAF production in India.

➢ ***China exhibits the lowest unit production cost (2005 $/tonne steel) among the ISEEM-IS model countries (i.e., the U.S., China, and India) throughout the planning horizon.*** Figure 29 shows that EAF unit production cost in the U.S. ranges between those of China and India. This implies that even without trading restrictions of the Base scenario (i.e., limitation to current trading shares), the model would not favor importing EAF steel from India to the U.S., while China would be the main steel production source favored by the ISEEM-IS model – i.e., the U.S. and India would import from China due to its lowest production cost associated with the assumptions in Base scenario.

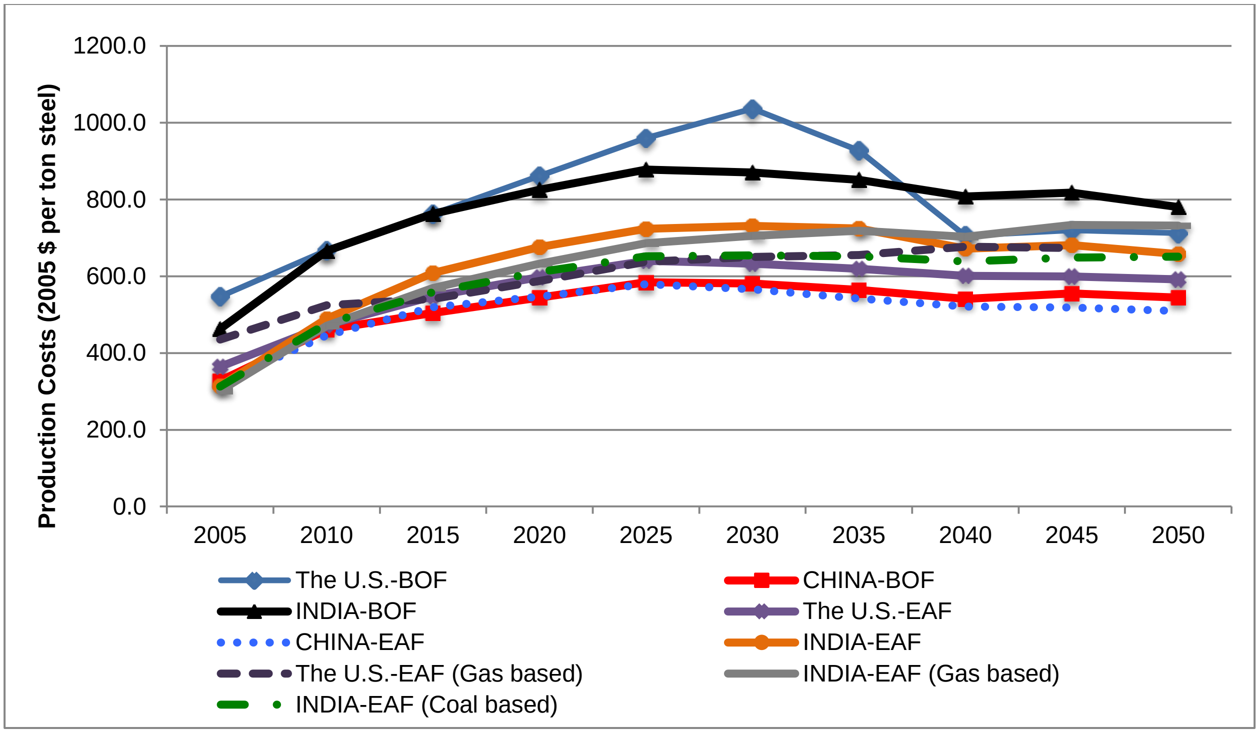

Figure 29. Process Based Production Costs of the U.S., China, and India's iron and steel sector Projected in the Base Scenario (2005 $/tonne steel)

- ***Energy and CO2 emission intensities of the iron and steel sectors of the three countries decrease continuously in the mid- and long-term under the Base scenario.*** Figure 30 and Figure 31 show that annual energy use per tonne steel production declines by 1.3%, 0.8%, and 0.9% per year on average from 2010 to 2050 in the U.S., China, and India, respectively. Annual CO2 emissions per tonne steel production declines by 1.5%, 0.6%, and 1.1% per year on average from 2010 to 2050 in the U.S., China, and India's iron and steel sector, respectively. There are two primary reasons for the observed trends: 1) process shift from the relatively expensive BOF production to the cheaper and less energy intensive EAF production improve the overall energy efficiency in each of the countries; and 2) advanced production technologies contribute to autonomous improvement of the energy efficiency throughout the planning horizon.
    - *Share of EAF production in the U.S. increases to 90% in 2050 (from 60% in 2010).*
    - *Share of EAF production in China increases to 20% in 2050 (from 10% in 2010).*
    - *Share of EAF production in India increases to 29% in 2050 (from 14% in 2010).*

- ***Energy and emission intensities of the U.S. iron and steel sector are the lowest among the three countries.*** Figure 30 also shows that energy intensity of the U.S. is approximately one-third to one half of that of India and China, respectively in each model year (e.g., energy intensity of the U.S., China, and India is 7.5 GJ/tonne, 15.1 GJ/tonne, and 20.1 GJ/tonne in 2030, respectively). This indicates that the U.S. iron and steel sector already includes a more efficient iron and steel production structure compared to that of China and India's iron and steel sectors. A predominantly higher capacity share of EAF production in the U.S., which is the more energy efficient iron and steel production process, results in lower energy intensity in the

U.S. Under the projected structural shift between 2010 and 2050, China and India would not be able to lower the energy intensity to the level of the U.S. due to structural limitations. In addition, Figure 31 shows that the average emission intensity of the India's iron and steel sector is initially higher than China in the base year, but this situation is reversed in the following years, due to decreasing share of BOF production and less coking coal and coke usages. The total consumption of coking coal and coke (which are the top highest emission contributors) in the India's iron and steel sector declines to 8.1% in 2050 from 30.5% in 2010. It is clear that investing in efficiency improvement in China and India's iron and steel sectors could help to decrease global emissions more effectively, simply because the production is more energy intensive and emission intensive in China and India.

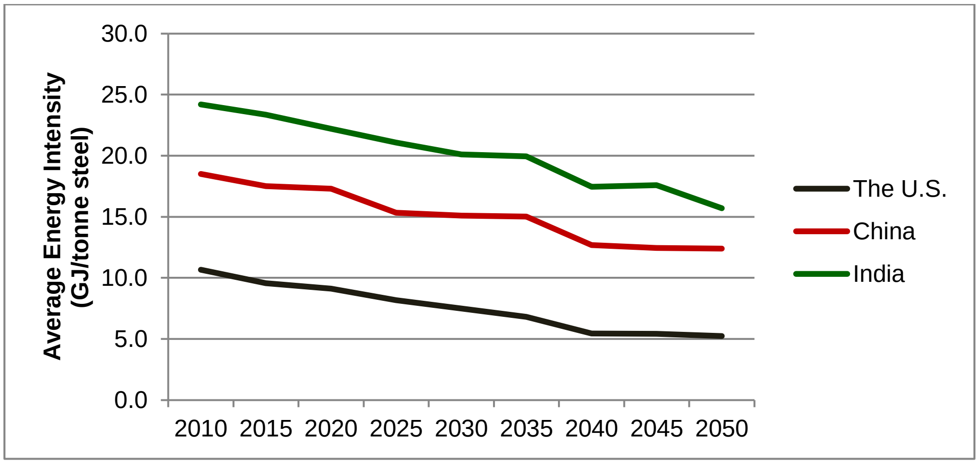

Figure 30. Average Energy Intensity of the U.S., China, and India's iron and steel Sectors Projected in the Base Scenario (GJ/tonne steel)

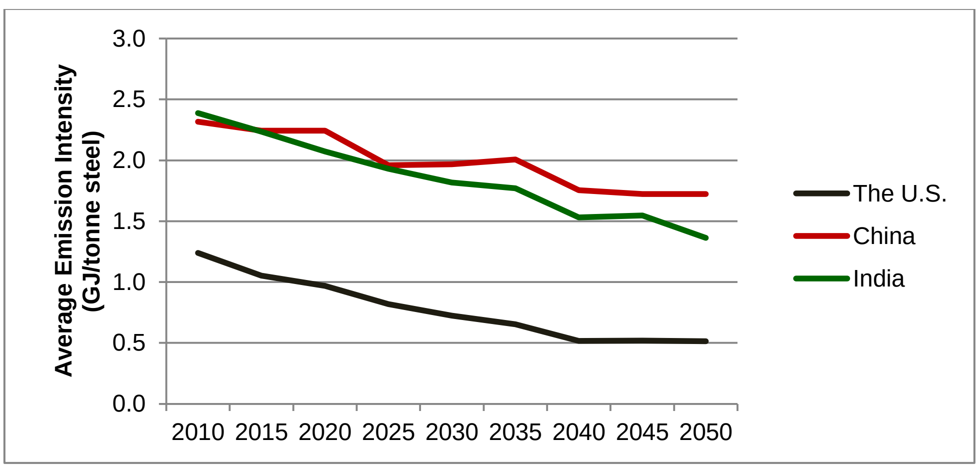

Figure 31. Average Emission Intensity of the U.S., China, and India's iron and steel Sectors Projected in the Base Scenario (ton CO_2/tonne steel)

- ***Annual CO_2 emissions of the U.S. iron and steel sector decline over the years in the Base scenario, while China and India emissions increase with the increase in steel production projections.*** Increased capacity and usage of EAF production in the U.S. is the primary reason for annual emission reduction by 50% in year 2050 compared to its base year (i.e., 2010). Autonomous adoption of advanced production technologies in the U.S. iron and steel sector contributes modestly to the emission reduction. The decreasing trend in energy intensity and carbon emissions attributed to structural shifts and significant increase in advanced production technologies, however, is insufficient for curbing annual CO_2 emissions in the China and India’s iron and steel sectors.

4.2. Base with Efficient Technologies (Base-E) Scenario

As presented earlier, the Base scenario itself accounts for autonomous improvement via advance production, but does not include the adoption of efficient production technologies which normally requires additional investment; while Base-E scenario accounts for progress on energy efficiency, i.e., penetration of new energy efficiency technologies throughout the planning horizons. The purpose of establishing Base-E scenario is to evaluate the impacts and the cost-effectiveness of the policies and measures, while accounting for the availability efficient production technologies. Similar to Base scenario, Base-E scenario can be used as a reference with which the alternative carbon emission reduction scenarios can be compared.

In essence, Base-E scenario is a projection of future production, energy use, carbon emissions, and production costs in the U.S., China, and India’s iron and steel sectors, reflecting business-as-usual trends (including autonomous improvement via advanced production) as well as the investments and implementation of energy efficient production technologies. Compared to Base scenario, Base-E scenario enables us to take into accounts of progress on energy efficiency attributed to the adoption of new energy efficiency technologies throughout the planning horizons.

4.2.1. Base-E Scenario Definition

The Base with efficient technologies (Base-E) scenario is defined to characterize the iron and steel sector’s development trends from 2010 to 2050, including production, trading, raw material prices that are driven by the growing steel production in China. Base-E scenario is based on the same supply, price, technology, and trading assumptions as the Base scenario as described in the previous section. In addition to the technologies reflected in the Base scenario, the Base-E scenario includes energy efficient production technologies that improve the energy efficiency of the current production technologies with extra costs and assumes that they are available starting from 2015. Some of these technologies are cost effective based on their parameters structures, which are exogenously input to the ISEEM-IS model. Thus, even though there are no efficiency improvement requirements, the optimization process may prefer to invest in the cost effective technologies that may contribute to cost reduction objective, therefore affecting the optimum solutions sought after by the ISEEM-IS model.

Establishing the Base-E scenario can help to understand the difference between the two baselines, which allow us to better understand the impacts of different pre-defined carbon reduction strategies while using one base scenario versus the other (i.e., Base-E that comes with adoption of available efficient production technologies). The differences between these two pre-defined base scenarios will be quantified based on

1) country-specific production and structure changes over time,
2) magnitudes and intensity of country-specific annual energy consumption and emissions, and

3) country-specific annual production costs.

4.2.2. Base-E Scenario Results

In this section, we discuss the projection of annual production and trading, production costs, energy consumption, and CO_2 emissions in the iron and steel sector of U.S., China, and India for the period 2010-2050 under the Base-E scenario, and compare them with those of the Base scenario.

4.2.2.1. Annual Production and Imports

Table 26, Table 27, and Table 28 present the annual steel production in the U.S, China, and India, respectively, under the Base and Base-E scenarios.

In Table 26, annual BOF and EAF production of the U.S. iron and steel sector is almost identical for both Base and Base-E scenarios. Annual BOF production approaches the lower bounds predefined for the ISEEM-IS model (in Table 5, Section 3.1.2.2) in both the Base and Base-E scenarios, except for year 2035, when BOF production does not drop to the lower bound in the Base scenario while BOF production approaches to the lower bound in 2035 in the Base-E scenario. In the meanwhile, there is an increase in EAF production in the Base-E scenario compared to the Base scenario throughout 2050, with the difference being the biggest in 2035. In addition, EAF-DRI (Gas based) production is lower in Base-E scenario compared to that of Base scenario throughout 2050. Overall, Base-E scenario reflects that there is an increase in more energy efficient production (i.e., EAF) throughout 2050, an indication that more energy efficient production technologies have been implemented for the Base-E scenario. This is particularly true for year 2035, when a portion of both BOF and EAF (Gas-based) shifted to EAF production is higher in the Base-E scenario for the U.S. sector. The optimization process prefers to investing in efficient production technologies (i.e., EAF production), instead of investing in EAF-DRI (Gas based) production in the Base-E scenario. The observed differences indicate that adoption of more energy efficiency measures is favored by the optimization process in the Base-E scenario.

Table 26. Annual Steel Production of the U.S. Projected in the Base and Base-E Scenarios (Mtonnes)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	31.2	24.6	20.8	16.9	13.3	10.8	9.4	9.6	9.7
Base-E	31.2	24.6	20.8	16.9	13.3	9.2	9.4	9.6	9.7
Difference	0.0	0.0	0.0	0.0	0.0	-1.6	0.0	0.0	0.0
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	48.6	56.0	59.5	64.9	72.4	79.0	83.6	85.1	87.2
Base-E	48.6	56.4	60.8	66.2	73.7	82.0	84.9	86.4	87.2
Difference	0.0	0.4	1.3	1.3	1.3	2.9	1.3	1.3	0.0
EAF-DRI (Gas based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	0.7	1.5	2.8	2.8	2.7	2.1	1.3	1.3	0.0
Base-E	0.7	1.1	1.5	1.4	1.4	0.8	0.0	0.0	0.0
Difference	0.0	-0.4	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	0.0

Table 27 exhibits the annual steel production of the China's iron and steel sector under the Base and Base-E scenarios. Compared to the U.S. iron and steel sector, BOF production is always dominant in the China's iron and steel sector. In Base-E scenario, there is an increased shift from BOF to EAF compared to that of Base scenario in years from 2025-2035 and 2050. This indicates that adoption of more energy efficiency measure in EAF processes is favored by the optimization process in the Base-E scenario in those years. The economic benefits of implementing efficient measures in EAF production outweigh that of BOF production, resulting in additional structural changes toward EAF in the Base-E scenario in China. In another word, investment in efficient production technologies in EAF can minimize total production cost more effectively than in BOF in the Base-E scenario.

Table 27. China's Annual Steel Production Projected in the Base and Base-E Scenarios (Mtonnes)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	572.4	645.4	716.7	777.9	761.0	722.9	657.6	657.6	640.8
Base-E	572.4	645.4	716.7	715.4	707.8	680.4	657.6	657.6	625.2
Difference	0.0	0.0	0.0	-62.5	-53.2	-42.5	0.0	0.0	-15.6
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	66.3	71.7	102.4	126.9	134.3	127.6	164.3	190.9	161.1
Base-E	66.3	71.7	102.4	189.3	187.4	170.1	164.3	190.9	176.7
Difference	0.0	0.0	0.0	62.5	53.2	42.5	0.0	0.0	15.6

Table 28 exhibits the annual steel production of India under the Base and Base-E scenarios. There is no difference in BOF production and EAF-DRI (Gas based) between the two scenarios. There is also no difference in the EAF and EAF-DRI (Coal based) production in the India's iron and steel sector between the Base and Base-E scenarios, except for future years (i.e., 2040-2050) in which EAF production becomes less favored in Base-E scenario compared to the dominant EAF-DRI (Coal based) production in Base scenario. In fact, the model projects decreased production in EAF process that corresponds to increasing EAF-DRI (Coal based) production in Base-E scenario. This indicates that investment in efficient production technologies in EAF-DRI (Coal based) is favored while minimizing total production cost more effectively in the Base-E scenario, compared to investment in energy efficient EAF production process. On the other hand, BOF and EAF-DRI (Gas based) production approaches the lower bounds defined for the ISEEM-IS model (in Table 5 and Table 6, Section 3.1.2.2) in both the Base and Base-E scenarios. Because the trading limitations defined for the Base and Base-E scenarios are identical, there is no change in import volumes of the U.S., China, and India between the Base and Base-E scenarios.

Table 28. Annual Steel Production of India Projected in the Base and Base-E Scenarios (Mtonnes)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	26.0	28.2	36.0	41.8	45.0	38.4	43.4	45.6	45.6
Base-E	26.0	28.2	36.0	41.8	45.0	38.4	43.4	45.6	45.6
Difference	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EAF production									

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	9.2	12.2	17.3	20.9	24.0	23.0	74.5	68.7	130.4
Base-E	9.2	12.2	17.3	20.9	24.0	23.0	72.0	60.1	95.5
Difference	0.0	0.0	0.0	0.0	0.0	0.0	-2.5	-8.6	-34.9
EAF-DRI (Gas based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	9.8	12.2	17.3	20.9	24.0	23.0	21.7	22.8	22.8
Base-E	9.8	12.2	17.3	20.9	24.0	23.0	21.7	22.8	22.8
Difference	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EAF-DRI (Coal based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	22.3	41.3	73.4	125.4	207.0	299.3	294.3	319.0	257.3
Base-E	22.3	41.3	73.4	125.4	207.0	299.3	296.8	327.7	292.2
Difference	0.0	0.0	0.0	0.0	0.0	0.0	2.5	8.7	34.9

4.2.2.2. Annual Production Costs

Table 29 summarizes the annual total costs of the U.S., China, and India's iron and steel sectors in the Base and Base-E scenarios. In general, annual total production costs are lower in Base-E scenario compared to those of Base scenario in each country. It is expected that adoption of some efficient measures in the steel production is favored by the optimization process in the model, leading to lowered total production costs throughout 2050 in Base-E scenario.

In addition, magnitudes of total annual cost reduction from Base to Base-E scenario in the India's iron and steel sector are much higher than those of the U.S. and China's iron and steel sectors. For example, in the Base-E scenario, annual total production cost of the India's iron and steel sector is 13.8 Billion U.S. dollars and 31.6 Billion U.S. dollars lower in 2030 and 2050, respectively, when compared with their counterparts in Base scenario.

Table 29. Annual Total Costs of the U.S., China, and India's iron and steel Sectors Projected in the Base and Base-E Scenarios (Billion 2005 $)

Annual Total Costs (Billion 2005 $)									
The U.S.	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	40.9	50.2	55.0	59.5	61.3	60.3	57.8	58.8	58.6
Base-E	40.9	50.1	54.9	59.4	61.1	59.7	57.1	58.0	57.8
Change	0	-0.1	-0.1	-0.1	-0.2	-0.6	-0.7	-0.8	-0.8
China	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	288.5	364.1	447.5	527.7	515.4	467.0	431.8	456.0	424.7
Base-E	288.5	363.9	446.8	526.9	513.8	464.6	427.7	451.8	420.7
Change	0	-0.2	-0.7	-0.8	-1.6	-2.4	-3.9	-4.2	-4.0
India	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	32.9	59.8	98.6	149.9	211.9	264.3	293.5	313.1	313.4
Base-E	33.2	58.6	94.4	141.5	198.1	243.7	269.6	285.0	281.8

Change	-0.7	-1.2	-4.2	-8.4	-13.8	-10.6	-23.9	-28.1	-31.6

Figure 32, Figure 33, and Figure 34 show the graphic differences in annual total costs between the Base and Base-E scenarios in each country. This indicates that while some efficiency measures are cost effective to implement in all three countries, the impact of their cost effectiveness is most evident for India and least for China.

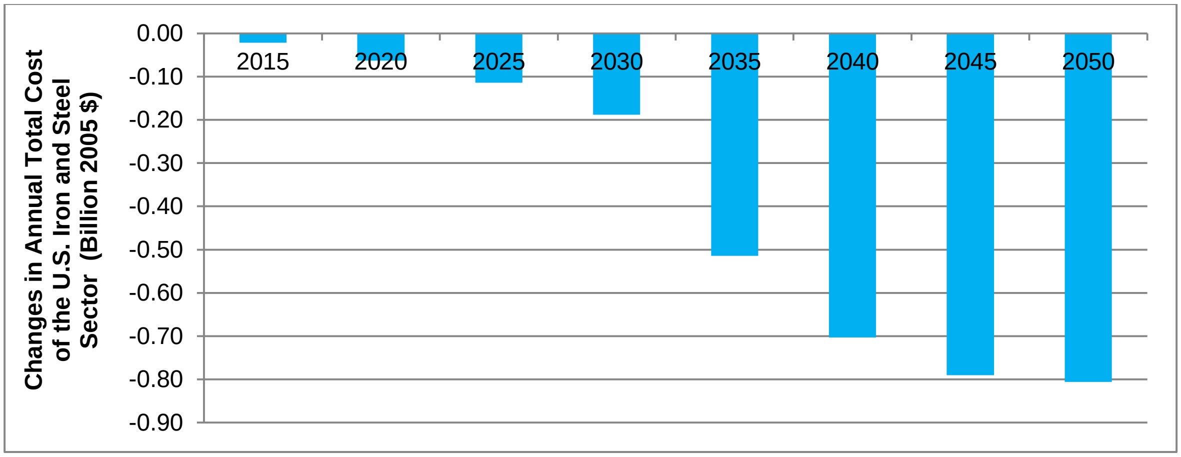

Figure 32. Changes in Annual Total Cost of the U.S. Iron and Steel Sector Projected in the Base and Base-E Scenarios (Billion 2005 $)

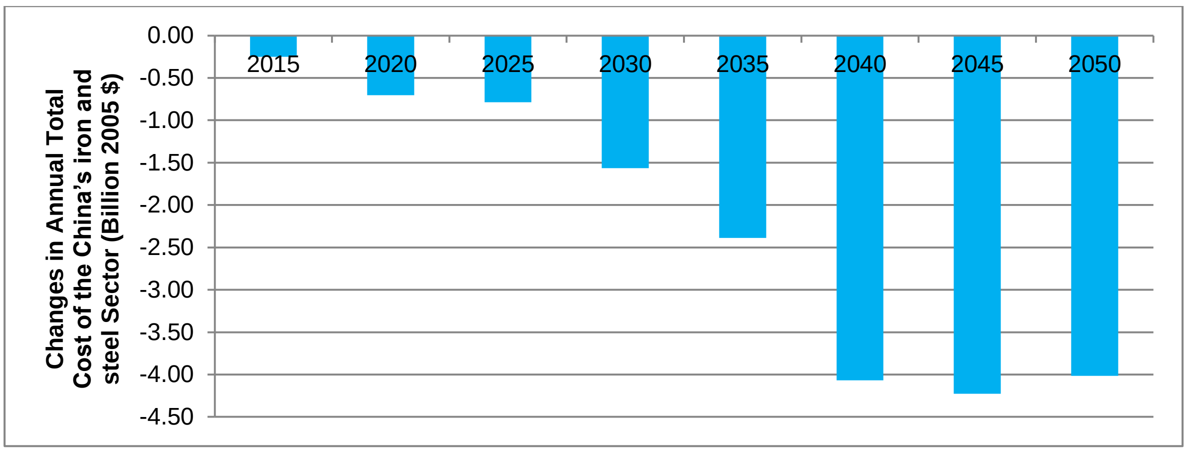

Figure 33. Changes in Annual Total Cost of the China's iron and steel sector Projected in the Base and Base-E Scenarios (Billion 2005 $)

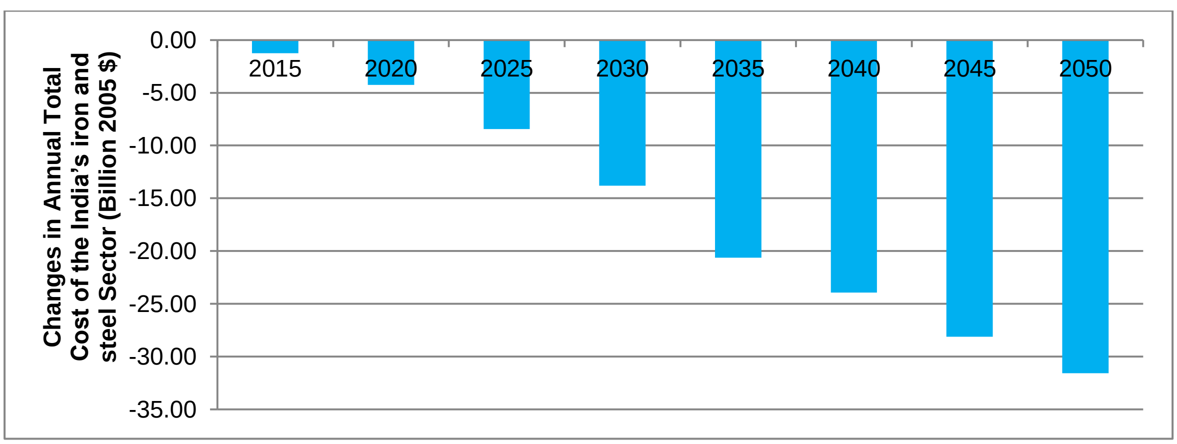

Figure 34. Changes in Annual Total Cost of the India's iron and steel sector Projected in the Base and Base-E Scenarios (Billion 2005 $)

Table 30 shows the annual average unit production costs in each of the three countries under each scenario. In general, the annual average unit production cost in China is lower than that of the U.S. by 11-18%. For China as well as U.S., average unit production cost is projected to increase annually and peak in 2025, followed by annual declines through 2050; in addition, there is slight difference in unit production costs between Base and Base-E scenarios in each year from 2010 to 2030, whereas the difference becomes bigger after 2035.

India's annual unit production cost is the highest among the three countries. The annual unit production cost for both scenarios is projected to increase through 2050; in addition, annual unit cost in Base-E is projected to be lower than that of Base scenario by a bigger margin in India over time. This confirm that in the Base-E scenario, the projected effects of adopting cost effective energy efficient production technologies are more significant in the India's iron and steel sector, compared to those in the U.S. and China's iron and steel sectors.

Table 30. Annual Unit Production Costs of the U.S., China, and India's iron and steel Sectors Projected in the Base and Base-E Scenarios (2005 $/tonne steel)

Annual Unit Production Total Costs (2005 $/t steel)									
The U.S.	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	508	611	662	703	693	656	612	612	605
Base-E	508	611	661	702	691	650	605	604	596
Change	0	0	-1	-1	-2	-6	-7	-8	-9
China	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	452	508	546	583	576	549	525	537	530
Base-E	452	507	545	582	574	546	520	532	525
Change	0	-1	-1	-1	-2	-3	-5	-5	-5
India	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	489	638	685	717	706	689	677	686	687
Base-E	494	624	655	677	660	635	621	625	618
Change	-5	-14	-30	-40	-46	-54	-56	-61	-69

4.2.2.3. Annual Energy Consumption

The U.S. Iron and Steel Sector

Differences in projected annual energy consumption of the U.S., China, and India's iron and steel sectors between the Base and Base-E scenarios are presented and analyzed in this section.

In general, Base-E scenario exhibits a lower annual total energy consumption level in the U.S. iron and steel sector than that of the Base scenario results (Figure 35). For example, in Base-E scenario annual energy consumption of the U.S. iron and steel sector is 3.4% and 6.2% less than that of Base scenario in 2025 and 2045, respectively. The highest difference (8.8%) is observed for year 2035, mainly because of the production shifts from BOF and EAF-DRI (gas-based) to EAF production and more energy efficient measures are adopted (including improved efficiency in

EAF production). Figure 36 shows little efficiency improvement in BOF production. Even though the EAF production slightly increases due to process shifts from BOF and EAF-DRI (Gas based), the net energy consumption of EAF production is lower throughout the planning horizon in Base-E scenario (Figure 37 and Figure 38).

In summary, without any mitigation instrument or requirements (e.g., emission caps or carbon taxes), annual total energy consumption of the U.S. iron and steel sector decreases with adoption of cost effective efficient measures in the Base-E scenario compared to the Base scenario in which such efficiency measures are not available.

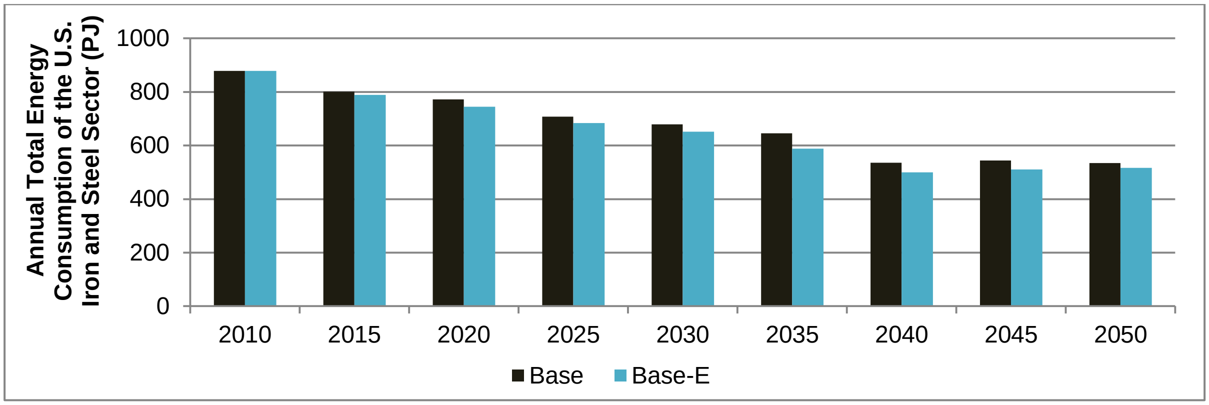

Figure 35. Annual Total Energy Consumption of the U.S. Iron and Steel Sector Projected in the Base and Base-E Scenarios (PJ)

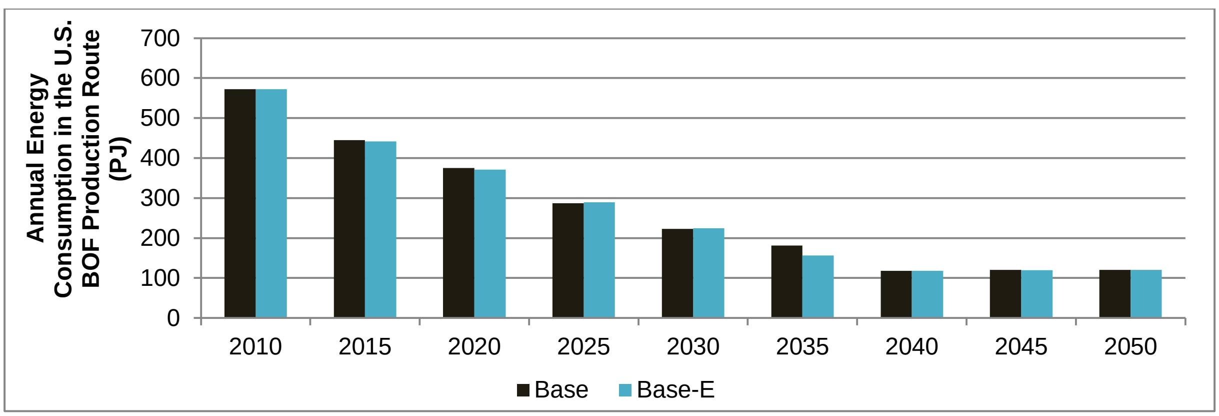

Figure 36. Annual Energy Consumption in the BOF Production of the U.S. Iron and Steel Sector Projected in the Base and Base-E Scenarios (PJ)

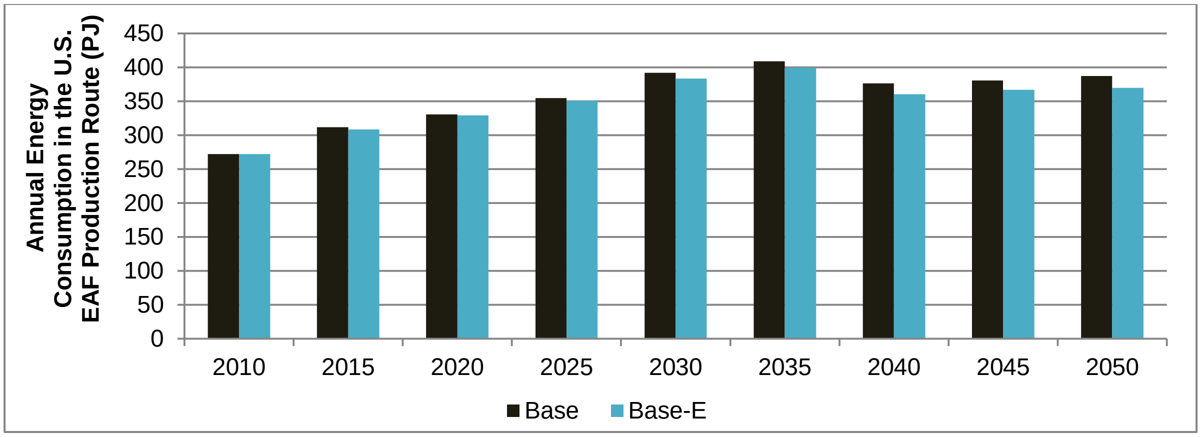

Figure 37. Annual Energy Consumption in the EAF Production of the U.S. Iron and Steel Sector Projected in the Base and Base-E Scenarios (PJ)

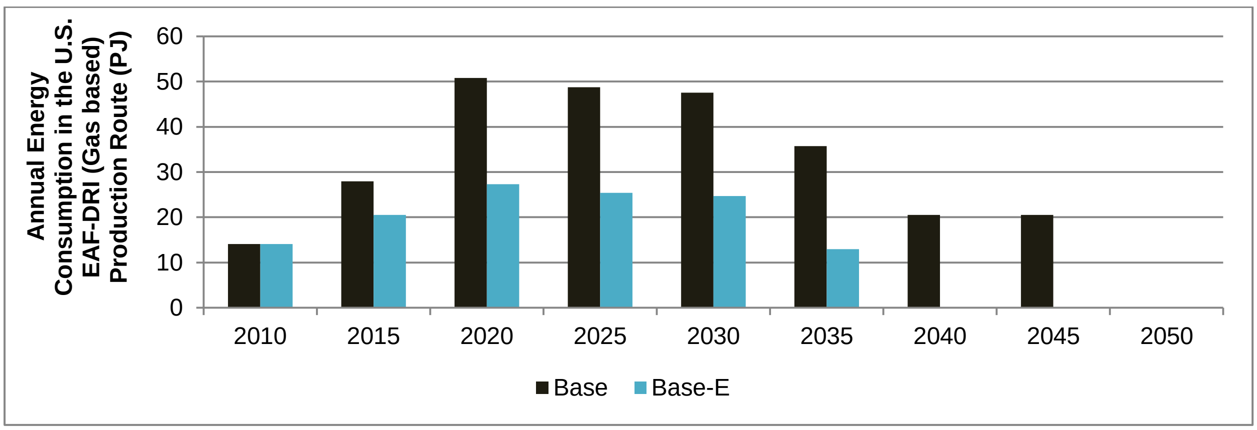

Figure 38. Annual Energy Consumption in the EAF-DRI (Gas based) Production of the U.S. Iron and Steel Sector Projected in the Base and Base-E Scenarios (PJ)

Table 31 provides the process based annual energy use in the U.S. Base-E scenario, while Table 32 shows the fuel based energy consumption in the U.S. iron and steel sector. All energy sources decreases over time corresponding to the decreasing annual production.

Table 31. Process Based Annual Energy Consumption of the U.S. Iron and Steel Sector Projected in the Base-E Scenario (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
BOF	572.4	442.0	370.8	289.6	224.9	156.3	117.6	119.9	120.5
EAF	272.2	311.7	330.5	354.4	391.7	408.7	376.3	380.4	387.3
EAF-DRI (Gas based)	14.1	20.5	27.3	25.4	24.7	13.0	0.0	0.0	0.0
Total Energy Consumption of the U.S. Iron and Steel Sector	878.9	788.3	744.4	683.4	651.4	588.0	499.2	510.4	516.3
Reduction in Total Energy Consumption Compared to	1.6%	3.6%	3.4%	4.1%	8.8%	6.7%	6.2%	3.3%	1.6%

the Base Scenario (%)									

Table 32. Fuel Based Annual Energy Consumption of the U.S. Iron and Steel Sector Projected in the Base-E Scenario (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Non-Coking Coal	13.1	11.0	9.6	8.3	7.0	5.7	4.7	4.7	4.8
Coking Coal	347.4	276.1	239.1	192.3	161.1	130.0	94.2	96.2	96.5
Coke Gas	23.3	18.7	16.4	13.2	11.1	9.1	6.3	6.5	6.5
Electricity	173.1	178.2	183.1	189.3	199.5	194.0	174.1	179.0	182.9
Natural Gas	271.0	256.5	250.2	237.0	231.3	215.1	191.5	195.1	196.5
Miscellaneous Oil	51.0	47.7	46.1	43.4	41.4	34.2	28.4	28.8	29.1
Total Energy Consumption of the U.S. Iron and Steel Sector	878.9	788.3	744.4	683.4	651.4	588.0	499.2	510.4	516.3

The China's iron and steel Sector

Figure 39 shows that the annual total energy consumption of the China's iron and steel sector under the Base-E scenario is lower compared to the Base scenario from 2010 to 2035, while energy consumption is higher in the Base-E scenario after 2040. Furthermore, Figure 40 and Figure 41 show process-based energy consumption, BOF and EAF respectively. Corresponding to different extent of projected production shifts from BOF to EAF between 2025 and 2035, energy consumption of the BOF production is lower while energy consumption of the EAF process is higher in Base-E scenario during 2025 and 2035. The combined effect is a reduction in total annual energy consumption (Figure 39). On the other hand, the higher annual total energy consumption between 2040 and 2050 in Base-E scenario is projected, largely due to model's optimization process that favors investing in efficient production technologies (EAF production) while decreasing autonomous improvement in BOF production for Base-E scenario. Because BOF production is still the dominant process in steel making, it is not unexpected that total energy use will increase from Base to Base-E scenarios during the period (Figure 40). A similar pattern is observed in the energy intensity levels exhibited in Table 34 .

In summary, adoption of available efficient technologies in the China's iron and steel sector in the Base-E scenario reduce annual energy consumption until 2035, after which investment decisions differ and a slight increase in annual energy consumption is observed for the Base-E scenario. Overall, the levels of total annual energy consumption and energy intensity are close between the Base and Base-E scenarios in China.

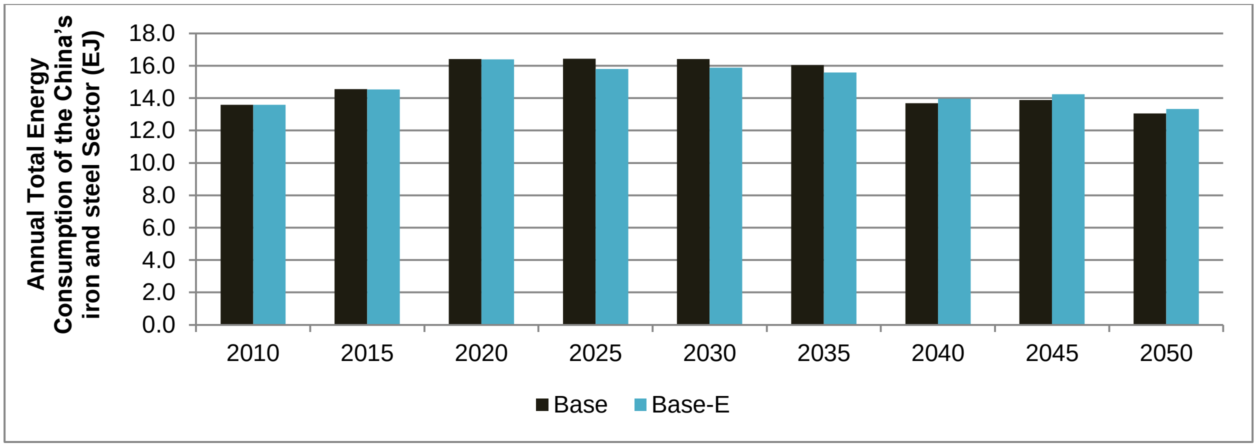

Figure 39. Annual Total Energy Consumption of the China's iron and steel sector Projected in the Base and Base-E Scenarios (EJ)

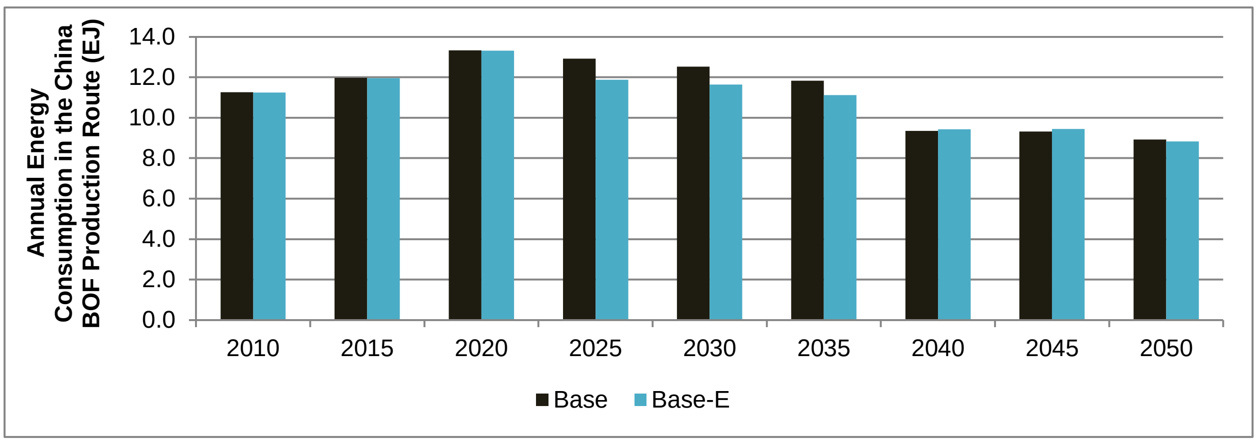

Figure 40. Annual Energy Consumption in the BOF Production of the China's iron and steel sector in Base and Base-E Scenarios (EJ)

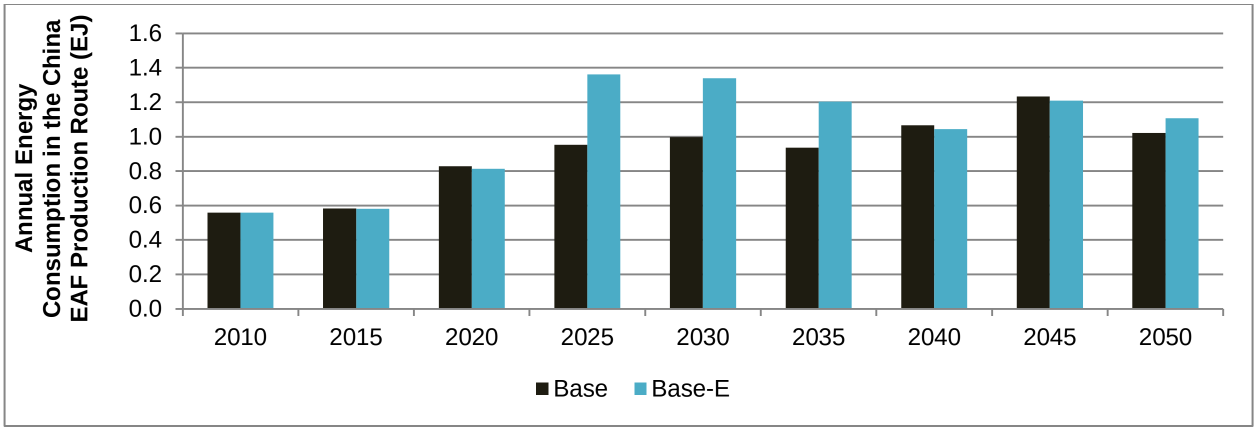

Figure 41. Annual Energy Consumption in the EAF Production of the China's iron and steel sector in Base and Base-E Scenarios (EJ)

Table 33. Process Based Annual Energy Consumption of the China's iron and steel sector in Base-E Scenario (EJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
BOF	11.3	12.0	13.3	11.9	11.6	11.1	9.4	9.4	8.8
EAF	0.56	0.58	0.81	1.36	1.34	1.20	1.04	1.21	1.11
Total Energy Consumption of the China Iron and Steel Sector	13.6	14.5	16.4	15.8	15.9	15.6	14.0	14.2	13.3
Reduction in Total Energy Consumption Compared to the Base Scenario (%)	0.1%	0.2%	3.9%	3.3%	2.8%	-2.1%	-2.5%	-2.1%	0.1%

Table 34 shows the energy intensity trend of the China's iron and steel sector projected in the Base-E Scenario, while Table 35 shows the fuel-based annual energy use over time.

Table 34. Energy Intensity Levels of the China's iron and steel sector Projected in the Base-E Scenario (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Average Energy Intensity									
Base	18.49	17.51	17.29	15.34	15.10	15.00	12.68	12.44	12.40
Base-E	18.49	17.49	17.24	14.64	14.50	14.49	12.74	12.55	12.40
BOF Energy Intensity									
Base	19.66	18.56	18.60	16.61	16.46	16.36	14.22	14.18	13.92
Base-E	19.66	18.53	18.57	16.60	16.44	16.34	14.34	14.35	14.13
EAF Energy Intensity									
Base	8.43	8.14	8.09	7.51	7.43	7.33	6.49	6.46	6.34
Base-E	8.43	8.10	7.94	7.19	7.15	7.08	6.35	6.33	6.26

Table 35. Fuel Based Annual Energy Consumption of the China's iron and steel sector Projected in the Base-E Scenario (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Non-Coking Coal	0.32	0.33	0.37	0.34	0.34	0.32	0.28	0.28	0.27
Coking Coal	3.17	3.70	4.54	3.87	3.72	3.56	2.85	2.88	2.59
Coke (Purchased & Import)	3.63	3.42	3.47	3.20	3.16	3.03	2.61	2.64	2.50
Coke Gas	0.05	0.06	0.08	0.07	0.06	0.06	0.05	0.05	0.04
Electricity	4.90	5.45	6.18	6.69	6.99	7.12	6.99	7.18	6.78
Natural Gas	1.34	1.40	1.57	1.46	1.44	1.38	1.19	1.21	1.14
Miscellaneous Oil	0.18	0.18	0.18	0.17	0.17	0.13	0.00	0.00	0.00
TOTAL Energy Consumption of the China's iron and steel Sector	13.58	14.54	16.38	15.80	15.87	15.58	13.97	14.24	13.33

The India's iron and steel Sector

Figure 42 through Figure 46 show the annual energy consumption of the India's iron and steel production projected for Base and Base-E Scenarios. The model optimization process favors adoption of energy efficient production technologies particularly in BOF and EAF-DRI (Coal based) production, resulting in significant difference in energy consumption between Base and Base-E scenarios. The larger reduction in India's steel sector than that of the U.S. and China indicates that investments in energy efficient production technologies are much more effective in reducing energy use as well as production cost.

For example, with identical BOF production in the Base and Base-E scenarios (Table 28 in Section 4.2.2.1), Figure 43 shows that BOF energy consumption in the Base-E scenario is lower compared to the Base scenario throughout the planning horizon. This indicates that the model's optimization process favors more investments in cost-effective efficient measures in BOF production in the Base-E scenario, thus improving energy efficiency in BOF production.

Figure 44 shows that energy consumption in EAF production between 2015 and 2040 in the Base-E scenario is slightly higher than that of Base case while there is also no difference in the EAF in the India's iron and steel sector between the Base and Base-E scenarios.

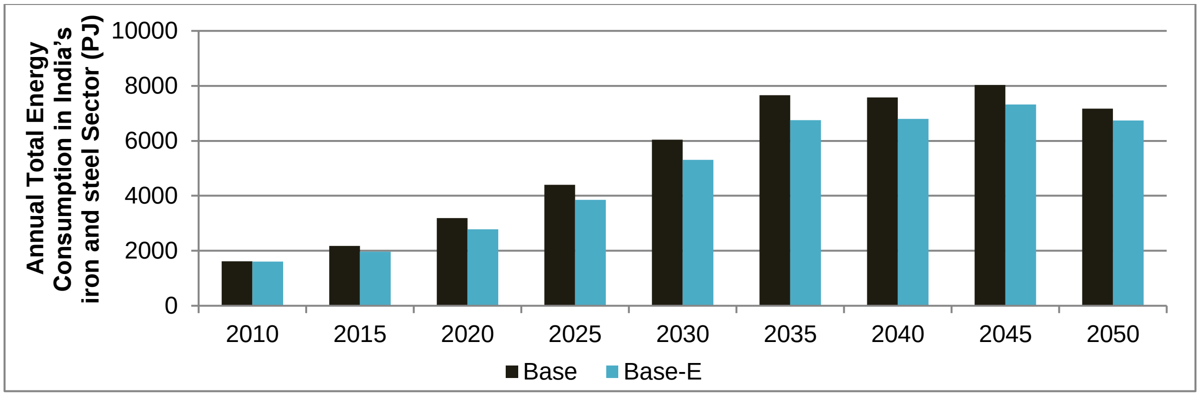

Figure 42. Annual Total Energy Consumption of the India's iron and steel sector Projected in the Base and Base-E Scenarios (PJ)

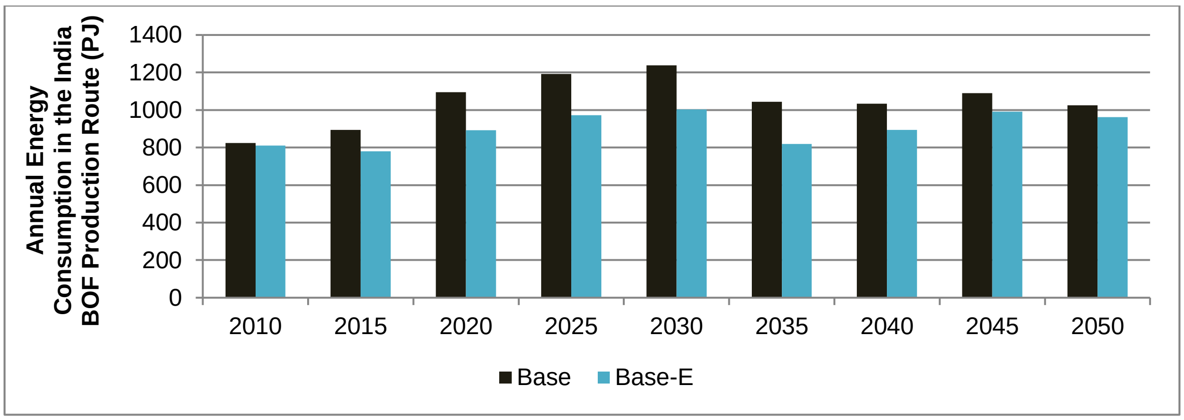

Figure 43. Annual Energy Consumption in the BOF Production of the India's iron and steel sector Projected in the Base and Base-E Scenarios (PJ)

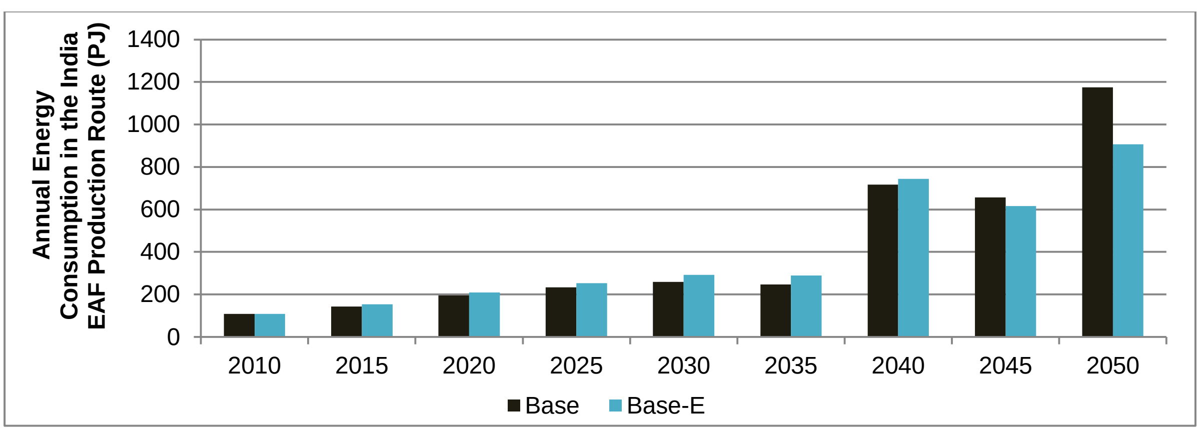

Figure 44. Annual Energy Consumption in the EAF Production of the India's iron and steel sector Projected in the Base and Base-E Scenarios (PJ)

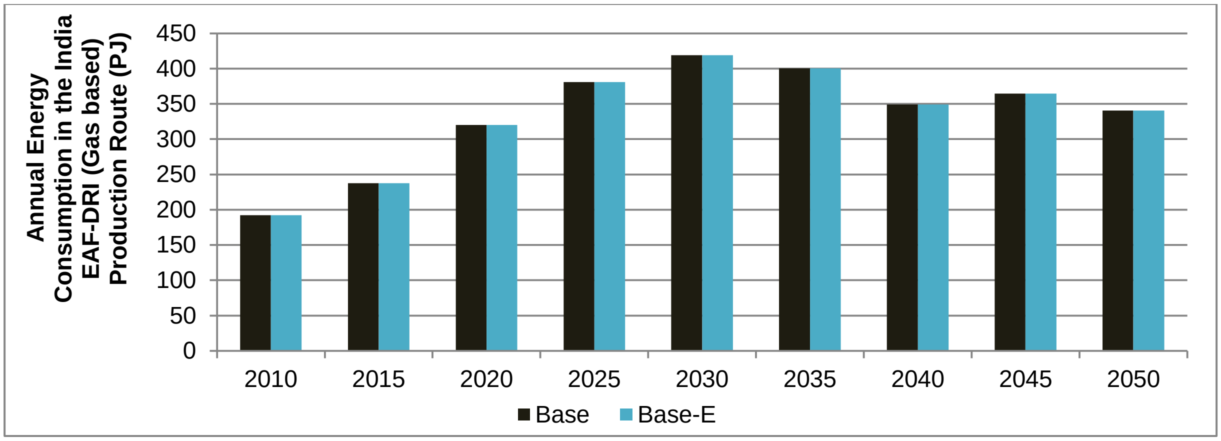

Figure 45. Annual Energy Consumption in the EAF-DRI (Gas based) Production of the India's iron and steel sector Projected in the Base and Base-E Scenarios (PJ)

Similar to BOF production, the annual production volume of EAF-DRI (Gas based) process does not differ between the Base and Base-E scenarios. Figure 45 shows almost identical energy use EAF-DRI (Gas based) production between Base and Base-E scenarios. This indicates that little implementation of efficient production technology in EAF-DRI (Gas based) process is favored in the Base-E scenario, when compared with the Base scenario.

Figure 46 indicates that production increases in EAF-DRI (Coal based) process in 2045 and 2050 do not increase the energy consumption in this production route. Therefore, it is clear that the model projects investments in cost-effective efficient production technologies in EAF-DRI (Coal based), helping to decrease the total energy consumption throughout the periods, while achieving the goal of production cost reduction.

As discussed earlier, for India's steel sector, the model's optimization process prefers to investing in efficiency in BOF and EAF-DRI (Coal based) processes instead of providing autonomous improvement in EAF process during the period. Table 36 exhibits the process-based and total annual energy consumption in the India's iron and steel sector. Compared to the Base scenario, total energy use is reduced in the Base-E scenario from 2010 to 2050, with largest contribution from in the EAF-DRI (Coal based) production. Table 37 exhibits the fuel based energy consumption in the India's iron and steel sector. Compared to the Base scenario, the largest reduction is observed on coking coal, which is the main source of BOF production, in the Base-E scenario.

The projection results show that availability of efficient production technologies in the India's iron and steel sector leads to major reduction in annual energy consumption. The reduction levels are significant compared to the U.S. and China's iron and steel sectors. This finding supports the earlier conclusion that there are more efficient production technologies that are cost effective in the India's iron and steel sector. However, this projection depends on the technology definitions and parameter structures used for the efficient production technologies in the U.S., China, and India's iron and steel sectors. With a different set of parameter structure (i.e., cost and energy savings potentials), the results can be different.

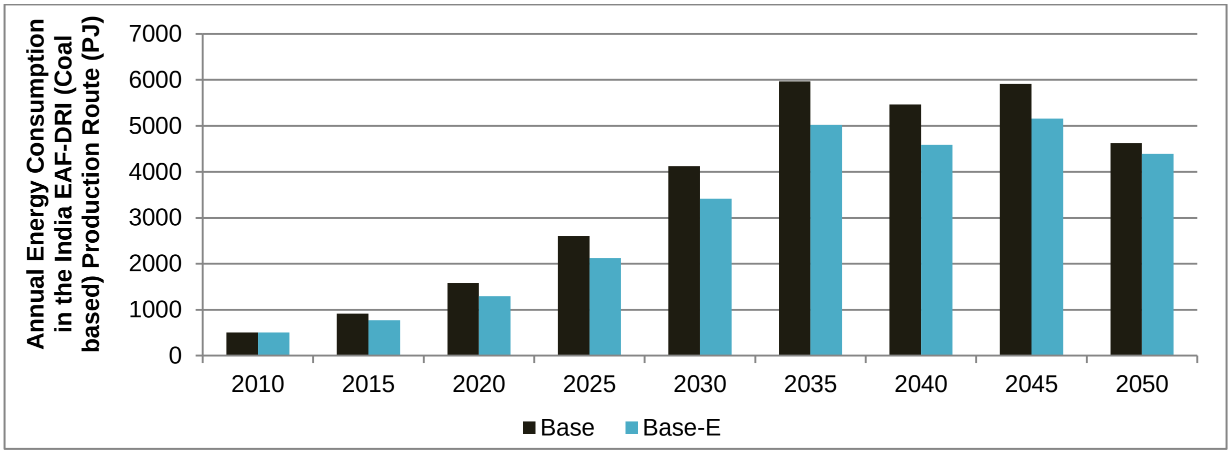

Figure 46. Annual Energy Consumption in the EAF-DRI (Coal based) Production of the India's iron and steel sector Projected in the Base and Base-E Scenarios (PJ)

Table 36. Process Based Annual Energy Consumption of the India's iron and steel sector Projected in the Base-E Scenario (GJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
BOF	811.0	780.1	891.8	971.7	1003.6	818.3	894.4	990.1	962.6
EAF	109.0	154.1	209.8	253.1	292.6	289.9	744.1	615.4	907.0
EAF-DRI (Coal based)	503.8	769.6	1292.6	2122.1	3419.3	5020.9	4588.9	5155.7	4389.2
EAF-DRI (Gas based)	192.4	237.7	320.3	381.1	419.2	400.4	349.1	364.4	340.4
TOTAL Energy Consumption of the U.S. Iron and Steel Sector	1607.3	1961.5	2787.6	3852.0	5305.7	6757.7	6799.9	7322.4	6744.1
Reduction in Total Energy Consumption (%)	10.0%	12.6%	12.5%	12.1%	11.8%	10.2%	8.8%	6.0%	10.0%

Table 37. Fuel Based Annual Energy Consumption of the India's iron and steel sector Projected in the Base-E Scenario (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Non-Coking Coal	568.8	856.4	1348.2	2032.9	3026.6	4191.7	3824.8	4226.7	3596.7
Coking Coal	227.3	198.4	219.0	229.9	220.8	166.6	196.1	257.1	248.8
Coke (Purchased & Import)	218.0	186.8	204.5	221.6	233.8	196.8	222.1	233.7	226.9
Coke Gas	36.8	41.7	50.4	54.4	61.2	50.9	55.4	56.2	48.9
Electricity	272.9	357.5	530.5	770.3	1124.9	1472.6	1604.3	1698.8	1648.9
Natural Gas	166.2	209.1	278.6	331.3	360.4	345.2	491.7	457.0	549.9
Miscellaneous Oil	117.1	111.8	156.4	211.7	278.1	333.8	405.5	392.9	424.0
TOTAL Energy Consumption of the China's iron and steel	1607.3	1961.5	2787.6	3852.0	5305.7	6757.7	6799.9	7322.4	6744.1

Sector									

Figure 47 and Table 38 represent the average annual energy intensities of the U.S., China, and India's iron and steel sectors under the Base and Base-E scenarios. Compared to the Base scenario, there is limited reduction of energy intensity in China's steel sector (average of 1%), a slight reduction of energy intensity in the U.S. steel sector (average of 4%), and significant reduction in energy intensity in India's steel sector in the Base-E scenario (average of 12%). These results support the finding that Base-E scenario for India's iron and steel sector exhibits the largest efficiency improvement from adopting efficient production technologies over the projection years when compared to the U.S. and China.

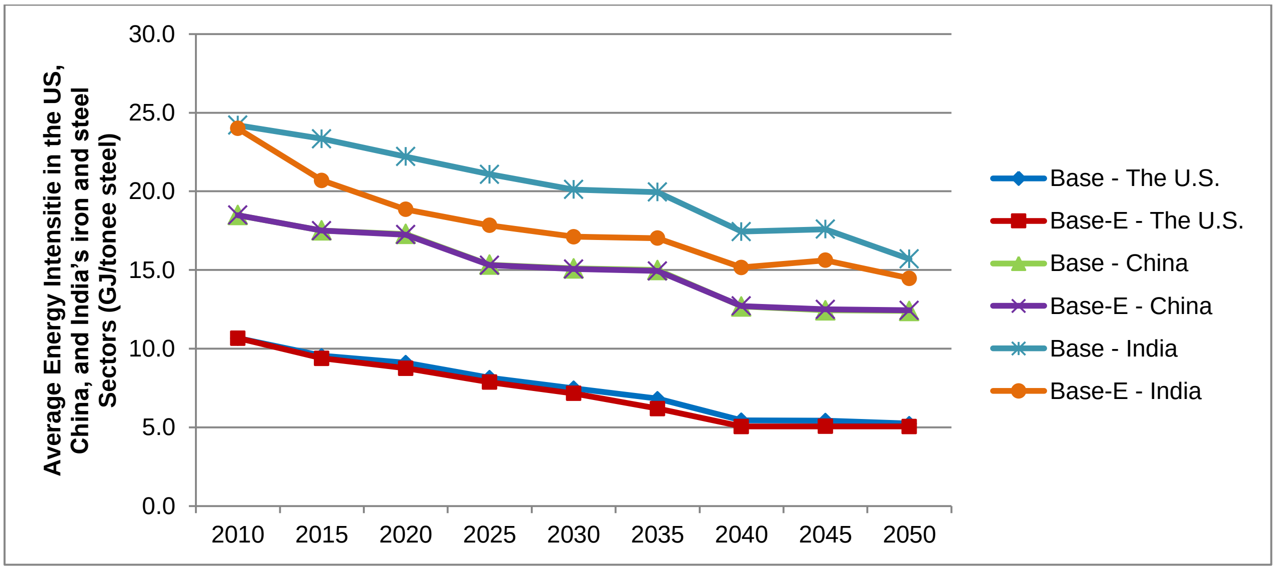

Figure 47. Average Energy Intensities of the U.S., China, and India's iron and steel Sectors Projected in the Base and Base-E Scenarios (GJ/tonne steel)

Table 38. Average Energy Intensities of the U.S., China, and India's iron and steel Sectors Projected in the Base and Base-E Scenarios (GJ/tonne steel)

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base - The U.S.	10.70	9.60	9.10	8.20	7.50	6.80	5.50	5.40	5.20
Base-E - The U.S.	10.70	9.40	8.80	7.90	7.20	6.20	5.10	5.10	5.10
Base - China	18.49	17.51	17.29	15.34	15.10	15.00	12.68	12.44	12.40
Base-E - China	18.49	17.49	17.24	14.64	14.50	14.49	12.74	12.55	12.40
Base - India	24.20	23.30	22.20	21.10	20.10	20.00	17.40	17.60	15.70
Base-E - India	24.00	20.70	18.90	17.80	17.10	17.00	15.20	15.60	14.50

4.2.2.4. Annual CO_2 Emissions

Figure 48, Figure 49, and Figure 50 show the country-specific total annual emissions of the U.S., China, and India's iron and steel sectors in the Base-E scenario, respectively, which exhibit trends similar to its total annual energy consumption, respectively. The Base-E scenario slightly reduces the total annual emissions in the U.S. iron and steel sector compared to the Base scenario results (Figure 48) with the highest difference of 8.4% reached in 2035. There is slight reduction in the total annual emissions in China's iron and steel sector from 2010 to 2035 as well; followed with modest increases after 2035 (Figure 49). India's iron and steel sector has the highest relative emission reduction among the model countries (e.g., 10% and more between 2015 and 2035) in the Base-E scenario when compared to the Base scenario (Figure 50). These results indicate that it is possible to have more than 10% CO_2 emission reduction in the India's iron and steel sector from adopting cost effective efficient production technologies (without any other scenario requirement) in the period 2015-2035.

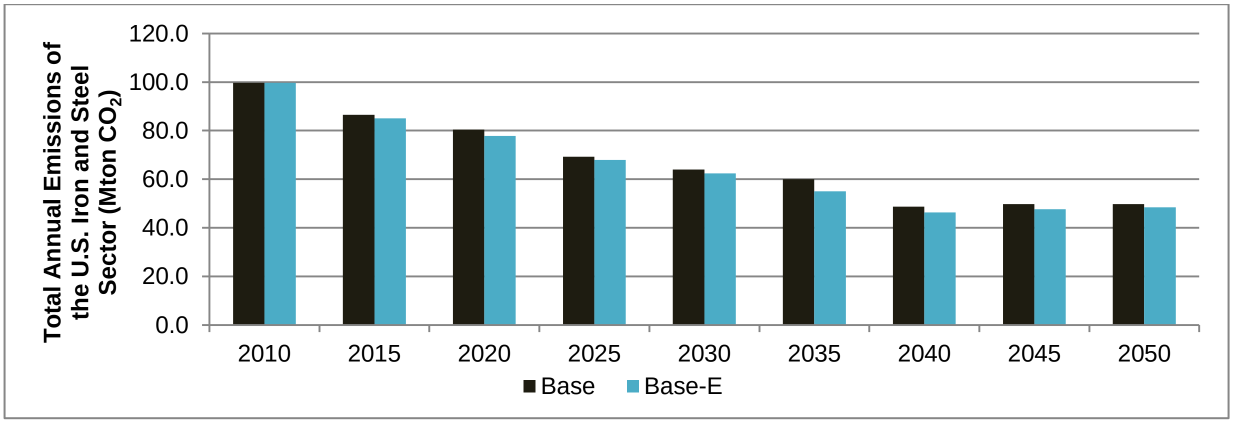

Figure 48. Total Annual CO_2 Emissions of the U.S. Iron and Steel Sector Projected in the Base and Base-E Scenarios (Mton CO_2)

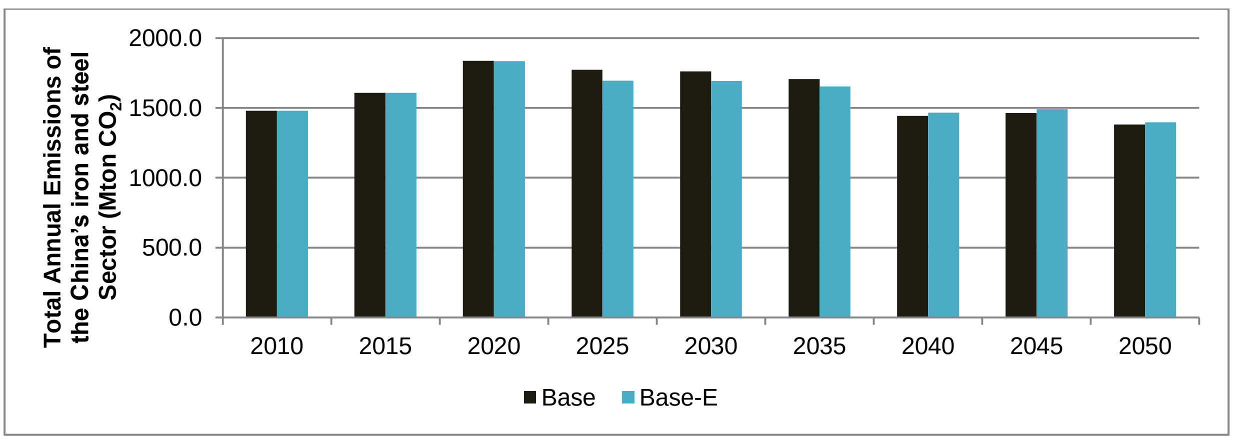

Figure 49. Total Annual CO_2 Emissions of the China's iron and steel sector Projected in the Base and Base-E Scenarios (Mton CO_2)

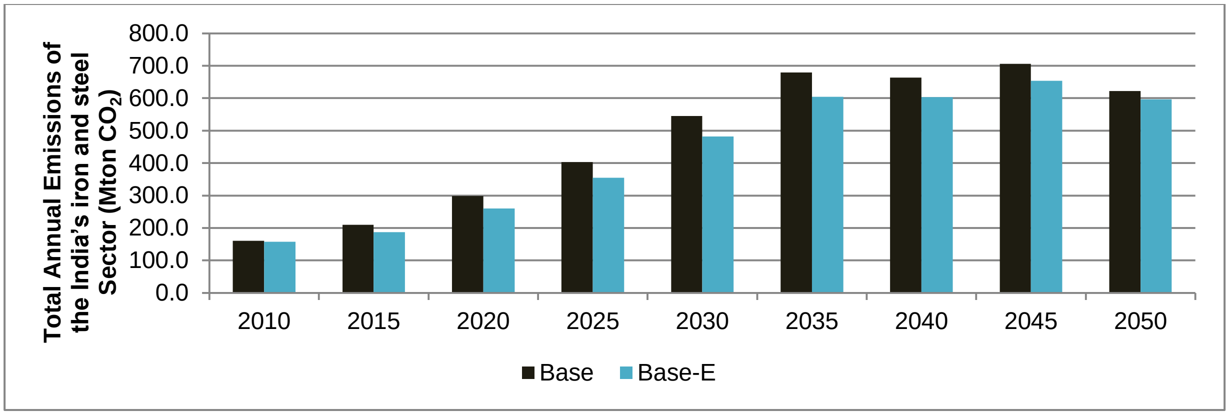

Figure 50. Total Annual CO_2 Emissions of the India's iron and steel sector Projected in the Base and Base-E Scenarios (Mton CO_2)

Table 39 further shows the relative difference in projected emissions between Base-E and Base Scenarios for the U.S., China, and India's Iron and Steel Sectors.

Table 39. Difference in Projected Annual Emissions between Base-E and Base Scenarios for the U.S., China, and India's Iron and Steel Sectors

	2015	2020	2025	2030	2035	2040	2045	2050
The U.S.	1.7%	3.3%	1.9%	2.5%	8.4%	4.8%	4.4%	2.6%
China	0.1%	0.2%	4.4%	3.8%	3.2%	-1.6%	-1.9%	-1.1%
India	10.6%	12.8%	12.1%	11.6%	11.0%	9.1%	7.4%	4.1%

Table 40 shows the relative difference in projected emissions between Base-E and Base Scenarios for the U.S., China, and India's Iron and Steel Sectors.

Table 40. Difference in Total Annual Energy Consumption between Base and Base-E Scenarios by Country

	2015	2020	2025	2030	2035	2040	2045	2050
The U.S.	1.6%	3.6%	3.4%	4.1%	8.8%	6.7%	6.2%	3.3%
China	0.1%	0.2%	3.9%	3.3%	2.8%	-2.1%	-2.5%	-2.1%
India	10.0%	12.6%	12.5%	12.1%	11.8%	10.2%	8.8%	6.0%

4.2.3. Base-E Scenario Summary

The Base-E scenario for 2010-2050 projection not only reflects business-as-usual practice, but allows adoption of energy efficient measures in all production, with the goal of achieving the least-cost iron and steel sector production in each period. The model projects what would happen given the assumptions predefined for the ISEEM-IS model with the cost-minimization objective. Similar to the case of Base scenario projection, in the Base-E scenario, there is no additional constraint such as any environmental constraint or policy measure to affect the costs or optimization process.

Base-E scenario allows new energy efficiency improvement with additional investments, and autonomous adoption of advance production technologies in any given time between 2010 and 2050. The following highlights the projection differences between Base-E and Base scenarios.

- ***Base-E scenario projection reflects production structure shifts guided by the objective in production cost minimization, and adoption of energy efficient measures in each country. Unless noted in the following,* annual production shares of the U.S. and *China's iron and steel sectors are very similar between the Base and Base-E scenarios.***
  - *In the U.S., shares of EAF and BOF production in the U.S. exhibited a trend similar to that of Base scenario in most of the years, except for year 2035 when there is a sudden drop in BOF. EAF-DRI (Gas based) production is mostly replaced by EAF in the Base-E scenario through the planning horizon. Because the share of BOF production is already close to the lower bounds predefined in ISEEM-IS, there is essentially no room for increasing EAF production share in the U.S.*
  - *In China, shares of EAF and BOF production in Base-E scenario exhibit similar trends of Base scenario, except that there is an enhanced shift from BOF to EAF (EAF share increased by 5%) compared to that of Base scenario in years from 2025-2035 and 2050.*
  - *In India, shares of BOF, EAF, EAF DRI (gas-based & coal-based) production in Base-E scenario exhibits a similar trend to that of Base scenario, except that between 2040 and 2050, a portion of EAF production shift to EFA-DRI (coal-based) production. Steel production from EAF-DRI (Coal based) process is projected to represent 64.1% of total Indian steel production in 2050 in the Base-E scenario, up from 56.4% in 2050 in the Base scenario.*

- ***Projected investments and applications of cost-effective efficiency technologies in the Base-E scenario lead to reduction in annual energy consumption and emissions in three countries. The Base-E scenario projection indicates that with available energy efficiency measures, and without any other scenario requirement, it is possible to reduce annual emissions by 2.9%, 0.9%, and 9.1% in the U.S., China, and India's iron and steel sectors, respectively, when compared with those of Base scenario from years 2010 to 2050.***
  - *The U.S. iron and steel sector exhibits modest reduction in annual energy consumption (i.e., from 1.6% to 8.8% reduction in annual energy consumption in the period from 2015 to 2050) and emissions (i.e., from 1.7% to 8.4% reduction in annual emissions in the period from 2015 to 2050) in the Base-E scenario.*
  - *China's iron and steel sector exhibits smaller reduction in annual energy consumption in the Base-E scenario between years 2010 and 2035, after which energy consumption and emission levels increase due to the different investment and process structure shifts that are projected in the Base-E scenario.*
  - *India's iron and steel sector exhibits reduction in annual energy consumption by 6.0% to 12.6%, and reduction in annual emissions by 4.1% to 12.8% in the Base-E scenario between years 2015 and 2050.*
- ***Annual energy and CO_2 emission intensities of the iron and steel sectors of the three countries decrease continuously in the mid- and long-term under the Base-E scenario. Compared to the Base scenario, adopting cost-effective efficient production technologies in the Base-E scenario leads to various reductions in energy and CO_2 emission intensity among the three countries.***

[Energy intensity, Figure 51]

- *In the U.S., energy intensity level of Base-E scenario is close to that of Base scenario, except that there is a slight reduction in Base-E scenario due to adoption of more efficient measures between years 2015 and 2045.*
- *In China, energy intensity levels of Base-E scenario is also close to that of Base scenario, except that there is a slight reduction in Base-E scenario due to adoption of more efficient measures observed in 2025-2035 period, in which EAF production is used more compared to the Base scenario.*
- *In India, energy intensity levels of Base-E scenario are significantly lower than that of Base scenario from years 2015 to 2050, due to adoption of significantly more efficient measures compared to the U.S. and China.*
- *Overall, U.S. exhibits the lowest level of energy intensity, with China higher and India the highest in the same year for each scenario.*

[Emission intensity, Figure 52]

- *In the U.S., emission intensity level of Base-E scenario is close to that of Base scenario, except that there is a slight reduction in Base-E scenario due to adoption of more efficient measures between years 2015 and 2045.*
- *In China, emission intensity levels of Base-E scenario is also close to that of Base scenario, except that there is a slight reduction in Base-E scenario due to adoption of more efficient measures observed in 2025-2035 period, in which EAF production is used more compared to the Base scenario.*
- *In India, emission intensity levels of Base-E scenario are significantly lower than that of Base scenario from years 2015 to 2050, due to adoption of significantly more efficient measures compared to the U.S. and China.*
- *Overall, U.S. exhibits the lowest level of emission intensity, with India higher and China the highest in the same year for each scenario. A higher level of emission intensity in China than that of India reflects the difference in carbon factors of energy sources and product mix.*

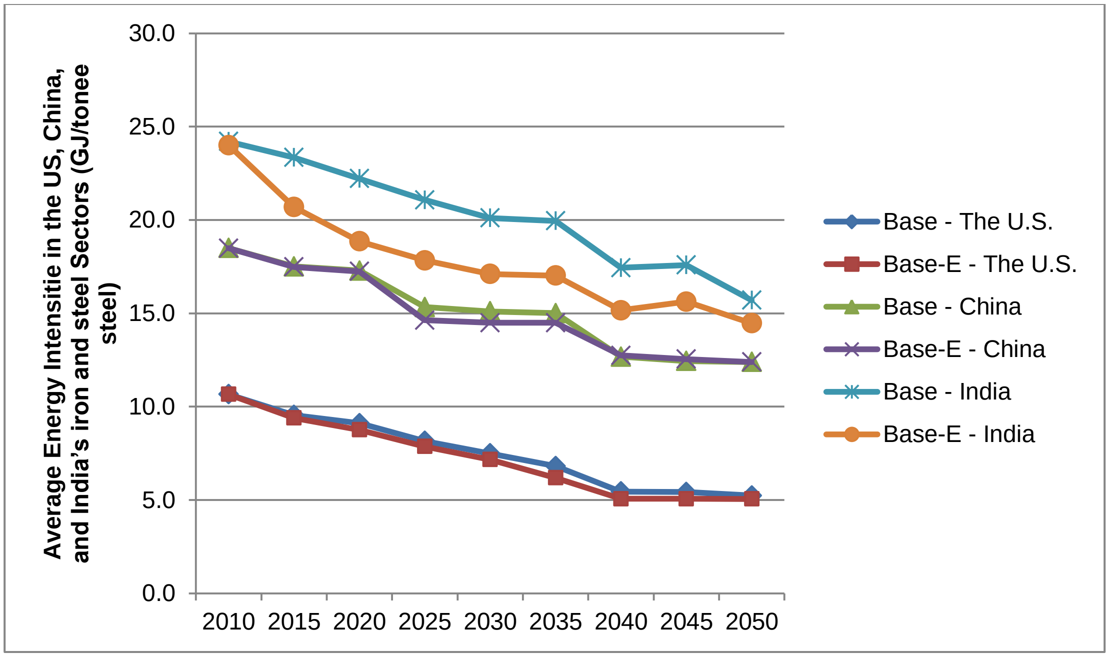

Figure 51. Average Energy Intensities of the U.S., China, and India's iron and steel Sectors Projected in the Base and Base-E Scenarios (GJ/tonne steel)

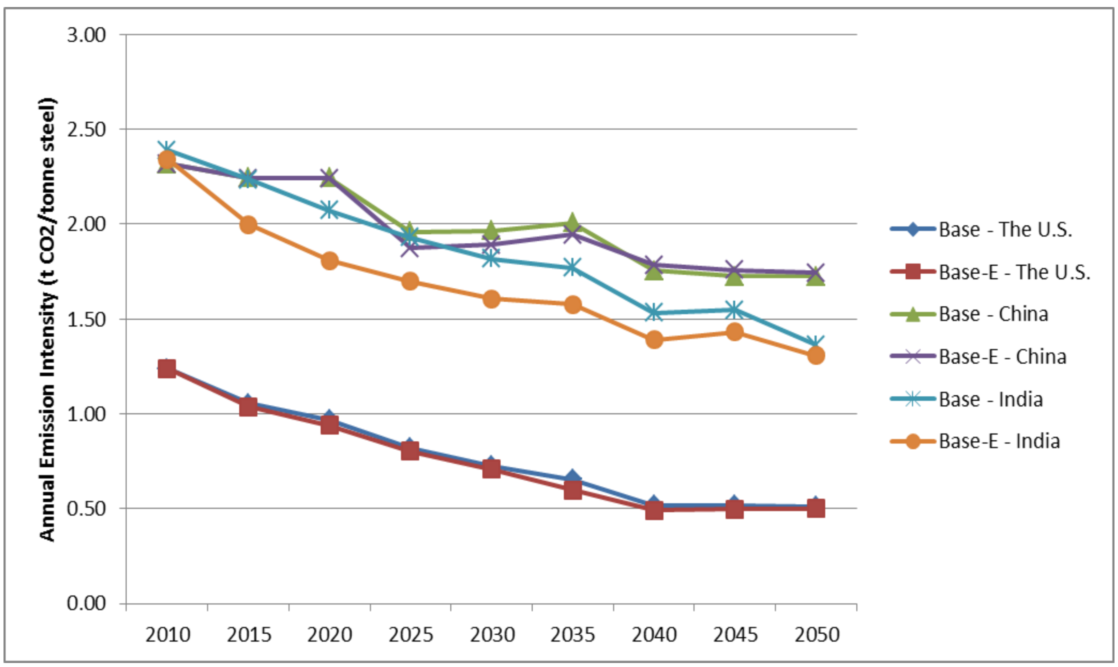

Figure 52 Average Emission Intensity of the U.S., China, and India's iron and steel Sectors Projected in the Base and Base-E Scenario (t CO_2/tonne steel)

- ***In Base-E scenario, total production costs exhibit trends similar to those of Base scenario in three countries, except that India exhibits significant lower total production costs in Base-E scenario compared to the Base scenario.*** Total cost of the iron and steel production in India between the periods 2010 and 2050 on average is 6.9% lower in the Base-E scenario compared to the Base scenario. This infers that efficient production technologies defined for the India's iron and steel sector in the ISEEM-IS model are more effective in achieving the least cost objective of the ISEEM-IS model (i.e., a lower minimum cost), compared to the U.S. and China's iron and steel sectors. In general, the annual average unit production cost in China is lower than that of the U.S. by 11-18%; while India's annual unit production cost is the highest among the three countries. In the Base-E scenario, the projected effects of adopting cost effective energy efficient production technologies are more significant in the India's iron and steel sector, compared to those in the U.S. and China's iron and steel sectors.

4.3. Emission Reduction without Trading Scenarios (ER)

This section presents details about the projection results from the ISEEM-IS model, with the first set of CO_2 emission reduction scenarios analyzed in this study: Emission reduction without trading (ER) scenarios. The purpose is to analyze the emission reduction potentials in iron and steel sectors of the each country by means of investing in advanced production technologies and efficient production technologies and switching to more efficient production processes, excluding any other instrument such as trading of commodities or carbon. Different than Base-E scenario that adopts cost-effective efficiency measures in additional to autonomous improvement, ER scenarios present additional investment in efficiency measures and autonomous improvement to meet the requirement of emission reduction targets. In the ER scenarios, we will examine ISEEM-IS model outcomes under three emission reduction targets (carbon caps) compared to Base scenarios.

Specific technical objectives are to:

1. examine the country-specific production and structure changes over time,
2. quantify the magnitudes and intensity of country-specific annual energy consumption and emissions,
3. estimate country-specific annual production cost and annual carbon abatement cost, and
4. understand the sensitivity of production, energy and emission intensity and costs to variations in carbon reduction targets or carbon caps.

In the ER scenarios, pre-determined carbon emission reduction targets (or carbon caps) are realized through investments in autonomous improvement and efficiency measures in each country, without any instrument such as trading of commodities or carbon. A summary table of key factors from the ER scenarios is available in the Appendix D to this document.

4.3.1. ER Scenario Definitions

In this study, we predefined three levels of carbon reduction targets (or carbon caps) for the ER scenarios, in which annual CO_2 emission levels are to be reduced by a specific percentage when compared to that of the Base scenario per country. Specifically, the annual CO_2 emission target for the ER scenarios is set initially with annual reduction by 5% of the Base scenario in 2015, and then at three reduction levels for years 2020 throughout 2050 (i.e., 10%, 20%, and 30%, respectively).

While existing levels of commodity (i.e., steel) trading defined in the Base scenario remains unchanged in the ER scenarios, trading is not purported or activated be an instrument to decrease CO_2 emissions for any given year or in any country. According to each predefined emission reduction target, the ISEEM-IS model seeks for the least cost solutions to meet CO_2 emission reduction without any instrument of trading. The three emission reduction levels are pre-defined as follows.

i. ER-10 Scenario: Upper bound of annual CO_2 emissions are restricted 10% lower than the annual CO_2 emissions of the Base scenario for each country (i.e., the U.S., China, and India) starting in 2020.
ii. ER-20 Scenario: Upper bound of annual CO_2 emissions are restricted 20% lower that the annual CO_2 emissions of the Base scenario for each country (i.e., the U.S., China, and India) starting in 2020.
iii. ER-30 Scenario: Upper bound of annual CO_2 emissions are restricted 30% lower than the annual CO_2 emissions of the Base scenario for each country (i.e., the U.S., China, and India) starting in 2020.

Table 41 presents the considered annual CO_2 emission limits corresponding to different reduction targets per country for three ER scenarios, and projected annual CO_2 emission levels of Base-E and the Base scenarios. For the three ER scenarios, the upper bounds of annual CO_2 emissions are set at a level lower than that of Base scenario by 10%, 20%, and 30%, respectively, starting in year 2020 throughout 2050. For the purpose of comparing the projected annual CO_2 emissions in three ER scenarios with that of the Base and Base-E scenarios, annual CO_2 emissions projected in the Base and Base-E scenarios are also included in the Table 41. For all countries, the upper bounds of annual CO_2 emission reduction are achieved throughout the planning horizon in each ER scenario.

Table 41. Country-Specific Annual CO_2 Emission Levels of the Base and Base-E Scenarios and Emission Projection for three ER Scenarios (Mton CO_2)

		2010	2015	2020	2025	2030	2035	2040	2045	2050
The U.S.	Base	99.7	86.5	80.5	69.3	64.0	60.0	48.7	49.8	49.7
	Base-E	99.7	85.1	77.8	68.0	62.4	55.0	46.4	47.6	48.4
	ER-10	99.7	82.2	72.5	62.4	57.6	54.0	43.8	44.8	44.7
	ER-20	99.7	82.2	64.4	55.4	51.2	48.0	39.0	39.8	39.8
	ER-30	99.7	82.2	56.4	48.5	44.8	42.0	34.1	34.9	34.8
		2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
China	Base	1479.1	1608.1	1837.0	1771.9	1760.1	1707.1	1442.8	1462.5	1381.8
	Base-E	1479.1	1607.4	1835.0	1769.3	1757.4	1702.2	1458.7	1483.0	1399.4
	ER-10	1479.1	1527.7	1653.3	1594.7	1584.1	1536.4	1298.5	1316.3	1243.6
	ER-20	1479.1	1527.7	1469.6	1417.5	1408.1	1365.7	1154.2	1170.0	1105.4
	ER-30	1479.1	1527.7	1285.9	1240.3	1232.1	1195.0	1010.0	1023.8	967.3
		2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
India	Base	160.8	209.7	298.2	403.4	545.1	679.1	663.9	705.6	621.9
	Base-E	157.6	187.4	260.1	354.7	482.0	604.6	603.3	653.3	596.5
	ER-10	160.8	199.2	268.4	363.1	490.6	611.2	597.5	635.0	559.7
	ER-20	160.8	199.2	238.6	322.7	436.1	543.3	531.1	564.5	497.5
	ER-30	160.8	199.2	208.7	282.4	381.6	475.4	464.7	493.9	435.3

4.3.2. ER Scenario Results

This section presents the projection of annual production, production costs, energy consumption, and CO_2 emissions in the U.S., China, and India's iron and steel sectors under the three ER scenarios, and compares the ER projection with the Base and Base-E scenarios.

4.3.2.1. Annual Production and Imports

Projections for annual steel production of the U.S., China, and India's iron and steel sectors in the three ER scenarios for the period 2010-2050 are presented in this section.

The U.S. Iron and Steel Sector

Table 42 shows the projected annual steel production in the U.S. iron and steel sector under the three ER scenarios, and those in the Base and Base-E scenarios. In general, the differences in annual production among the five scenarios from 2010 to 2050 are either none or negligibly small. In other words, model projections of the U.S. steel production in each scenario (including the Base and Base-E scenarios) are similar through the planning horizon.

Because EAF production is more energy efficient compared to other processes such as BOF and EAF-DRI (Gas based), one would expect production shifts to EAF production from other production processes under the emission restrictions. However, annual BOF production of the Base scenario is already on the lower bounds, as discussed in Section 4.1. Therefore, there is no additional process shifts from BOF to EAF production, while there is noticeable reduction in EAF-DRI (Gas based) production as it is shifted to EAF production.

Table 42. Annual Steel Production of the U.S. Projected in the Base, Base-E, and ER scenarios (Mtonnes)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	31.2	24.6	20.8	16.9	13.3	10.8	9.4	9.6	9.7
Base-E	31.2	24.6	20.8	16.9	13.3	9.2	9.4	9.6	9.7
ER-10	31.2	24.6	20.8	16.9	13.3	9.2	9.4	9.6	9.7
ER-20	31.2	24.6	20.8	16.9	13.3	9.2	9.4	9.6	9.7
ER-30	31.2	24.6	20.8	16.9	13.3	9.2	9.4	9.6	9.7
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	48.6	56.0	59.5	64.9	72.4	79.0	83.6	85.1	87.2
Base-E	48.6	56.4	60.8	66.2	73.7	82.0	84.9	86.4	87.2
ER-10	48.6	56.6	61.4	66.8	74.3	82.6	84.9	86.4	87.2
ER-20	48.6	56.6	61.4	66.8	74.4	82.7	84.9	86.4	87.2
ER-30	48.6	56.6	61.4	66.8	74.4	82.7	84.9	86.4	87.2
EAF-DRI (Gas based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	0.7	1.5	2.8	2.8	2.7	2.1	1.3	1.3	0.0
Base-E	0.7	1.1	1.5	1.4	1.4	0.8	0.0	0.0	0.0
ER-10	0.7	0.9	0.9	0.9	0.8	0.2	0.0	0.0	0.0

ER-20	0.7	0.9	0.9	0.9	0.7	0.0	0.0	0.0	0.0
ER-30	0.7	0.9	0.9	0.9	0.7	0.0	0.0	0.0	0.0

The China's iron and steel Sector

Table 43 shows the annual steel production in the China's iron and steel sector under the three ER scenarios, and those in the Base and Base-E scenarios. Different from the no-shift observed in the U.S., there are major shifts from annual BOF production to EAF production in each ER scenario starting in 2015 and the structure changes continues to become more evident as the year goes by into 2050. For example, under the ER-10 scenario, EAF production share is 12.5% of annual steel production in 2015 and increases until leveling at 50% around 2045 (Figure 52). For a given year, the share of EAF production becomes higher with the more aggressive CO_2 emission reduction targets (i.e., 10%, 20%, and 30%). For example, in year 2025, EAF production share in the ER-30 scenario is the highest (reaching 50% compared to 33% in the ER-20 scenario and 27% in the ER-10 scenario). However, starting from 2045, share of EAF production approaches to the same levels in each of the ER scenario. This means that independent from the degree of emission restrictions, EAF production in the China's iron and steel sector approaches to the same levels in all three ER scenarios in the long term. Obviously this projection is highly dependent on structural limitations predefined in the assumptions.

Table 43. Annual Steel Production of China Projected in the Base, Base-E, and ER scenarios (Mtonnes)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	572.4	645.4	716.7	777.9	761.0	722.9	657.6	657.6	640.8
Base-E	572.4	645.4	716.7	715.4	707.8	680.4	657.6	657.6	625.2
ER-10	572.4	627.8	665.8	660.3	649.0	529.7	424.3	424.3	424.3
ER-20	572.4	628.2	656.2	605.6	550.8	489.0	424.3	424.3	401.0
ER-30	572.4	620.1	582.8	453.4	447.6	425.2	411.0	424.3	401.0
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	66.3	71.7	102.4	126.9	134.3	127.6	164.3	190.9	161.1
Base-E	66.3	71.7	102.4	189.3	187.4	170.1	164.3	190.9	176.7
ER-10	66.3	89.3	153.2	244.5	246.3	320.8	397.6	424.3	377.6
ER-20	66.3	88.9	162.9	299.2	344.4	361.5	397.6	424.3	401.0
ER-30	66.3	97.0	236.2	451.3	447.6	425.2	411.0	424.3	401.0

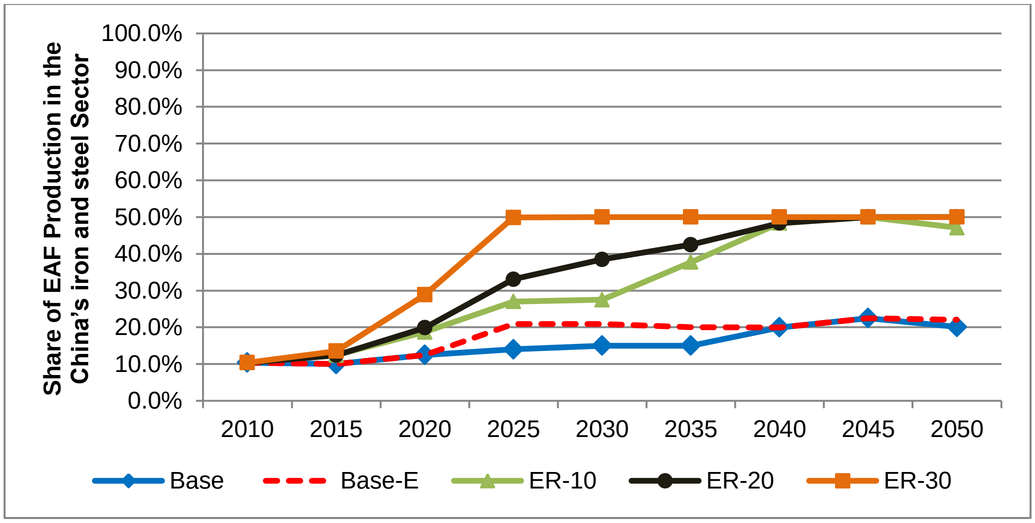

Figure 53. Shares of EAF Production in the China's iron and steel sector projected in the Base, Base-E, and ER scenarios (%)

The India's iron and steel Sector

Table 44 shows the annual steel production in the India's iron and steel sector under the three ER scenarios, and those in the Base and Base-E scenarios. As indicated in the previous section, the Base-E scenario results approximately 10-13% annual emission reductions in the India's iron and steel sector compared to the Base scenario from 2015 to 2035, and the reductions exhibit a declining trend from this year onward; approximately 9% in 2040 to 4% in 2050. Therefore, in the ER-10 scenario, in which CO_2 emissions are capped with a restriction of 10% below of those in the Base scenario, projected annual production will automatically follow that of Base-E scenario until 2035, and then the optimization process will adjust the annual production to meet the 10% emission reduction goal from 2040 to 2050. Steel production in India is dominated by EAF-DRI (Coal based) process in the Base and Base-E scenarios. This production process provides more than half of the steel production through the planning horizon in both of those scenarios. This trend continues in the ER-10 scenario as well (with some changes starting from 2040).

In the ER-20 and ER-30 scenarios, in which the CO2 emissions are restricted to lower levels compared to the ER-10 scenario, increased shifts from EAF-DRI (Coal based) production to EAF production are observed (see Figure 53). EAF-DRI (Coal based) nevertheless remains to be the most dominant production route through the planning horizon (46% share in 2050) in the ER-20 scenario, while it drops to 28% share in 2050 in the ER-30 scenario. The relative shares of the EAF-DRI (Coal based) production declines starting from 2035 in all ER scenarios. This is mainly in response to the increasing domestic iron ore scarcity and domestic scrap availability from that year onward.

Corresponding to the decreasing EAF-DRI production shares under more aggressive carbon reduction targets, the EAF production shares exhibit an increasing trend after 2035 till 2050 (see Figure 54) and EAF production becomes the most predominant production in India's iron and steel production in over the long term in the ER-30 scenario (57% share in 2050 in the ER-30 scenario). BOF and EAF-DRI (Gas based) production, on the other hand, has reached their lower bounds in the Base scenario. Therefore these production levels are not expected to be reduced more in the three ER scenarios. In the ER-30 scenario, EAF-DRI (Gas based) production that uses natural gas, a cleaner fuel compared to coal increases in year 2020 (Figure 55), while a part of EAF-DRI (Coal based) production switches with the EAF-DRI (Gas based) production (Figure 56).

Table 44. Annual Steel Production of India Projected in the Base, Base-E, and ER scenarios (Mtonnes)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	26.0	28.2	36.0	41.8	45.0	38.4	43.4	45.6	45.6
Base-E	26.0	28.2	36.0	41.8	45.0	38.4	43.4	45.6	45.6
ER-10	26.0	28.2	36.0	41.8	45.0	38.4	43.4	45.6	45.6
ER-20	26.0	28.2	36.0	41.8	45.0	38.4	43.4	45.6	45.6
ER-30	26.0	28.2	36.0	41.8	45.0	38.4	43.4	45.6	45.6
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	9.2	12.2	17.3	20.9	24.0	23.0	74.5	68.7	130.4
Base-E	9.2	12.2	17.3	20.9	24.0	23.0	72.0	60.1	95.5
ER-10	9.2	12.2	17.3	20.9	24.0	23.0	74.5	71.6	117.1
ER-20	9.2	12.2	17.3	20.9	36.6	55.8	129.6	129.5	177.4
ER-30	9.2	12.2	29.0	57.9	99.3	134.4	216.7	220.5	259.6
EAF-DRI (Gas based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	9.8	12.2	17.3	20.9	24.0	23.0	21.7	22.8	22.8
Base-E	9.8	12.2	17.3	20.9	24.0	23.0	21.7	22.8	22.8
ER-10	9.8	12.2	17.3	20.9	24.0	23.0	21.7	22.8	22.8
ER-20	9.8	12.2	17.3	20.9	24.0	23.0	21.7	22.8	22.8
ER-30	9.8	12.2	31.4	30.1	29.9	27.9	21.7	22.8	22.8
EAF-DRI (Coal based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	22.3	41.3	73.4	125.4	207.0	299.3	294.3	319.0	257.3
Base-E	22.3	41.3	73.4	125.4	207.0	299.3	296.8	327.7	292.2
ER-10	22.3	41.3	73.4	125.4	207.0	299.3	294.3	316.1	270.6
ER-20	22.3	41.3	73.4	125.4	194.4	266.5	239.2	258.3	210.3
ER-30	22.3	41.3	47.6	79.2	125.9	182.9	152.1	167.2	128.1

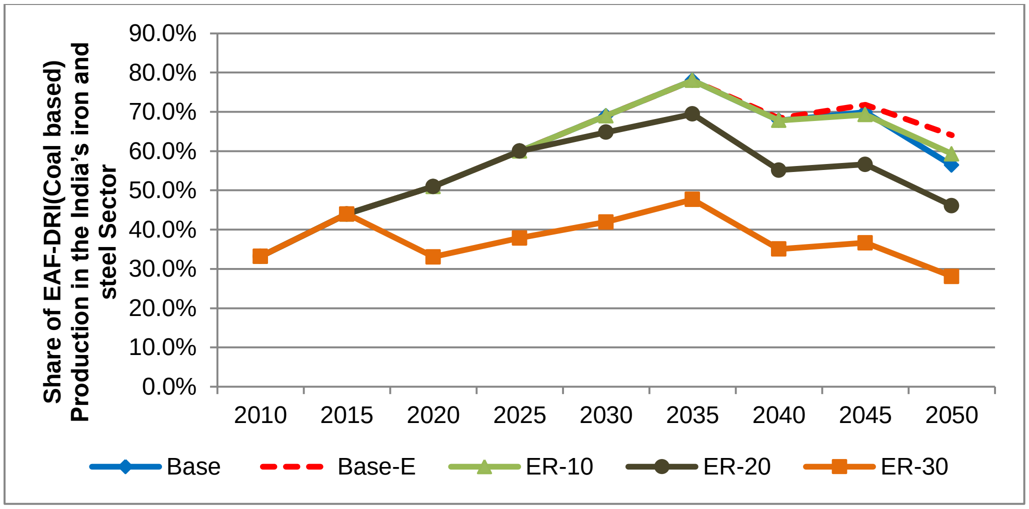

Figure 54. Shares of EAF-DRI (Coal based) Production in the India's iron and steel sector projected in the Base, Base-E, and ER scenarios (%)

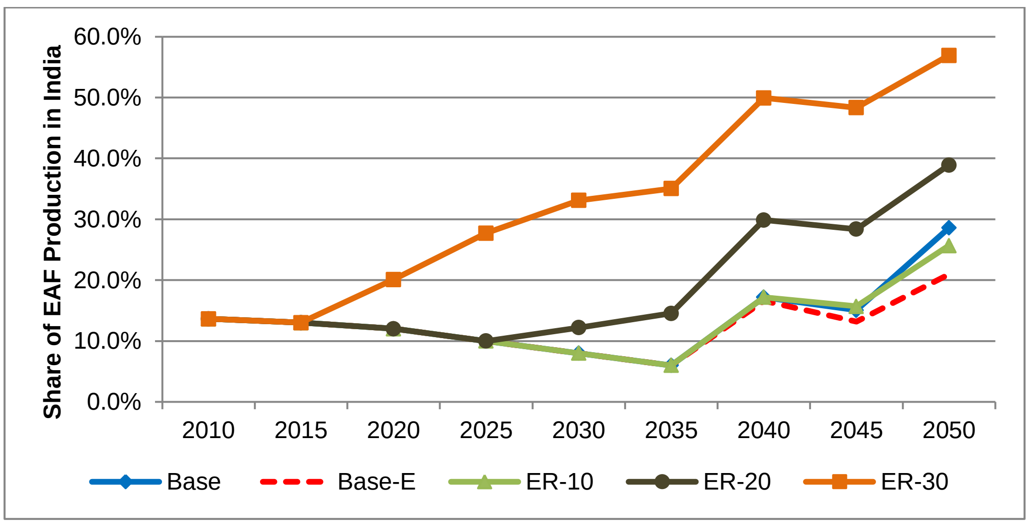

Figure 55. Shares of EAF Production in the India's iron and steel sector projected in the Base, Base-E, and ER scenarios (%)

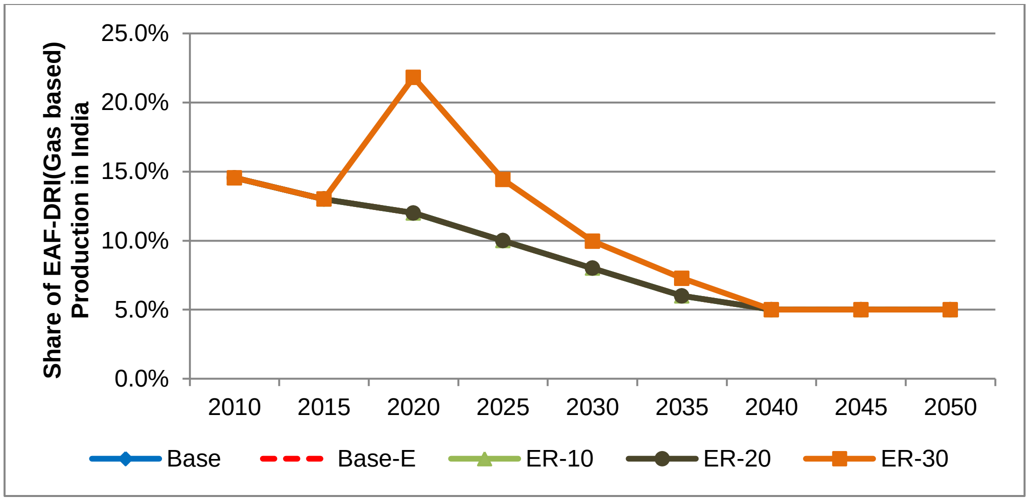

Figure 56. Shares of EAF-DRI (Gas based) Production in India's iron and steel sector projected in the Base, Base-E, and ER scenarios (%)

4.3.2.2. Annual Energy Consumption

This section presents the annual energy consumption of the U.S., China, and India's iron and steel sectors in the three ER scenarios for the period 2010-2050.

The U.S. Iron and Steel Sector

Figure 57 and Table 45 display the total annual energy consumption of the U.S. iron and steel sector in the three ER scenarios along with the Base and Base-E scenarios. Each ER scenario results in lower annual energy consumption in the U.S. iron and steel sector, compared to the Base and Base-E scenarios. A higher level of emission-reduction target corresponds to a lower level of annual energy consumption in the U.S. iron and steel sector. For example, in year 2030 the ER-10, ER-20, and ER-30 scenarios lead to 9%, 14%, and 18% reduction in annual energy consumption compared to the Base scenario, respectively. In addition, starting in year 2040 the energy use reduction rates become lower than those of previous years. For example, in year 2045 the ER-10 scenario reduces total energy consumption by 8%, while the ER-20 and ER-30 scenarios by 11% and 13.5%, respectively. This is primarily attributed to the increase of advanced production technologies that are expected to replace retiring production starting in 2040 in the Base scenario.

Figure 58 and Figure 59 show the trends of process-based annual energy consumption in the U.S. iron and steel sectors. Similar to the trend observed in total annual energy consumption in Figure 57, annual energy consumption of BOF and EAF production exhibits decreasing trends throughout the planning horizon.

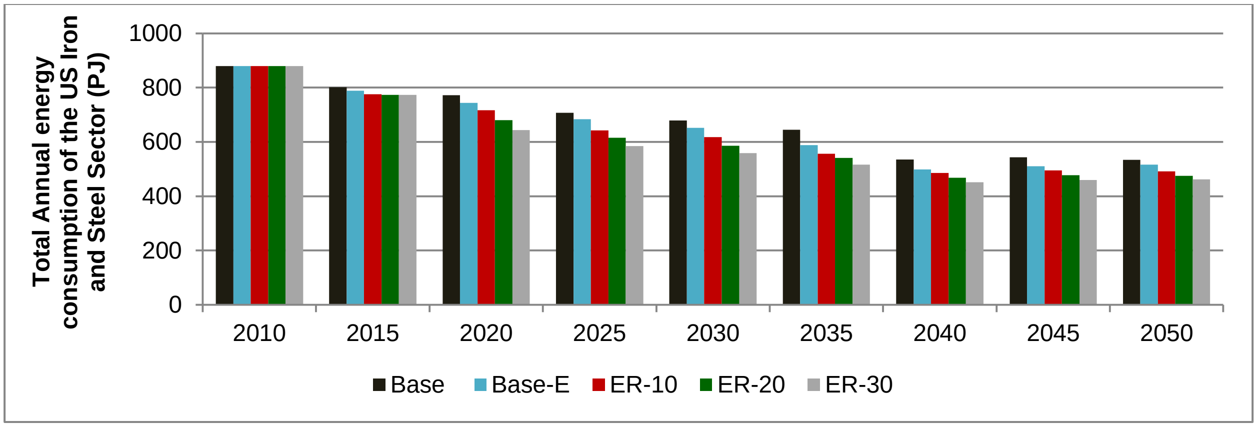

Figure 57. Total Annual Energy Consumption of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ER scenarios (PJ)

Table 45. Total Annual Energy Consumption of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ER scenarios (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	878.9	801.1	772.2	707.2	679.4	644.9	535.3	544.0	534.0
Base-E	878.9	788.3	744.4	683.4	651.4	588.0	499.2	510.4	516.3
ER-10	878.9	775.3	717.3	642.4	618.3	556.0	485.9	495.3	491.3
ER-20	878.9	773.4	679.7	615.7	586.0	541.7	467.9	477.1	475.4
ER-30	878.9	773.0	643.9	584.7	558.5	515.9	451.5	460.2	461.7

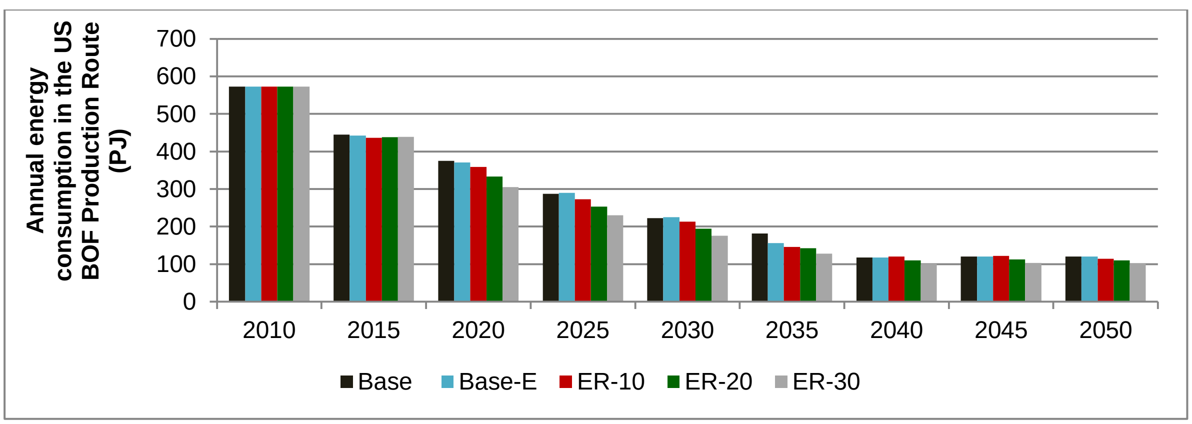

Figure 58. Annual Energy Consumption in the BOF Production of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ER scenarios (PJ)

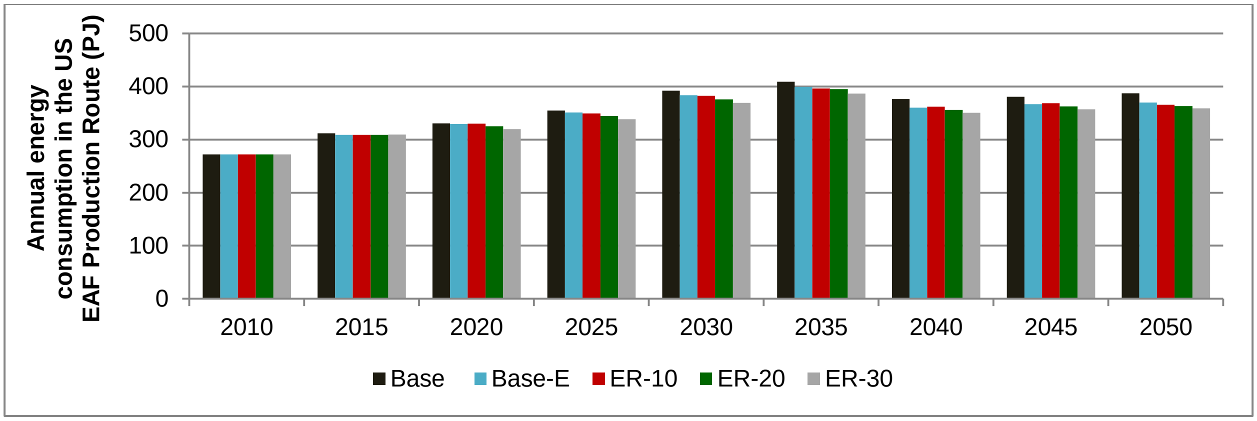

Figure 59. Annual Energy Consumption in the EAF Production of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ER scenarios (PJ)

Because the same steel production volume is made by using less energy consumption in future years, specific energy use (i.e., energy intensity defined by energy use per unit of production) is expected to decrease over time in each ER scenario. Figure 60 and Table 46 illustrate the annual energy intensity of steel production in the U.S. from 2010 to 2050 for the Base, Base-E and three ER scenarios. The efficiency of the U.S. iron and steel sector is improved in each ER scenario when compared to that of the Base and Base-E scenarios. Because energy intensity levels of the Base-E and ER-10 scenarios are close to each other, efficiency improvement in ER scenarios starts to moderate from 2040 to 2050 when compared to Base-E scenario. On the other hand, among three ER scenarios, the ER-30 scenario exhibits biggest reduction in energy intensity – indicating the highest improvement in energy efficiency. In addition, Table 47 and Table 48 further show process-based energy intensities of the U.S. iron and steel sector.

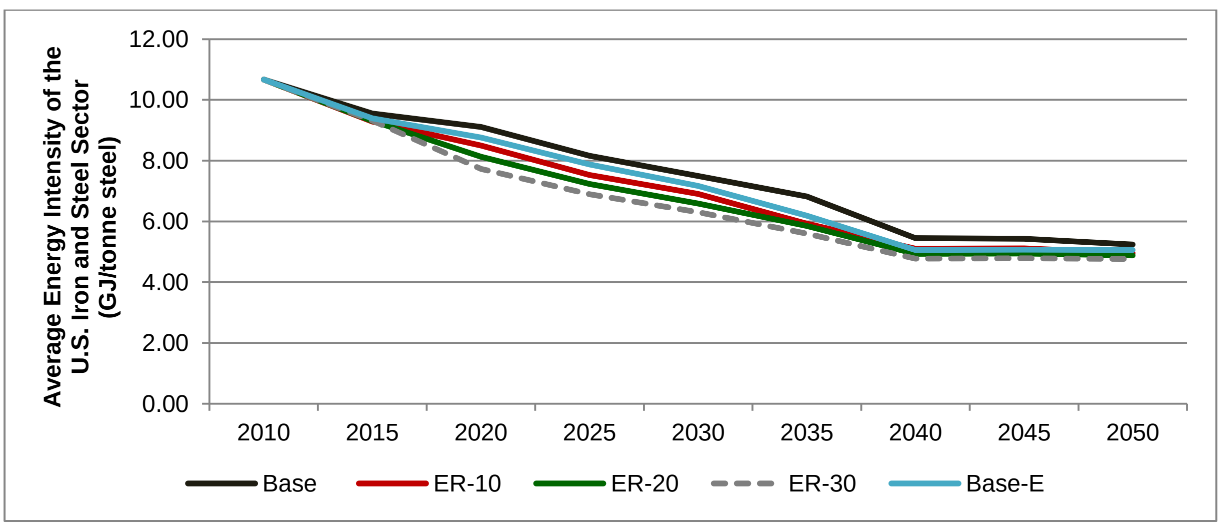

Figure 60. Average Energy Intensities of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ER Scenarios (GJ/tonne steel)

Table 46. Average Energy Intensities of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ER Scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	10.67	9.55	9.11	8.16	7.49	6.82	5.45	5.43	5.24
Base-E	10.67	9.39	8.76	7.87	7.16	6.19	5.06	5.07	5.06
ER-10	10.67	9.29	8.50	7.53	6.90	5.92	5.10	5.11	4.95
ER-20	10.67	9.31	8.12	7.23	6.59	5.85	4.93	4.94	4.88
ER-30	10.67	9.32	7.72	6.89	6.30	5.60	4.78	4.79	4.76

Table 47. Annual Energy Intensity in the BOF Production of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ER scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	18.38	18.06	18.07	16.98	16.81	16.81	12.49	12.50	12.43
Base-E	18.38	17.95	17.86	17.12	16.96	17.00	12.46	12.48	12.44
ER-10	18.38	17.73	17.30	16.11	16.10	15.82	12.71	12.73	11.75
ER-20	18.38	17.79	16.05	14.94	14.67	15.52	11.63	11.68	11.32
ER-30	18.38	17.83	14.71	13.58	13.26	13.90	10.67	10.71	10.57

Table 48. Annual Energy Intensity in the EAF Production of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ER scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	5.60	5.57	5.55	5.46	5.41	5.17	4.50	4.47	4.44
Base-E	5.60	5.47	5.42	5.30	5.20	4.87	4.24	4.24	4.24
ER-10	5.60	5.46	5.38	5.23	5.14	4.80	4.26	4.26	4.19
ER-20	5.60	5.46	5.29	5.15	5.05	4.78	4.19	4.19	4.16
ER-30	5.60	5.46	5.21	5.06	4.96	4.67	4.12	4.13	4.12

The China's iron and steel Sector

Total annual energy consumption of the China's iron and steel sector decreases in the three ER scenarios when compared to that of the Base and Base-E scenarios (Figure 61 and Table 49). The relative reduction levels in China are higher than those of the U.S. counterparts. In year 2030, ER-10, ER-20, and ER-30 scenarios lead to 9.5%, 18.6%, and 26.2% total energy reduction, respectively. The energy reduction is the combined results of progressive process shifts from BOF to EAF production and energy efficiency improvements in production processes. Figure 62 and Figure 63 show that energy consumption of the BOF production exhibits sharp decreases under all three emission reduction targets, while energy consumption of the EAF production increases through the planning horizon. However, the magnitude of energy reduction in BOF production is higher than the magnitude of energy increase in EAF production through 2035 in Base-E scenario, resulting in net reduction of total energy use. In addition, the amount of energy consumed in the EAF production approaches to similar levels after 2040 among all three ER scenarios, corresponding to the increased share of EAF production approaching 50%.

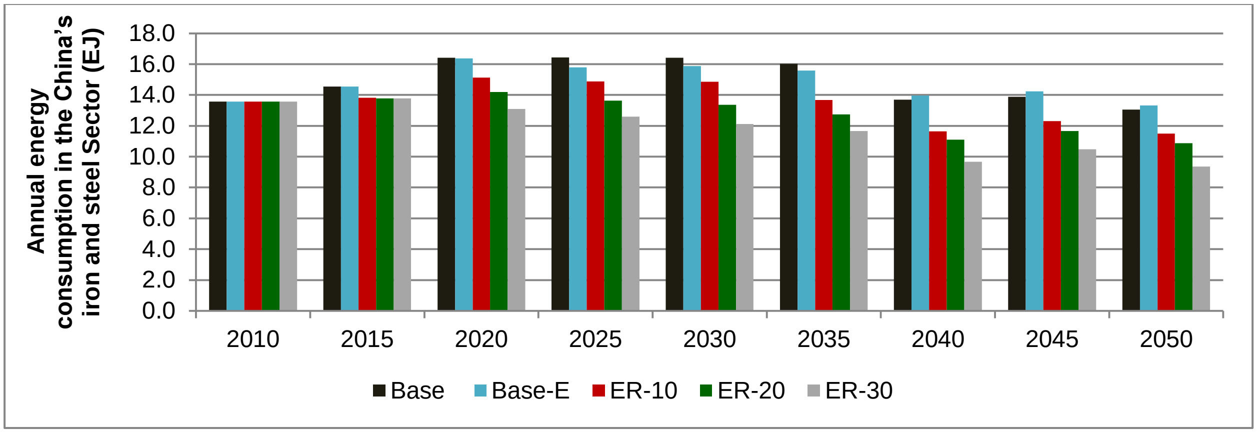

Figure 61. Total Annual Energy Consumption of the China's iron and steel sector Projected in the Base, Base-E, and ER scenarios (EJ)

Table 49. Total Annual Energy Consumption of the China's iron and steel sector Projected in the Base, Base-E, and ER scenarios (EJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	13.58	14.56	16.42	16.43	16.42	16.03	13.69	13.89	13.05
Base-E	13.58	14.54	16.38	15.80	15.87	15.58	13.97	14.24	13.33
ER-10	13.58	13.81	15.13	14.89	14.86	13.69	11.64	12.31	11.50
ER-20	13.58	13.77	14.19	13.63	13.36	12.73	11.10	11.66	10.87
ER-30	13.58	13.77	13.09	12.60	12.12	11.66	9.67	10.48	9.37

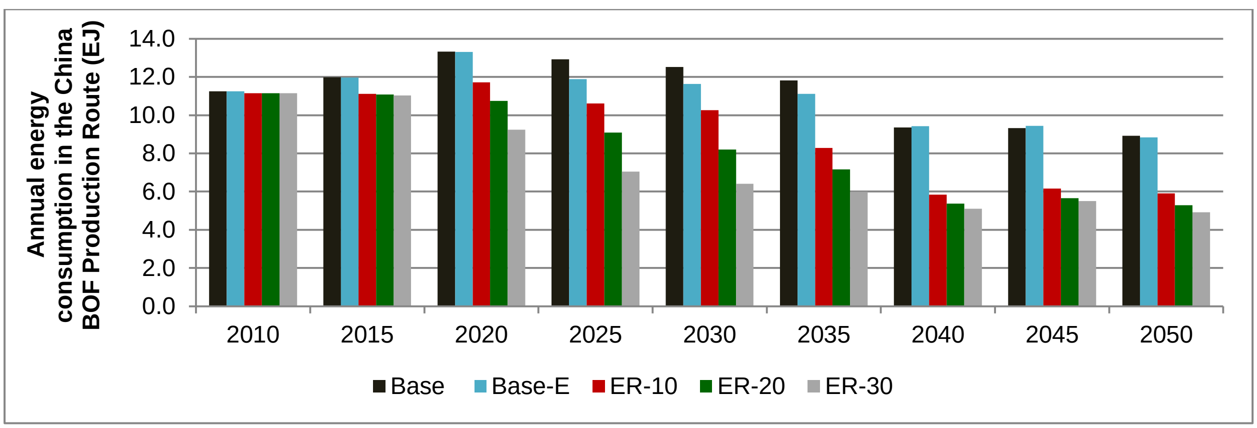

Figure 62. Annual Energy Consumption in the BOF Production of the China's iron and steel sector Projected in the Base, Base-E, and ER scenarios (EJ)

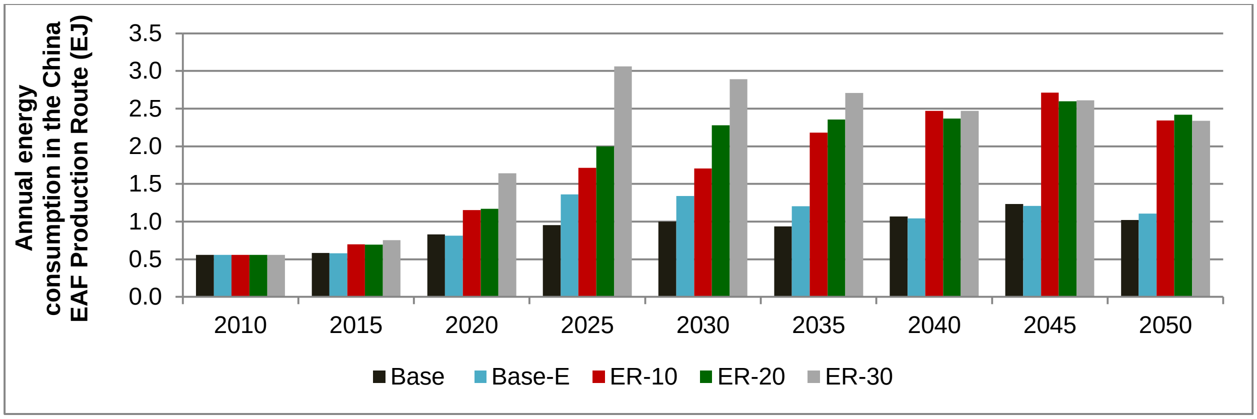

Figure 63. Annual Energy Consumption in the EAF Production of the China's iron and steel sector Projected in the Base, Base-E, and ER scenarios (EJ)

Figure 64 and Table 50 show the average energy intensity China's iron and steel production, which indicates a trend of efficiency improvement especially under three ER scenarios. Table 51 and Table 52 show process-based energy intensities. Because of the major production shifts from BOF production to EAF production that is more energy efficient, the average energy intensity of the China's iron and steel sector is improved more significantly when compared to that of remaining BOF process. Compared to the Base scenario, we estimated from the tables that ER-10, ER-20, and ER-30 scenarios lead to 11.2%, 20.2%, and 27.2% reduction in average energy intensities, respectively, in 2025; and 17.0%, 22.5%, and 27.1% reduction in average energy intensities, respectively, in 2050.

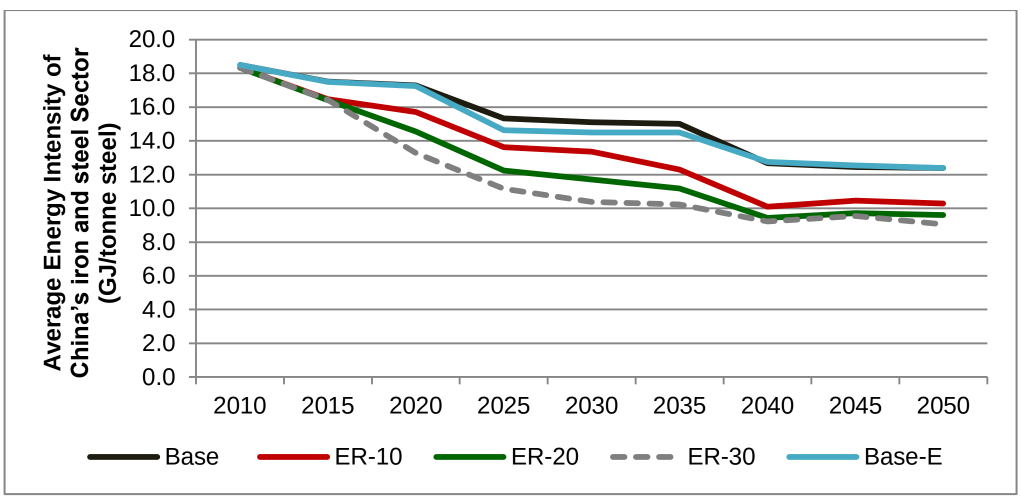

Figure 64. Average Energy Intensities of the China's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (GJ/tonne steel)

Table 50. Average Energy Intensities of the China's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	18.49	17.51	17.29	15.34	15.10	15.00	12.68	12.44	12.40

Base-E	18.49	17.49	17.24	14.64	14.50	14.49	12.74	12.55	12.40
ER-10	18.33	16.48	15.71	13.62	13.37	12.30	10.10	10.46	10.29
ER-20	18.33	16.42	14.55	12.24	11.71	11.19	9.42	9.73	9.61
ER-30	18.33	16.43	13.29	11.16	10.39	10.22	9.22	9.55	9.04

Table 51. Annual Energy Intensity in the BOF Production of the China's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (GJ/tonne steel)

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	19.66	18.56	18.60	16.61	16.46	16.36	14.22	14.18	13.92
Base-E	19.66	18.53	18.57	16.60	16.44	16.34	14.34	14.35	14.13
ER-10	19.48	17.72	17.60	16.07	15.81	15.63	13.74	14.52	13.93
ER-20	19.48	17.64	16.38	14.99	14.89	14.64	12.68	13.32	13.19
ER-30	19.48	17.78	15.85	15.53	14.31	14.08	12.42	12.96	12.25

Table 52. Annual Energy Intensity in the EAF Production of the China's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (GJ/tonne steel)

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	8.43	8.14	8.09	7.51	7.43	7.33	6.49	6.46	6.34
Base-E	8.43	8.10	7.94	7.19	7.15	7.08	6.35	6.33	6.26
ER-10	8.43	7.79	7.52	7.01	6.93	6.79	6.21	6.40	6.21
ER-20	8.43	7.78	7.19	6.67	6.62	6.51	5.96	6.13	6.03
ER-30	8.43	7.75	6.94	6.78	6.46	6.36	6.02	6.15	5.83

The India's iron and steel Sector

In the India's iron and steel sector, the Base-E scenario projects more than 10% emission reduction from 2010 to 2035, which already meets or exceeds the ER-10 scenario reduction target predefined for ER-10 scenario. **Figure 65** and **Figure 66** (**Table 53** and **Table 54**) show similar levels of energy consumption and energy intensities between the Base-E and the ER-10 scenarios between 2010 and 2035. From this year onward, total annual energy consumption energy intensities are lower in the ER-10 scenario than those of Base-E scenario. In ER-20 and ER-30 scenarios energy consumption and energy intensities are reduced more, corresponding to more stringent emission reduction targets. **Figure 66** also shows that similar to the projections for the U.S. and China's iron and steel sectors, the ER-30 scenario projects the highest efficiency improvement compared to other scenarios in India's iron and steel sector. **Table 54** shows decreasing annual energy intensity in all ER scenarios (the lowest energy consumption is in the ER-30 scenario), and lower energy intensity corresponds to a higher level of emission reduction target.

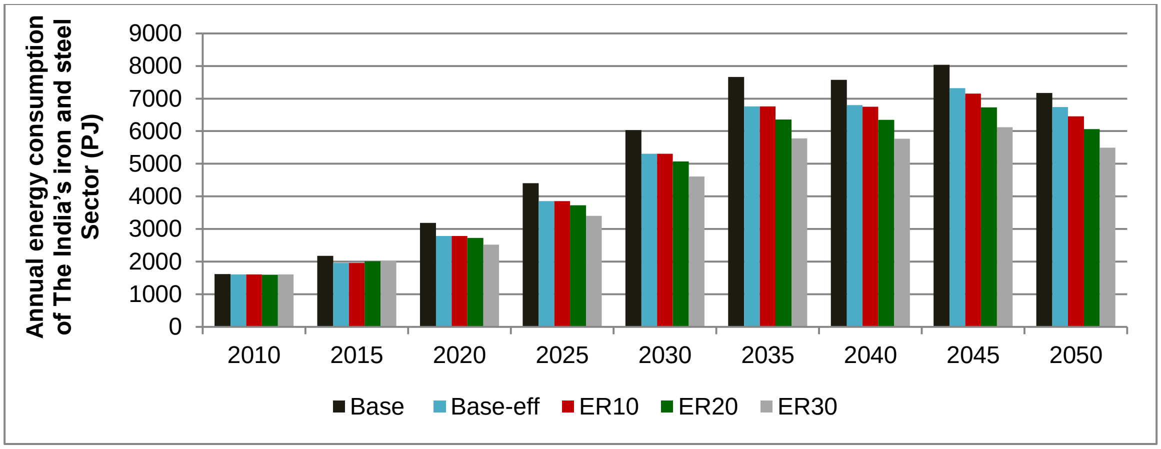

Figure 65. Total Annual Energy Consumption of the India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (PJ)

Table 53. Total Annual Energy Consumption of the India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	1620.8	2178.5	3191.1	4402.9	6036.6	7659.3	7574.5	8031.2	7171.0
Base-E	1607.3	1961.5	2787.6	3852.0	5305.7	6757.7	6799.9	7322.4	6744.1
ER-10	1607.3	1961.5	2787.6	3855.6	5309.1	6755.3	6749.4	7153.2	6460.2
ER-20	1603.4	2005.8	2726.8	3731.1	5075.8	6357.1	6352.2	6729.4	6061.3
ER-30	1604.0	2023.8	2520.6	3399.7	4613.8	5777.9	5769.1	6119.9	5494.9

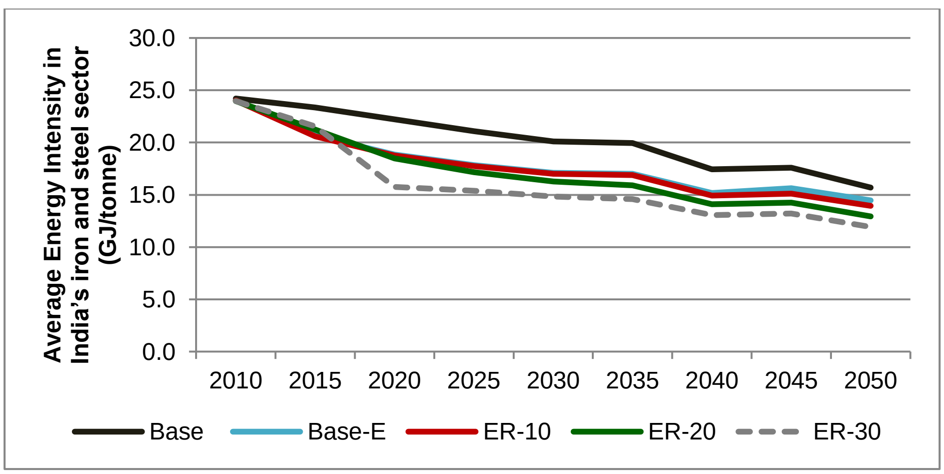

Figure 66. Average Energy Intensities of the India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (GJ/tonne steel)

Table 54. Average Energy Intensities of the India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050

Base	24.20	23.34	22.21	21.08	20.11	19.95	17.44	17.59	15.70
Base-E	24.00	20.69	18.85	17.84	17.11	17.02	15.16	15.62	14.47
ER-10	24.00	20.58	18.76	17.74	17.02	16.90	14.94	15.12	13.93
ER-20	23.95	21.22	18.49	17.15	16.28	15.90	14.11	14.24	12.94
ER-30	23.96	21.53	15.74	15.37	14.84	14.59	13.07	13.21	11.92

Figure 67 and Table 55 show annual energy consumption and intensity of the EAF-DRI (Coal based) production in India declines through the planning horizon in all three ER scenarios. Compared to the Base scenario, annual energy consumption in the EAF-DRI (Coal based) process starts to reduce after 2020 in the ER-30 scenario, after 2030 in the ER-20 scenario, and after 2040 in the ER-10 scenario. The changes are similar to that of production.

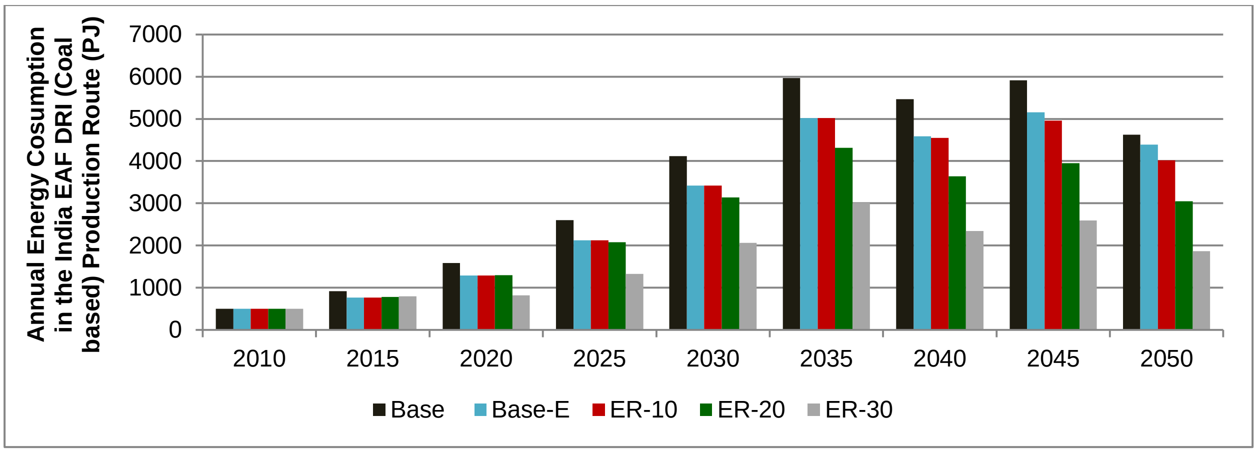

Figure 67. Annual Energy Consumption in the EAF-DRI (Coal based) Production of the India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (PJ)

Table 55. Annual Energy Intensity in the EAF-DRI (Coal based) Production of the India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	22.56	22.17	21.62	20.72	19.89	19.93	18.58	18.54	17.97
Base-E	22.56	18.64	17.60	16.92	16.52	16.78	15.46	15.74	15.02
ER-10	22.56	18.64	17.60	16.92	16.52	16.78	15.46	15.68	14.85
ER-20	22.56	18.90	17.71	16.56	16.13	16.20	15.20	15.30	14.50
ER-30	22.56	19.29	17.18	16.73	16.38	16.47	15.39	15.53	14.56

Figure 68 shows annual energy consumption as it corresponds to the combination of production increase and efficiency improvement in EAF production in India. In the ER-20 and ER-30 scenarios, energy consumption of the EAF production in India increases with the increase in EAF production volumes as presented in Section 4.3.2.1. Table 56 shows that efficiency of the EAF production is actually improved in all ER scenarios.

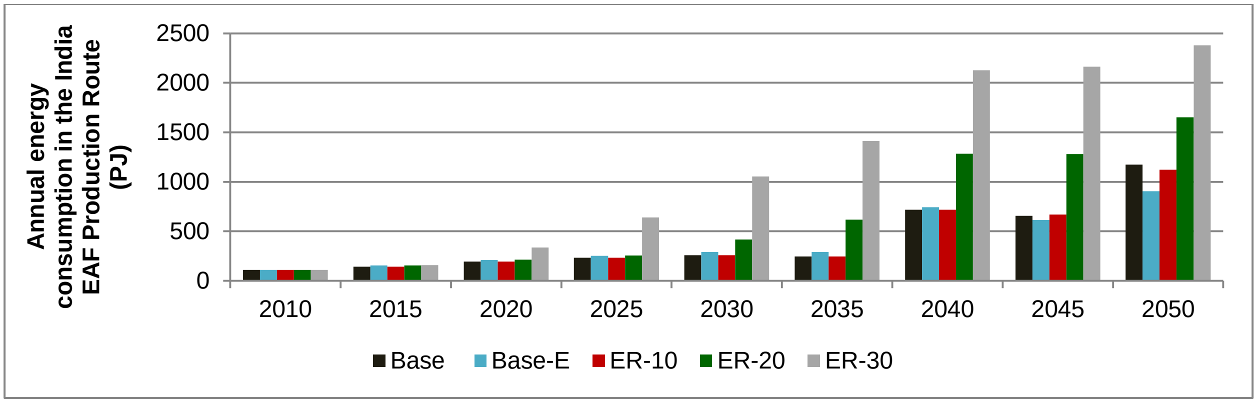

Figure 68. Annual Energy Consumption in the EAF Production of the India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (PJ)

Table 56. Annual Energy Intensity in the EAF Production of the India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (GJ/tonne steel)

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	11.88	11.78	11.33	11.15	10.80	10.76	9.63	9.56	9.01
Base-E	11.88	12.64	12.14	12.11	12.19	12.59	10.33	10.25	9.50
ER-10	11.88	11.78	11.33	11.15	10.80	10.76	9.63	9.35	9.57
ER-20	11.88	12.64	12.32	12.25	11.42	11.08	9.90	9.90	9.31
ER-30	11.88	13.00	11.61	11.04	10.61	10.51	9.81	9.81	9.16

Figure 69 shows annual energy consumption in the BOF production in the Base, Base-E, and ER Scenarios in India. Annual energy consumption of the BOF production in India decreases in all ER scenarios when compared to that of the Base scenario, while annual BOF production reaches the lower bounds predefined for the ISEEM-IS model (in Table 5, Section 3.1.2.2) in the Base, Base-E, and three ER scenarios. Table 57 shows that compared to the Base scenario, all ER scenarios improve the efficiency of the BOF production; in addition, more stringent emission reduction targets (e.g., ER-30) corresponds to lower energy intensity of BOF production, indicating a higher level of energy efficiency improvement.

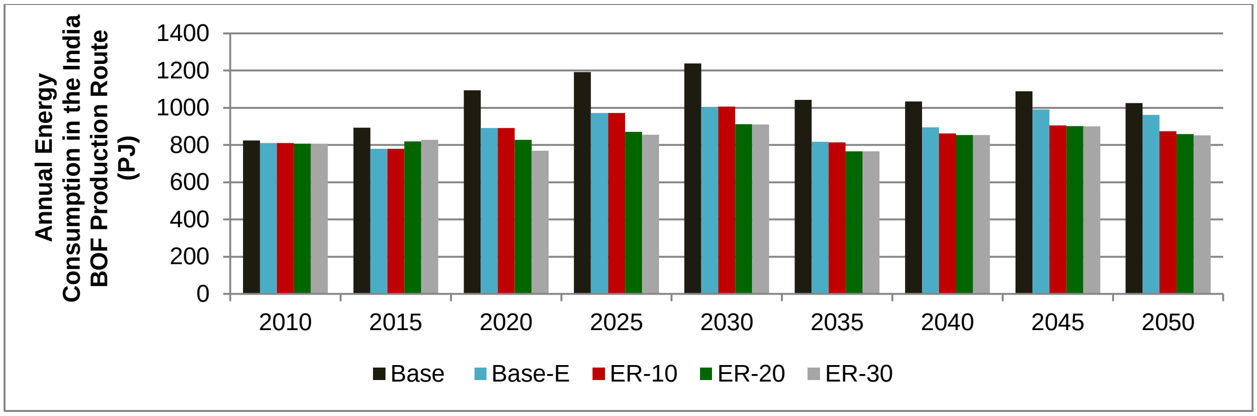

Figure 69. Annual Energy Consumption in the BOF Production of the India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (PJ)

Table 57. Annual Energy Intensity in the BOF Production of the India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	31.71	31.75	30.41	28.53	27.51	27.19	23.83	23.87	22.47
Base-E	31.19	27.71	24.77	23.25	22.30	21.33	20.62	21.71	21.10
ER-10	31.19	27.71	24.77	23.25	22.34	21.24	19.89	19.83	19.18
ER-20	31.04	29.10	23.02	20.83	20.24	19.97	19.69	19.75	18.84
ER-30	31.07	29.40	21.39	20.47	20.22	19.95	19.66	19.74	18.66

Figure 70 illustrates the annual energy consumption of EAF-DRI (Gas based) production in India in each scenario. Figure 70 and Table 58 show that energy intensities of EAF-DRI (Gas based) production stay identical across scenarios, except for the ER-30 scenario between years 2020 and 2035. Corresponding to the production increases in EAF-DRI (Gas based) process in the ER-30 scenario between years 2020 and 2035 is the net annual energy consumption increase while the intensity levels are lower than that of other scenarios, due to investments in energy efficiency.

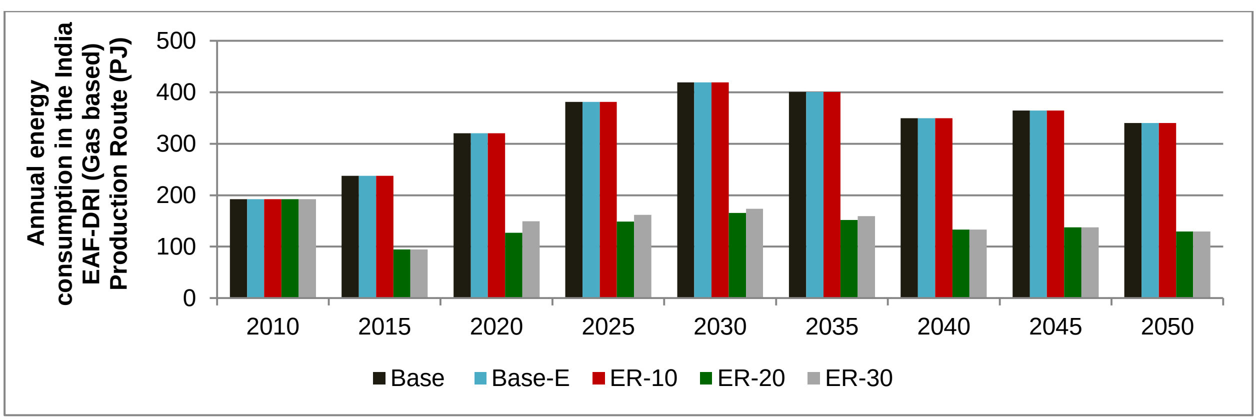

Figure 70. Annual Energy Consumption in the EAF-DRI (Gas based) Production of the India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (PJ)

Table 58. Annual Energy Intensity in the EAF-DRI (Gas based) Production of the India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	19.65	19.49	18.54	18.23	17.46	17.39	16.10	15.98	14.93
Base-E	19.65	19.49	18.54	18.23	17.46	17.39	16.10	15.98	14.93
ER-10	19.65	19.49	18.54	18.23	17.46	17.39	16.10	15.98	14.93
ER-20	19.65	19.49	18.54	18.23	17.45	17.38	16.10	15.98	14.93
ER-30	19.65	19.49	10.89	13.08	14.31	14.58	16.10	15.98	14.93

4.3.2.3. Annual CO_2 Emissions

This section presents annual CO2 emissions of the U.S., China, and India's iron and steel sectors in the three ER scenarios for the period 2010-2050.

Based upon the country-specific annual CO2 emissions (Table 41) and production (Table 42, Table 43, and Table 44) from the ISEEM-IS model results, we calculated the annual CO2 emission intensity for each country from year 2010 to 2050. Figure 71, Figure 72, and Figure 73 show the annual CO2 emission intensity of the iron and steel sector of the each country for all ER scenarios, compared to the Base and Base-E scenarios. CO2 emission intensity of each scenario exhibits decreasing trends over time. Especially for the three ER scenarios, emission restrictions in each country lead to reduction in emission intensities via shifts to production processes that are less energy intensive (such as EAF) and investments in efficient production technologies. Among the ER scenarios, the ER-30 scenario projects the lowest emission intensity throughout the planning horizon for each country.

On the other hand, because Base-E scenario already satisfies 10% emission reduction requirements of the ER-10 scenario in India from 2010 to 2035, the emission intensity levels of the ER-10 and Base-E scenarios are close to each other, as shown in Figure 73.

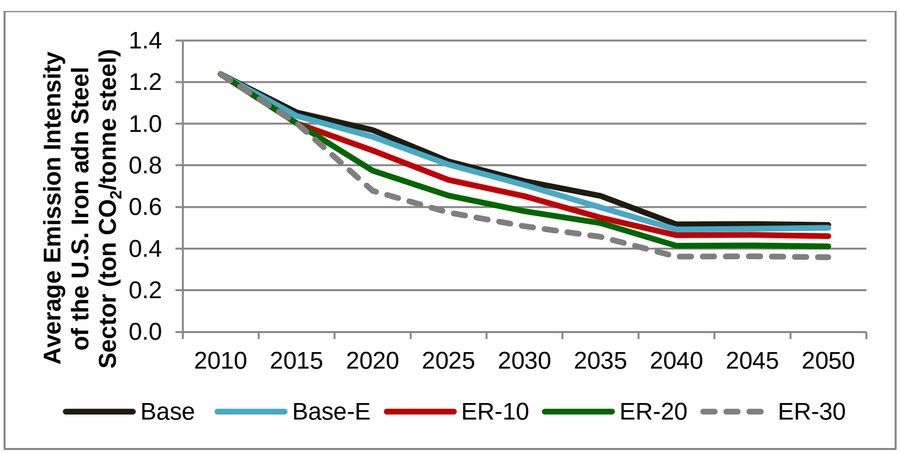

Figure 71. Average Emission Intensity of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ER Scenarios (ton CO_2/tonne steel)

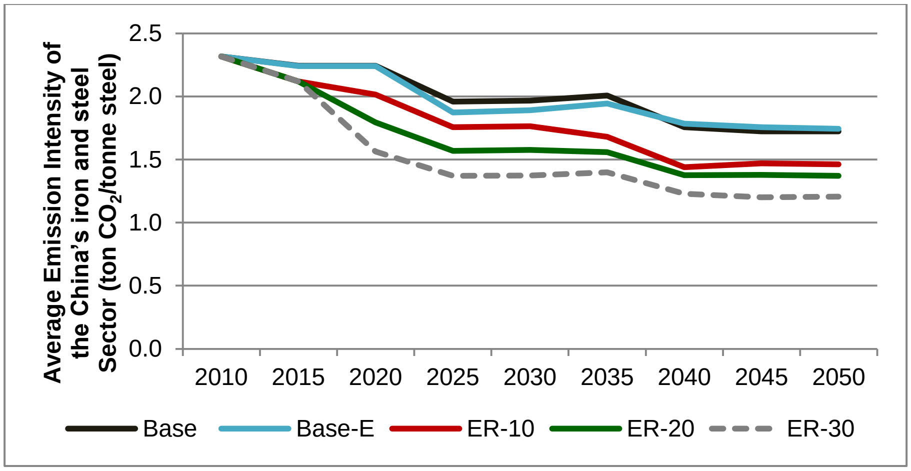

Figure 72. Average Emission Intensity of the China's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (ton CO_2/tonne steel)

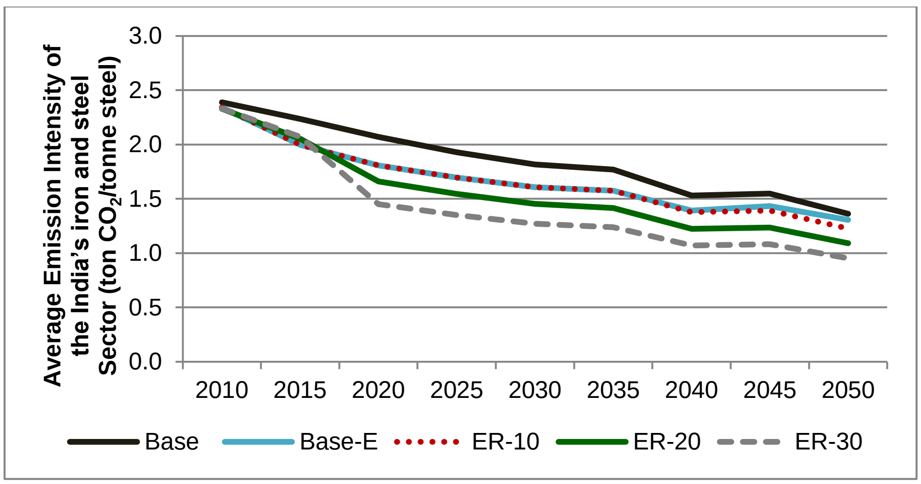

Figure 73. Average Emission Intensity of the India's iron and steel Sectors Projected in the Base, Base-E, and ER scenarios (ton CO_2/tonne steel)

4.3.2.4. Annual Production Costs

This section presents annual steel production costs of the U.S., China, and India's iron and steel sectors in the three ER scenarios for the period 2010-2050.

The U.S. Iron and Steel Sector

Table 59 shows the annual total costs of the U.S. iron and steel sector projected in the Base, Base-E, and each of the three ER scenarios. The annual total costs of the ER-10 and ER-20 scenarios become less than its Base scenario counterparts starting in 2035 and 2045, respectively. This result indicates that the steel production becomes cost effective after 2030 and 2045 in the ER-10 and ER-20 scenarios, respectively. In the ER-30 scenarios, annual production costs decrease over time, although at levels slightly higher than that of Base scenario.

Table 59. Annual Total Costs of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ER Scenarios (Billion 2005 $)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	40.9	50.2	55.0	59.5	61.3	60.2	57.8	58.8	58.6
Base-E	40.9	50.1	54.9	59.4	61.1	59.7	57.1	58.0	57.8
ER-10	40.9	50.3	55.1	59.8	61.5	60.1	57.6	58.4	58.1
ER-20	40.9	50.3	55.4	60.2	61.9	60.3	57.9	58.7	58.5
ER-30	40.9	50.2	55.8	60.5	62.1	60.5	58.1	59.0	58.8

Figure 74 exhibits the carbon abatement cost for the U.S. iron and steel sector in three ER scenarios using Base scenario emissions as the baseline. The carbon abatement cost in each ER scenario is defined here as the change in annual production costs for each ER scenario per the carbon emission reduction using Base scenario as the baseline. We have found that the carbon abatement cost become negative in E-R10 scenario starting in 2035 and ER-20 scenario starting in 2045 – meaning that investments in efficient production technologies to reduce emissions become cost effective in the U.S. iron and steel sector in the later periods (i.e., negative annual carbon abatement costs starting in 2035 and 2045 for the ER-10 and ER-20 scenarios, respectively). This observation corresponds well with the production cost presented in the preceding table (Table 59). The ER-30 scenario still results in positive carbon costs at the end of the planning horizon (although the costs are lower in the second half of the planning horizon). This indicates that ER-30 scenario (in which larger investments are needed to decrease emissions by 30%) may need a longer period of time for the investment to be paid off, or to become cost effective.

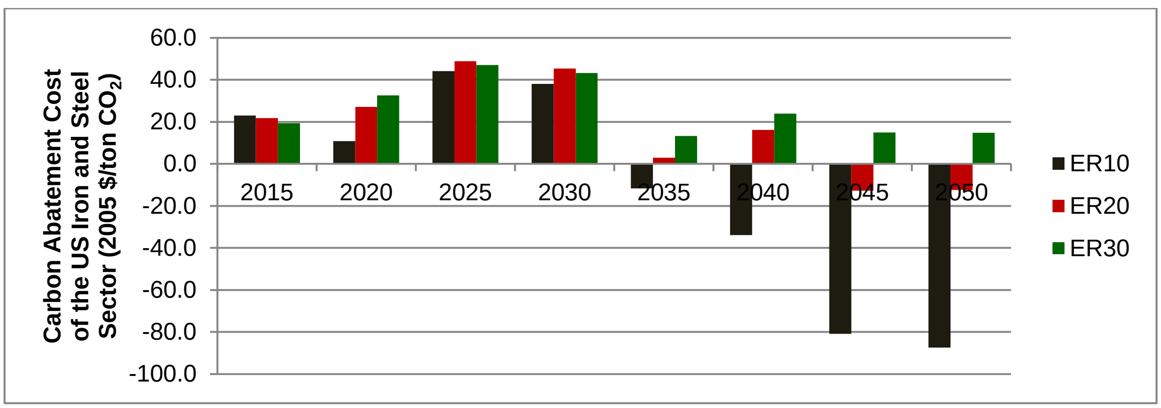

Figure 74. Annual Carbon Abatement Costs of the U.S. Iron and Steel Sector Projected in the ER Scenarios, Compared to the Base Scenario (2005 $/ton CO_2 reduction)

The China's iron and steel Sector

Table 60 lists the total annual costs and Figure 75 shows the annual carbon abatement costs of the China's iron and steel sector in the three ER scenarios. The results indicate that the ER-10 and ER-20 scenarios become cost effective in China in the later periods similar to the projection for the U.S. ER-10 scenario has negative abatement costs after 2045, while the ER-20 scenario has negative abatement costs starting in 2050. This also indicates that investments in efficient production technologies to reduce emissions become economically attractive in the long run (for ER-10 and ER-20 reduction) in the China's iron and steel sector. More investments and structural shifts would be expected in China's iron and steel sector to achieve the same rate of emission reduction as that of the U.S. for each ER scenario.

Table 60. Annual Total Costs of the China's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (Billion 2005 $)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	288.5	364.1	447.5	527.7	515.4	467.0	431.8	456.0	424.7
Base-E	288.5	363.9	446.8	526.9	513.8	464.6	427.7	451.8	420.7
ER-10	288.5	371.2	454.5	534.6	521.4	472.3	435.8	448.8	415.6
ER-20	288.5	371.9	468.1	550.1	533.2	480.3	443.0	457.1	419.3
ER-30	288.5	371.0	478.5	567.8	549.9	489.2	459.4	477.2	432.4

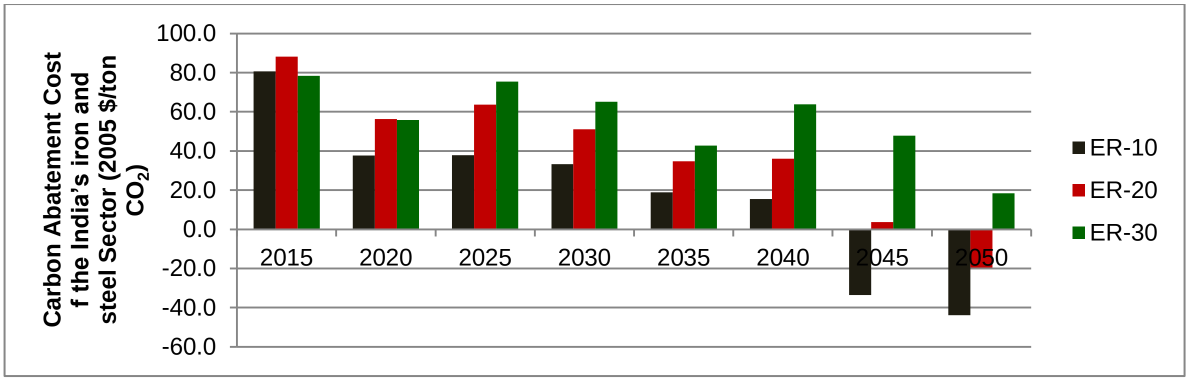

Figure 75. Annual Carbon Abatement Costs of the China's iron and steel sector Projected in the ER Scenarios, Compared to the Base Scenario (2005 \$/ton CO_2 reduction)

The India's iron and steel Sector

Table 61 shows total annual production cost of the India's iron and steel sector. In the Base-E scenario, annual production cost is lower than that of the Base scenario. All three ER scenarios call for additional investments to decrease emissions per the scenario requirements for emission reduction, while costs of each ER scenario are lower than that of Base scenario. As discussed in Section 4.2.2, availability of efficient production technologies in India's iron and steel sector contributes to the significant reduction in total cost objective. This might be a good indicator that those technologies would be in the baseline production in the near future.

For the India's case, we calculate the carbon abatement costs using the comparisons with Base-E scenario (Figure 77) as well as the Base scenario (Figure 76), respectively. Figure 76 shows that annual carbon abatement costs are negative in all three ER scenarios when compared to that of the Base scenario. Figure 77, on the other hand, shows the annual carbon abatement costs of each ER scenario when compared to that of the Base-E scenario. The abatement costs are zero until 2035 in the ER-10 scenario and become positive after 2040. This is expected because Base-E scenario already satisfies the emission reduction requirements set forth in the ER-10 scenario from 2010 to 2035. Additional modeling analysis including 10%, 20%, and 30% emission reduction using Base-E scenario as the baseline would benefit the understanding of the projection in carbon abatement costs.

Table 61. Annual Total Costs of the India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (Billion 2005 $)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	32.9	59.8	98.6	149.9	211.9	264.3	293.5	313.1	313.4
Base-E	33.2	58.6	94.4	141.5	198.1	243.7	269.6	285.0	281.8
ER-10	32.9	58.6	94.4	141.5	198.0	243.7	270.4	286.9	286.1
ER-20	32.8	58.4	94.3	142.8	201.6	249.1	279.7	294.9	294.6
ER-30	32.8	58.1	97.6	148.4	210.1	259.8	290.6	307.6	307.6

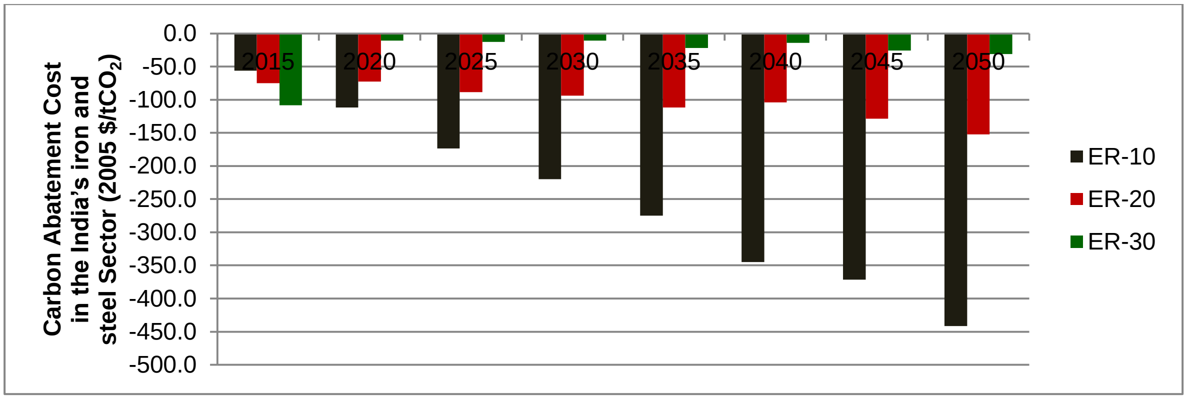

Figure 76. Annual Carbon Abatement Costs of the India's iron and steel sector Projected in the three ER Scenarios, compared to the Base Scenario (2005 \$/ton CO_2 reduction)

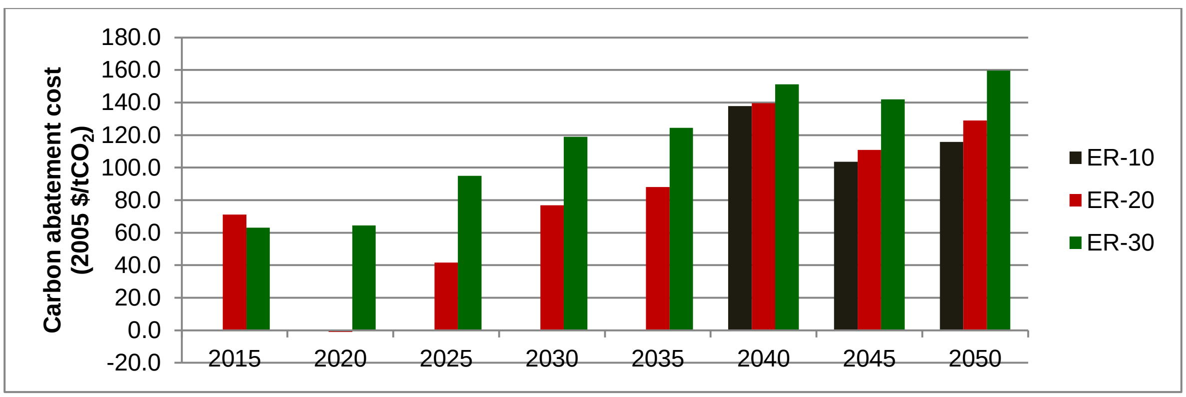

Figure 77. Annual Carbon Abatement Costs of the India's iron and steel sector Projected in the three ER Scenarios, compared to the Base-E Scenario (2005 \$/ton CO_2 reduction)

4.3.3. ER Scenario Summary

- ***Under each ER scenario that predefines a specific emission-reduction target (i.e., 10%, 20%, and 30% less than that of the Base scenario for each country), modeling with the goal of production cost minimization projects structural shifts to EAF production over time (i.e., a higher production share with the lowest SEC) while gradually replacing other production process (e.g., BOF, gas-based EAF-DRI, and/or coal-based EAF-DRI) in each country.*** In the U.S. iron and steel sector, BOF production is already at the lower bound of production shares set exogenously in the model assumptions in the Base scenario as discussed in Section 4.1. As a result, there is practically not much room for process shifts from BOF to EAF production in any ER scenarios. Instead, the model projects shifts from the remaining EAF-DRI (Gas based) to EAF production that is more efficient in each

ER scenario. China's iron and steel sector exhibits significant shifts from BOF to EAF production in each ER scenario over time, and shares of EAF production increase with the increase in emission reduction targets. For example, EAF production share in the ER-30 scenario is the highest, reaches 50% in 2025 compared to 33% in the ER-20 scenario and 27% in the ER-10 scenario in the same year. However, starting from 2045, EAF production share starts to approach the same levels regardless of the emission reduction targets. In Indian iron and steel sector, the Base-E scenario results in approximately 10-13% annual emission reduction when compared with that of Base scenario from 2015 to 2035. Therefore, in the ER-10 scenario annual production projection will automatically follow the Base-E scenario projection in India (without additional investment in any production) from 2015 to 2035, and then the model's optimization process adjusts the annual production to meet the 10% emission-reduction target from years 2040 to 2050. In the ER-20 and ER-30 scenarios, on the other hand, shifts from EAF-DRI (Coal based) production to EAF production are observed. As a result, in 2050 approximately 57% of the total production comes from EAF process in the ER-30 scenario, and approximately 39% of the total production is from EAF process in the ER-20 scenario, compared to approximately 26% of the total production in the ER-10 scenario.

- ***When compared to the Base and Base-E scenarios, each ER scenario results in lower annual energy consumption and energy intensity for each country. In addition, a higher level of emission-reduction target corresponds to a lower level of annual energy consumption and intensity in each country.*** For example, compared to the Base scenario in 2030, the ER-10, ER-20, and ER-30 scenarios lead to 9%, 14%, and 18% reduction in annual energy consumption in the U.S. iron and steel sector, respectively, which is are mainly due to investments in both advanced and efficient production technologies; while ER-10, ER-20, and ER-30 scenarios lead to 10%, 19%, and 26% reduction in annual energy consumption in the China's iron and steel sector, respectively, which is the combined results of major process shifts from BOF to EAF production and the efficiency improvements in production processes (i.e., investments in both advanced and efficient production technologies). In India's case, ER-10, ER-20, and ER-30 scenarios lead to 12%, 16%, and 24% reduction in annual energy consumption in India's iron and steel sector, respectively, in 2030. The reduction is the combined results of major process shifts from EAF-DRI (Coal based) to EAF production and the efficiency improvements in production processes (i.e., investments in both advanced and efficient production technologies).

  Table 62 exhibits the annual energy intensity of the each country over the years for all five scenarios. Improvement in energy intensity levels is more significant in the China and India's iron and steel sectors compared to those of the U.S. iron and steel sector. For example, in the ER-20 scenario, energy intensity levels are lowered by 6.9%, 22.5%, and 17.6% in 2050 in the U.S., China, and India's iron and steel sectors, respectively when compared to those of the Base scenario. However, even though the energy intensity levels are projected to have significant improvements in the China and India's iron and steel sectors throughout the years under each ER scenario, they cannot be reduced to the levels projected for the U.S. in any of the given scenarios. It is clear that higher capacity and shares of EAF production process, which is the most energy efficient iron and steel production process, leads to lowest energy intensity levels in the U.S. Thus, as mentioned earlier, even though China and India had higher efficiency improvement potentials via efficient production technologies (compared to the U.S.), they would never reach the U.S. levels due to structural limitations and the production cost minimization goals.

Table 62. Average Energy Intensities of the U.S., China, and India's iron and steel sector Projected in the Base, Base-E, and ER Scenarios (GJ/tonne steel)

		2010	2015	2020	2025	2030	2035	2040	2045	2050
The U.S.	Base	10.67	9.55	9.11	8.16	7.49	6.82	5.45	5.43	5.24
	Base-E	10.67	9.39	8.76	7.87	7.16	6.19	5.06	5.07	5.06
	ER-10	10.67	9.29	8.50	7.53	6.90	5.92	5.10	5.11	4.95
	ER-20	10.67	9.31	8.12	7.23	6.59	5.85	4.93	4.94	4.88
	ER-30	10.67	9.32	7.72	6.89	6.30	5.60	4.78	4.79	4.76
China	Base	18.49	17.51	17.29	15.34	15.10	15.00	12.68	12.44	12.40
	Base-E	18.49	17.49	17.24	14.64	14.50	14.49	12.74	12.55	12.40
	ER-10	18.33	16.48	15.71	13.62	13.37	12.30	10.10	10.46	10.29
	ER-20	18.33	16.42	14.55	12.24	11.71	11.19	9.42	9.73	9.61
	ER-30	18.33	16.43	13.29	11.16	10.39	10.22	9.22	9.55	9.04
India	Base	24.20	23.34	22.21	21.08	20.11	19.95	17.44	17.59	15.70
	Base-E	24.00	20.69	18.85	17.84	17.11	17.02	15.16	15.62	14.47
	ER-10	24.00	20.58	18.76	17.74	17.02	16.90	14.94	15.12	13.93
	ER-20	23.95	21.22	18.49	17.15	16.28	15.90	14.11	14.24	12.94
	ER-30	23.96	21.53	15.74	15.37	14.84	14.59	13.07	13.21	11.92

- ***Abatement costs of emission reduction differ from country to country. Normally, a positive carbon abatement cost is expected for emission reduction. However, depending on efficient production technology set defined in ISEEM-IS model, negative carbon abatement costs may be observed in some years.*** For example, negative annual carbon abatement costs are exhibited starting in 2035 and 2045 for both ER-10 and ER-20 scenarios in the U.S. iron and steel sector. Compared to the U.S., China's sector exhibited negative annual carbon abatement costs a few years later in both ER-10 and ER-20 scenarios: The ER-10 scenario corresponds to negative abatement costs after 2045, while the ER-20 scenario corresponds to negative abatement costs in 2050. Our model results for ER-30 scenario in both the U.S. and China's iron and steel sectors (in which larger investments are needed to decrease emissions by 30%) indicate that a longer period of time beyond 2050 would be expected for the added investments to be paid off, or become cost effective. Table 63 shows that the carbon abatement costs (i.e., added production costs per tonne of emission reduction) are lower in the U.S iron and steel sector compared to those of China in most of the scenarios. With the efficient production technology structure assumed in the model, India's iron and steel sector reaches the targeted emission reduction with greatest cost reduction (i.e., added production costs being negative, leading to lowest abatement costs). As discussed in Section 4.2.2, availability of efficient production technologies in India's iron and steel sector brings the largest reduction in total cost objective in the model. Compared to the Base scenario levels, carbon abatement costs of the India's iron and steel sectors are negative in all three ER scenarios.

Table 63. Annual Carbon Abatement Costs of the U.S., China, and India's iron and steel sector Projected in the three ER scenarios (2005 \$/ton CO_2 reduction)

		2015	2020	2025	2030	2035	2040	2045	2050
The U.S.	ER-10	23.0	10.8	44.1	38.0	-11.7	-33.8	-80.9	-87.4
	ER-20	21.9	27.2	48.8	45.4	2.9	16.2	-12.7	-12.5
	ER-30	19.4	32.6	47.1	43.2	13.2	24.0	14.9	14.8
China	ER-10	80.6	37.7	37.9	33.3	18.9	15.5	-33.5	-43.8
	ER-20	88.2	56.3	63.7	51.0	34.8	36.1	3.7	-19.4
	ER-30	78.3	55.8	75.5	65.1	42.8	63.8	47.8	18.4
India	ER-10	-56.3	-111.8	-173.3	-220.0	-274.7	-344.9	-371.3	-441.5
	ER-20	-75.1	-72.4	-88.6	-94.1	-111.6	-104.1	-128.6	-152.2
	ER-30	-108.4	-11.0	-12.6	-10.9	-22.0	-14.3	-25.9	-31.0

4.4. Emission Reduction with Commodity Trading Scenarios (ET)

This section presents the results of the ISEEM-IS model with the second set of CO_2 emission reduction scenarios: Emission reduction with commodity trading (ET) scenarios. The purpose is to analyze the emission reduction potential in the U.S. iron and steel sector, when commodity trading (i.e., import or export) from China and India is available and is considered as an instrument to reduce carbon emissions in the U.S. Advanced and efficient production technologies are available in this scenario set as well. Thus, this scenario set provides a base to evaluate the investments in advanced and efficient production technologies in the U.S., China, and India's iron and steel sectors, while commodity trading (i.e., import or export) of the U.S. from China and India is available. There is no emission reduction target defined for China and India in this scenario set. However, increases in steel production of China and India, due to increasing exports to the U.S., may lead to more efficient production in those countries. On the other hand, the U.S. may slow or cease investing in efficiency and go through direct steel import from China and/or India while reducing domestic production.

The ET scenarios examine the potential impacts of commodity trading on the U.S. production, energy consumption, and emissions under three pre-defined emission reduction targets, and to understand implications for potential trades, investment strategies, and associated determinants such as environmental regulations. We examine ISEEM-IS model outcomes under three emission reduction targets (carbon caps) compared to Base scenarios.

Specific technical objectives are to:

1. examine the country-specific production and structure changes over time,
2. quantify the magnitudes and intensity of country-specific annual energy consumption and emissions,
3. estimate country-specific annual production cost and annual carbon abatement cost, and

4. understand the sensitivity of production, energy and emission intensity and cost to different levels of carbon caps

In the ET scenarios, pre-determined carbon emission reduction targets (or carbon caps) in the U.S. iron and steel sector are realized with the availability of the U.S. commodity trading with China and India, in addition to added investments in advanced production technologies and efficient production technologies projected in each country.

4.4.1. ET Scenario Definitions

ET scenarios are a group of scenarios, in which annual CO_2 emission levels are to be restricted, compared to the Base scenario, in the U.S. iron and steel sector. They are based on the same restriction levels of the U.S. as emission reduction without trading (ER) scenarios. Specifically, the annual CO_2 emission restriction of the U.S. iron and steel sector is set at 5% annual reduction from that of the Base scenario in 2015, and is set at three different levels (i.e., 10%, 20%, and 30%) starting in year 2020 throughout 2050. In ET scenarios, emissions from the China and India's iron and steel sectors are not restricted. The primary purpose is to analyze the emission reduction potential of the U.S. iron and steel sector, with commodity trading as an alternative instrument to efficiency investment for emission reduction. Basically, restrictions on the U.S. steel import defined in the Base scenario (i.e., existing levels of commodity trading remain unchanged in the Base scenario) will vary for each ET scenario.

The U.S. import from countries other than China and India is currently 90% of the total. In the Base scenario, this share is kept constant through the planning horizon. However, to purpose of this scenario group is to analyze the trading relationships of the U.S with the China and India. Thus, emissions related to the production of the import from other countries are also bounded with the same restrictions defined for ET scenarios.

On the other hand, in the Base and Base-E scenarios, China has the lowest production costs, compared to the U.S. and India, through the planning horizon. Thus, the optimization processes tends to realize all dynamic imports of the U.S. from China and none from India. We set 75% as the upper bound for shares of China in dynamic import of the U.S. from China. Therefore, once the dynamic import from China (of the U.S.) reaches to 75% share, import from India (to the U.S.) if any may be realized.

> *Dynamic import: Dynamic import represents the import from the countries modeled in the ISEEM-IS model.*
> *Static import: Static import represents the import from the rest of the world (i.e., total import from the countries not modeled in the ISEEM-IS model).*

i. ET-10 Scenario: Annual CO_2 emissions of the U.S. iron and steel sector are 10% below of those in the Base scenario starting in 2020.
ii. ET-20 Scenario: Annual CO_2 emissions of the U.S. iron and steel sector are restricted 20% below of those in the Base scenario starting in 2020.
iii. ET-30 Scenario: Annual CO_2 emissions of the U.S. iron and steel sector are restricted 30% below of those in the Base scenario starting in 2020.

4.4.2. ET Scenario Results

This sub section represents the annual production, production costs, energy consumption, and CO_2 emissions projections of the U.S., China, and India's iron and steel sectors under the three ET scenario assumptions by comparing with the Base and Base-E scenarios.

4.4.2.1. Annual Production and Imports

Annual steel production of the U.S., China, and India's iron and steel sectors in the three ET scenarios for the period 2010-2050 is presented in this sub section.

The U.S. Iron and Steel Sector

Total annual steel production of the U.S. iron and steel sector is replaced with imports from China and India under emission reduction with commodity (steel) trading scenarios (see Figure 78 and Figure 79). As you can see from Table 64, the level of replacement increases when the emission restrictions are higher. For example, the ET-10, ET-20, and ET-30 scenarios lead to 6.6%, 19.9%, and 26.5% decline in steel production in the U.S iron and steel sector in 2020 (see Table 65). Clearly, the U.S. reduces its emissions from iron and steel sector by cutting down the production in the country and importing from China and India in ET scenario group. On the other hand, since the existing levels of commodity trading is kept unchanged in the Base and Base-E scenarios, there is no difference in production and import levels of the Base and Base-E scenarios.

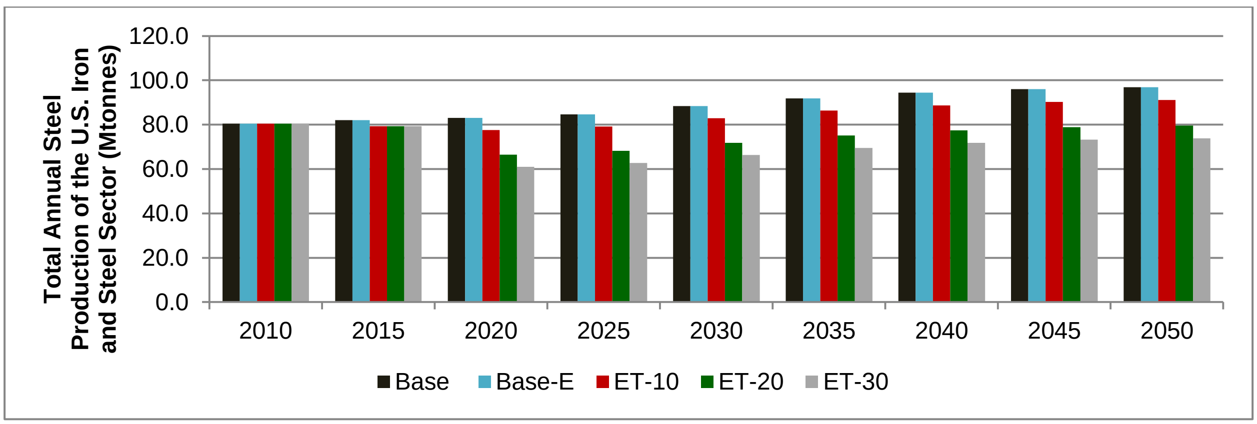

Figure 78. Total Annual Steel Production of the U.S. Projected in the Base, Base-E, and ET scenarios (Mtonnes)

Table 64. Total Annual Steel Production of the U.S. Projected in the Base, Base-E, and ET scenarios (Mtonnes)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	80.5	82.1	83.0	84.6	88.4	91.9	94.4	96.0	96.9
Base-E	80.5	82.1	83.0	84.6	88.4	91.9	94.4	96.0	96.9
ET-10	80.5	79.3	77.5	79.1	82.9	86.3	88.7	90.3	91.1
ET-20	80.5	79.3	66.5	68.2	71.8	75.2	77.4	78.9	79.5
ET-30	80.5	79.3	61.0	62.8	66.3	69.6	71.8	73.2	73.8

Table 65. Declines in Total Annual Steel Production of the U.S. Iron and Steel Sector Projected in the ET scenarios, compared to the Base Scenario (%)

	2015	2020	2025	2030	2035	2040	2045	2050
ET-10	3.4%	6.6%	6.5%	6.2%	6.1%	6.0%	5.9%	6.0%
ET-20	3.4%	19.9%	19.4%	18.7%	18.2%	18.0%	17.8%	17.9%
ET-30	3.4%	26.5%	25.8%	25.0%	24.3%	23.9%	23.8%	23.9%

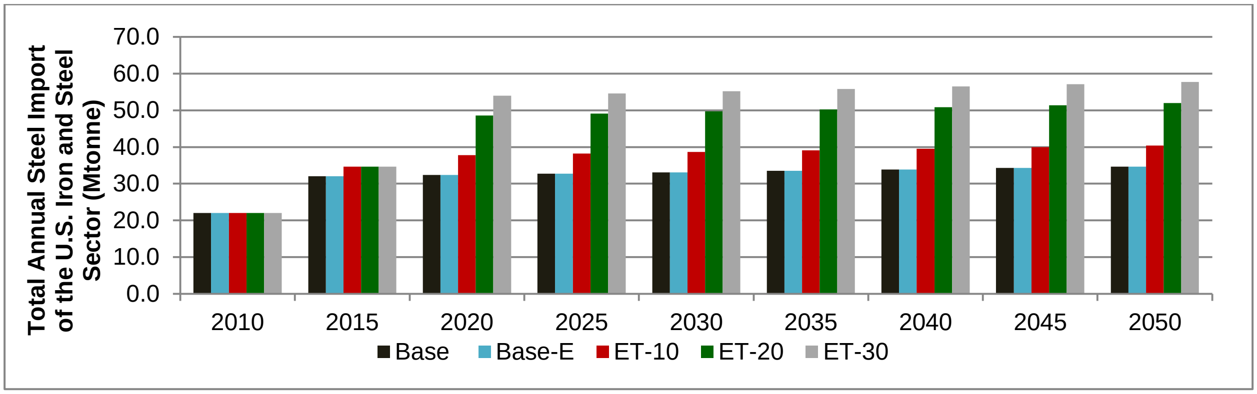

Figure 79. Total Annual Steel Imports of the U.S. Projected in the Base, Base-E, and ET Scenarios (Mtonnes)

Table 66 indicates that U.S. steel import from China is higher than that from India in each ET scenario. This is mainly because of the lower steel production costs in China, compared to India. The optimization process goes for import from China until the upper limits defined for China in Section 4.4.1 is reached (i.e., 75% of the dynamic import of the U.S.). Then, the rest of the U.S. dynamic import comes from India.

On the other hand, increases of the U.S. import from China and India include replacement of domestic production, and replacement of import from other countries. Since the same emission restrictions are applied to the steel products imported from other countries, this result is expected. The U.S. static import (i.e., import from other countries) decreases depending on the level of emission restrictions (i.e., 10%, 20%, 30% reduction in emission) in each ET scenario.

Table 66. Annual Steel Imports of the U.S. Projected in the Base, Base-E, and ET Scenarios (Mtonnes)

Base									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total Import	22.0	32.0	32.4	32.8	33.1	33.5	33.9	34.3	34.7
From China	0.8	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4
From India	0.8	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4
*From Others**	20.4	29.5	29.8	30.1	30.5	30.8	31.2	31.5	31.9
Base-E									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total Import	22.0	32.0	32.4	32.8	33.1	33.5	33.9	34.3	34.7
From China	0.8	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4
From India	0.8	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4
*From Others**	20.4	29.5	29.8	30.1	30.5	30.8	31.2	31.5	31.9
ET-10									

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Total Import	22.0	34.7	37.8	38.2	38.6	39.1	39.5	40.0	40.4
From China	0.8	3.8	5.7	5.7	5.8	5.9	5.9	6.0	6.1
From India	0.8	1.4	1.9	1.9	1.9	2.0	2.0	2.0	2.0
*From Others**	20.4	29.5	30.2	30.6	30.9	31.3	31.6	32.0	32.4
ET-20									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total Import	22.0	34.7	48.6	49.1	49.7	50.3	50.8	51.4	52.0
From China	0.8	3.8	10.9	11.1	11.2	11.3	11.4	11.6	11.7
From India	0.8	1.4	3.6	3.7	3.7	3.8	3.8	3.9	3.9
*From Others**	20.4	29.5	34.0	34.4	34.8	35.2	35.6	36.0	36.4
ET-30									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total Import	22.0	34.7	54.0	54.6	55.2	55.8	56.5	57.1	57.8
From China	0.8	3.8	16.2	16.4	16.6	16.8	16.9	17.1	17.3
From India	0.8	1.4	5.4	5.5	5.5	5.6	5.6	5.7	5.8
*From Others**	20.4	29.5	32.4	32.8	33.1	33.5	33.9	34.3	34.7

** The U.S. total import from countries other than China and India*

Table 67 and Table 68 show that while annual production changes across different scenarios, production shares in all ET scenarios remained practically unchanged from those of Base and Base-E scenarios. In addition, BOF production shares in the U.S. exhibit a decreasing trend toward its lower bound 10% in the long term due to its higher production costs. On the other hand, there are minor shifts from EAF-DRI (Gas based) production to the EAF production in the Base-E and ET scenarios with the availability of efficient technologies in the EAF production route.

Table 67. Process Based Annual Steel Production of the U.S. Projected in the Base, Base-E, and ET Scenarios (Mtonnes)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	31.2	24.6	20.8	16.9	13.3	10.8	9.4	9.6	9.7
Base-E	31.2	24.6	20.8	16.9	13.3	9.2	9.4	9.6	9.7
ET-10	31.2	23.8	19.4	15.8	12.4	8.6	8.9	9.0	9.1
ET-20	31.2	23.8	16.6	13.6	10.8	7.5	7.7	7.9	8.0
ET-30	31.2	23.8	15.3	12.6	9.9	7.0	7.2	7.3	7.4
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	48.6	56.0	59.5	64.9	72.4	79.0	83.6	85.1	87.2
Base-E	48.6	56.4	60.8	66.2	73.7	82.0	84.9	86.4	87.2
ET-10	48.6	54.4	56.7	61.9	69.0	76.9	79.9	81.3	82.0
ET-20	48.6	54.4	48.4	53.1	59.6	66.9	69.7	71.0	71.6
ET-30	48.6	54.4	44.7	49.6	55.4	62.3	64.6	65.9	66.4
EAF-DRI (Gas based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	0.7	1.5	2.8	2.8	2.7	2.1	1.3	1.3	0.0
Base-E	0.7	1.1	1.5	1.4	1.4	0.8	0.0	0.0	0.0

ET-10	0.7	1.1	1.5	1.4	1.4	0.8	0.0	0.0	0.0
ET-20	0.7	1.1	1.5	1.4	1.4	0.8	0.0	0.0	0.0
ET-30	0.7	1.1	1.1	0.6	1.0	0.4	0.0	0.0	0.0

Table 68. Process Based Annual Steel Production Shares of the U.S. Projected in the Base, Base-E, and ET Scenarios (%)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	38.7%	30.0%	25.0%	20.0%	15.0%	11.8%	10.0%	10.0%	10.0%
Base-E	38.7%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
ET-10	38.7%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
ET-20	38.7%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
ET-30	38.7%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	60.4%	68.2%	71.6%	76.7%	81.9%	86.0%	88.6%	88.6%	90.0%
Base-E	60.4%	68.7%	73.2%	78.3%	83.4%	89.2%	90.0%	90.0%	90.0%
ET-10	60.4%	68.6%	73.1%	78.2%	83.3%	89.1%	90.0%	90.0%	90.0%
ET-20	60.4%	68.6%	72.8%	77.9%	83.0%	89.0%	90.0%	90.0%	90.0%
ET-30	60.4%	68.6%	73.2%	79.0%	83.5%	89.5%	90.0%	90.0%	90.0%
EAF-DRI (Gas based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	0.9%	1.8%	3.4%	3.3%	3.1%	2.2%	1.4%	1.4%	0.0%
Base-E	0.9%	1.3%	1.8%	1.7%	1.6%	0.8%	0.0%	0.0%	0.0%
ET-10	0.9%	1.4%	1.9%	1.8%	1.7%	0.9%	0.0%	0.0%	0.0%
ET-20	0.9%	1.4%	2.2%	2.1%	2.0%	1.0%	0.0%	0.0%	0.0%
ET-30	0.9%	1.4%	1.8%	1.0%	1.5%	0.5%	0.0%	0.0%	0.0%

The China's iron and steel Sector

Figure 80 and Table 69 display the increasing steel production in China with respect to the increasing steel export to the U.S. Table 70 shows additional production of China due to export to the U.S., although minor when compared to the Base scenario (e.g., ranging from 0.4% to 2.0% in ET scenarios), satisfies 6.6%, 14.0%, and 22.1% of the U.S. steel demand on average in the ET-10, ET-20, and ET-30 scenarios, respectively.

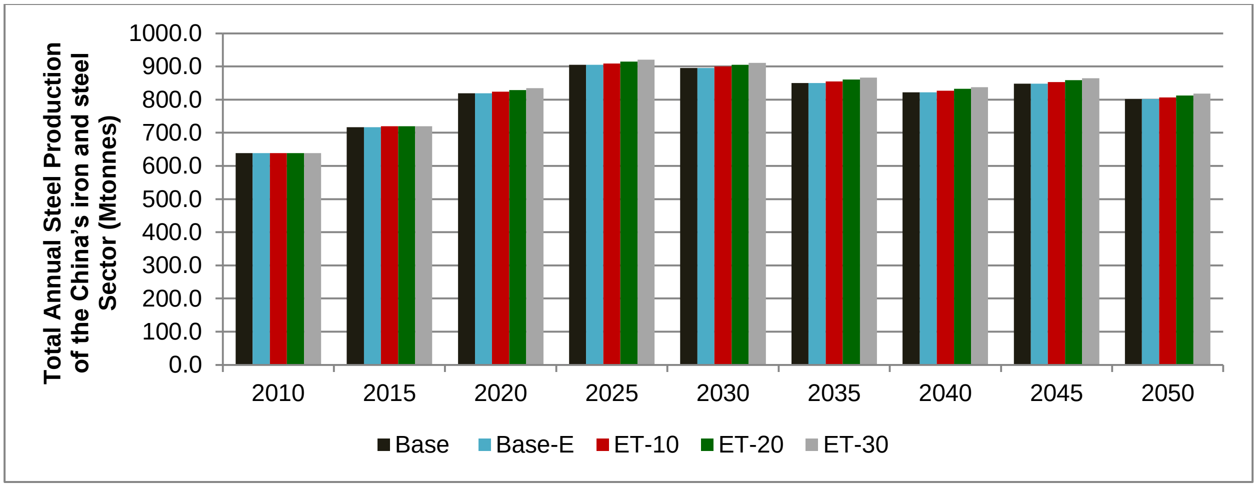

Figure 80. Total Annual Steel Production of China Projected in the Base, Base-E, and ET Scenarios (Mtonnes)

Table 69. Total Annual Steel Production of China Projected in the Base, Base-E, and ET Scenarios (Mtonnes)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	638.7	717.1	819.0	904.8	895.2	850.5	821.9	848.6	801.9
Base-E	638.7	717.1	819.0	904.8	895.2	850.5	821.9	848.6	801.9
ET-10	638.7	719.8	823.6	909.4	899.9	855.1	826.6	853.3	806.7
ET-20	638.7	719.8	829.1	914.9	905.5	860.8	832.3	859.1	812.5
ET-30	638.7	719.8	834.6	920.5	911.1	866.4	837.9	864.8	818.3

Table 70. Increases in Total Annual Steel Production of the China's iron and steel sector projected in the ET Scenarios, Compared to the Base Scenario (%)

	2015	2020	2025	2030	2035	2040	2045	2050
ET-10	0.4%	0.6%	0.5%	0.5%	0.5%	0.6%	0.6%	0.6%
ET-20	0.4%	1.2%	1.1%	1.1%	1.2%	1.3%	1.2%	1.3%
ET-30	0.4%	1.9%	1.7%	1.8%	1.9%	2.0%	1.9%	2.0%

Table 71 and Table 72 show that shares of production processes in the China's iron and steel sector are very similar (mostly identical) to the Base and Base-E scenarios in all ET scenarios. Apparently, there is little impact of increases in carbon reduction targets in all three ET scenarios on changing production shares of the China's iron and steel sector.

Table 71. Process Based Steel Production in the China's iron and steel sector in the Base and three ET Scenarios (Mtonnes)

BOF production									
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	572.4	645.4	716.7	777.9	761.0	722.9	657.6	657.6	640.8
Base-E	572.4	645.4	716.7	715.4	707.8	680.4	657.6	657.6	625.2
ET10	572.4	647.8	720.7	719.1	711.5	684.1	661.3	661.3	629.5

ET20	572.4	647.8	725.5	723.6	716.0	688.6	665.8	665.8	634.7
ET30	572.4	647.8	730.3	728.0	720.4	693.1	670.4	670.3	639.9
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	66.3	71.7	102.4	126.9	134.3	127.6	164.3	190.9	161.1
Base-E	66.3	71.7	102.4	189.3	187.4	170.1	164.3	190.9	176.7
ET10	66.3	72.0	103.0	190.3	188.4	171.0	165.3	192.0	177.2
ET20	66.3	72.0	103.6	191.4	189.5	172.2	166.5	193.2	177.8
ET30	66.3	72.0	104.3	192.5	190.6	173.3	167.6	194.5	178.4

Table 72. Process Based Steel Production in the China's iron and steel sector in the Base and three ET Scenarios (%)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	89.6%	90.0%	87.5%	86.0%	85.0%	85.0%	80.0%	77.5%	79.9%
Base-E	89.6%	90.0%	87.5%	79.1%	79.1%	80.0%	80.0%	77.5%	78.0%
ET10	89.6%	90.0%	87.5%	79.1%	79.1%	80.0%	80.0%	77.5%	78.0%
ET20	89.6%	90.0%	87.5%	79.1%	79.1%	80.0%	80.0%	77.5%	78.1%
ET30	89.6%	90.0%	87.5%	79.1%	79.1%	80.0%	80.0%	77.5%	78.2%
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	10.4%	10.0%	12.5%	14.0%	15.0%	15.0%	20.0%	22.5%	20.1%
Base-E	10.4%	10.0%	12.5%	20.9%	20.9%	20.0%	20.0%	22.5%	22.0%
ET10	10.4%	10.0%	12.5%	20.9%	20.9%	20.0%	20.0%	22.5%	22.0%
ET20	10.4%	10.0%	12.5%	20.9%	20.9%	20.0%	20.0%	22.5%	21.9%
ET30	10.4%	10.0%	12.5%	20.9%	20.9%	20.0%	20.0%	22.5%	21.8%

On the other hand, since restrictions on China steel import defined in the Base and Base-E scenarios are kept unchanged in ET scenarios, there is no change in China import levels. However, total export levels increase due to growing exports to the U.S.

India's iron and steel Sector

Figure 81 and Table 73 display the increasing steel production in India with respect to the increasing steel export to the U.S. from India. Even though the U.S. import from India is less than China in absolute terms, in percentage wise they are close (see also Table 70 and Table 74). With those relatively small production increases (e.g., ranging from 0.1% to 5.2%) in ET scenarios, India satisfies 1.5%, 4.7%, and 6.2% of the U.S. steel demand as period averages in the ET-10, ET-20, and ET-30 scenarios, respectively. Clearly, China's share in U.S. total import is significantly higher than India's.

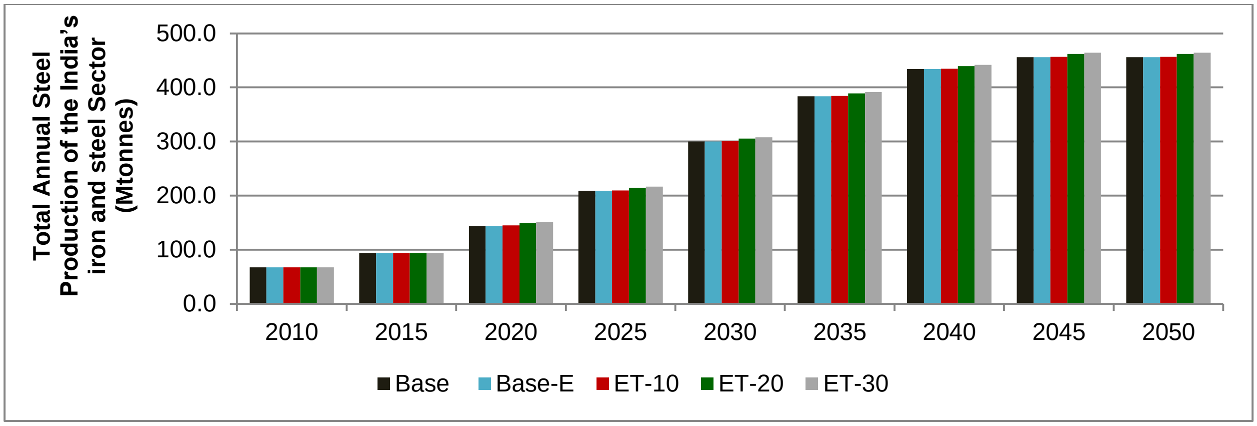

Figure 81. Total Annual Steel Production of India Projected in the Base, Base-E, and ET Scenarios (Mtonnes)

Table 73. Total Annual Steel Production of India Projected in the Base, Base-E, and ET Scenarios (Mtonnes)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	67.3	93.8	144.0	209.0	300.1	383.7	433.8	456.1	456.1
Base-E	67.3	93.8	144.0	209.0	300.1	383.7	433.8	456.1	456.1
ET-10	67.3	93.9	144.6	209.7	300.7	384.3	434.5	456.8	456.8
ET-20	67.3	94.2	149.3	214.4	305.5	389.2	439.4	461.8	461.8
ET-30	67.3	94.2	151.5	216.7	307.8	391.5	441.8	464.2	464.3

Table 74. Increases in Total Annual Steel Production of the India's iron and steel sector projected in the ET Scenarios, Compared to the Base Scenario (%)

	2015	2020	2025	2030	2035	2040	2045	2050
ET-10	0.1%	0.4%	0.3%	0.2%	0.2%	0.2%	0.1%	0.2%
ET-20	0.5%	3.7%	2.6%	1.8%	1.4%	1.3%	1.2%	1.2%
ET-30	0.5%	5.2%	3.7%	2.6%	2.0%	1.8%	1.8%	1.8%

All the ET scenarios provide similar results to the Base-E scenario starting from 2045 (see Table 75 and Table 76). There is no difference across scenarios in production shares of the India's iron and steel sector until 2040 (see Table 76). From this year onward, some shifts from EAF production to EAF-DRI (Coal based) production are observed. However, those shifts are not due to increase in the total steel production of India but because the optimization process prefer to invest more on EAF-DRI (Coal based) production with the availability of efficient technologies. For example, the share of EAF-DRI (Coal based) production increases to 64.1% in 2050 under Base-E scenario, in which the efficient production technologies available but there is no other scenario requirements, from 56.4% in the Base scenario.

Table 75. Process Based Steel Production in the India's iron and steel sector in the Base and three ET- Scenarios (Mtonnes)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**

Base	26.0	28.2	36.0	41.8	45.0	38.4	43.4	45.6	45.6
Base-E	26.0	28.2	36.0	41.8	45.0	38.4	43.4	45.6	45.6
ET-10	26.0	28.2	36.2	41.9	45.1	38.4	43.5	45.7	45.7
ET-20	26.0	28.3	37.3	42.9	45.8	38.9	43.9	46.2	46.2
ET-30	26.0	28.3	37.9	43.3	46.2	39.2	44.2	46.4	46.4
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	9.2	12.2	17.3	20.9	24.0	23.0	74.5	68.7	130.4
Base-E	9.2	12.2	17.3	20.9	24.0	23.0	72.0	60.1	95.5
ET-10	9.2	12.2	17.4	21.0	24.1	23.1	71.9	59.9	95.7
ET-20	9.2	12.3	17.9	21.4	24.4	23.4	71.1	59.1	98.2
ET-30	9.2	12.3	18.2	21.7	24.6	23.5	70.7	58.8	99.6
EAF-DRI (Gas based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	9.8	12.2	17.3	20.9	24.0	23.0	21.7	22.8	22.8
Base-E	9.8	12.2	17.3	20.9	24.0	23.0	21.7	22.8	22.8
ET-10	9.8	12.2	17.4	21.0	24.1	23.1	21.7	22.8	22.8
ET-20	9.8	12.3	17.9	21.4	24.4	23.4	22.0	23.1	23.1
ET-30	9.8	12.3	18.2	21.7	24.6	23.5	22.1	23.2	23.2
EAF-DRI (Coal based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	22.3	41.3	73.4	125.4	207.0	299.3	294.3	319.0	257.3
Base-E	22.3	41.3	73.4	125.4	207.0	299.3	296.8	327.7	292.2
ET-10	22.3	41.3	73.8	125.8	207.5	299.8	297.4	328.4	292.6
ET-20	22.3	41.5	76.1	128.6	210.8	303.6	302.4	333.4	294.3
ET-30	22.3	41.5	77.3	130.0	212.4	305.4	304.8	335.7	295.0

Table 76. Process Based Steel Production in the India's iron and steel sector in the Base and three ET- Scenarios (%)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	38.6%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
Base-E	38.6%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
ET-10	38.6%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
ET-20	38.6%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
ET-30	38.6%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	13.6%	13.0%	12.0%	10.0%	8.0%	6.0%	17.2%	15.1%	28.6%
Base-E	13.6%	13.0%	12.0%	10.0%	8.0%	6.0%	16.6%	13.2%	20.9%
ET-10	13.6%	13.0%	12.0%	10.0%	8.0%	6.0%	16.5%	13.1%	21.0%
ET-20	13.6%	13.0%	12.0%	10.0%	8.0%	6.0%	16.2%	12.8%	21.3%
ET-30	13.6%	13.0%	12.0%	10.0%	8.0%	6.0%	16.0%	12.7%	21.5%
EAF-DRI (Gas based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**

Base	14.5%	13.0%	12.0%	10.0%	8.0%	6.0%	5.0%	5.0%	5.0%
Base-E	14.5%	13.0%	12.0%	10.0%	8.0%	6.0%	5.0%	5.0%	5.0%
ET-10	14.5%	13.0%	12.0%	10.0%	8.0%	6.0%	5.0%	5.0%	5.0%
ET-20	14.5%	13.0%	12.0%	10.0%	8.0%	6.0%	5.0%	5.0%	5.0%
ET-30	14.5%	13.0%	12.0%	10.0%	8.0%	6.0%	5.0%	5.0%	5.0%
EAF-DRI (Coal based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	33.2%	44.0%	51.0%	60.0%	69.0%	78.0%	67.8%	69.9%	56.4%
Base-E	33.2%	44.0%	51.0%	60.0%	69.0%	78.0%	68.4%	71.8%	64.1%
ET-10	33.2%	44.0%	51.0%	60.0%	69.0%	78.0%	68.5%	71.9%	64.0%
ET-20	33.2%	44.0%	51.0%	60.0%	69.0%	78.0%	68.8%	72.2%	63.7%
ET-30	33.2%	44.0%	51.0%	60.0%	69.0%	78.0%	69.0%	72.3%	63.5%

4.4.2.2. Annual Energy Consumption

This sub section presents the annual energy consumption of the U.S., China, and India's iron and steel sectors in the three ET scenarios for the period 2010-2050.

The U.S. Iron and Steel Sector

Figure 82 and Table 77 show that annual energy consumption in the U.S. iron and steel sector decreases in accordance with the production decline. There is less production, thus, less energy need in each ET scenario. Among the ET scenarios, since the ET-30 scenario leads to the lowest steel production (but the highest steel import) in the U.S iron and steel sector, energy consumption are the lowest in this scenario.

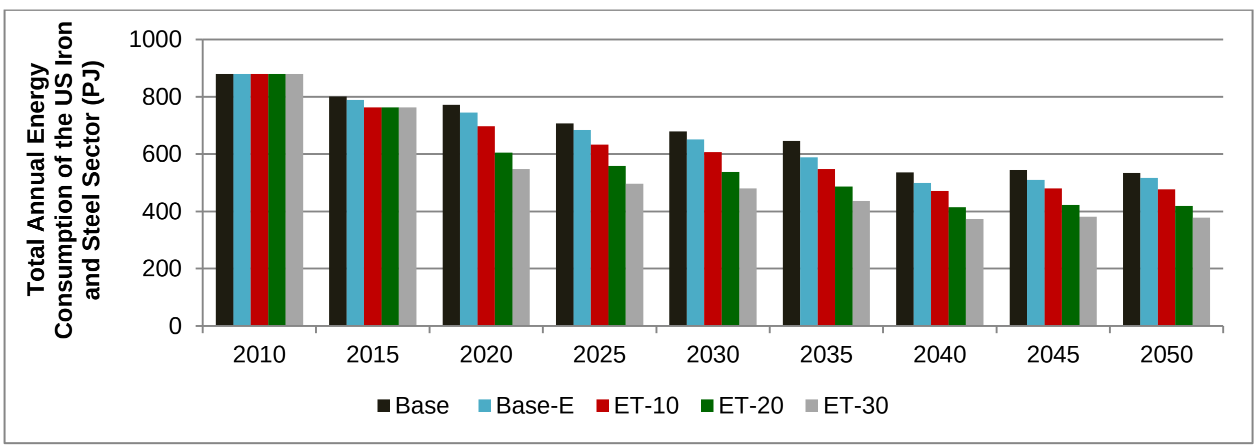

Figure 82. Total Annual Energy Consumption of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ET scenarios (PJ)

Table 77. Total Annual Energy Consumption of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ET scenarios (PJ)

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	878.9	801.1	772.2	707.2	679.4	644.9	535.3	544.0	534.0

Base-E	878.9	788.3	744.4	683.4	651.4	588.0	499.2	510.4	516.3
ET-10	878.9	762.9	696.8	632.7	606.2	546.6	470.7	479.9	476.8
ET-20	878.9	762.9	605.5	558.3	537.4	486.3	413.8	422.9	420.1
ET-30	878.9	762.9	546.5	496.6	479.9	435.9	374.2	381.9	378.5

Figure 83 and Table 78 display the energy intensities of the U.S. iron and steel sector in the ET scenarios. The three energy intensity lines of the ET scenarios almost overlap with each other and the energy intensity of the Base-E scenarios. There is no improvement on sector energy efficiencies under ET scenarios, compared to the Base-E scenario. It is clear that when compared to the Base scenario, efficiency improvements in ET scenarios come from cost-effective production technologies (used in the Base-E scenario as well) not additional efficiency investments to decrease emissions as scenario requirements. Therefore, it is clear that the U.S. iron and steel sector decreases its emissions to the scenario levels by importing the steel from outside instead of investing in efficient production technologies and producing in the U.S. under the ET scenarios.

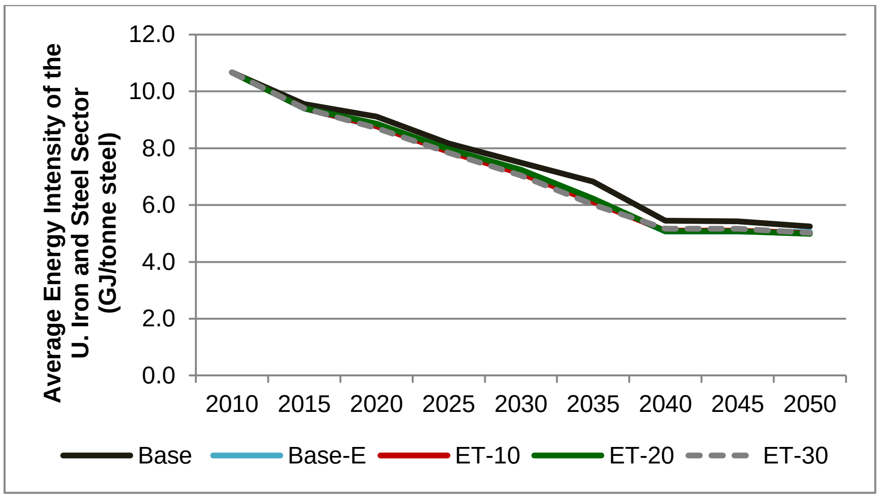

Figure 83. Average Energy Intensities of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ET Scenarios (GJ/tonne steel)

Table 78. Average Energy Intensities of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ET Scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	10.67	9.55	9.11	8.16	7.49	6.82	5.45	5.43	5.24
Base-E	10.67	9.39	8.76	7.87	7.16	6.19	5.06	5.07	5.06
ET-10	10.67	9.41	8.77	7.88	7.10	6.11	5.10	5.10	5.00
ET-20	10.67	9.41	8.87	7.96	7.24	6.23	5.08	5.08	4.98
ET-30	10.67	9.41	8.70	7.84	7.04	6.01	5.16	5.17	5.02

China's iron and steel Sector

To produce the extra volume of steel to export to the U.S., more energy is consumed in the China's iron and steel sector (see Figure 84 and Table 79). However, there is almost no improvement on China energy intensities due to increasing production volumes. The energy intensity lines overlap each other in each scenario, including the Base-E scenario in some periods as well (see Figure 85 and Table 80).

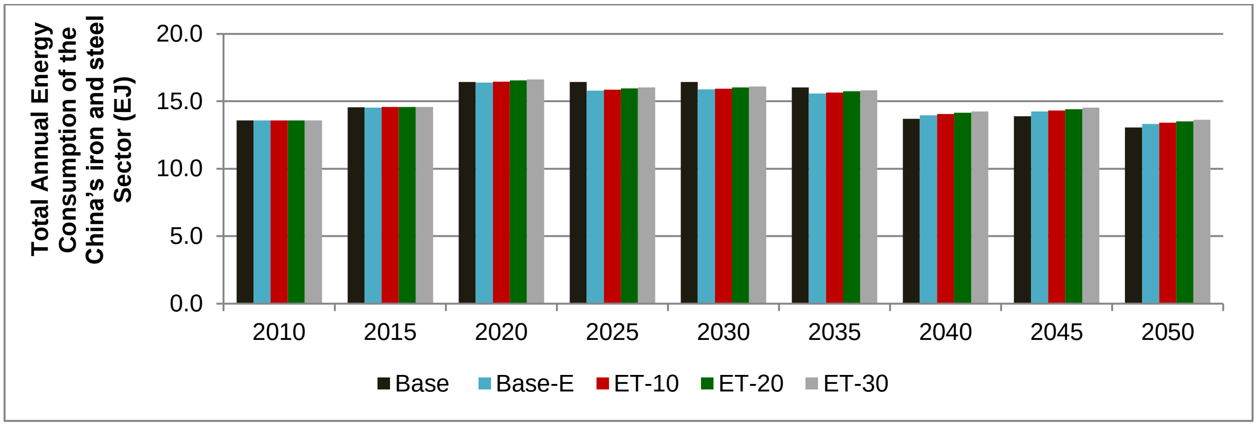

Figure 84. Total Annual Energy Consumption of the China's iron and steel sector Projected in the Base, Base-E, and ET scenarios (EJ)

Table 79. Total Annual Energy Consumption of the China's iron and steel sector Projected in the Base, Base-E, and ET scenarios (EJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	13.58	14.56	16.42	16.43	16.42	16.03	13.69	13.89	13.05
Base-E	13.58	14.54	16.38	15.80	15.87	15.58	13.97	14.24	13.33
ET-10	13.58	14.58	16.46	15.87	15.94	15.65	14.05	14.32	13.41
ET-20	13.58	14.58	16.54	15.95	16.02	15.73	14.15	14.42	13.52
ET-30	13.58	14.58	16.63	16.03	16.11	15.81	14.25	14.52	13.62

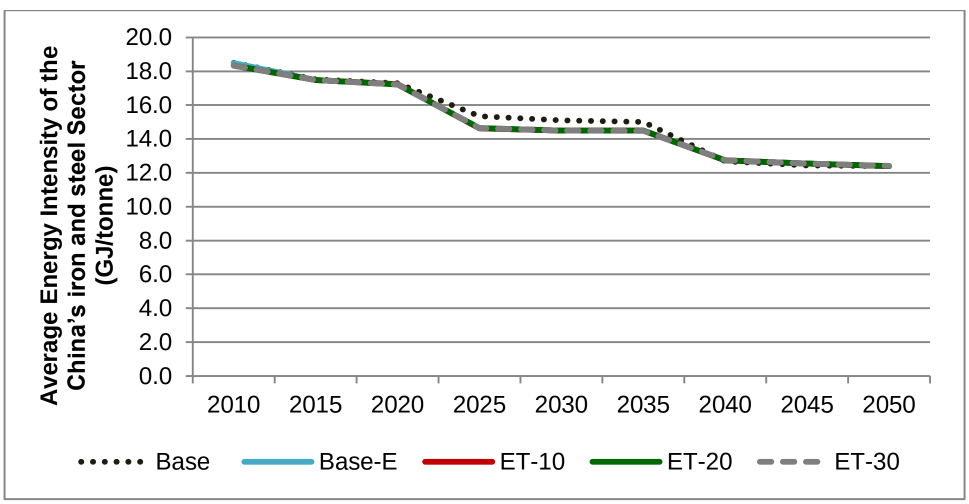

Figure 85. Average Energy Intensities of the China's iron and steel sector Projected in the Base, Base-E, and ET Scenarios (GJ/tonne steel)

Table 80. Average Energy Intensities of the China's iron and steel sector Projected in the Base, Base-E, and ET Scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	18.49	17.51	17.29	15.34	15.10	15.00	12.68	12.44	12.40
Base-E	18.49	17.49	17.24	14.64	14.50	14.49	12.74	12.55	12.40
ET-10	18.33	17.49	17.23	14.64	14.50	14.49	12.74	12.55	12.40
ET-20	18.33	17.49	17.22	14.64	14.50	14.49	12.75	12.55	12.40
ET-30	18.33	17.49	17.21	14.64	14.50	14.49	12.75	12.55	12.41

India's iron and steel Sector

As discussed in the Section 4.2, energy consumption of the India's iron and steel sector drastically decreases with the availability of the efficient production technologies in the Base-E scenario. The optimization process invests on cost-effective efficient production technologies and satisfies the same demand with less energy consumption. Since the same technologies are available in the ET scenarios, comparing the energy consumption results with the Base-E scenario is more meaningful. As can be seen from Figure 86 and Table 81, comparing to the Base-E scenario, energy consumption increases due to increasing production. However, compared to the Base-E scenario, improvement on sector efficiencies in the additional production is low (see Figure 87 and Table 82).

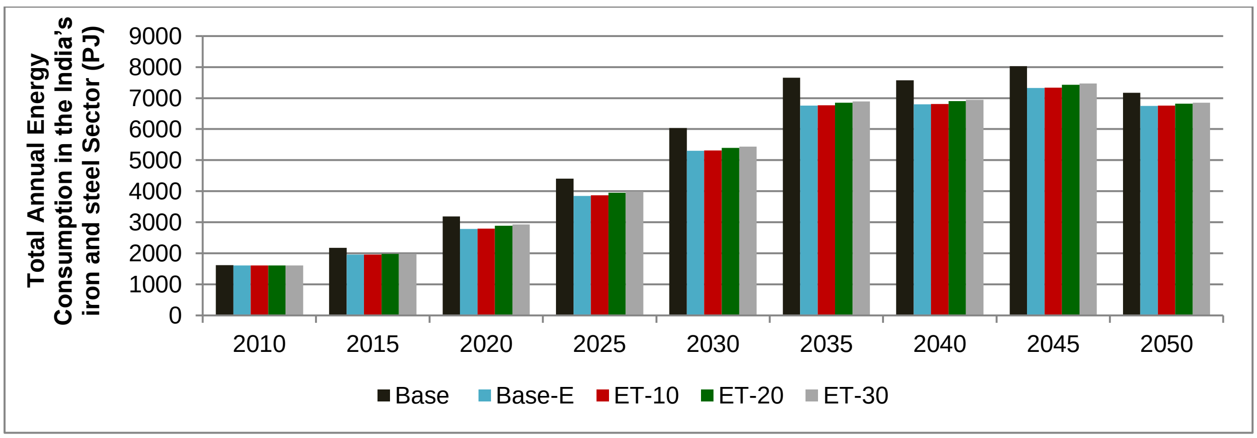

Figure 86. Total Annual Energy Consumption of the India's iron and steel sector Projected in the Base, Base-E, and ET Scenarios (PJ)

Table 81. Total Annual Energy Consumption of the India's iron and steel sector Projected in the Base, Base-E, and ET Scenarios (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	1620.8	2178.5	3191.1	4402.9	6036.6	7659.3	7574.5	8031.2	7171.0
Base-E	1607.3	1961.5	2787.6	3852.0	5305.7	6757.7	6799.9	7322.4	6744.1
ET-10	1607.6	1964.6	2800.0	3867.1	5317.3	6770.3	6813.3	7336.9	6756.2
ET-20	1608.8	1969.2	2837.8	3901.0	5350.1	6804.2	6848.3	7372.4	6781.7
ET-30	1609.0	1970.7	2871.2	3934.5	5382.5	6838.1	6883.3	7407.5	6806.3

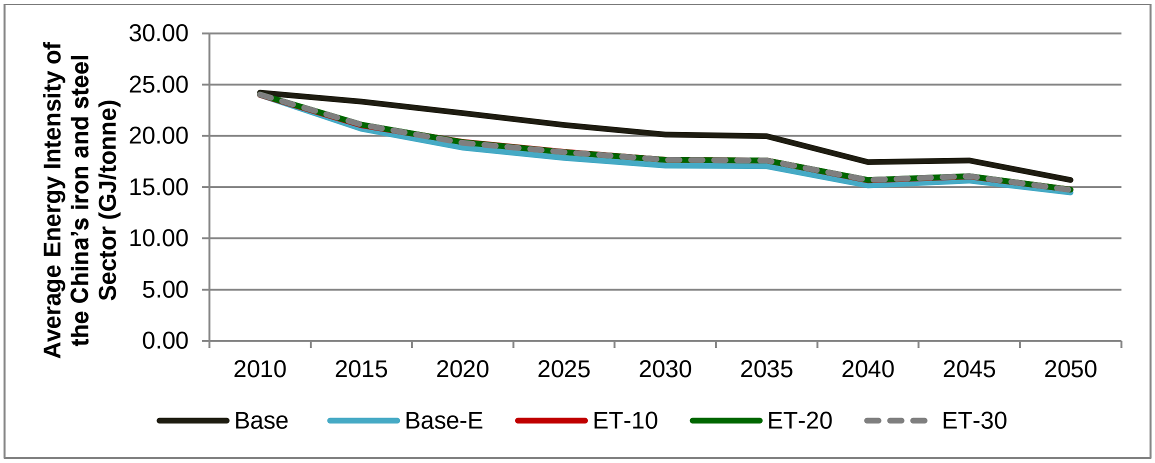

Figure 87. Average Energy Intensities of the India's iron and steel sector Projected in the Base, Base-E, and ET Scenarios (GJ/tonne steel)

Table 82. Average Energy Intensities of the India's iron and steel sector Projected in the Base, Base-E, and ET Scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	24.20	23.34	22.21	21.08	20.11	19.95	17.44	17.59	15.70
Base-E	24.00	20.69	18.85	17.84	17.11	17.02	15.16	15.62	14.47
ET-10	24.02	21.03	19.39	18.45	17.67	17.60	15.67	16.05	14.77
ET-20	24.04	21.09	19.36	18.42	17.65	17.59	15.68	16.06	14.75
ET-30	24.04	21.10	19.33	18.41	17.64	17.59	15.69	16.06	14.73

4.4.2.3. Annual CO_2 Emissions

This subsection presents annual CO2 emissions of the U.S., China, and India's iron and steel sectors in the three ET scenarios for the period 2010-2050.

Total annual CO2 emissions of the U.S. iron and steel sector decreases through the planning horizon in the ET scenarios in accordance with the scenario requirements (see Figure 88). However, average emission intensity is close to each other in all three ET scenarios (see Figure 89). This indicates that the total annual CO2 emissions of the U.S. iron and steel sector decrease in the ET scenarios is mainly due to replacement of domestic production with import from China and India instead of by investments in efficient technologies.

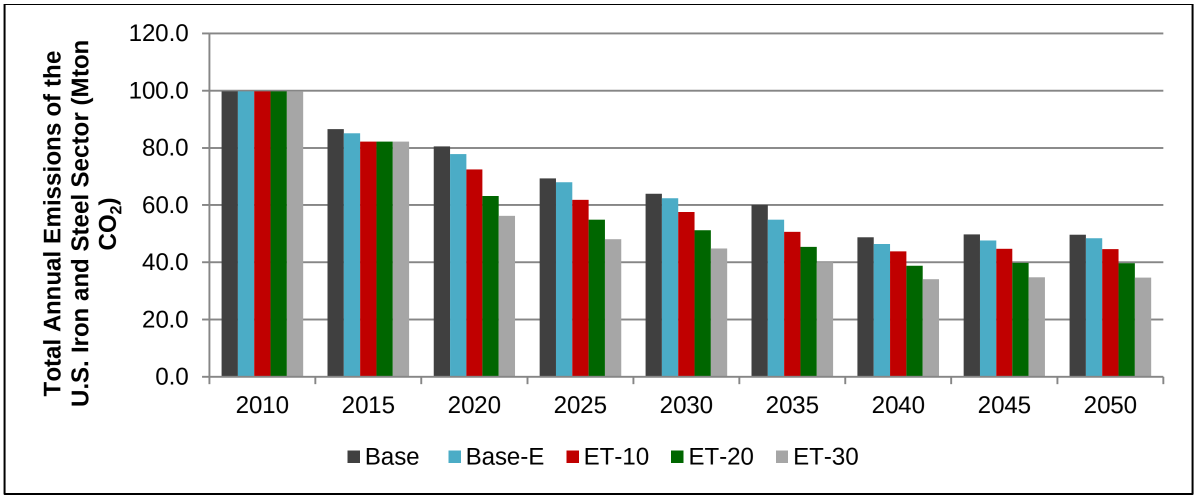

Figure 88. Total Annual CO_2 Emissions of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ET Scenarios (Mton CO_2)

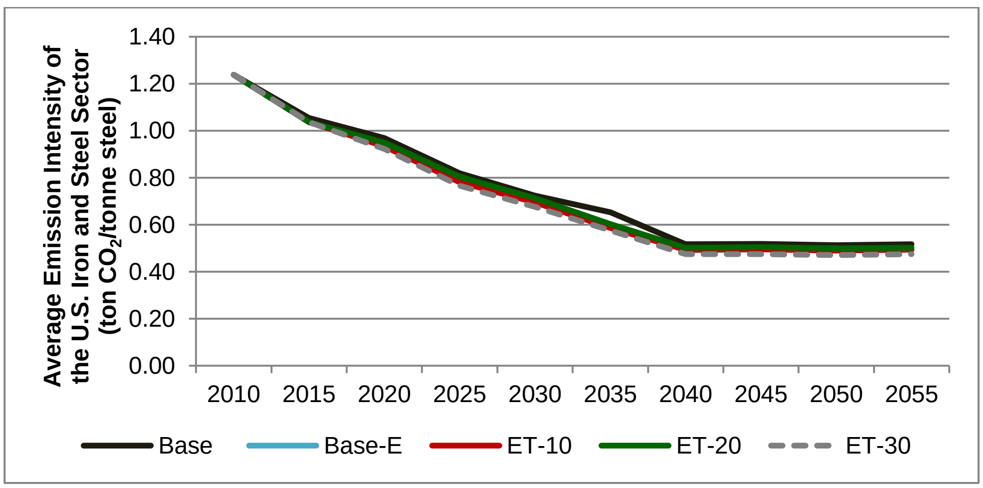

Figure 89. Average Emission Intensity of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ET Scenarios (ton CO_2/tonne steel)

On the other hand, total annual CO2 emissions of the China and India's iron and steel sectors follows their energy consumption patterns; CO2 emissions increase are largely due to the increasing production, while little difference in carbon intensity across ET scenarios is found in each year (see Figure 90, Figure 91, Figure 92, and Figure 93).

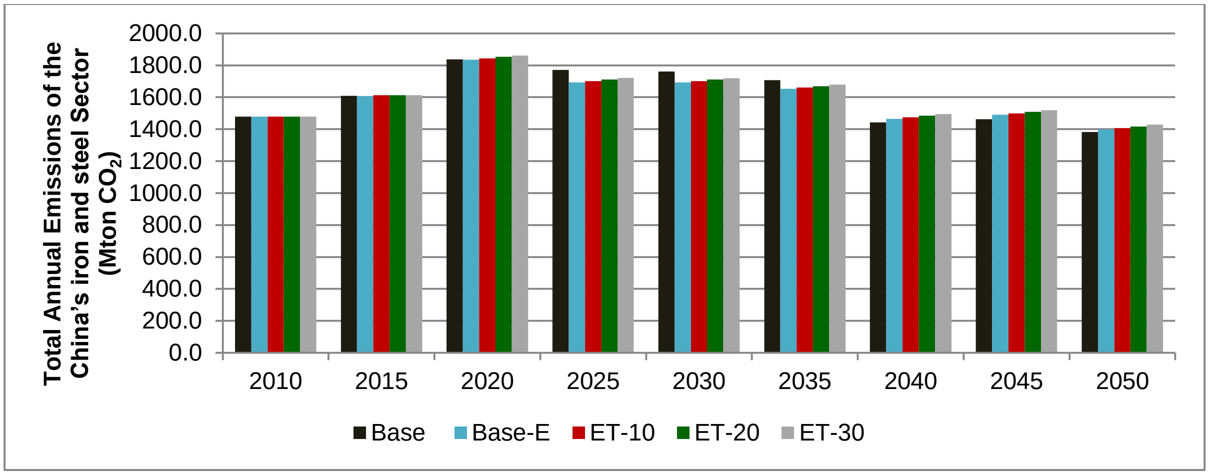

Figure 90. Total Annual CO_2 Emissions of the China's iron and steel sector Projected in the Base, Base-E, and ET Scenarios (Mton CO_2)

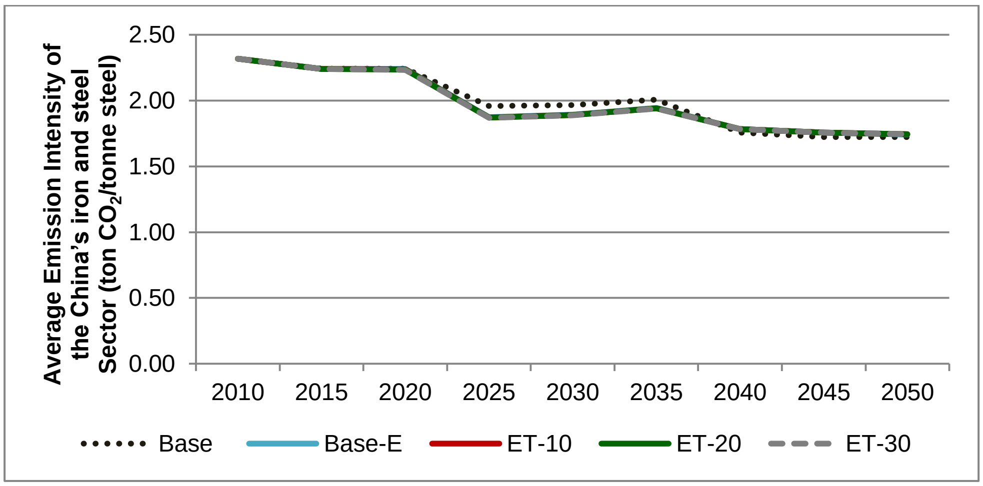

Figure 91. Average Emission Intensity of the China's iron and steel sector Projected in the Base, Base-E, and ET Scenarios (ton CO_2/tonne steel)

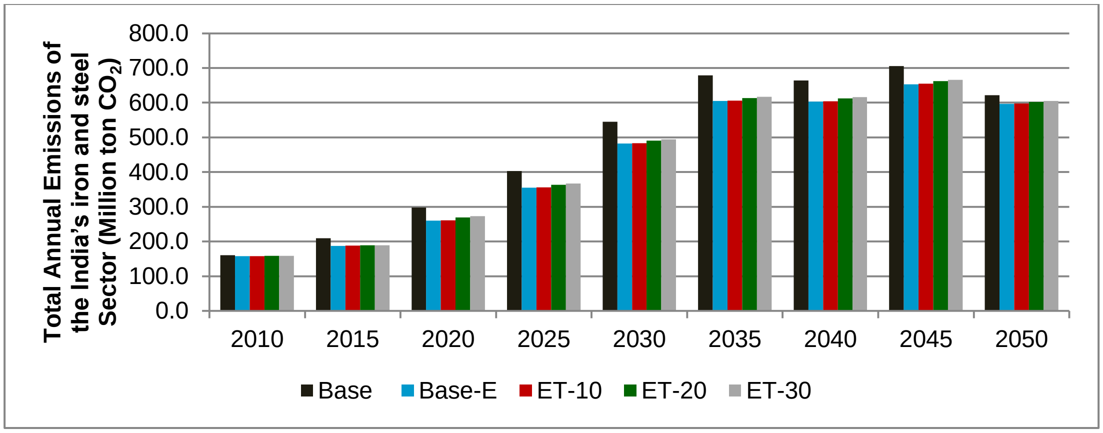

Figure 92. Total Annual CO_2 Emissions of the India's iron and steel sector Projected in the Base, Base-E, and ET Scenarios (Mton CO_2)

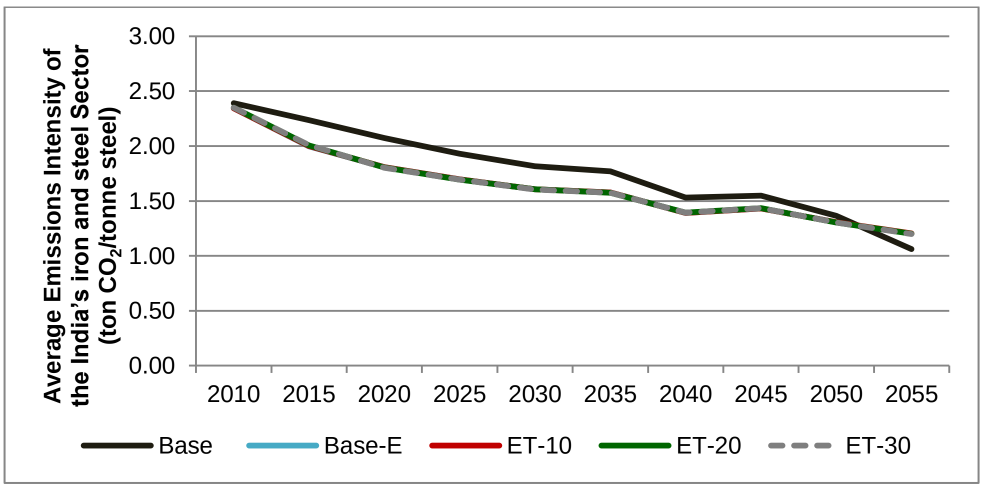

Figure 93. Average Emission Intensity of the India's iron and steel sector Projected in the Base, Base-E, and ET Scenarios (ton CO_2/tonne steel)

4.4.2.4. Annual Production Costs

This subsection presents annual steel production costs of the U.S., China, and India's iron and steel sectors in the three ET scenarios for the period 2010-2050.

Table 83 shows that total annual production cost of the U.S. iron and steel sector drops through the planning horizon in each ET scenario, in accordance with the decreasing production volumes. Since the production is lower, spending on each of the cost item (i.e., costs that spent on energy, raw materials, labor, other operational necessities, and investment) decreases. However, declines in investment cost are different than the other cost items, since investment is not an annual decision payment. The investments (so the associated annualized payments) of the initial periods (such as 2010 and 2015) are still there in the later periods (because of the 30 year lifetime of the current production technologies). However, due to the decreasing production needs, some of those production capacities invested at the initial periods are not fully used in the later periods. Therefore, even though the total annual production cost of the U.S. iron and steel sector decreases, production cost of per tonne steel from each production process increase each period until 2040 (in which the initial capacity investments reach end of their lifetimes) (Table 84 and Table 85).

Table 83. Total Annual Costs of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ET Scenarios (Billion 2005 $)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	40.9	50.2	55.0	59.5	61.3	60.2	57.8	58.8	58.6
Base-E	40.9	50.1	54.9	59.4	61.1	59.7	57.1	58.0	57.8
ET-10	40.9	48.8	52.0	56.3	58.1	56.7	54.0	54.9	54.7
ET-20	40.9	48.9	46.7	50.4	52.2	50.7	48.0	49.0	49.0
ET-30	40.9	48.9	44.1	47.6	49.4	47.8	45.2	46.1	46.1

Table 84. Annual Production Costs of BOF Production in the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ET Scenarios (2005 $/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	667.2	762.5	861.6	960.0	1036.6	927.8	705.8	719.6	712.0
Base-E	659.3	750.9	844.8	937.9	1005.6	932.6	673.7	681.7	674.0
ET-10	659.3	759.9	865.5	961.3	1036.6	959.5	678.0	684.4	679.3
ET-20	659.3	759.9	915.8	1017.7	1100.1	1008.7	676.9	682.4	680.0
ET-30	659.3	759.9	948.6	1056.8	1148.6	1049.6	684.4	689.0	682.7

Table 85. Annual Production Costs of EAF Production in the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ET Scenarios (2005 $/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	472.5	547.7	597.9	640.3	633.1	619.3	601.1	599.4	592.3
Base-E	477.6	552.0	601.9	643.7	636.0	618.7	596.8	595.0	587.4
ET-10	477.6	553.8	605.3	646.8	638.7	619.9	597.1	595.2	587.7
ET-20	477.6	553.8	618.0	654.5	645.4	622.0	597.0	595.0	587.7
ET-30	477.6	553.8	626.3	660.4	649.9	624.0	597.4	595.4	587.8

On the other hand, total annual production costs of the China’s and India’s iron and steel sectors increase in accordance with the increasing production volumes (see Table 86 and Table 87). In India case, total annual production costs increase compared to the Base-E scenario. The cost-effective efficient production technologies leads to major reduction in total annual production cost of the India’s iron and steel sector in the Base-E scenario.

Table 86 Total Annual Costs of the China’s iron and steel sector Projected in the Base, Base-E, and ET Scenarios (Billion 2005 $)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	132.0	288.5	364.1	447.5	527.7	515.4	467.0	431.8	456.0
Base-E	132.0	288.5	363.9	446.8	526.9	513.8	464.6	427.7	451.8
ET-10	132.0	288.5	365.1	449.3	529.6	516.5	467.3	430.2	454.3
ET-20	132.0	288.5	365.1	452.3	532.9	519.8	470.4	433.1	457.4
ET-30	132.0	288.5	365.1	455.3	536.1	523.0	473.5	436.1	460.5

Table 87 Total Annual Costs of the India's iron and steel sector Projected in the Base, Base-E, and ET Scenarios (Billion 2005 $)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	32.9	59.8	98.6	149.9	211.9	264.3	293.5	313.1	313.4
Base-E	33.2	58.6	94.4	141.5	198.1	243.7	269.6	285.0	281.8
ET-10	33.3	58.6	94.8	141.9	198.5	244.1	269.9	285.4	282.3
ET-20	33.7	58.8	97.7	144.9	201.5	247.1	272.7	288.3	285.4
ET-30	33.9	58.8	99.2	146.4	203.0	248.5	274.0	289.7	286.9

4.4.3. ET Scenario Summary

Under the Emission Reduction with Commodity Trading scenarios, which predefine emission reduction targets (i.e., 10%, 20%, and 30% below of those in the Base scenario for the U.S. only), the ISEEM-IS model projects that part of annual steel production of the U.S. iron and steel sector will be replaced with imports from China and India, and the level of replacement increases when the emission reduction targets for the U.S. are higher. The model projects that it is favorable for the U.S. to import from China and India compared to investment in efficient production technologies in national steel production. Between China and India, production cost in China is lower, therefore ISEEM-IS model projects preference to importing more from China to the U.S. until the pre-defined import upper bound is reached (i.e., 75% of the dynamic import from China). With the annual production increase ranging from 0.4% to 2.0% through the planning horizon, China satisfies 6.6%, 14.0%, and 22.1% of the U.S. steel demand as period averages in the ET-10, ET-20, and ET-30 scenarios, respectively. With the annual production increase ranging from 0.1% to 5.2%, India satisfies 1.5%, 4.7%, and 6.2% of the U.S. steel demand as period averages in the ET-10, ET-20, and ET-30 scenarios, respectively. Table 88 indicates that the reduction in U.S. annual steel production becomes bigger with the increase in carbon reduction targets.

Table 88. Relative Reduction in Total Annual Steel Production of the U.S. Iron and Steel Sector Projected in the ET Scenarios, Compared to the Base Scenario (%)

	2015	2020	2025	2030	2035	2040	2045	2050
ET-10	3.4%	6.6%	6.5%	6.2%	6.1%	6.0%	5.9%	6.0%
ET-20	3.4%	19.9%	19.4%	18.7%	18.2%	18.0%	17.8%	17.9%
ET-30	3.4%	26.5%	25.8%	25.0%	24.3%	23.9%	23.8%	23.9%

- ***There is little difference in energy or emission intensities of the U.S., China, and India's iron and steel sectors under each ET scenario when compared to the Base-E scenarios.*** Our modeling results show that while annual energy consumption and emissions of the U.S. iron and steel sector decline through the planning horizon in the ET scenarios compared to the Base and Base-E scenarios, the energy and emission intensity levels are very close to those in Base-E scenario. This indicates that compared to the Base scenario, efficiency improvements in the ET scenarios are expected to come from efficient production technologies that bring cost reduction to the least cost objective as in the Base-E scenario. Compared to the Base-E scenario levels, no additional efficiency investments are projected by ISEEM–IS model in the ET scenarios to meet emission targets in the U.S. Therefore, it is clear that the U.S. iron and steel sector decreases its emission simply by importing the steel from China and India instead of investing in efficient production technologies and producing in the U.S. under each of the ET scenarios.

- **The ET scenarios indicate that decreasing emissions in the U.S. iron and steel sector alone by increasing steel imports result in net increase in total emissions from the three countries.** The increased emissions from the China and India's iron and steel sectors with no investment in efficiencies show that commodity trading strategy of the U.S. result in simply transferring actual production burdens to China and India where actual intensities of energy use and emissions are higher. To produce the extra volumes of steel to export to the U.S., much more energy consumption and increased carbon emissions from China and India's iron and steel sectors are projected. This result in net increase of total energy consumption and carbon emissions from the three countries collectively because the U.S. plants exhibit much lower levels of energy intensity compared to that of China and India. Figure 94 exhibits the total annual emissions from the U.S., China, and India's iron and steel sectors. With emission reduction from the U.S. iron and steel sector, total emissions from the three countries increase in each ET scenario when compared to Base-E scenario.

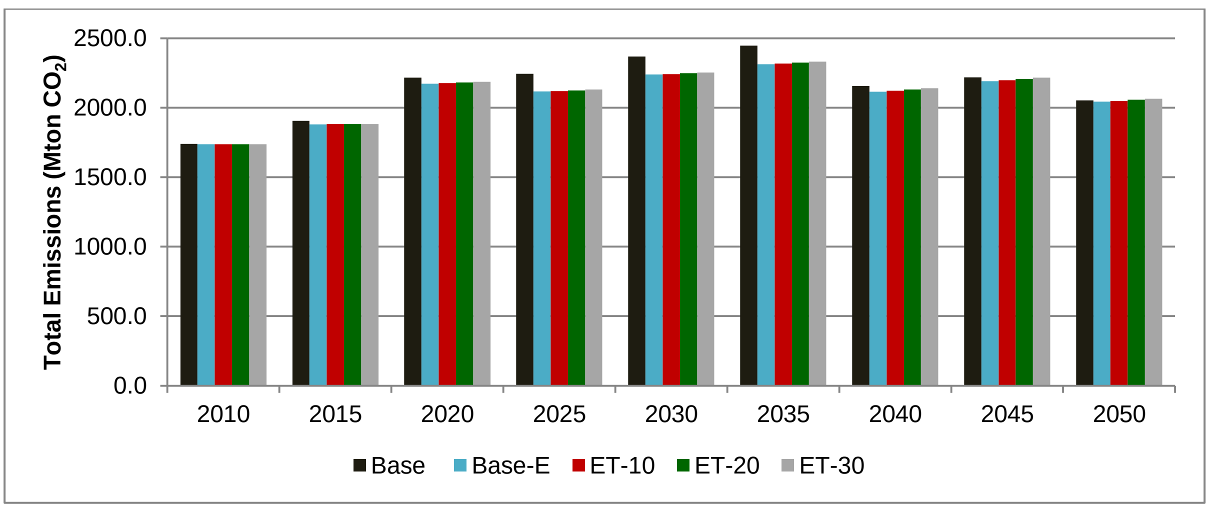

Figure 94. Total Annual CO_2 Emissions from the U.S., China, and India's iron and steel Sectors Projected in the Base, Base-E, and ET Scenarios (Mton CO_2)

- ***Total annual production costs of the U.S. iron and steel sector drop through the planning horizon in each ET scenario, corresponding to the decreasing production volumes due to imports.*** Unit cost (cost per tonne of steel) of each production process increases when compared to the Base and Base-E scenarios, however. For example, while total annual production cost of the U.S. iron and steel sector in 2030 decreases by 4.9%, 14.6%, and 19.1% in the ET-10, ET-20, and ET-30 scenarios, respectively; unit cost of BOF products increases by 3.1%, 9.4%, and 14.2% and unit cost of EAF products increases by 0.4%, 1.5%, and 2.1% in the ET-10, ET-20, and ET-30 scenarios, respectively. The capacity invested or established in initial periods (e.g., year 2010 and 2015) may not be fully utilized or in operation in the later periods (e.g., year 2030), increasing the unit cost of U.S. production in later years.

4.5. Emission Reduction with Carbon Trading Scenarios (EC)

This section presents the results of the ISEEM-IS model with the third set of CO_2 emission reduction scenarios analyzed in this project: emission reduction with carbon trading (EC) scenarios. EC scenario set assumes that a specific global emission reduction level will be accomplished with the availability of carbon trading of the U.S. from China and India. The ET scenario results, discussed in Section 4.4, show that decreasing emissions in the U.S. iron and steel sector alone by commodity trading strategy (i.e., increasing steel imports) does not result in reducing net global emissions, but simply transferring actual production burdens to China and India where actual intensities of energy use and emissions are higher. Therefore, in this section we aim to examine the impacts on net total emissions through another alternative in this scenario set, i.e., carbon trading of the U.S. via carbon offsets from China and India.

Advanced and efficient production technologies are available in this scenario set as well. EC scenario set provides a base to evaluate the investments in advanced and efficient production technologies in the U.S., China, and India's iron and steel sectors, when the carbon trading of the U.S. from China and India is available. The aim of EC scenarios is to examine the impacts of incorporating carbon trading under three pre-defined carbon-reduction targets, and implications for potential trades and investment strategies.

Specific technical objectives are to:

1. examine the country-specific production and structure changes over time,
2. quantify the magnitudes and intensity of country-specific annual energy consumption and emission,
3. estimate country-specific annual production cost and annual carbon abatement cost, and
4. understand the sensitivity of production, energy and emission intensity and cost to different levels of carbon caps via three EC scenarios in which emission reductions in the U.S. iron and steel sector are realized when carbon trading is among the U.S., China, and India. A summary table of key factors in EC scenarios is available in the Appendix D to this document.

4.5.1. EC Scenario Definitions

In EC scenarios, annual CO_2 emission levels are to be restricted as in the ER scenarios, compared to the Base scenario, in the U.S., China, and India's iron and steel sectors. Specifically, the annual CO_2 emission restrictions of the U.S., China, and India's iron and steel sectors are set at 5% annual reduction from that of the Base scenario in 2015 for each country, respectively, and are set at three different levels (i.e., 10%, 20%, and 30%) starting in year 2020 throughout 2050 for each country, respectively.

The primary purpose is to analyze the emission reduction potentials of the U.S., China, and India's iron and steel sectors as in ER scenarios. Furthermore, carbon trading of the U.S. from China and India is allowed in EC scenarios, different from ER in that investments in efficiency measures are not restricted by the country boundary. In EC scenarios, it is possible for the U.S. to invest in efficiency improvements in China and India where actual intensities of energy use and emissions are higher, and to import from both China and India. For this purpose, restrictions on the U.S. steel import pre-defined in the Base scenario are lifted for EC scenarios as in ET scenarios (i.e., existing levels of commodity trading remain unchanged in the Base scenario and may change in EC scenarios), while restrictions on China and India steel imports remain unchanged from the Base scenarios.

The U.S. import from countries other than China and India is currently 90% of the total import. In the Base scenario, this share is kept constant from 2010 to 2050.

In order to analyze the carbon trading relationships of the U.S with the China and India for the EC scenarios, emissions associated with imported production in other countries are also bounded by the same restrictions defined for EC scenarios. In the Base and Base-E scenarios from 2010 to 2050, China has the lowest unit production cost compared to the U.S. and India. Therefore, optimization processes favors all dynamic imports of the U.S. from China and none from India. We define the upper bound for the shares of dynamic import from China to be 75%, similar to ET scenarios.

The three emission reduction targets applied in EC scenarios are pre-defined as follows.

i. EC-10 Scenario: Annual CO_2 emissions are restricted 10% below of the annual CO_2 emissions of the Base scenario for each country (i.e., the U.S., China, and India, respectively) starting in 2020.
ii. EC-20 Scenario: Annual CO_2 emissions are restricted 20% below of the annual CO_2 emissions of the Base scenario for each country (i.e., the U.S., China, and India, respectively) starting in 2020.
iii. EC-30 Scenario: Annual CO_2 emissions are restricted 30% below of the annual CO_2 emissions of the Base scenario for each country (i.e., the U.S., China, and India, respectively) starting in 2020.

4.5.2. EC Scenario Results

This section presents model projections of annual production, production costs, energy consumption, and CO_2 emissions the U.S., China, and India's iron and steel sectors under the three EC scenarios in comparison with the Base and Base-E scenarios.

4.5.2.1. Annual Production and Imports

Annual steel production of the U.S., China, and India's iron and steel sectors in the three EC scenarios for the period 2010-2050 is presented in this sub section.

The U.S. Iron and Steel Sector

Total annual steel production of the U.S. iron and steel sector decreases through the planning horizon with the availability of carbon trading with China and India (see Figure 95 and Table 89).

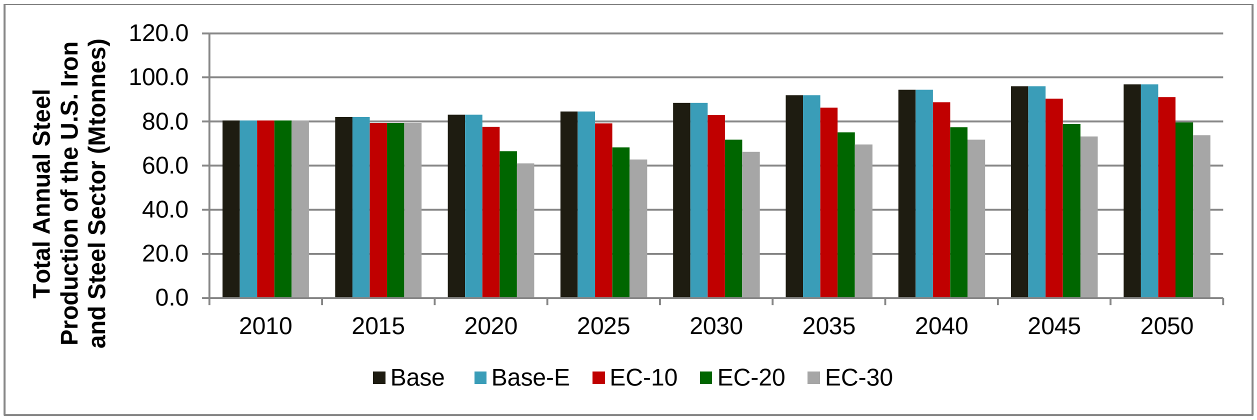

Figure 95. Total Annual Steel Production of the U.S. Projected in the Base, Base-E, and EC Scenarios (Mtonnes)

Table 89. Total Annual Steel Production of the U.S. Projected in the Base, Base-E, and EC Scenarios (Mtonnes)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	80.5	82.1	83.0	84.6	88.4	91.9	94.4	96.0	96.9
Base-E	80.5	82.1	83.0	84.6	88.4	91.9	94.4	96.0	96.9
EC-10	80.5	79.3	77.5	79.1	82.9	86.3	88.7	90.3	91.1
EC-20	80.5	79.3	66.5	68.2	71.8	75.2	77.4	78.9	79.5
EC-30	80.5	79.3	61.0	62.8	66.3	69.6	71.8	73.2	73.8

It is interesting to note that annual production levels achieved in each of the EC scenarios are identical to that of the ET scenario with the same emission reduction target. In another word, both the ET-'X' ('X' is for 10, 20, and 30) and the EC-'X' ('X' is for 10, 20, and 30) scenarios lead to the same production reduction in each period (see **Error! Not a valid bookmark self-reference.**). No difference in the U.S. iron and steel sector production is projected between commodity trading and carbon trading with the same emission reduction goal. Even with anticipated price increases of China and India steels in the EC scenarios due to allowable investments in efficient production technologies when compared to the ET scenarios, the model still favors imports from China or India to the U.S.

Table 90. Declines in Total Annual Steel Production of the U.S. Iron and Steel Sector Projected in the EC and ET Scenarios, Compared to the Base Scenario (%)

	2015	2020	2025	2030	2035	2040	2045	2050
EC-10	3.4%	6.6%	6.5%	6.2%	6.1%	6.0%	5.9%	6.0%
ET-10	3.4%	6.6%	6.5%	6.2%	6.1%	6.0%	5.9%	6.0%
EC-20	3.4%	19.9%	19.4%	18.7%	18.2%	18.0%	17.8%	17.9%
ET-20	3.4%	19.9%	19.4%	18.7%	18.2%	18.0%	17.8%	17.9%
EC-30	3.4%	26.5%	25.8%	25.0%	24.3%	23.9%	23.8%	23.9%
ET-30	3.4%	26.5%	25.8%	25.0%	24.3%	23.9%	23.8%	23.9%

Figure 96 shows the total annual import to U.S. in Base, Base-E, and all EC scenarios. Imported steel replaces with the domestic steel production, similar to ET scenarios. In addition, Table 91 shows breakdowns of the U.S. imports realized in all EC scenarios, which are identical to those in ET scenarios. In other words, there is no difference in import volumes of the U.S. from China, India, and rest of the world between the ET and EC scenarios. Those results indicate that even though the carbon abatement costs are lower (or even negative in some cases) in India, the net cost of steel for the U.S. to import is cheaper from China. Once the U.S. imports from China reach the pre-defined upper bound (i.e., 75% of total dynamic import), imports from India become possible in the model.

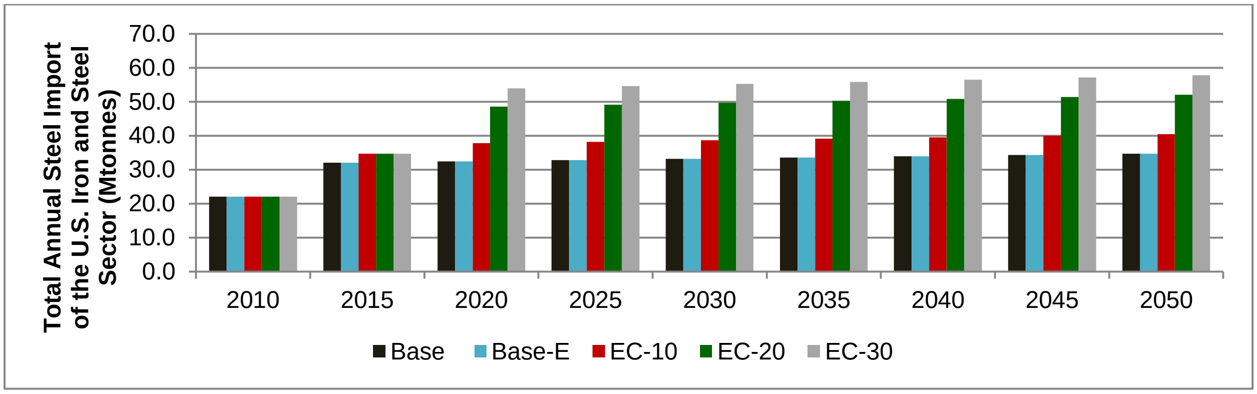

Figure 96. Total Annual Steel Imports of the U.S. Projected in the Base, Base-E, and EC Scenarios (Mtonnes)

Table 91. Annual Steel Imports of the U.S. Projected in the Base, Base-E, and EC Scenarios (Mtonnes)

Base									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total Import	22	32	32.4	32.8	33.1	33.5	33.9	34.3	34.7
From China	0.8	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4
From India	0.8	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4
*From Others**	20.4	29.5	29.8	30.1	30.5	30.8	31.2	31.5	31.9
Base-E									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total Import	22	32	32.4	32.8	33.1	33.5	33.9	34.3	34.7
From China	0.8	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4
From India	0.8	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4
*From Others**	20.4	29.5	29.8	30.1	30.5	30.8	31.2	31.5	31.9
EC-10									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total Import	22.0	34.7	37.8	38.2	38.6	39.1	39.5	40.0	40.4
From China	0.8	3.8	5.7	5.7	5.8	5.9	5.9	6.0	6.1
From India	0.8	1.4	1.9	1.9	1.9	2.0	2.0	2.0	2.0
*From Others**	20.4	29.5	30.2	30.6	30.9	31.3	31.6	32.0	32.4
EC-20									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total Import	22.0	34.7	48.6	49.1	49.7	50.3	50.8	51.4	52.0
From China	0.8	3.8	10.9	11.1	11.2	11.3	11.4	11.6	11.7

From India	0.8	1.4	3.6	3.7	3.7	3.8	3.8	3.9	3.9
*From Others**	20.4	29.5	34.0	34.4	34.8	35.2	35.6	36.0	36.4
EC-30									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Total Import	22.0	34.7	54.0	54.6	55.2	55.8	56.5	57.1	57.8
From China	0.8	3.8	16.2	16.4	16.6	16.8	16.9	17.1	17.3
From India	0.8	1.4	5.4	5.5	5.5	5.6	5.6	5.7	5.8
*From Others**	20.4	29.5	32.4	32.8	33.1	33.5	33.9	34.3	34.7

Table 92 and Table 93 show process based production volumes and shares of the U.S. iron and steel sector in the EC scenarios, which turn out to be identical to those observed in ET scenarios (Table 67 and Table 68 in Section 4.4). This result again indicate that there is no difference in the U.S. iron and steel sector production with the availability of commodity and carbon trading from China and India under the same emission restrictions.

Table 92. Process Based Annual Steel Production of the U.S. Projected in the Base, Base-E, and EC Scenarios (Mtonnes)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	31.2	24.6	20.8	16.9	13.3	10.8	9.4	9.6	9.7
Base-E	31.2	24.6	20.8	16.9	13.3	9.2	9.4	9.6	9.7
EC-10	31.2	23.8	19.4	15.8	12.4	8.6	8.9	9.0	9.1
EC-20	31.2	23.8	16.6	13.7	10.8	7.5	7.7	7.9	8.0
EC-30	31.2	23.8	15.3	12.6	10.0	7.0	7.2	7.3	7.4
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	48.6	56.0	59.5	64.9	72.4	79.0	83.6	85.1	87.2
Base-E	48.6	56.4	60.8	66.2	73.7	82.0	84.9	86.4	87.2
EC-10	48.6	54.4	56.7	61.9	69.0	76.9	79.9	81.3	82.0
EC-20	48.6	54.4	48.4	53.1	59.6	66.9	69.7	71.0	71.6
EC-30	48.6	54.4	44.7	49.6	55.4	62.3	64.6	65.9	66.4
EAF-DRI (Gas based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	0.7	1.5	2.8	2.8	2.7	2.1	1.3	1.3	0.0
Base-E	0.7	1.1	1.5	1.4	1.4	0.8	0.0	0.0	0.0
EC-10	0.7	1.1	1.5	1.4	1.4	0.8	0.0	0.0	0.0
EC-20	0.7	1.1	1.5	1.4	1.4	0.8	0.0	0.0	0.0
EC-30	0.7	1.1	1.1	0.6	1.0	0.4	0.0	0.0	0.0

Table 93 Process Based Annual Steel Production of the U.S. Projected in the Base, Base-E, and EC Scenarios (%)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	38.7%	30.0%	25.0%	20.0%	15.0%	11.8%	10.0%	10.0%	10.0%
Base-E	38.7%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%

EC-10	38.7%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
EC-20	38.7%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
EC-30	38.7%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	60.4%	68.2%	71.6%	76.7%	81.9%	86.0%	88.6%	88.6%	90.0%
Base-E	60.4%	68.7%	73.2%	78.3%	83.4%	89.2%	90.0%	90.0%	90.0%
EC-10	60.4%	68.6%	73.1%	78.2%	83.3%	89.1%	90.0%	90.0%	90.0%
EC-20	60.4%	68.6%	72.8%	77.9%	83.0%	89.0%	90.0%	90.0%	90.0%
EC-30	60.4%	68.6%	73.2%	79.0%	83.5%	89.5%	90.0%	90.0%	90.0%
EAF-DRI (Gas based) production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	0.9%	1.8%	3.4%	3.3%	3.1%	2.2%	1.4%	1.4%	0.0%
Base-E	0.9%	1.3%	1.8%	1.7%	1.6%	0.8%	0.0%	0.0%	0.0%
EC-10	0.9%	1.4%	1.9%	1.8%	1.7%	0.9%	0.0%	0.0%	0.0%
EC-20	0.9%	1.4%	2.2%	2.1%	2.0%	1.0%	0.0%	0.0%	0.0%
EC-30	0.9%	1.4%	1.8%	1.0%	1.5%	0.5%	0.0%	0.0%	0.0%

The China's iron and steel Sector

Figure 97 and Table 94 show annual steel production in China in the Base, Base-E, and EC Scenarios. Table 95 shows no difference in total annual production levels of China's iron and steel sector between EC scenario and ET scenario.

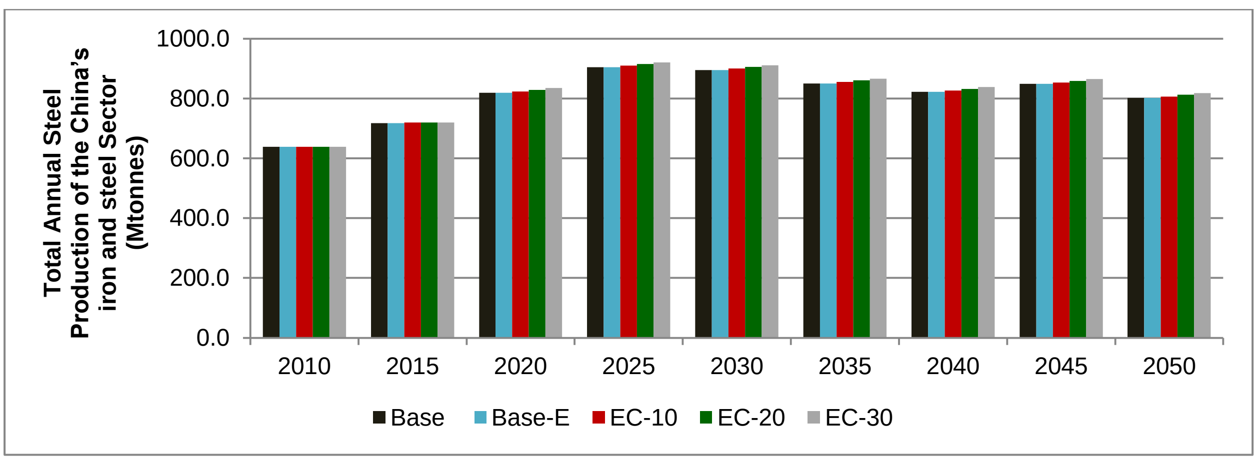

Figure 97. Total Annual Steel Production of the China Projected in the Base, Base-E, and EC Scenarios (Mtonnes)

Table 94. Total Annual Steel Production of the China Projected in the Base, Base-E, and EC Scenarios (Mtonnes)

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	638.7	717.1	819.0	904.8	895.2	850.5	821.9	848.6	801.9
Base-E	638.7	717.1	819.0	904.8	895.2	850.5	821.9	848.6	801.9
EC-10	638.7	719.8	823.6	909.4	899.9	855.1	826.6	853.3	806.7

EC-20	638.7	719.8	829.1	914.9	905.5	860.8	832.3	859.1	812.5
EC-30	638.7	719.8	834.6	920.5	911.1	866.4	837.9	864.8	818.3

Table 95. Declines in Total Annual Steel Production of the China's iron and steel sector Projected in the EC and ET Scenarios, Compared to the Base Scenario (%)

	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
EC-10	0.4%	0.6%	0.5%	0.5%	0.5%	0.6%	0.6%	0.6%
ET-10	0.4%	0.6%	0.5%	0.5%	0.5%	0.6%	0.6%	0.6%
EC-20	0.4%	1.2%	1.1%	1.1%	1.2%	1.3%	1.2%	1.3%
ET-20	0.4%	1.2%	1.1%	1.1%	1.2%	1.3%	1.2%	1.3%
EC-30	0.4%	1.9%	1.7%	1.8%	1.9%	2.0%	1.9%	2.0%
ET-30	0.4%	1.9%	1.7%	1.8%	1.9%	2.0%	1.9%	2.0%

Table 96 and Table 97 show process-based production breakdowns of the China's iron and steel sector. Annual production shares of BOF process are reduced while EAF shares increase over time. Compared to ET scenarios, even though China steel production increases (due to increasing imports to the U.S.), steel production in China shifts to much more efficient EAF processes under EC scenario requirements.

Table 96. Process Based Annual Steel Production of China Projected in the Base, Base-E, and EC Scenarios (Mtonnes)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	572.4	645.4	716.7	777.9	761.0	722.9	657.6	657.6	640.8
Base-E	572.4	645.4	716.7	773.1	756.2	680.4	657.6	657.6	625.2
EC-10	572.4	630.9	671.1	656.4	644.6	523.7	426.7	426.7	426.7
EC-20	572.4	629.9	649.9	595.9	545.9	489.0	429.5	429.5	406.7
EC-30	572.4	623.2	590.6	462.7	455.5	433.2	419.0	432.4	409.1
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	66.3	71.7	102.4	126.9	134.3	127.6	164.3	190.9	161.1
Base-E	66.3	71.7	102.4	131.6	139.0	170.1	164.3	190.9	176.7
EC-10	66.3	88.9	152.5	253.0	255.3	331.5	399.9	426.7	380.0
EC-20	66.3	89.9	179.3	319.0	359.6	371.8	402.7	429.5	405.8
EC-30	66.3	96.6	244.0	457.8	455.5	433.2	419.0	432.4	409.1

Table 97. Process Based Annual Steel Production of China Projected in the Base, Base-E, and EC Scenarios (%)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	89.6%	90.0%	87.5%	86.0%	85.0%	85.0%	80.0%	77.5%	79.9%
Base-E	89.6%	90.0%	87.5%	85.5%	84.5%	80.0%	80.0%	77.5%	78.0%
EC-10	89.6%	87.6%	81.5%	72.2%	71.6%	61.2%	51.6%	50.0%	52.9%
EC-20	89.6%	87.5%	78.4%	65.1%	60.3%	56.8%	51.6%	50.0%	50.1%
EC-30	89.6%	86.6%	70.8%	50.3%	50.0%	50.0%	50.0%	50.0%	50.0%

EAF production									
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	10.4%	10.0%	12.5%	14.0%	15.0%	15.0%	20.0%	22.5%	20.1%
Base-E	10.4%	10.0%	12.5%	14.5%	15.5%	20.0%	20.0%	22.5%	22.0%
EC-10	10.4%	12.4%	18.5%	27.8%	28.4%	38.8%	48.4%	50.0%	47.1%
EC-20	10.4%	12.5%	21.6%	34.9%	39.7%	43.2%	48.4%	50.0%	49.9%
EC-30	10.4%	13.4%	29.2%	49.7%	50.0%	50.0%	50.0%	50.0%	50.0%

The India's iron and steel Sector

Since imports of the U.S. from India are similar in ET and EC scenarios (as mentioned earlier in this section), the total annual production levels of India's iron and steel sector in each of the EC scenario are also similar and mostly identical with the production levels achieved in ET scenarios (see Figure 98, Table 98, and Table 99).

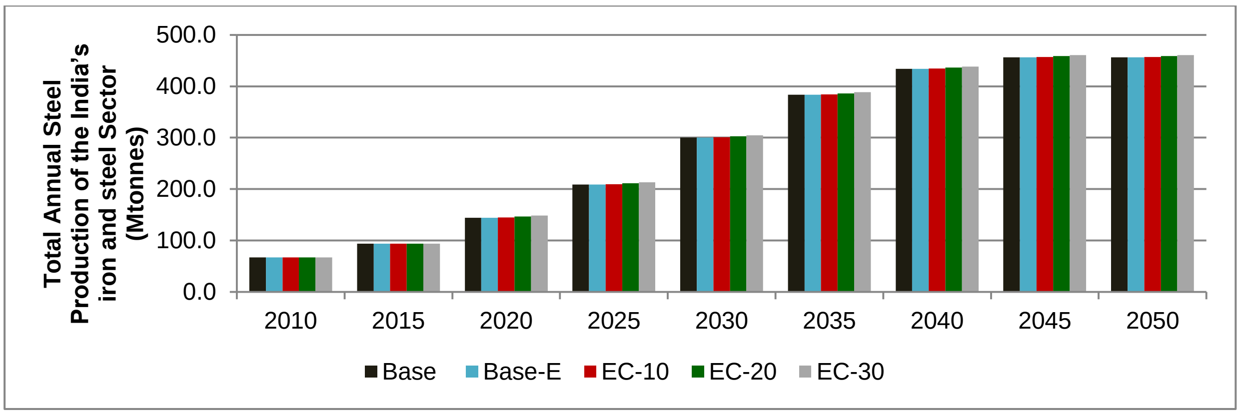

Figure 98. Total Annual Steel Production of the India Projected in the Base, Base-E, and EC Scenarios (Mtonnes)

Table 98. Total Annual Steel Production of the India Projected in the Base, Base-E, and EC Scenarios (Mtonnes)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	67.3	93.8	144.0	209.0	300.1	383.7	433.8	456.1	456.1
Base-E	67.3	93.8	144.0	209.0	300.1	383.7	433.8	456.1	456.1
EC-10	67.3	94.2	145.6	210.6	301.7	385.3	435.5	457.8	457.8
EC-20	67.3	94.2	149.3	214.4	305.5	389.2	439.4	461.8	461.8
EC-30	67.3	94.2	151.5	216.7	307.8	391.5	441.8	464.2	464.3

Table 99. Declines in Total Annual Steel Production of the India's iron and steel sector Projected in the EC and ET Scenarios, Compared to the Base Scenario (%)

	2015	2020	2025	2030	2035	2040	2045	2050
EC-10	0.5%	1.1%	0.8%	0.5%	0.4%	0.4%	0.4%	0.4%
ET-10	0.5%	1.1%	0.8%	0.5%	0.4%	0.4%	0.4%	0.4%
EC-20	0.5%	3.7%	2.6%	1.8%	1.4%	1.3%	1.2%	1.2%

ET-20	0.5%	3.7%	2.6%	1.8%	1.4%	1.3%	1.2%	1.2%
EC-30	0.5%	5.2%	3.7%	2.6%	2.0%	1.8%	1.8%	1.8%
ET-30	0.5%	5.2%	3.7%	2.6%	2.0%	1.8%	1.8%	1.8%

Effects of pre-defined emission targets (i.e., 10%, 20%, and 30% reduction from base scenario) on process breakdowns of the India's iron and steel sector under EC scenarios are also observed, similar to that of China: Process shifts from less efficient production processes to more efficient production processes are realized through the planning horizon. Since the production cost of the BOF process route is the highest, the optimization process tends to abandon it when model assumptions do not constitute an intervention exogenously. For example, BOF production in India drops to the lower bounds defined for the ISEEM-IS model in Section 3.1.2.2, in each scenario (including the Base and Base-E scenarios). Besides, this particular production route has the highest energy intensity and emission intensity values.

EAF production, on the other hand, increases its share in each EC scenario (compared to the Base and Base-E scenarios). The higher the emission targets are, the higher the EAF production. Thus, the EAF production has the highest production shares in the EC-30 scenario.

Table 100 and Table 101 show that shares of EAF-DRI (coal based) reduce with the increase of emission targets and are largely replaced with those of EAF. In addition, EAF production realized in each of the EC scenario become higher than those in ER (emission reduction without trading) scenarios. In ER scenarios, emissions targets are the same as EC scenarios, but trading shares remain constant at the existing levels. The EC modeling results show that the optimization process favors investments in additional EAF production and less EAF-DRI (Coal based) production, if there are higher production needs for India's exports to the U.S.

EAF-DRI (Gas based) production, on the other hand, is mostly similar to the Base and Base-E scenario levels. The only difference is the EC-30 scenario. In this scenario, EAF-DRI (Gas based) production increases in the first half of the planning horizon. This can be explained by natural gas usage in this process. Compared to the coal usage in the EAF-DRI (Coal based) process, natural gas has a lower CO_2 emission factor that is more favorable in the model's optimization processes.

Table 100. Process Based Annual Steel Production of India Projected in the Base, Base-E, and EC Scenarios (Mtonnes)

BOF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	26.0	28.2	36.0	41.8	45.0	38.4	43.4	45.6	45.6
Base-E	26.0	28.2	36.0	41.8	45.0	38.4	43.4	45.6	45.6
EC-10	26.0	28.3	36.4	42.1	45.3	38.5	43.6	45.8	45.8
EC-20	26.0	28.3	37.3	42.9	45.8	38.9	43.9	46.2	46.2
EC-30	26.0	28.3	37.9	43.3	46.2	39.2	44.2	46.4	46.4
EAF production									
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base	9.2	12.2	17.3	20.9	24.0	23.0	74.5	68.7	130.4
Base-E	9.2	12.2	17.3	20.9	24.0	23.0	72.0	60.1	95.5
EC-10	9.2	12.3	17.5	21.1	24.1	23.1	77.3	76.7	131.5
EC-20	9.2	12.3	17.9	25.2	46.7	65.8	140.1	140.1	188.2
EC-30	9.2	12.3	44.4	73.4	115.1	151.3	231.8	235.7	274.0

EAF-DRI (Gas based) production									
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	9.8	12.2	17.3	20.9	24.0	23.0	21.7	22.8	22.8
Base-E	9.8	12.2	17.3	20.9	24.0	23.0	21.7	22.8	22.8
EC-10	9.8	12.3	17.5	21.1	24.1	23.1	21.8	22.9	22.9
EC-20	9.8	12.3	17.9	24.4	24.4	23.4	22.0	23.1	23.1
EC-30	9.8	12.3	29.3	28.0	27.8	25.8	22.1	23.2	23.2
EAF-DRI (Coal based) production									
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	22.3	41.3	73.4	125.4	207.0	299.3	294.3	319.0	257.3
Base-E	22.3	41.3	73.4	125.4	207.0	299.3	296.8	327.7	292.2
EC-10	22.3	41.5	74.2	126.4	208.2	300.5	292.9	312.4	257.6
EC-20	22.3	41.5	76.1	121.9	188.6	261.1	233.4	252.4	204.4
EC-30	22.3	41.5	40.0	72.0	118.9	175.3	143.7	158.8	120.6

Table 101. Process Based Annual Steel Production of India Projected in the Base, Base-E, and EC Scenarios (%)

BOF production									
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	38.6%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
Base-E	38.6%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
EC-10	38.6%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
EC-20	38.6%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
EC-30	38.6%	30.0%	25.0%	20.0%	15.0%	10.0%	10.0%	10.0%	10.0%
EAF production									
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	13.6%	13.0%	12.0%	10.0%	8.0%	6.0%	17.2%	15.1%	28.6%
Base-E	13.6%	13.0%	12.0%	10.0%	8.0%	6.0%	16.6%	13.2%	20.9%
EC-10	13.6%	13.0%	12.0%	10.0%	8.0%	6.0%	17.7%	16.8%	28.7%
EC-20	13.6%	13.0%	12.0%	11.7%	15.3%	16.9%	31.9%	30.4%	40.7%
EC-30	13.6%	13.0%	29.3%	33.9%	37.4%	38.6%	52.5%	50.8%	59.0%
EAF-DRI (Gas based) production									
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	14.5%	13.0%	12.0%	10.0%	8.0%	6.0%	5.0%	5.0%	5.0%
Base-E	14.5%	13.0%	12.0%	10.0%	8.0%	6.0%	5.0%	5.0%	5.0%
EC-10	14.5%	13.0%	12.0%	10.0%	8.0%	6.0%	5.0%	5.0%	5.0%
EC-20	14.5%	13.0%	12.0%	11.4%	8.0%	6.0%	5.0%	5.0%	5.0%
EC-30	14.5%	13.0%	19.3%	12.9%	9.0%	6.6%	5.0%	5.0%	5.0%
EAF-DRI (Coal based) production									
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	33.2%	44.0%	51.0%	60.0%	69.0%	78.0%	67.8%	69.9%	56.4%
Base-E	33.2%	44.0%	51.0%	60.0%	69.0%	78.0%	68.4%	71.8%	64.1%
EC-10	33.2%	44.0%	51.0%	60.0%	69.0%	78.0%	67.3%	68.2%	56.3%
EC-20	33.2%	44.0%	51.0%	56.9%	61.7%	67.1%	53.1%	54.6%	44.3%
EC-30	33.2%	44.0%	26.4%	33.2%	38.6%	44.8%	32.5%	34.2%	26.0%

4.5.2.2. Annual Energy Consumption

This sub section presents the annual energy consumption of the U.S., China, and India's iron and steel sectors in the three EC scenarios for the period 2010-2050.

The U.S. Iron and Steel Sector

Corresponding to the reduction in production volumes, annual energy consumption of the U.S. iron and steel sector decrease through the planning horizon in the EC scenarios (see Figure 99 and Table 102). In fact, because total annual production volumes and process shares are the same as those of ET scenarios, annual energy consumption and energy intensity of the EC scenarios are the same as those of ET scenarios. Annual energy consumption of the U.S. iron and steel sector are decreased via import from China and India in both ET (where emissions are restricted locally in the U.S., not in China and India) and EC (where emissions are restricted globally) scenarios.

In addition, Figure 100 and Table 103, there is little improvement in energy efficiency in any EC scenarios when compared to the Base-E scenario; furthermore, energy intensity levels may become even slightly higher under some EC scenarios when compared to the Base-E scenario (similarly found for some ET scenarios, see Table 78 in Section 4.4.2.2).

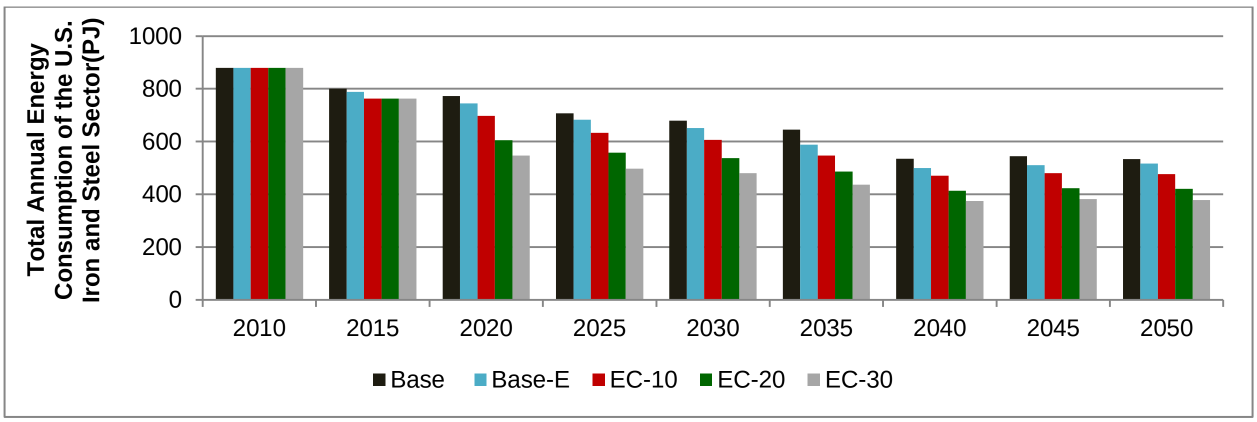

Figure 99. Total Annual Energy Consumption of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and EC Scenarios (PJ)

Table 102. Total Annual Energy Consumption of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and EC Scenarios (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	878.9	801.1	772.2	707.2	679.4	644.9	535.3	544.0	534.0
Base-E	878.9	788.3	744.4	683.4	651.4	588.0	499.2	510.4	516.3
EC-10	878.9	762.9	696.8	632.7	606.2	546.6	470.7	479.9	476.8
EC-20	878.9	762.9	605.5	558.3	537.4	486.3	413.8	422.9	420.1
EC-30	878.9	762.9	546.5	496.6	479.9	435.9	374.2	381.9	378.3

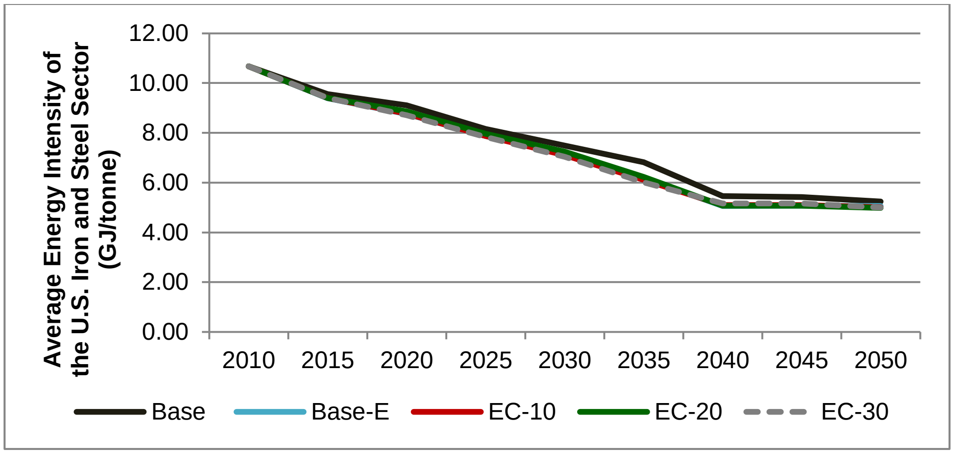

Figure 100. Average Energy Intensities of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and EC Scenarios (GJ/tonne steel)

Table 103. Average Energy Intensities of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and EC Scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	10.67	9.55	9.11	8.16	7.49	6.82	5.45	5.43	5.24
Base-E	10.67	9.39	8.76	7.87	7.16	6.19	5.06	5.07	5.06
EC-10	10.67	9.41	8.77	7.88	7.10	6.11	5.10	5.10	5.00
EC-20	10.67	9.41	8.87	7.96	7.24	6.23	5.08	5.08	4.98
EC-30	10.67	9.41	8.70	7.84	7.04	6.01	5.16	5.17	5.03

The China's iron and steel Sector

Annual energy consumption of the China's iron and steel sector declines through the planning horizon with respect to the global emission restrictions. Even though steel production increases because of the increasing export to the U.S., annual energy consumption becomes lower in each EC scenario largely due to effects of emission targets and improvement in efficiency (see Figure 101, Table 104, and Table 105). Energy efficiency improvements exhibited by reduced energy intensity of the China's iron and steel sector in the EC scenarios can be observed from Figure 102 and Table 105. Average energy intensity levels of each EC scenario become significantly lower than those in the Base and Base-E scenarios. On the other hand, even though the EC-30 scenario leads to the lowest energy intensities in the short and medium terms, the gaps among the scenarios (i.e., the EC-10 and EC-20 scenarios) narrow starting from 2040.

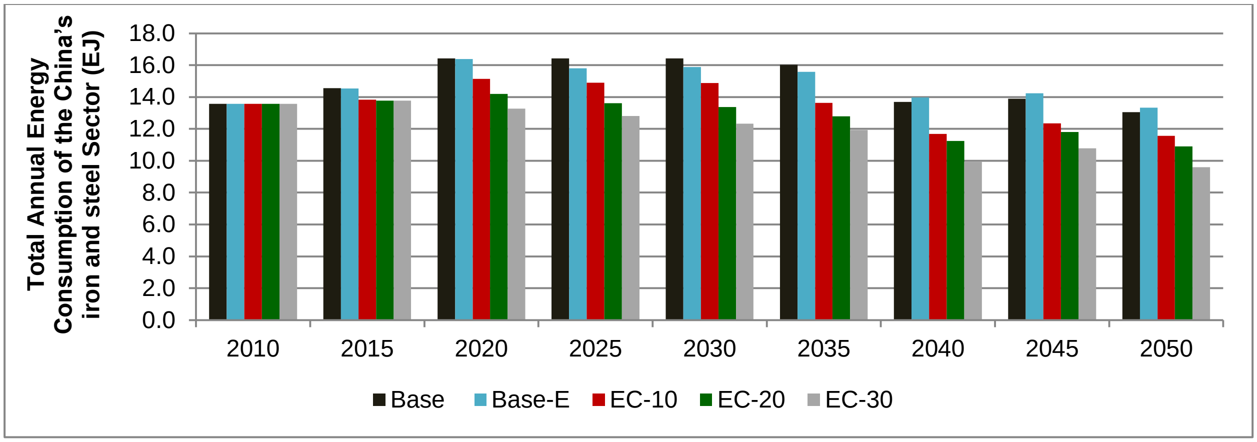

Figure 101. Total Annual Energy Consumption of the China's iron and steel sector Projected in the Base, Base-E, and EC Scenarios (EJ)

Table 104. Total Annual Energy Consumption of the China's iron and steel sector Projected in the Base, Base-E, and EC Scenarios (EJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	13.58	14.56	16.42	16.43	16.42	16.03	13.69	13.89	13.05
Base-E	13.58	14.54	16.38	15.80	15.87	15.58	13.97	14.24	13.33
EC-10	13.58	13.83	15.14	14.89	14.87	13.63	11.68	12.34	11.57
EC-20	13.58	13.77	14.20	13.61	13.37	12.79	11.24	11.81	10.89
EC-30	13.58	13.78	13.28	12.81	12.32	11.93	9.93	10.79	9.59

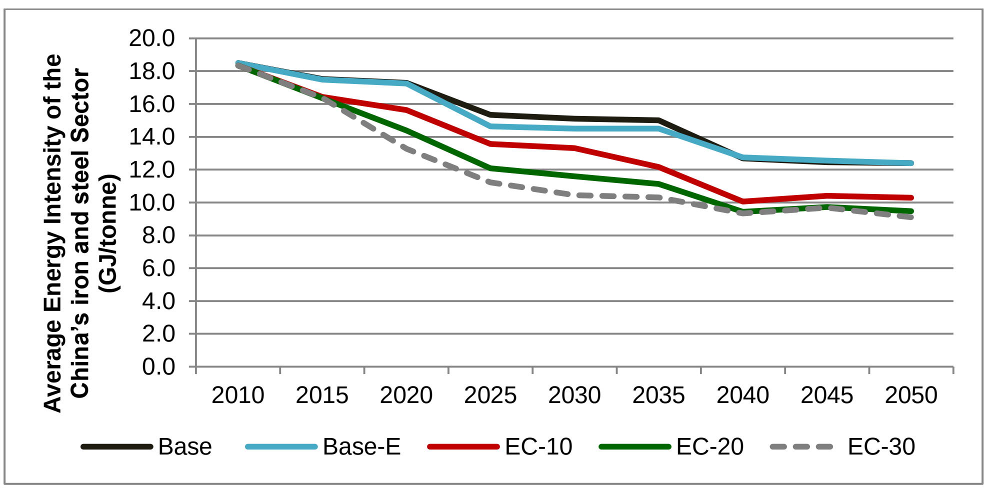

Figure 102. Average Energy Intensities of the China's iron and steel sector Projected in the Base, Base-E, and EC Scenarios (GJ/tonne steel)

Table 105. Average Energy Intensities of the China's iron and steel sector Projected in the Base, Base-E, and EC Scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	18.49	17.51	17.29	15.34	15.10	15.00	12.68	12.44	12.40

Base-E	18.49	17.49	17.24	14.64	14.50	14.49	12.74	12.55	12.40
EC-10	18.33	16.43	15.63	13.56	13.30	12.16	10.06	10.42	10.30
EC-20	18.33	16.36	14.39	12.08	11.59	11.12	9.42	9.73	9.48
EC-30	18.33	16.37	13.28	11.22	10.45	10.32	9.33	9.69	9.09

The India's iron and steel Sector

Energy consumption of the India's iron and steel sector decrease through the planning horizon in the EC scenarios as well (Figure 103 and Table 106), even though the annual production increases. Figure 104 and Table 107 show that the highest efficiency improvements are achieved in the EC-30 scenario; while energy intensity levels of the EC-10 scenarios are higher (worse efficiency) than those of the Base-E scenario. This indicates that the extra capacities invested for the increasing production needs for exports to the U.S. are associated with less efficient technologies in the EC-10 scenario. Nevertheless efficiency levels would increase in the EC-20 and EC-30 scenarios, in which case production increases sufficiently to prompt India's iron and steel sector to start investing in efficiency.

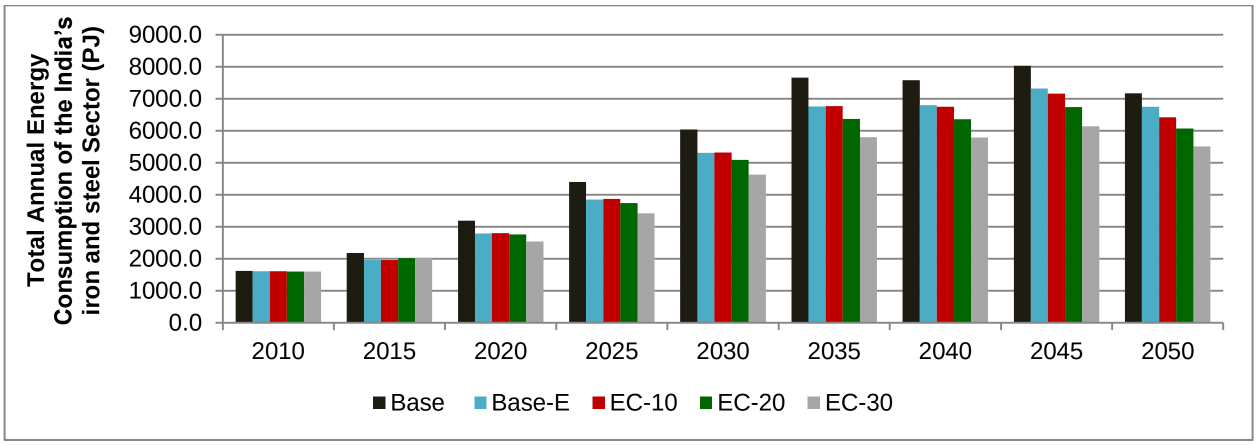

Figure 103. Total Annual Energy Consumption of the India's iron and steel sector Projected in the Base, Base-E, and EC Scenarios (PJ)

Table 106. Total Annual Energy Consumption of the India's iron and steel sector Projected in the Base, Base-E, and EC Scenarios (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	1620.8	2178.5	3191.1	4402.9	6036.6	7659.3	7574.5	8031.2	7171.0
Base-E	1607.3	1961.5	2787.6	3852.0	5305.7	6757.7	6799.9	7322.4	6744.1
EC-10	1607.6	1964.6	2800.0	3867.1	5320.2	6766.8	6752.1	7155.4	6420.0
EC-20	1603.6	2019.0	2759.2	3744.5	5086.2	6367.5	6362.5	6740.0	6071.5
EC-30	1604.1	2034.0	2538.4	3417.7	4632.1	5796.6	5787.8	6138.5	5507.8

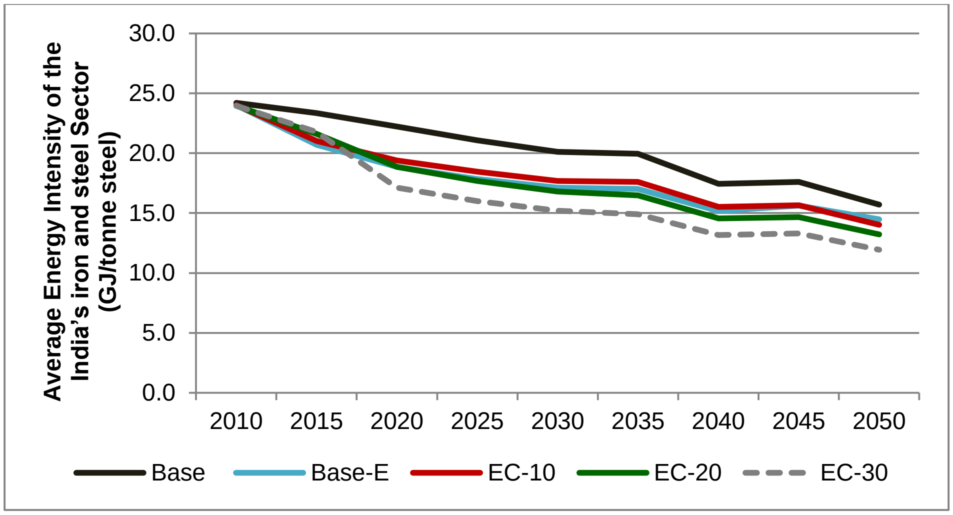

Figure 104. Average Energy Intensities of the India's iron and steel sector Projected in the Base, Base-E, and EC Scenarios (GJ/tonne steel)

Table 107. Average Energy Intensities of the India's iron and steel sector Projected in the Base, Base-E, and EC Scenarios (GJ/tonne steel)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	24.20	23.34	22.21	21.08	20.11	19.95	17.44	17.59	15.70
Base-E	24.00	20.69	18.85	17.84	17.11	17.02	15.16	15.62	14.47
EC-10	24.02	21.03	19.39	18.45	17.68	17.59	15.50	15.58	13.99
EC-20	23.95	21.51	18.57	17.55	16.68	16.38	14.49	14.60	13.15
EC-30	23.96	21.79	16.79	15.79	15.05	14.81	13.11	13.23	11.87

4.5.2.3. Annual CO_2 Emissions

As mentioned earlier in Section 4.5.2.2, there is little efficiency investment in the U.S. iron and steel sector through the planning horizon under the EC scenarios; therefore, there is no improvement in emission intensities in EC scenarios, compared to the Base-E scenario. This is reflected in Figure 105 indicating that emission reductions of the U.S. iron and steel sector in EC scenarios are the result of the increasing steel import (which replaces with the domestic production).

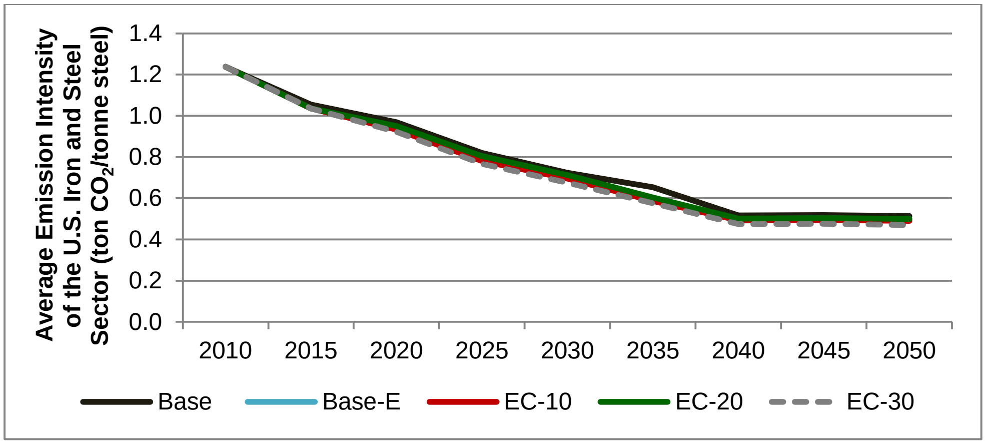

Figure 105. Average Emission Intensity of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and EC Scenarios (ton CO_2/tonne steel)

Levels of emission intensity (as energy intensity) are reduced through the planning horizon in the China and India's iron and steel sectors (Figure 106 and Figure 107), largely due to investments in efficiency improvement in China and India (to decrease the CO2 emissions to the scenario requirements of the EC scenarios). In Figure 106 and Figure 107, the EC-30 scenario leads to the lowest emission intensity levels: 1.18 ton CO2/tonne steel in China and 0.94 ton CO2/tonne steel in India in 2050. However, even the lowest emission intensity levels that achieved in 2050 are still higher than those in the U.S. iron and steel sector in the Base scenario in 2020 partly due to the differences in sectoral structures of China and India from that of the U.S.

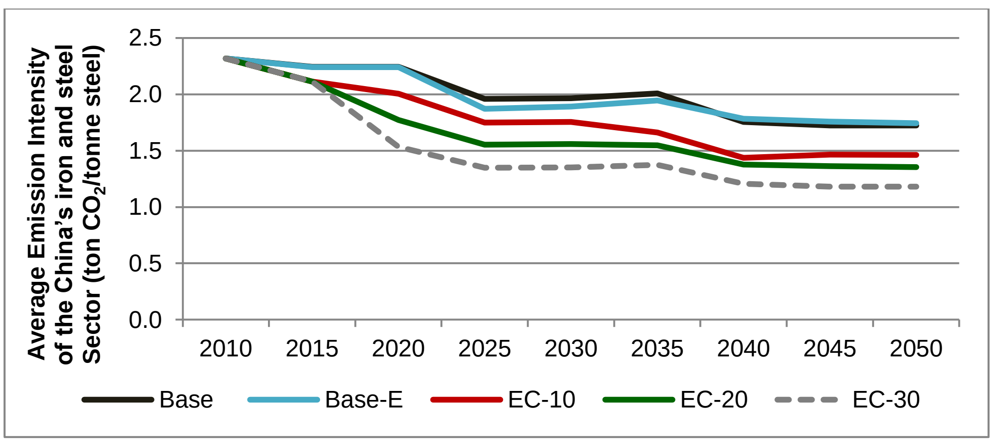

Figure 106. Average Emission Intensity of the China's iron and steel sector Projected in the Base, Base-E, and EC Scenarios (ton CO_2/tonne steel)

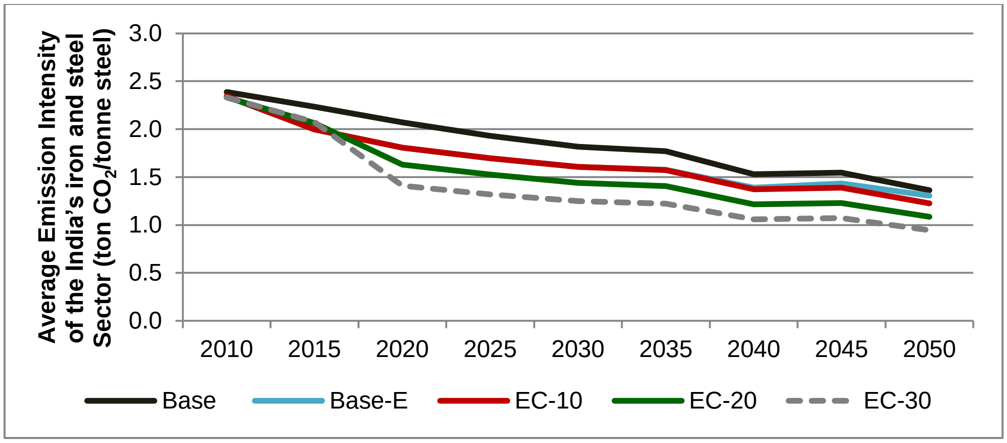

Figure 107. Average Emission Intensity of the India's iron and steel sector Projected in the Base, Base-E, and EC Scenarios (ton CO_2/tonne steel)

4.5.2.4. Annual Production Costs

This subsection presents annual steel production costs of the U.S., China, and India's iron and steel sectors in the three EC scenarios for the period 2010-2050.

The U.S. Iron and Steel Sector

Table 108 lists the annual total costs of the U.S. iron and steel sector realized in the Base, Base-E, and each of the three EC scenarios. The annual total costs of each EC scenario become lower than its Base scenario counterparts through the planning horizon. In the EC-30 scenario, in which the U.S. imports from China and India become the highest, the annual total cost of the iron and steel sector is the lowest. Because no efficiency improvement in the U.S. iron and steel sector is realized in this scenario set, no associated abatement cost is displayed. In this scenario set, the model favors investments in efficiency in China and India in lieu of the U.S. via carbon trading.

Table 108. Annual Total Costs of the U.S. Iron and Steel Sector Projected in the Base, Base-E, and EC Scenarios (Billion 2005 $)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	40.9	50.2	55.0	59.5	61.3	60.2	57.8	58.8	58.6
Base-E	40.9	50.1	54.9	59.4	61.1	59.7	57.1	58.0	57.8
EC-10	40.9	48.9	52.2	56.5	58.2	56.8	54.2	55.1	55.0
EC-20	40.9	48.9	46.7	50.4	52.2	50.7	48.0	49.0	49.0
EC-30	40.9	48.9	44.1	47.6	49.4	47.8	45.2	46.1	46.2

The China's iron and steel Sector

Figure 108 shows that the annual carbon abatement costs are mostly positive when compared to the Base scenario in China's iron and steel sector in the three EC scenarios. Similar to the ER-10 scenario, the EC-10 scenario exhibits negative abatement costs from 2045 to 2060 while the EC-20 scenario starts to show negative abatement cost in 2050. This indicates that investments in efficient production technologies to reduce emissions seem to become economically attractive in the long run in the EC-10 scenario for the China's iron and steel sector.

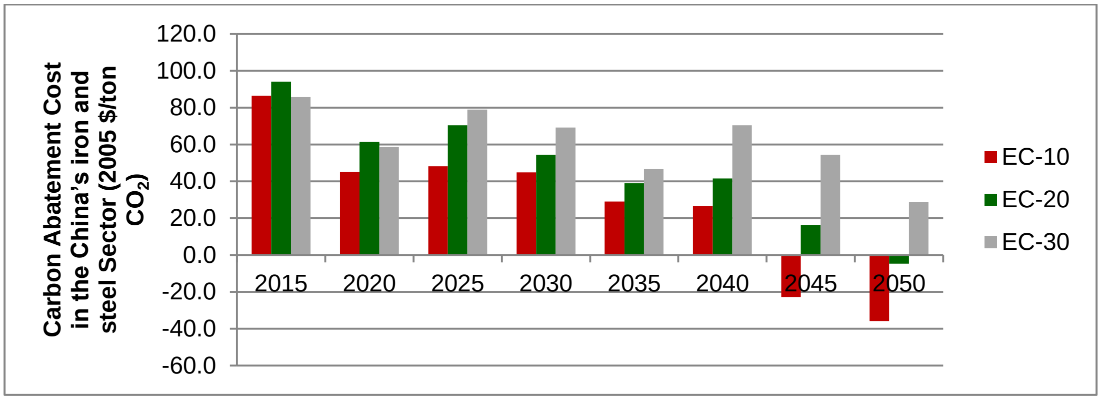

Figure 108. Annual Carbon Abatement Costs of the China's iron and steel sector Projected in the EC scenarios, compared to the Base Scenario (2005 $/ton CO_2 reduction)

The India's iron and steel Sector

Figure 109 shows that annual carbon abatement costs are mostly negative in the EC-10 and EC-20 scenarios and approaches to zero in the EC-30 scenario compared to the Base scenario. Even though EC scenarios need additional investments to decrease emissions to the scenario requirements, the abatement costs stay below of the Base scenario in the EC-10 and EC-20 scenarios.

However, as mentioned earlier, this result highly depends on the parameter structure of the efficient production technologies used in this modeling analysis for India's iron and steel sector. As discussed in Section 4.2.2, availability of efficient production technologies in India's iron and steel sector brings a great reduction in total cost objective. This might be a good indicator that those technologies would be in the baseline production in the near future. Thus, we calculate the carbon abatement costs compared to the Base-E scenario (see Figure 110) as well as the Base scenario to observe the difference that could come if the Base-E scenario was the baseline of India. Comparison with the Base-E scenario shows positive carbon abatement costs. Those costs are even higher than those in China.

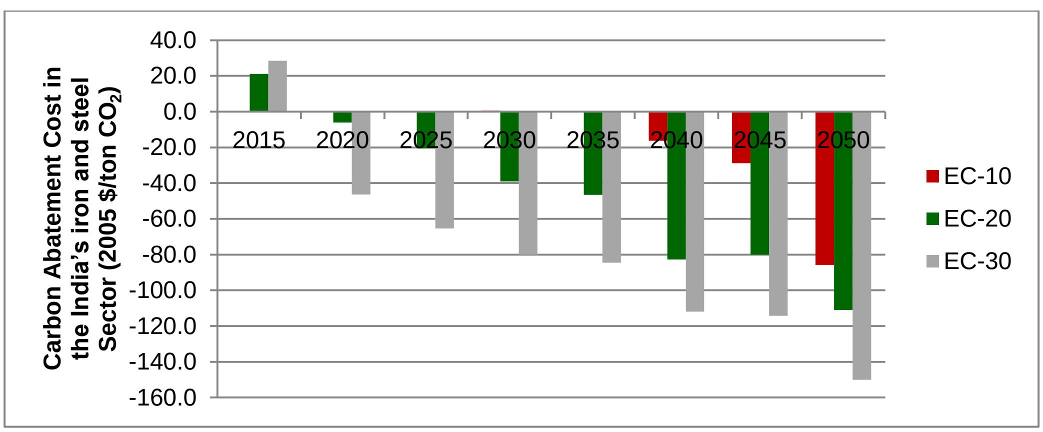

Figure 109. Annual Carbon Abatement Costs of the India's iron and steel sector Projected in the EC scenarios, compared to the Base Scenario (2005 $/ton CO_2 reduction)

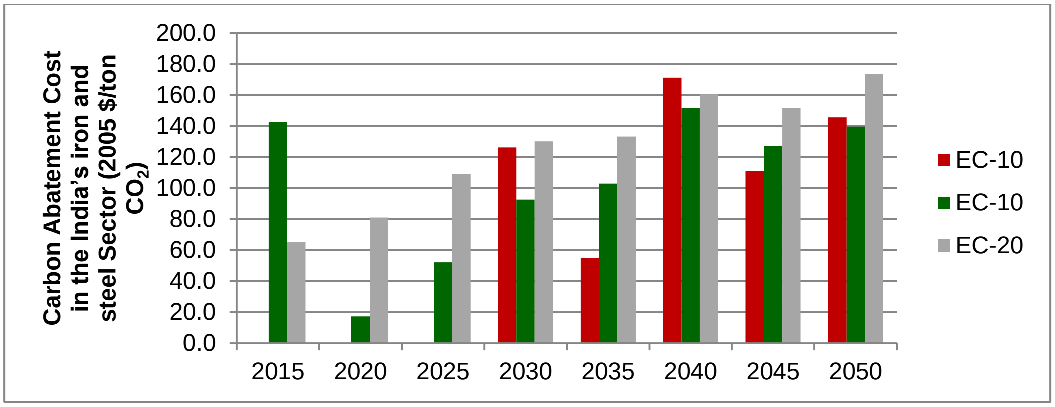

Figure 110. Annual Carbon Abatement Costs of the India's iron and steel sector Projected in the EC scenarios, compared to the Base-E Scenario 2005 ($/ton CO_2 reduction)

4.5.3. EC Scenario Summary

- ***Under the Emission Reduction with Carbon Trading scenarios, which predefine emission targets (i.e., 10%, 20%, and 30% below of those in the Base scenario for each country), the ISEEM-IS model projects that part of the total annual steel production of the U.S. iron and steel sector will be replaced with imports from China and India.*** It is interesting to note that the annual production levels projected for each of the EC scenarios are identical to their counterparts projected for ET scenarios (i.e., emission reduction with commodity trading scenarios). Apparently, the expected increases in China's and India's steel prices in EC scenarios (compared to the ET scenarios) due to additional investments in efficient production technologies, results in no difference in the amounts of U.S. steel imports from China or India from what are projected for the same emission targets in ET scenarios. In another word, it still costs less for the U.S. to import from China and India under ISEEM-IS model assumptions (such as technology costs, energy prices, transportation costs, tariffs, and so on) with the three emission targets. The level of the U.S. steel import remains the same between commodity and carbon trading under the same emission targets, so are the production increases in China and India. First, as discussed in Section 4.1, cost of per tonne steel production in China is the lowest among all model countries (i.e., the U.S., China, and India) with the parameter structure used in the ISEEM-IS model. Even though carbon abatement costs are higher in China compared to the U.S. (see Section 4.3), the production cost plus carbon abatement cost is still lower in China compared to the production cost plus carbon abatement cost in the U.S. Second, carbon abatement costs in India are mostly negative and much lower than that of the U.S. (see Section 4.3). The significant difference makes direct carbon trading with India attractive for the U.S., instead of investing in efficiency measures in the U.S. We also note that the modeling results are affected by a set of parameters assumed for the model, including energy prices, capital and O&M costs, material prices in modeled countries, the tariffs on imported and exported products, and transportation and fuel costs, etc. In a perfect competitive market (e.g., no financial incentives or subsidies to steel production are included), with different tariffs, transportation costs and other assumptions, the magnitudes of projected production, energy consumption, and carbon emissions in EC scenarios could be different from those of ET scenarios.

- ***Shares of steel production processes change in China and India with time and emission targets for different EC scenarios, with higher emission reduction targets corresponding to higher efficiencies in China and India's iron and steel sectors, while the U.S. has the same production pattern with the Base and Base-E scenarios.*** Although total production decreases through the planning horizon compared to the Base scenario, there is no difference in process shares in the U.S. iron and steel sector across three EC scenarios. In other words, even though the sector production capacity shrinks, production profile stay identical, when the carbon trading used as emission reduction strategy in the U.S. On the other hand, production in China and India switches to the most efficient steel production process, EAF, from BOF production in China and from EAF-DRI (Coal based) production in India. Share of EAF production reaches to 50% in each scenario in China, and approximately 30%, 40%, and 50% in the EC-10, EC-20, and EC-30 scenarios, respectively, in India in 2050. Clearly, efficiencies of the China and India's iron and steel sectors are projected to increase in all EC scenarios.

- ***Corresponding to the reduction in annual production volumes, annual energy consumption of the U.S. iron and steel sector decrease through the planning horizon in all EC scenarios, while there is no change in energy intensity levels across EC scenarios compared to Base-E scenarios in any given years.*** With the increases in annual steel production in China and India due to export increases, national annual energy consumption is lower however largely due to the effects of emission restrictions and reduced energy and emission intensities in each EC scenario when compared to Base-E scenarios. In addition, although the energy intensities are dramatically reduced in China and India for each EC scenario, Figure 111, Figure 112, and Figure 113 indicate that U.S. maintains the lowest energy intensity in the sector compared to China and India in each year from 2010 to 2050.

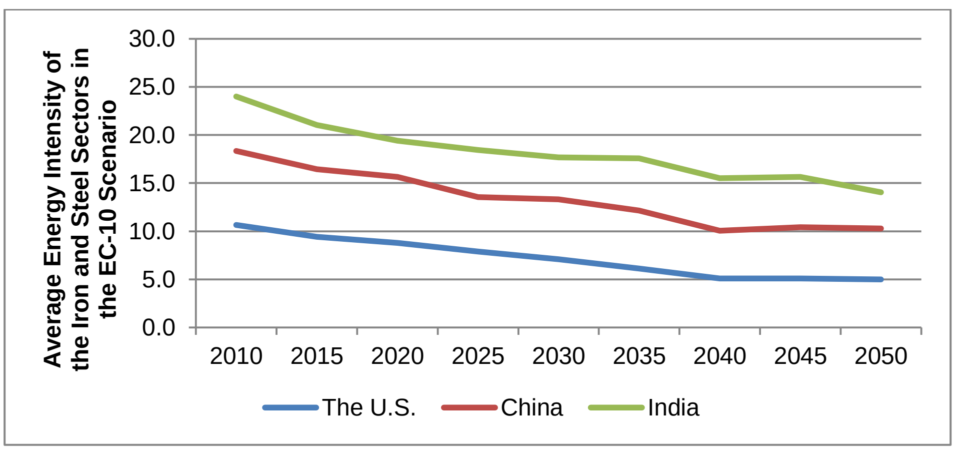

Figure 111. Average Energy Intensities of the U.S., China, and India's iron and steel sector Projected in the EC-10 Scenario (GJ/tonne steel)

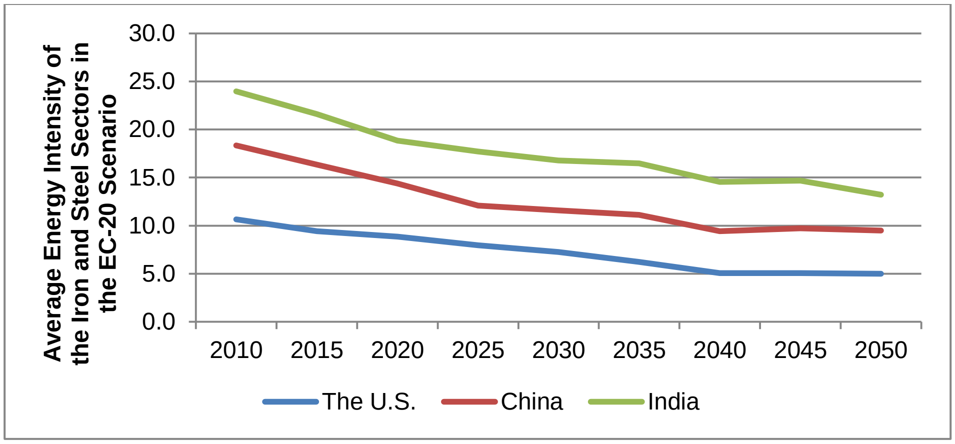

Figure 112. Average Energy Intensities of the U.S., China, and India's iron and steel sector Projected in the EC-20 Scenario (GJ/tonne steel)

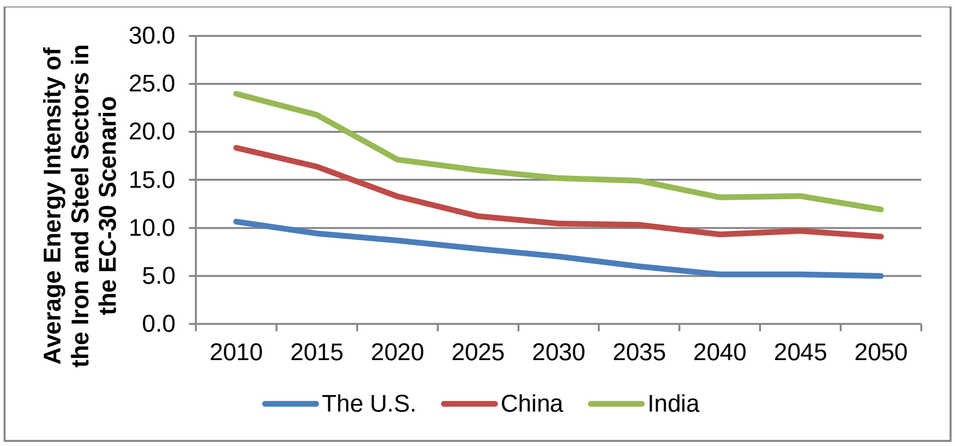

Figure 113. Average Energy Intensities of the U.S., China, and India's iron and steel sector Projected in the EC-30 Scenario (GJ/tonne steel)

- ***Total annual production costs of the U.S. iron and steel sector in the EC scenarios are lower than those in the Base, Base-E, and ER scenarios and very close to those in the ET scenarios. As expected, total annual sector cost of China and India's iron and steel sectors in EC scenarios are higher than the other scenarios (i.e., Base, Base-E, ER, and ET scenarios).*** For example, in 2030 annual production cost of China's iron and steel sector in the EC-20 scenarios is 1.1% and 3.6% higher than those in the ER-20 and ET-20 scenarios for each year, respectively; while annual production cost of India's iron and steel sector in the EC-20 scenarios is 1.1% and 2.1% higher than those in the ER-20 and ET-20 scenarios for each year, respectively. Higher annual production costs in China and India in the EC scenarios compared to those of ER scenarios are largely due to added production in EC scenarios to satisfy demand for exporting to the U.S. from China and India. Higher annual production costs in China and India in the EC scenarios compared to those of ET scenarios are largely due to added investments in efficiency measures induced by emission reduction targets predefined in the EC scenarios for each country, while there is no emission-reduction target predefined for China's and India's iron and steel sectors in the ET scenarios.

5. Comparison and Discussion of Scenarios

In this study we have applied an ISEEM model to project long-term CO_2 emission reduction potentials and to quantify production, energy and cost characteristics of iron and steel sectors in the U.S, China and India that adopt different strategies such as national energy efficiency measurements, commodity trading, and carbon trading. While the main purpose is set out to examine emission reduction strategies and emission reduction potentials in the U.S. iron and steel sector, we also examine emission reduction potentials in China's and India's iron and steel sectors. This helps to advance understanding of national and global scales of emission reduction and to evaluate the effects of the U.S. mitigation strategies and related potential trade policies with China and India (i.e., commodity and carbon trading).

In this project, Base scenario represents continuation of existing trends in iron and steel sector over the next four decades without imposing any energy or emission reduction targets, while allowing autonomous improvement of production technologies. This scenario is established and calibrated against annual production, energy consumption, emissions, and cost statistics obtained from the historical data in each country. In Base scenario, penetration of new energy efficient production technologies is excluded; while Base-E scenario allows efficiency improvement with investments to account for impacts from adopting cost effective energy efficient production technologies. Base and Base-E scenarios have the same model assumptions (e.g., iron ore reserve capacities, annual scrap availabilities, energy source and raw material prices, and so on), except that there is no input for including energy efficient production technologies in Base scenario.

In this modeling study, we pre-define the carbon-emission reduction targets at three levels for all strategies, i.e., 10%, 20%, and 30% reduction from those of the Base scenario for each strategy in each year. Each mitigation strategy is expected to meet remission reduction targets, by adopting different technologies under a set of assumptions. Three major strategies are defined as the following scenarios:

1. The 'Emission Reduction without Trading (ER)' scenario. In this set of scenarios the mitigation strategy focuses on national scale energy efficiency measures. The purpose of this scenario set is to analyze the emission reduction potentials in iron and steel sectors of the each country by means of investing in advanced production technologies and/or efficient production technologies, without any policy instrument such as trading of commodities or carbon. Specifically, the annual CO_2 emission restriction is initially set at 5% annual reduction from that of the Base scenario in 2015, and is set at three different levels (i.e., 10%, 20%, and 30%) starting in year 2020 throughout 2050 in each model country iron and steel sectors (i.e., the U.S., China, and India).
2. The 'Emission Reduction with Commodity Trading (ET)' scenario. In this set of scenarios the mitigation strategy focuses mainly on commodity trading in order to meet the emission reduction target of the U.S. The emission restrictions are only applicable to the U.S. iron and steel sector while there is no emission-reduction target predefined for China or India. The primary purpose is to analyze the emission reduction potential of the U.S. iron and steel sector via commodity trading from China and India as an alternative strategy to ER scenario in which national scale efficiency investment is an strategy for emission reduction. Changes in annual production, energy consumption and emissions of the China and India's

iron and steel sectors due to increasing exports to the U.S. are also examined. For this the U.S. strategy, the annual CO_2 emission restriction is set at 5% annual reduction from that of the Base scenario in 2015, and is set at three different levels (i.e., 10%, 20%, and 30%) starting in year 2020 throughout 2050 in the U.S. iron and steel sector. The ET scenarios aim to decrease emissions in the U.S. iron and steel sector alone by commodity trading strategy (i.e., increasing steel imports); however, ET strategy does not result in reducing net total emissions or global risks in climate change, instead it results in simply transferring actual production burdens from the U.S. to China and India, where intensities of energy use and emissions are actually higher.

3. The 'Emission Reductions with Carbon Trading (EC)' scenario. In this set of scenarios the mitigation strategy focuses on carbon trading of the U.S. with China and India. This scenario set assumes that emission reduction targets in each of the three countries will be accomplished simultaneously, while carbon trading mechanism for the U.S. is available from China and India as an option to decrease emissions in the U.S. In contrast to the ET scenario strategy, in this scenario set the U.S. may invest in efficiency improvements in China and India iron and steel sectors before importing from them. Specifically, the annual CO_2 emission restriction is set at 5% annual reduction from that of the Base scenario in 2015, and is set at three different levels (i.e., 10%, 20%, and 30%) starting in year 2020 throughout 2050 in each country's iron and steel sectors (i.e., the U.S., China, and India).

All three scenarios (i.e., ER, ET, and EC) project reductions in annual energy consumption in the U.S. iron and steel sector (due to the emission restrictions applied in the U.S. in each scenario). In China's and India's iron and steel sectors, on the other hand, reductions in annual energy consumption are projected in ER and EC scenarios only, in which emission reduction targets are applied for each country. As is expected, a higher emission-reduction target results in a lower level of annual energy consumption throughout the projections.

The modeling results indicate that ET and EC scenarios lead to the lowest (and identical) level of annual production and energy consumption in the U.S. iron and steel sector when compared to the ER scenarios with the same emission-reduction target (see Figure 114 and Table 109).

Figure 114 shows trends of annual energy consumption in the U.S. iron and steel sector in the Base, Base-E, ER-20, ET-20, and EC-20 scenarios. It is interesting to note that the same emission target is achieved with a higher level of annual energy consumption in the ER scenarios for any given year when compared to other strategies (ET and EC). Table 109 shows that although annual energy consumption of the U.S. iron and steel sector is higher in the ER scenarios compared to the ET and EC scenarios, energy intensity is lower than that of ET and EC scenarios.

Figure 115 through Figure 119 display the fuel based energy consumption, and Table 110 summarizes the on-site electricity generation in the U.S. iron and steel sector in the Base, Base-E, ER-20, ET-20, and EC-20 scenarios. First, fuel consumption of the U.S. iron and steel sector is the same for both ET and EC scenarios, since the production is almost identical. Second, in the ER scenario, an increase in purchased coke usage is observed; while in the other scenarios, coke is produced in the U.S. iron and steel sector by using coking coal that is less expensive but with higher emission factors. Normally, the emission factor of burning coke (107 kg/GJ) is lower than the sum of emission factor of burning coking coal (94.6 kg/GJ) and that of process based emissions to produce coke (20.5 kg/GJ). In addition, average emission factor of offsite electricity remains lower than that of onsite electricity generation mainly from coal-burning. As a result, the U.S. iron and steel sector tends to purchase coke and off-site electricity in the ER scenarios. In summary, the model projections favor the fuels with lower emission factors (such as purchased coke and offsite electricity) as well as efficiency measures in the ER scenarios in the U.S. steel sector.

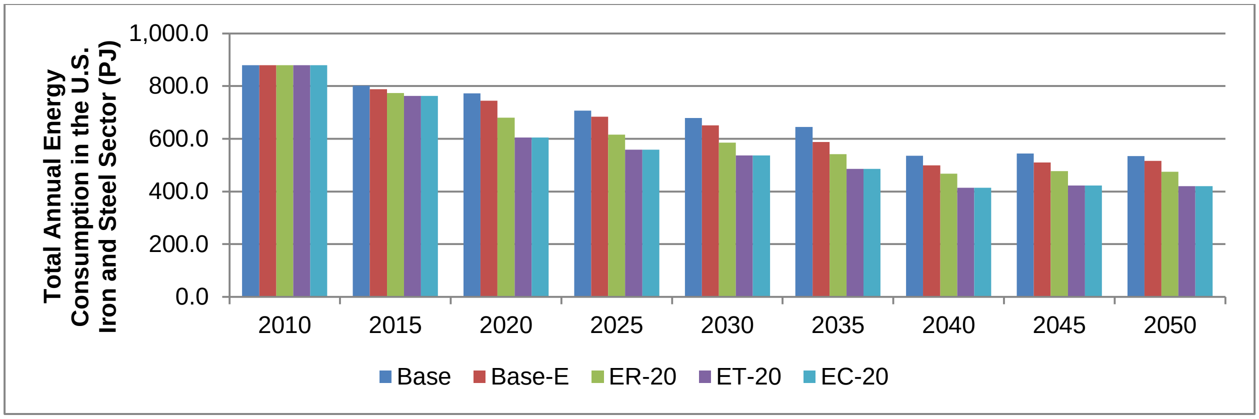

Figure 114. Total Annual Energy Consumption in the U.S. Iron and Steel Sector Projected in the Base, Base-E, ER-20, ET-20, and, EC-20 Scenarios

Table 109. Annual Energy Consumption and Intensity in the U.S. Iron and Steel Sector Projected in the Base, Base-E, ER, ET, and, EC Scenarios

		Consumption of Energy (PJ)	Energy Saving (% reduction compared to the Base scenario)	Energy Intensity (annual average rate, GJ/tonne steel)
2030	Base Scenario	679.4		7.5
	Base-E Scenario	651.4	4.1%	7.2
	ER-10 Scenario	618.3	9.0%	6.9
	ET-10 Scenario	606.2	10.8%	7.1
	EC-10 Scenario	606.2	10.8%	7.1
	ER-20 Scenario	586.0	13.7%	6.6
	ET-20 Scenario	537.4	20.9%	7.2
	EC-20 Scenario	537.4	20.9%	7.2
	ER-30 Scenario	558.5	17.8%	6.3
	ET-30 Scenario	479.9	29.4%	7.0
	EC-30 Scenario	479.9	29.4%	7.0
2050	Base Scenario	534.0		5.2
	Base-E Scenario	516.3	3.3%	5.1
	ER-10 Scenario	491.3	8.0%	5.0
	ET-10 Scenario	476.8	10.7%	5.0
	EC-10 Scenario	476.8	10.7%	5.0
	ER-20 Scenario	475.4	11.0%	4.9
	ET-20 Scenario	420.1	21.3%	5.0
	EC-20 Scenario	420.1	21.3%	5.0
	ER-30 Scenario	461.7	13.5%	4.8

	ET-30 Scenario	378.5	29.1%	5.0
	EC-30 Scenario	378.3	29.2%	5.0

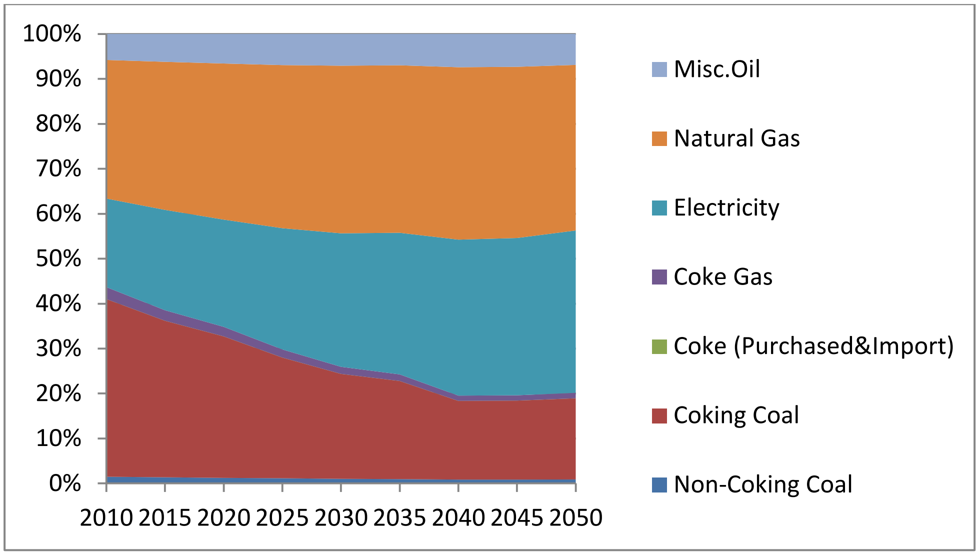

Figure 115. Fuel Based Energy Consumption of the U.S. Iron and Steel Sector in the Base Scenario (%)

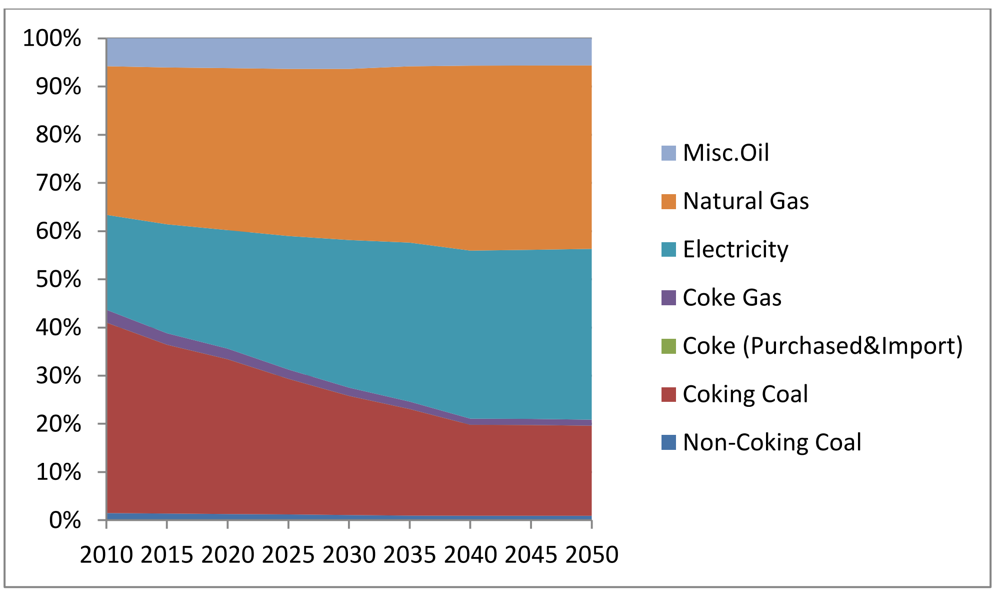

Figure 116. Fuel Based Energy Consumption of the U.S. Iron and Steel Sector in the Base-E Scenario (%)

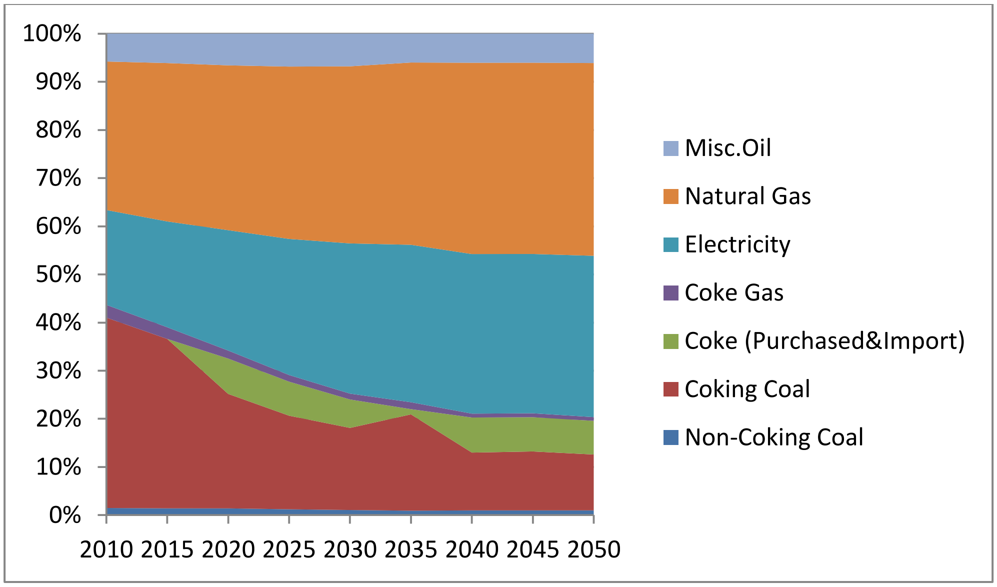

Figure 117. Fuel Based Energy Consumption of the U.S. Iron and Steel Sector in the ER-20 Scenario (%)

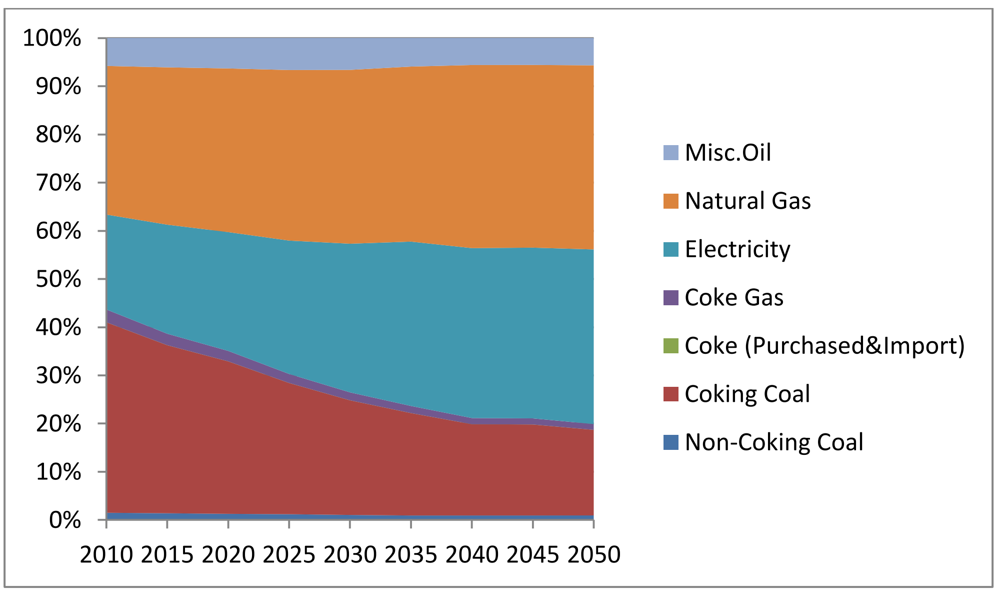

Figure 118. Fuel Based Energy Consumption of the U.S. Iron and Steel Sector in the ET-20 Scenario (%)

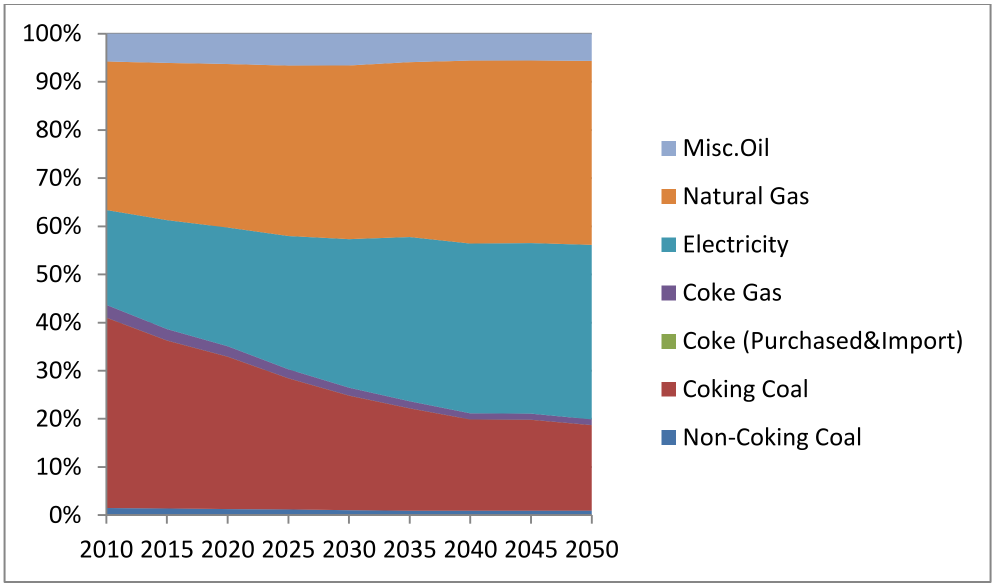

Figure 119. Fuel Based Energy Consumption of the U.S. Iron and Steel Sector in the EC-20 Scenario (%)

Table 110. On-site Electricity Generation in the U.S. Iron and Steel Sector Projected in the Base, Base-E, ER-20, ET-20, and, EC-20 Scenarios (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	20.9	18.1	18.1	18.8	19.4	20.4	21.3	23.6	26.2
Base-E	20.9	18.1	18.2	18.7	19.3	19.9	21.3	23.6	26.2
ER-20	20.9	10.0	5.6	4.2	3.6	3.9	2.5	2.6	2.7
ET-20	20.9	17.8	16.6	16.1	18.1	18.9	20.6	22.2	23.6
EC-20	20.9	17.8	16.6	16.1	18.1	18.9	20.6	22.2	23.6

Each country (i.e., the U.S., China, and India) is capable of reducing CO_2 emissions and emission intensities via country-specific energy efficiency measures (ER scenario). In ET and EC scenarios the U.S. is projected to reduce its iron and steel sector emissions via steel import instead of investing in efficiency measures due to much lower steel production prices in the other countries - China and India.

Figure 120 and Table 111 show that in China, the ER and EC scenarios project the lowest level of annual energy consumption. The levels of annual energy consumption in the ER and EC scenarios are very close to each other. For example, despite the peak in steel production in China's iron and steel sector in 2030, energy consumption of the sector reaches almost the same level as in 2005 under the ER-20 and EC-20 scenarios (and even lower levels under the ER-30 and EC-30 scenarios). In 2050, annual energy consumption of the China's iron and steel sector is lower than that of 2005. Figure 120 and Table 111 also show that annual energy consumption in the China's iron and steel sector is the highest in ET scenario, while the associated energy intensity remains the same as that of Base-E scenario - higher than the other two scenarios (ER and EC). This corresponds to the production increase in the China's iron and steel sector due to growing export to the U.S. with little or no improvement in energy efficiency.

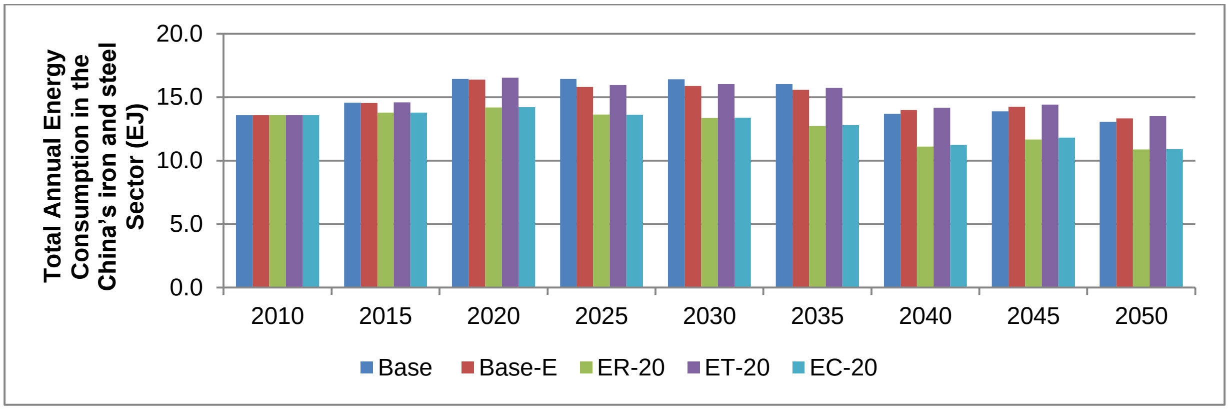

Figure 120. Annual Energy Consumption in the China's iron and steel sector projected in the Base, Base-E, ER-20, ET-20, and, EC-20 Scenarios

Table 111. Annual Energy Consumption in the China's iron and steel sector projected in the Base, Base-E, ER, ET, and, EC Scenarios

		Consumption of Energy (PJ)	Energy Saving (% reduction compared to the Base scenario)	Energy Intensity (annual average rate, %)
2030	Base Scenario	16419.2		15.10
	Base-E Scenario	15875.0	3.3%	14.50
	ER-10 Scenario	14872.5	9.5%	13.37
	ET-10 Scenario	15942.7	2.9%	14.50
	EC-10 Scenario	13374.6	9.4%	13.30
	ER-20 Scenario	13362.5	18.6%	11.71
	ET-20 Scenario	16024.2	2.4%	14.50
	EC-20 Scenario	13381.4	18.5%	11.59
	ER-30 Scenario	12120.7	26.2%	10.39
	ET-30 Scenario	16105.7	1.9%	14.50
	EC-30 Scenario	12322.8	24.9%	10.45
2050	Base Scenario	13050.3		12.40
	Base-E Scenario	13330.3	-2.1%	12.40
	ER-10 Scenario	11498.4	11.9%	10.29
	ET-10 Scenario	13414.4	-2.8%	12.40
	EC-10 Scenario	11570.2	11.3%	10.30
	ER-20 Scenario	10870.7	16.7%	9.61
	ET-20 Scenario	13516.4	-3.6%	12.40
	EC-20 Scenario	10892.9	16.5%	9.48
	ER-30 Scenario	9365.2	28.2%	9.04
	ET-30 Scenario	13617.9	-4.3%	12.41
	EC-30 Scenario	9588.4	26.5%	9.09

Figure 121 through Figure 125 show the fuel based energy consumption and Table 112 summarizes the on-site electricity generation in the China's iron and steel sector in the Base, Base-E, ER-20, ET-20, and EC-20 scenarios. Similar to the U.S., purchased coke and off-site electricity are favored over coke production and on-site electricity generation in the sector. Fuel consumption of the China's iron and steel sector differ in the ER and EC scenarios (compared to the Base, Base-E, and ET scenarios): There is a decrease in total consumption of coke and coking coal and an increase in consumption of electricity in the ER and EC scenarios, largely due to increasing EAF production shares and decreasing BOF production shares in China. Electricity is the main energy source of the EAF production and coking coal and coke are the main energy sources of the BOF production. Share of electricity in total energy consumption increases from 47.6% in the Base scenario to 58.2% in the ER-20 scenario and 58.7% in the EC-20 scenario in 2050.

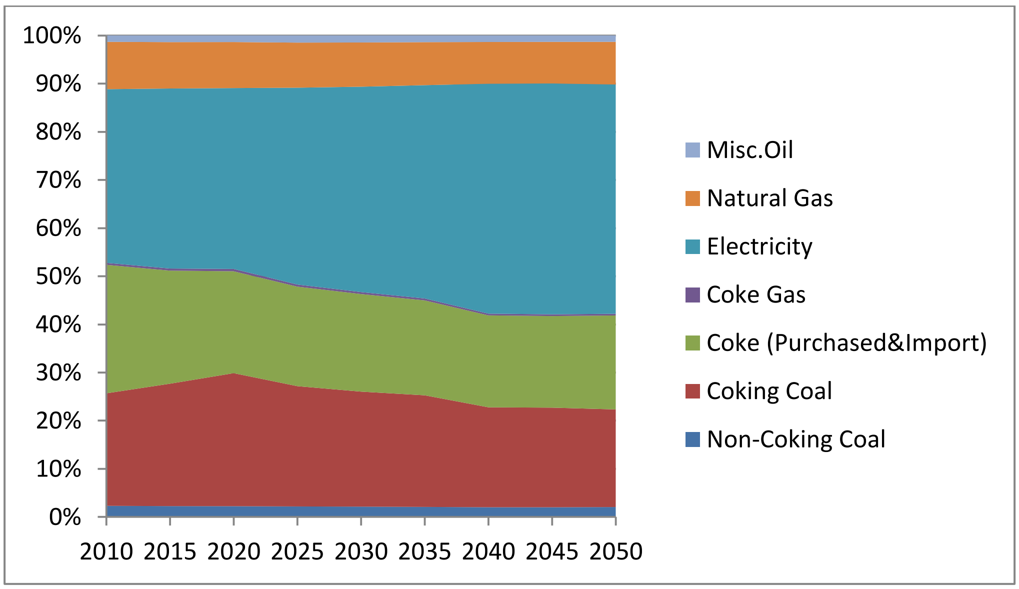

Figure 121. Fuel Based Energy Consumption of the China's iron and steel sector in the Base Scenario (%)

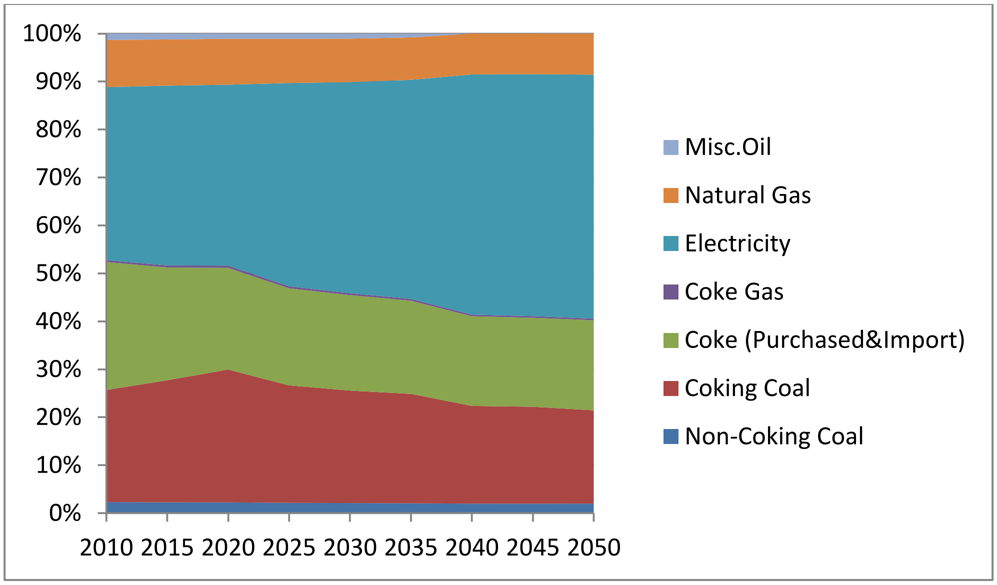

Figure 122. Fuel Based Energy Consumption of the China's iron and steel sector in the Base-E Scenario (%)

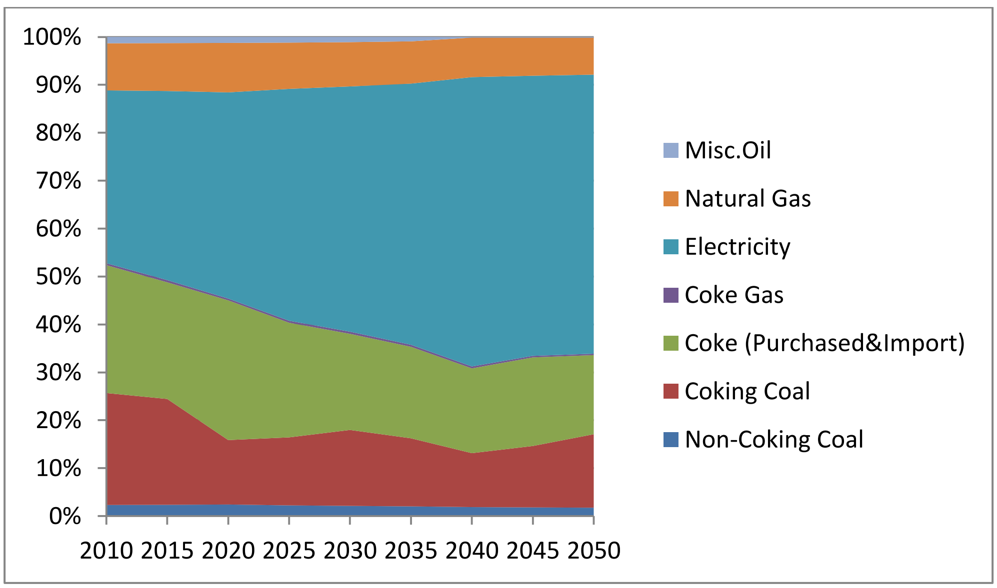

Figure 123. Fuel Based Energy Consumption of the China's iron and steel sector in the ER-20 Scenario (%)

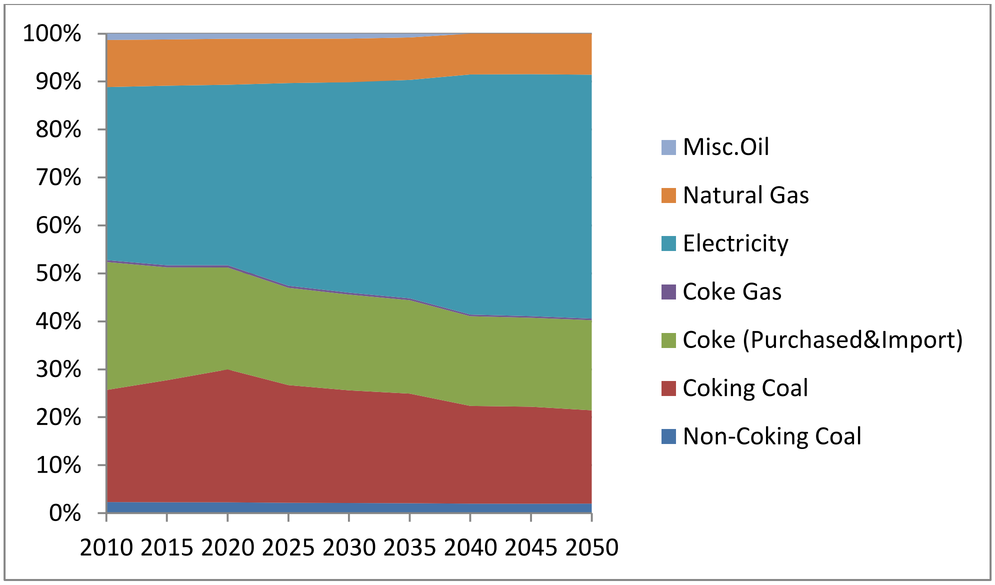

Figure 124. Fuel Based Energy Consumption of the China's iron and steel sector in the ET-20 Scenario (%)

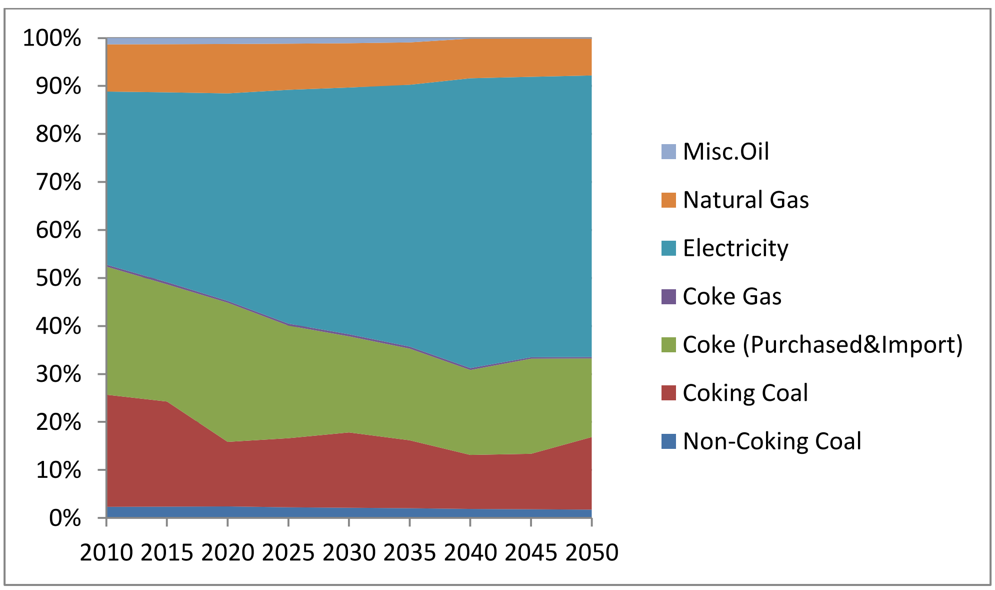

Figure 125. Fuel Based Energy Consumption of the China's iron and steel sector in the EC-20 Scenario (%)

Table 112. On-site Electricity Generation in the China's iron and steel sector Projected in the Base, Base-E, ER-20, ET-20, and, EC-20 Scenarios (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base	1765.0	1996.4	2257.0	2558.6	2898.4	3268.0	3267.4	3328.8	3106.9
Base-E	1765.0	1996.4	2257.0	2559.8	2899.3	3259.4	3497.2	3591.9	3390.4
ER-20	1765.0	1996.6	2264.5	2552.0	2880.0	3219.5	3350.3	3408.2	3165.3

ET-20	1765.0	1996.3	2256.7	2559.5	2899.1	3261.8	3542.3	3637.4	3436.7
EC-20	1765.0	1996.6	2264.5	2554.0	2879.7	3220.3	3392.2	3449.0	3194.8

Figure 126 and Table 113 show that the ER scenarios exhibit the lowest level of energy consumption in India, and a slightly higher level of energy consumption EC scenarios due to production increases for export to the U.S. Energy intensity levels in ET scenario are almost identical to that of Base-E scenario. Compared to the Base scenario, all three strategies lower the levels of energy intensities in the India's iron and steel sector, while the ER scenario exhibits the lowest level of energy intensity for all emission reduction targets.

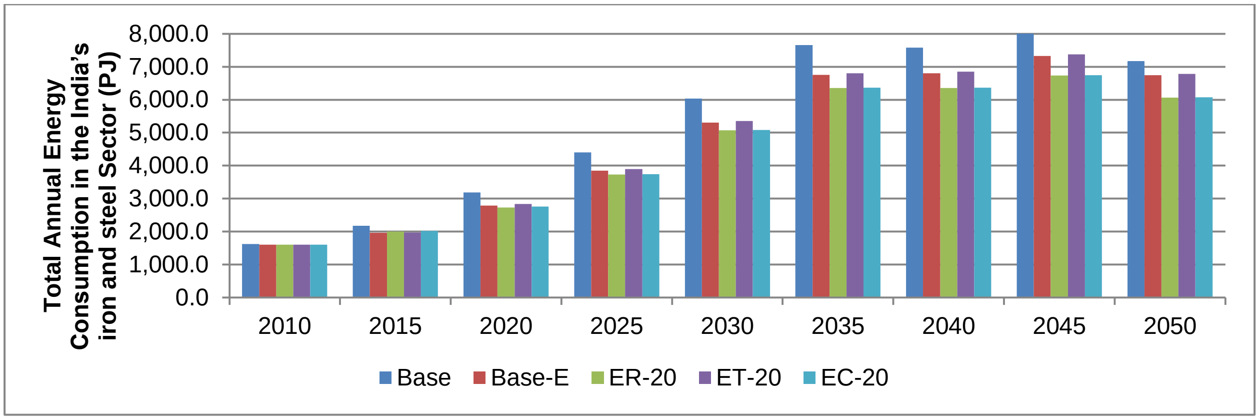

Figure 126. Total Annual Energy Consumption in the India's iron and steel sector Projected in the Base, Base-E, ER-20, ET-20, and, EC-20 Scenarios

Table 113. Energy Consumption in the India's iron and steel sector Projected in the Base, Base-E, ER, ET, and, EC Scenarios

		Consumption of Energy (PJ)	Energy Saving (% reduction compared to the Base scenario)		Energy Intensity (annual average rate, %)
2030	Base Scenario	6036.6			20.11
	Base-E Scenario	5305.7	12.1%		17.11
	ER-10 Scenario	5309.1	12.1%	-0.1%	17.02
	ET-10 Scenario	5317.3	11.9%	-0.2%	17.67
	EC-10 Scenario	5320.2	11.9%	-0.3%	17.68
	ER-20 Scenario	5075.8	15.9%	4.3%	16.28
	ET-20 Scenario	5350.1	11.4%	-0.8%	17.66
	EC-20 Scenario	5086.2	15.7%	4.1%	16.79
	ER-30 Scenario	4613.8	23.6%	13.0%	14.84
	ET-30 Scenario	5382.5	10.8%	-1.4%	17.65
	EC-30 Scenario	4632.1	23.3%	12.7%	15.19
2050	Base Scenario	7171.0			15.70
	Base-E Scenario	6744.1	6.0%		14.47
	ER-10 Scenario	6460.2	9.9%	4.2%	13.93

	ET-10 Scenario	6756.2	5.8%	-0.2%	14.77
	EC-10 Scenario	6420.0	10.5%	4.8%	14.03
	ER-20 Scenario	6061.3	15.5%	10.1%	12.94
	ET-20 Scenario	6781.7	5.4%	-0.6%	14.76
	EC-20 Scenario	6071.5	15.3%	10.0%	13.21
	ER-30 Scenario	5494.9	23.4%	18.5%	11.92
	ET-30 Scenario	6806.3	5.1%	-0.9%	14.75
	EC-30 Scenario	5507.8	23.2%	18.3%	11.93

Figure 129 through Figure 131 show variations of fuel consumption shares of the India's iron and steel sector for all scenarios from 2010 to 2050. Similar to the U.S. and China, purchased coke and on-site electricity generation are favored over coke production and off-site electricity generation within the sector. In the Base, Base-E, and ET scenarios, total share of coke and coking coal in total energy consumption of the India's iron and steel sector decreases throughout the planning horizon in accordance with the decreasing production in BOF process. However, there is still a certain amount of coke production in the sector by using coking coal at the end of the planning horizon in the Base, Base-E, and ET scenarios (Figure 127, Figure 128, and Figure 130). On the other hand, Figure 129 and Figure 131 show that coke production in the sector reaches to zero starting from 2030 under emission restriction in the ER and EC scenarios, respectively. In addition, natural gas is used more in the ER and EC scenarios (compared to the Base, Base-E, and ET scenarios). Share of non-coking coal usage, on the other hand, in total energy consumption decreases from 51.4% in the Base-E scenario to almost 43% in the ER and EC scenarios in 2050, corresponding to decreasing EAF-DRI (Coal based) production shares in the ER and EC scenarios.

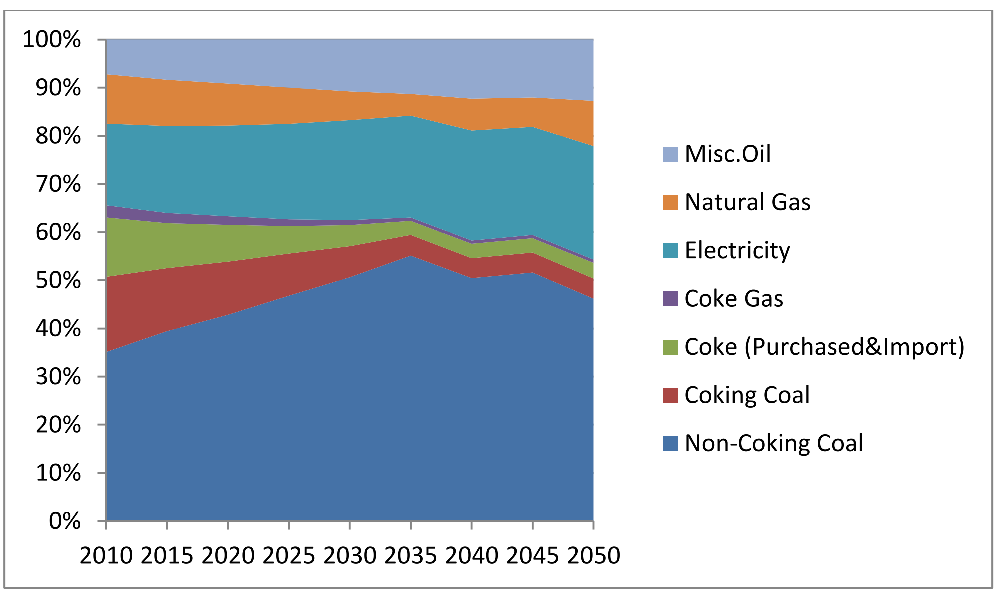

Figure 127. Fuel Based Energy Consumption of the India's iron and steel sector in the Base Scenario (%)

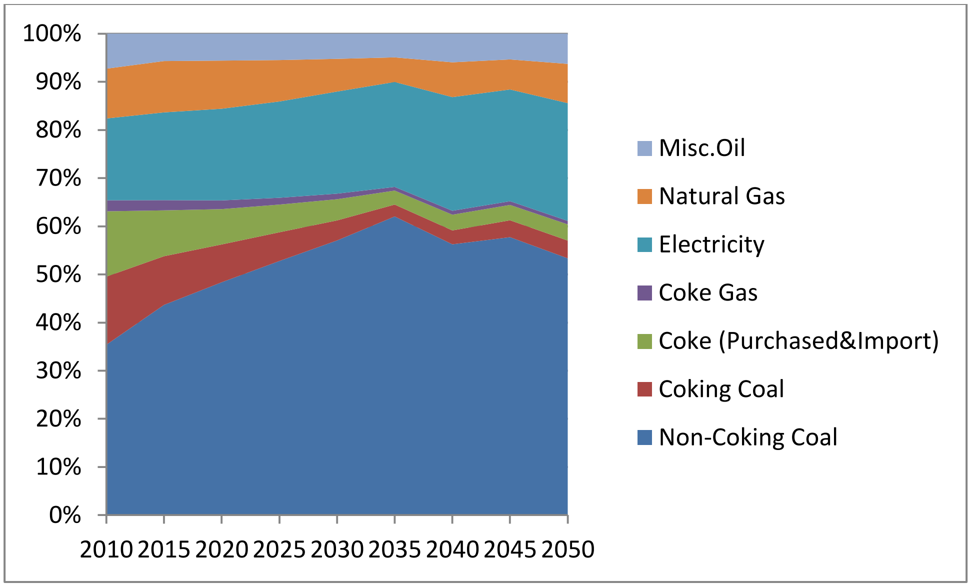

Figure 128. Fuel Based Energy Consumption of the India's iron and steel sector in the Base-E Scenario (%)

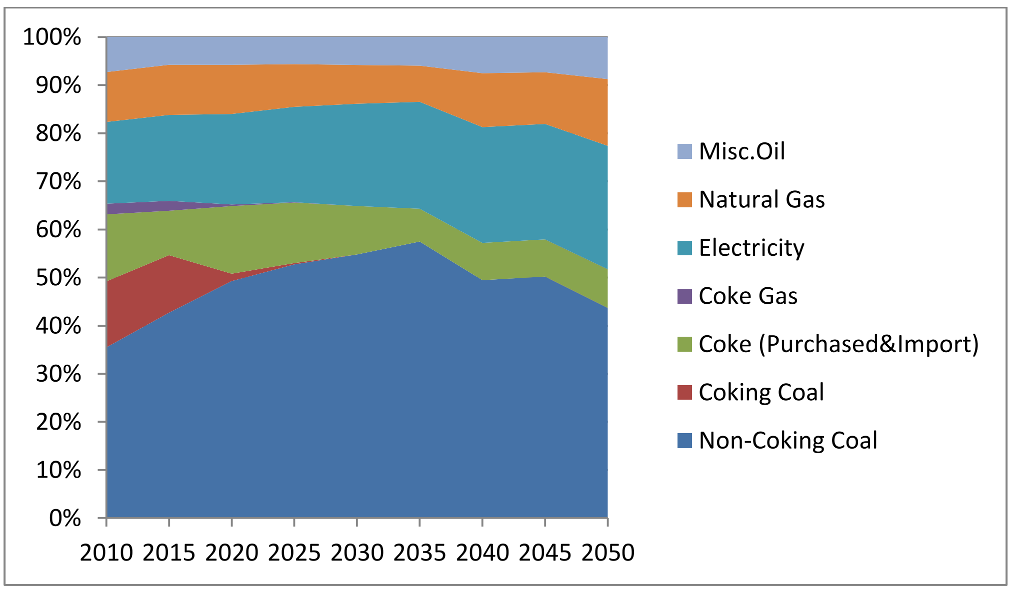

Figure 129. Fuel Based Energy Consumption of the India's iron and steel sector in the ER-20 Scenario (%)

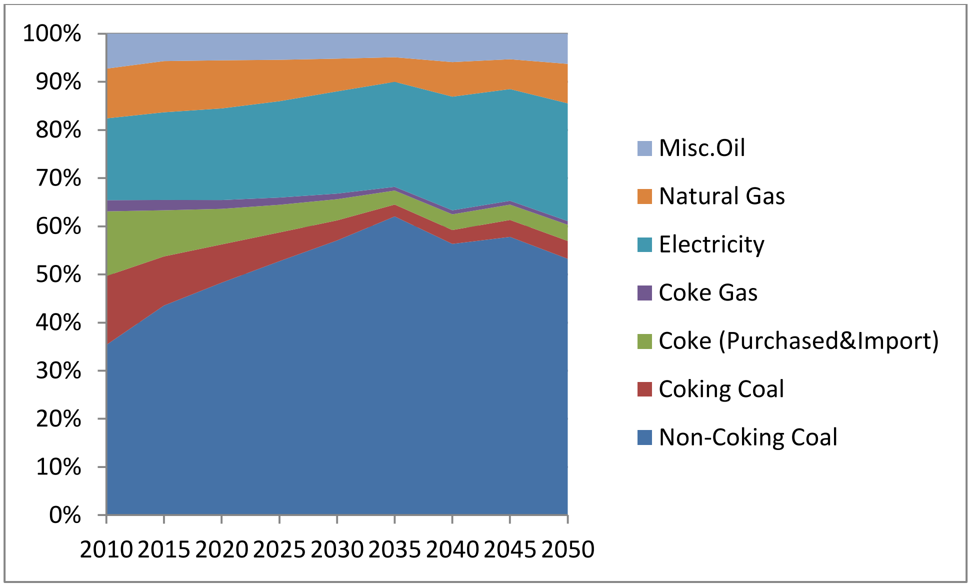

Figure 130. Fuel Based Energy Consumption of the India's iron and steel sector in the ET-20 Scenario (%)

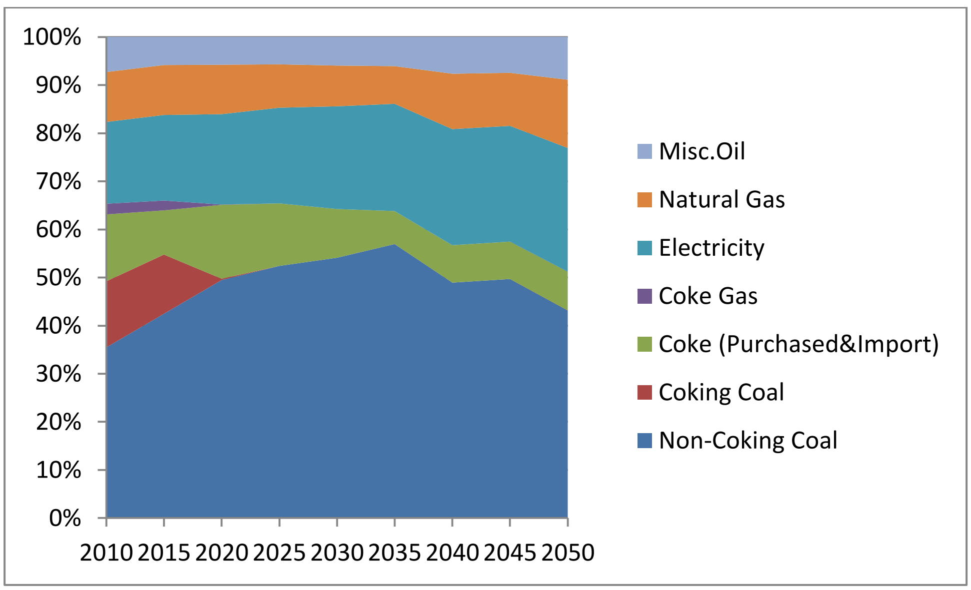

Figure 131. Fuel Based Energy Consumption of the India's iron and steel sector in the EC-20 Scenario (%)

In general, efficiency improvements (i.e., reduction in energy intensity) projected in the scenarios are the results of production shifts to the more energy efficient processes such as EAF production and investments in efficiency measures in the production systems. First, because the unit cost of EAF production is lower in the U.S. iron and steel sector compared to the other processes (i.e., BOF production), the modeling's optimization process tends to abandon BOF production and increase EAF production even without any emission-reduction target being imposed. Second, in the China's iron and steel sector, because BOF production is the cheapest among all production processes, BOF production will dominate the steel sector when there is no emission reduction restriction such as the case for ET scenarios. China's EAF production share will increase when there is requirement for emission reduction, such as the cases in ER and EC scenarios. Third, in India's iron and steel sector, EAF-DRI (Coal based) production is the most dominant process with more than 50% shares starting from 2020 through 2050 in the Base and Base-E scenarios. This production trend does not change when there is no emission restriction such as the case with ET scenarios. In contrast, India's EAF-DRI (Coal based) production shares are projected to be replaced with EAF production shares in the ER and EC scenarios.

Table 114 shows the projected shares of EAF production in each country under different scenarios in 2030 and 2050. Increasing shares of EAF production in China and India in the ER and EC scenarios are the major factors for emission reduction in those scenarios.

Table 114. Share of EAF Production in Total Steel Production Projected in the Base, Base-E, ER, ET, and EC Scenarios

	Share of EAF Production in Total Steel Production (%)					
	The U.S.		China		India	
	2030	2050	2030	2050	2030	2050
Base Scenario	81.9%	90.0%	15.0%	20.1%	8.0%	28.6%
Base-E Scenario	83.4%	90.0%	20.9%	22.0%	8.0%	20.9%
ER-10 Scenario	84.1%	90.0%	27.5%	47.1%	8.0%	25.7%
ET-10 Scenario	83.3%	90.0%	20.9%	22.0%	8.0%	21.0%
EC-10 Scenario	83.3%	90.0%	28.4%	47.1%	8.0%	27.9%
ER-20 Scenario	84.2%	90.0%	38.5%	50.0%	12.2%	38.9%
ET-20 Scenario	83.0%	90.0%	20.9%	21.9%	8.0%	21.1%
EC-20 Scenario	83.0%	90.0%	39.7%	49.9%	13.7%	39.8%
ER-30 Scenario	84.2%	90.0%	50.0%	50.0%	33.1%	56.9%
ET-30 Scenario	83.5%	90.0%	20.9%	21.8%	8.0%	21.3%
EC-30 Scenario	83.5%	90.0%	50.0%	50.0%	35.4%	58.0%

Emissions projected for the ER scenarios result from additional investments in energy efficiency improvement in response to pre-defined different emission targets in each country. In EC scenarios, additional investments in efficiency measures in China and India are also expected due to export and emission targets; while in ET scenarios, the U.S. decreases its emissions by import from the other countries without committing to additional expense for energy efficiency investments in any countries.

For the U.S., there is no associated carbon abatement cost under the ET and EC scenarios; while for China's and India's iron and steel sectors, there is no carbon abatement cost in ET scenarios. From the data presented in Table 115 and Table 116 for ER-20 scenario, total production costs of iron and steel sector in the U.S. and China are projected to rise 0.3% and 2.3%, respectively, up from the Base scenario in cumulative terms for the period 2010 - 2050. In contrast, Table 117 shows that total cumulative cost of India's iron and steel sector is projected to drop by 4.8% and 4.0% in the ER-20 scenario, when compared to the Base and Base-E scenarios, respectively. This is due to the efficiency measures that bring cost reduction while satisfying the requirements for the least cost objective of the ISEEM-IS model.

Table 115. Production Costs in the U.S. Iron and Steel Sector Projected in the Base, Base-E, and ER Scenarios

	Base Scenario	Base-E Scenario	ER-10 Scenario	ER-20 Scenario	ER-30 Scenario
Cumulative Total Cost between 2010-2050 (Billion $)	502.2	499.0	501.9	504.0	505.9
Share of Investment Cost (%)	9.2%	9.8%	10.2%	10.4%	10.2%
Share of O&M Cost (%)	21.7%	21.2%	21.2%	21.2%	21.4%
Share of Raw Material Cost (%)	56.4%	57.0%	56.8%	57.3%	57.9%
Share of Energy Cost (%)	12.6%	12.0%	11.8%	11.2%	10.5%
Abatement Cost of CO_2 in 2030 (\$/ton CO_2)			38.0	45.4	43.2
Abatement Cost of CO_2 in 2050 (\$/ton CO_2)			-87.4	-12.5	14.8

Table 116. Production Costs in the China's iron and steel sector Projected in the Base, Base-E, ER, and EC scenarios

	Base Scenario	Base-E Scenario	ER-10 Scenario	ER-20 Scenario	ER-30 Scenario
Cumulative Total Cost between 2010-2050 (Billion $)	3922.7	3904.7	3942.6	4011.5	4113.9
Share of Investment Cost (%)	9.8%	10.3%	11.6%	13.4%	14.0%
Share of O&M Cost (%)	7.6%	7.9%	7.4%	7.3%	7.4%
Share of Raw Material Cost (%)	47.2%	50.3%	52.4%	52.4%	53.9%
Share of Energy Cost (%)	35.4%	31.5%	28.6%	26.9%	24.7%
Abatement Cost of CO_2 in 2030 (\$/ton CO_2)			33.3	51.0	65.1
Abatement Cost of CO_2 in 2050 (\$/ton CO_2)			-43.8	-19.4	18.4
			EC-10 Scenario	EC-20 Scenario	EC-30 Scenario
Cumulative Total Cost between 2010-2050 (Billion $)			3964.1	4057.7	4182.2
Share of Investment Cost (%)			11.7%	13.5%	13.6%
Share of O&M Cost (%)			7.4%	7.3%	7.4%
Share of Raw Material Cost (%)			52.4%	52.6%	54.6%
Share of Energy Cost (%)			28.5%	26.6%	24.3%
Abatement Cost of CO_2 in 2030 (\$/ton CO_2)			44.8	54.4	69.2
Abatement Cost of CO_2 in 2050 (\$/ton CO_2)			-35.4	-4.6	28.8

Table 117. Production Costs in the India's iron and steel sector Projected in the Base, Base-E, ER, and EC scenarios

	Base Scenario	Base-E Scenario	ER-10 Scenario	ER-20 Scenario	ER-30 Scenario
Cumulative Total Cost between 2010-2050 (Billion $)	1737.4	1605.8	1612.4	1648.1	1712.8
Share of Investment Cost (%)	5.4%	9.0%	9.2%	8.5%	7.7%
Share of O&M Cost (%)	11.0%	9.8%	9.8%	9.4%	8.7%
Share of Raw Material Cost (%)	47.2%	46.8%	46.8%	47.4%	49.0%
Share of Energy Cost (%)	35.4%	34.4%	34.2%	34.6%	34.6%
Abatement Cost of CO_2 in 2030 (\$/ton CO_2)			-13.8	-10.3	-1.8
Abatement Cost of CO_2 in 2050 (\$/ton CO_2)			-27.3	-18.9	-5.8
			EC-10 Scenario	EC-20 Scenario	EC-30 Scenario
Cumulative Total Cost between 2010-2050 (Billion $)			1616.7	1664.9	1741.8
Share of Investment Cost (%)			9.2%	8.2%	7.7%
Share of O&M Cost (%)			9.7%	9.3%	8.6%
Share of Raw Material Cost (%)			46.9%	47.5%	49.2%
Share of Energy Cost (%)			34.2%	35.0%	34.5%
Abatement Cost of CO_2 in 2030 (\$/ton CO_2)			0.5	-39.0	-80.1
Abatement Cost of CO_2 in 2050 (\$/ton CO_2)			-85.7	-111.0	-150.1

The model projections of U.S. production, energy use, and emissions in the ET and EC scenarios are the same for a given year, due to the much lower unit production costs of Chinese steel import and Indian steel import to the U.S. market. Particularly, the unit cost of steel import from China in the model is much lower than that of the U.S. unit production cost in both commodity trading (ET scenarios) and carbon trading (EC scenarios) scenarios. Although there are added costs associated with the carbon trading strategy, the unit cost of imported steel production remains much lower than that of the U.S. domestic production. As a result, the model's optimization process favors importing from China as long as the amount of import is within the allowable import boundary (e.g., 75% of dynamic import).

It is important to note that many other factors can influence the optimization process with cost minimization objective, such as added costs due to transportation, tariff structure, environmental regulations pertaining to steel production and local pollutions, capital and operational expenses, raw material and energy costs, and labor costs, etc. In the ISEEM-IS model, a lower unit production cost in China alone does not necessarily mean that the U.S. would need to import from China before achieving the maximum import limitations. In fact, the optimization process makes the decision according to all information collected for the modeled system and provides the least cost fuel-technology-production-import combination that satisfies the specified demand with the cost minimization objective. For example, one can argue that the magnitude of added cost for complying with environmental regulations in the U.S. can be quite different than that of other countries (e.g., much higher than that of China or India). In the future, it would be useful to perform sensitivity analysis by applying different input to the ISEEM-IS model runs to further investigate the influence of the relevant model input on the projected outcomes. For discussion purpose, we assume that the magnitudes of unit production cost in China will be increased by 10%, 20% and 40% due to increased environmental regulations, and use them in the ISEEM-IS model runs while other input are held unchanged. The preliminary runs indicate that an increase by 10% in unit production cost in China still does not change the model output on steel trading volumes. An increase of China production cost by 20% starts to affect the projection outcomes, e.g., decreases in steel import of the U.S. in the last two periods. An increase of China unit production cost by 40%, on the other hand, does change the landscape of steel trading volumes significantly, reflecting the impacts of large increase in China unit production cost (e.g., 20-30% higher than the unit production cost in the U.S.).

It should also be noted that the discussion of results is under a set of assumptions pertaining to the model parameters and input such as the prices and availabilities of energy sources, raw materials, and technologies (data set and details of the assumptions can be found in Karali et al. 2012). Under a different set of model data, the model results may indicate different options for the U.S. iron and steel market. In addition, there is a need to further investigate the impacts of variations in different scenarios in the China and India's iron and steel sectors to gain a better understanding of the emission effects of the U.S. policies. For example, the projection of the Chinese annual steel demand was established through a previous LBNL study (Zhou et al. 2011). Our model assumption includes a stipulated constraint for EAF production shares, while the optimization process in ISEEM-IS model seeking for cost minimization may favor much higher EAF production shares when the constraint is lifted. Future work on the ISEEM-IS model can include further improvement and updating of the input data sets, and the analysis of the U.S., China's and India's iron and steel sectors under various scenarios and constraints.

6. Summary of Modeling Outcomes

The overall goal of the ISEEM-IS model in this study was to quantify emission reduction potentials in the iron and steel sectors of three major economies (i.e., U.S., China, India) under various long-term scenarios. In this project, we set out to model and evaluate the impacts of several U.S. mitigation strategies that include commodity and carbon trading with China and India's iron and steel sectors, considering various targets for national and global scale emission reductions.

For this purpose, the ISEEM bottom-up energy modeling framework has been applied to provide detailed projections starting from 2010 through 2050. The ISEEM-IS model was developed to carry out a high level of detail analysis on a country-by-country basis for the U.S., China, and India's iron and steel sectors. The database used for the modeling was compiled using updated data and information from various resources including WSA, USGS, China Steel Year Books, IBM, EIA, and recent studies performed by the LBNL team on techno-economic analysis of energy efficiency measures and production in the iron and steel sector in the three countries. Development of the ISEEM-IS model provides an analytical tool for environmental energy policy analysis and information for decision making in the U.S., China, and India's iron and steel sectors.

The model can produce results favoring lower-cost production technologies, raw materials, and energy sources under a set of usage constraints and emission reduction targets.

6.1. Base and Base-E Scenarios

The ISEEM-IS model is used to establish and quantify a Base scenario, Base-E scenario, and then three alternative scenarios with different mitigation strategies. In addition to Base scenario that reflects business-as-usual case, we also quantify another base scenario, namely Base-E scenario, which is a projection of future production, energy use, carbon emissions, and production costs, not only reflecting business-as-usual trends including autonomous improvement via advanced production, but also considering the investments and implementation of energy efficient production technologies without any specific emission target. Compared to Base scenario, Base-E scenario accounts for progress on energy efficiency attributed to the adoption of new energy efficiency technologies throughout the planning horizon. While Base scenario does not take into account of adopting energy efficiency measures, it reflects business-as-usual practice and allows autonomous energy efficiency improvement associated with adoption of advanced production technologies in any given year between 2010 and 2050 that is subject to cost minimization goal and/or replacement requirements for retiring production equipment.

The Base scenario results indicate that energy and emission intensities of the iron and steel sectors of the three countries show a decreasing trend autonomously (in absence of any emission target). For example, energy intensity (i.e., energy use per tonne steel production) declines by 1.3%, 0.8%, and 0.9% annually on average for the period 2010-2050 in the U.S., China, and India's iron and steel sectors, respectively; corresponding to annual reduction in carbon emission intensity by 1.5%, 0.6%, and 1.1% on average between 2010 and 2050. The decreases in energy intensity over time were partly attributed to structural changes exhibited by gradual process shifts from the relatively expensive BOF production to the less expensive and more efficient production processes (e.g., EAF production). In addition, advanced production technologies also contributed to autonomous improvement of the energy efficiency throughout the planning horizon. For example, the share of BOF production in the U.S. gradually decreases in the medium- and long-term in the Base scenario - down from 38.7% in 2010 to 15.0% in 2030 and 10.0% 2050, due to relatively expensive technological, energy, and raw material costs compared to those of EAF production. Under the model assumptions, BOF production is less favorable in the ISEEM-IS model optimization process. In contrast, steel production in China is dominated by BOF production throughout the period. However, the share of EAF production rises from 10.4% in 2010 to 15.0% in 2030 and 20.1% in 2050 with the increasing availability of domestic scrap starting in 2025. The increased share of EAF production in China is projected to be closely linked with increased availability of lower-cost domestic scrap in the Base scenario. On the other hand, cost of EAF-DRI (Coal based) production is the lowest for India's iron and steel sector. Thus, steel production in India is mostly dominated by EAF-DRI (Coal based) process throughout the period; however, scarcity in domestic iron ore availability leads to the usage of more expensive imported iron ore especially after 2040. The increases in production cost of EAF-DRI (Coal based) make EAF production more attractive over time in the model for India. The share of EAF-DRI (Coal based) production rises from 33% in 2010 to 78% in 2035, and then drops to 56% in 2050 in India. In addition, due to increasing domestic scrap availability, EAF production cost becomes lower in the second half of the planning horizon. The Base scenario results show that once scrap becomes more abundant in China and India, scrap prices would drop to reasonable levels over time (e.g., in 2020 for China, and in 2040 for India). The increases in EAF production will then help reducing energy and CO_2 emission intensities over time. This implies that the scrap price drops indirectly contribute to decreasing energy and emission intensity of the iron and steel sector.

In addition, the U.S. iron and steel sector exhibits the lowest energy intensity level in the Base scenario compared to China and India: Energy intensity of the U.S. is approximately half of those in China and India in each model year (e.g., energy intensity of the U.S., China, and India is 7.5 GJ/tonne, 15.1 GJ/tonne, and 20.1 GJ/tonne in 2030, respectively). This result indicates that the U.S. iron and steel sector has a more energy-efficient iron and steel production structure and technologies compared to the China and India's iron and steel sectors. This is largely due to much higher shares of EAF production process that is most energy efficient in the U.S. Although China and India exhibit higher efficiency improvement potentials via increasing efficient production technologies, the energy intensity level would still be higher than that of the U.S. due to the structural limitations assumed for the model.

In the Base scenario China exhibits the lowest steel production cost compared to the U.S. and India throughout the planning horizon, while EAF production cost in the U.S. is lower than production cost in India (with any process). Therefore, the model would not favor U.S. import from India even though the trading restrictions were to be relaxed in the Base scenario; while China would become the main export for steel production to the U.S. and India markets.

Compared to the Base scenario, the Base-E scenario projects an average annual emission reduction by 2.9%, 0.9%, and 9.1% in the U.S., China, and India's iron and steel sectors, respectively, from 2010 to 2050. It is interesting to note that both the U.S. and India exhibit moderate to high emission reduction opportunities in the Base-E scenario due to investments and implementation of energy efficient production technologies without imposing any emission restriction. In the ISEEM-IS model, a number of efficient technologies identified for India and the U.S. are cost effective, and are favored by model's the optimization process due to the least cost objective for the ISEEM-IS model. As a result, investments and applications of cost-effective efficiency technologies in the Base-E scenario lead to major reductions in the India's iron and steel sector annual energy consumption and emissions (e.g., 6-13% annual reduction in energy consumption, and 4%-13% annual reduction in emissions from 2015 to 2050); smaller reductions for the U.S. iron and steel sector (2-9% annual reduction in energy consumption and emissions from 2015 to 2050). Annual energy consumption and emissions of the China's iron and steel sector are also reduced in the Base-E scenario, by 0.1% - 4% reduction in annual energy consumption and emissions from 2015 to 2035. After 2035, however, energy consumption and emission levels increase due to the different investments and process structure projected by optimization processes for the Base-E scenario. In the Base-E scenario, India also exhibits the largest reduction in annual total cost of the iron and steel production when compared to Base scenario, by an annual difference of 6.9% during 2010 and 2050. In particular, the efficient production technologies used in pig iron and any type of scrap based steel production (i.e., EAF or EAF/DRI) in India contribute to the objective of total cost reduction.

Annual production shares of the U.S. and China's iron and steel sectors do not change from the Base to Base-E scenarios during the period of 2010 and 2050, while there are some changes in India in the long term. For the U.S., because the BOF production share for the Base scenario is already close to the lower bounds predefined in the model, there is practically not any room for process shifts from BOF to EAF production in the U.S. iron and steel sector. Even though there is some cost-effective efficiency improvement in BOF production, it would not be sufficient to make BOF production more favorable than EAF production because BOF production is still more expensive in the U.S. for the Base-E scenario. For China, availability of efficient production technologies leads to a slight increase of EAF production share between 2025 and 2035 (by 5%). For India, availability of efficient production technologies in the India's iron and steel sector in the Base-E scenario increases the production of EAF-DRI (Coal based) process while decreasing production in EAF process in the long term. India's production share of EAF-DRI (Coal based) process is projected to change from 56% for the Base scenario to 64% for the Base-E scenario in 2050.

6.2. Scenarios for Emission Reduction Strategies

Three alternative scenarios applied in this project reflect different CO_2 emission reduction strategies and potentials of the U.S. iron and steel sector under different strategies or tools such as national-scale energy efficiency measurements, commodity trading, and carbon trading. The following highlights the three mitigation strategies with various emission targets, and the projection outcomes.

The 'Emission Reduction without Trading (ER)' scenario group assumes that the strategy focuses on implementing energy efficiency measures on the national scale. The purpose of this scenario is to analyze the emission reduction potentials in iron and steel sectors of the each country by means of investing in advanced production technologies and/or efficient production technologies, without any carbon reduction instrument such as trading commodities or carbon. In ER scenarios, three levels of emission reduction targets will be set for each country.

As an alternative, the 'Emission Reduction with Commodity Trading (ET)' scenario group assumes that the strategy focuses mainly on commodity trading in order to meet the emission restrictions for a selected region or country (i.e., The U.S.). In ET scenarios, three levels of emission reduction targets are only applicable to the U.S. iron and steel sector, while there is no emission targets set for its trading partners – China or India in this case. The primary purpose is to analyze the emission reduction potential of the U.S. iron and steel sector, and commodity trading with China and India is considered to be an alternative instrument to national scale efficiency investment for U.S. domestic emission reduction.

As another alternative, the 'Emission Reductions with Carbon Trading (EC)' scenario group assumes that the strategy focuses on carbon trading of the U.S. from China and India. This scenario assumes that a specific global emission reduction level will be accomplished by implementing carbon trading mechanism for the U.S. from China and India. In EC scenarios, three levels of emission reduction targets will be set for each country.

We apply consistent targets for reducing energy-related CO_2 emissions across three scenarios, i.e., the targeted annual carbon emissions for each scenario will be lower than the annual carbon emissions in Base scenario by 10%, 20%, and 30%, respectively, for the selected countries. All three emission reduction scenarios result in reducing total energy consumption in the U.S. iron and steel sector (due to the emission restrictions applied in each scenario). For China and India's iron and steel sectors, the ER and EC scenarios leads to significant reductions in sector energy consumption. In general, a higher level of emission restrictions results in a lower level of annual energy consumption for each country. For example, energy consumption is higher in the scenarios where 10% emission restrictions are applied compared to the scenarios in which 20% or more emission restrictions are applied for the selected country.

All three countries modeled are capable of reducing CO_2 emissions and emission intensities via country-specific energy efficiency measures applied in this study, while the model's optimization process favors the U.S. to reduce its iron and steel sector emissions via steel import (instead of investing in efficiency measures in the country) because of much cheaper steel production in China and India compared to the U.S.

Effects of commodity or carbon trading strategies on annual energy consumption, CO_2 emissions, and cost reductions are more apparent in both commodity and carbon trading scenarios (EC and ET) than in ER scenarios. For example, corresponding to the 20% annual carbon reduction target, annual energy consumption decreases by 11% in ER20 scenario and 19% in both ET20 and EC20 scenarios in 2030; and by 10% in ER20 scenario and 20% in both ET20 and EC20 scenarios in 2050. The larger reduction in ET20 and EC20 scenarios reflects domestic production decreases instead of improvements in energy and emission structure of the iron and steel sector, because importing steel from China and India is preferred in the model's optimization process. The ER20 scenario, in contrast, forces the model to make relatively cleaner energy choices (such as implementing energy efficiency measures and using fuels with lower emission factors), which would require additional investments and expenses throughout the planning horizon. For example, the added cost associated with cleaner energy choices that result in 11% decline in annual energy consumption for the ER20 scenario is 0.8 billion US dollars in 2030. In general, the results show that the ET and EC scenarios lead to a lower level of energy consumption in the U.S. iron and steel sector compared to the ER scenarios. However, in the ET and EC scenarios, decreasing share of steel production due to increasing imports is the reason for lower domestic energy demand in the U.S. It is interesting to note that the production levels projected for the U.S. iron and steel sector from each of the EC scenarios are identical to their counterparts projected for ET scenarios (i.e., emission reduction with commodity trading scenarios). Apparently, higher steel prices expected in the EC scenarios than the ET scenarios due to investments in efficient production technologies in China and India do not lower U.S. import from China or India. In addition, the projected U.S. steel import is the same between EC and ET scenarios under the same emission target.

Because the model favors the energy sources with lower emission factors (e.g., purchased coke and offsite electricity) as well as efficiency measures in the ER scenarios, carbon emission intensities are lower despite of higher levels of energy consumption of the U.S. iron and steel sector in the ER scenarios when compared to their counterparts in ET and EC scenarios.

As expected, iron and steel sector of each country (the U.S., China, and India) tends to switch to EAF production over time, which has the lowest energy intensity, and to gradually avoid or abandon other production processes including BOF and EAF-DRI (Gas based and Coal based) in the ER scenarios. However, as mentioned earlier, BOF production of the U.S. iron and steel sector in the Base scenario is already close to its lower bound of production shares predefined in the model. As a result, there is practically not much room for process shifts from BOF to EAF production in the U.S. iron and steel sector. Instead, the model projects some minor shifts from EAF-DRI (Gas based) to EAF production. In the China's iron and steel sector, on the other hand, there are significant shifts from BOF to EAF production in each ER scenario. For the same year, EAF production share increases with the increase of CO_2-emission reduction targets (i.e., 10%, 20%, and 30%). For example, EAF production share in the ER-30 scenario is the highest, reaches 50% in 2030 compared to 33% in the ER-20 scenario and 27% in the ER-10 scenario in the same year. However, starting from 2045, share of EAF production start to approach to the same level regardless of difference in emission reduction targets. For example, EAF production share in the

China’s iron and steel sector approaches to the same level for all three ER scenarios in the long term, independent of variation in emission reduction targets (10-30%). In the India’s iron and steel sector, the Base-E scenario already results in approximately 10-13% annual emission reduction when compared to the Base scenario from 2015 to 2035. Therefore, in the ER-10 scenario, annual production projections will automatically follow those in the Base-E scenario until 2035, and then the optimization process will adjust the annual production to meet the 10% emission reduction goal from 2040 to 2050. In the ER-20 and ER-30 scenarios, on the other hand, with higher emission reduction, major shifts from EAF-DRI (Coal based) production to EAF production are observed. Approximately 57% of the total production comes from EAF process in 2050 in the ER-30 scenario, and approximately 39% of the total production comes from EAF process in 2050 in the ER-20 scenario (compared to approximately 26% of the total production in 2050 in the Base scenario).

Compared to the Base scenario, the ER-10, ER-20, and ER-30 scenarios lead to 9.0%, 13.7%, and 17.8% reduction in annual energy consumption levels of the U.S. iron and steel sector, respectively in 2030. Since there is not much change in production structure of the U.S. iron and steel sector, those reductions are mainly the results from investments in both advanced and efficient production technologies and usage of low-emission energy sources. On the other hand, in China and India’s iron and steel sectors, reduction of annual energy consumption is also attributed to switches between the steel production processes. For example, the ER-10, ER-20, and ER-30 scenarios lead to 9.5%, 18.6%, and 26.2% reduction in annual energy consumption levels of the China’s iron and steel sector, respectively in 2030. Those reductions are the combined results of major process shifts from BOF to EAF production, the efficiency improvements in production processes (i.e., investments in both advanced and efficient production technologies), and usage of low-emission energy sources in China. The ER-10, ER-20, and ER-30 scenarios lead to 12.1%, 15.9%, and 23.6% reduction in annual energy consumption levels of the India’s iron and steel sector, respectively in 2030. The energy reductions are the combined results of major process shifts from EAF-DRI (Coal based) to EAF production, the efficiency improvements in production processes (i.e., investments in both advanced and efficient production technologies), and usage of low-emission energy sources in India.

On the other hand, improvement in energy intensity levels is higher in the China and India’s iron and steel sectors compared to the U.S. iron and steel sector in the ER scenarios. For example, in the ER-20 scenario, energy intensity levels are decreased by 6.9%, 22.5%, and 17.6% in 2050 in the U.S., China, and India’s iron and steel sectors, respectively, compared to those of the Base scenario. However, even though the energy intensities are projected to reduce remarkably in the China’s and India’s iron and steel sectors throughout the years under the ER scenarios, they cannot be reduced to the levels projected for the U.S. Higher capacity and usage of EAF production process always leads to lower energy intensity levels in the U.S. Thus, even though China and India had higher efficiency improvement potentials via efficient production technologies (compared to the U.S.), they would never reach the U.S. levels due to structural limitations.

Emission reduction targets achieved in the ER scenarios are accompanied by additional costs for energy efficiency improvement in each country. Costs of emission reduction in the ER scenarios differ from country to country. Negative carbon abatement costs are observed in some years for the U.S. and China, and all model years for India. The results indicate that with the efficient production technology structure defined in the ISEEM-IS model, India’s iron and steel sector reaches the targeted emission reduction or more with great cost reduction. As mentioned earlier, the Base-E scenario leads to major emission reduction (i.e., approximately 10-13% annual emission reduction from 2015 to 2035), compared to the Base scenario, without any emission cap or target but with cost effective efficiency measures that bring cost reduction to the least cost objective of the ISEEM-IS model. Total cumulative cost of the iron and steel production in India between the periods 2010 and 2050 is already 6.9% less in the Base-E scenario, compared to the Base scenario. In contrast, for example, total cumulative cost of India's iron and steel sector is projected to drop 4.8% in the ER-20 scenario, compared to the Base scenario. The difference of 2.9% indicates that additional efficient production technologies used in the ER-20 scenario are not cost-effective for the least cost objective. However, compared to the Base scenario, the net total cumulative cost is always lower than those in the Base scenario. Therefore, carbon abatement costs (which is the cost of per tonne emission reduction compared to the Base scenario) of the India's iron and steel sectors are observed negative in all three ER scenarios, even though there are additional efficient production technology investments. On the other hand, negative annual carbon abatement costs are exhibited starting in 2035 and 2045 for both ER-10 and ER-20 scenarios in the U.S. iron and steel sector. Compared to the U.S., China's sector exhibited negative annual carbon abatement costs a few years later in both ER-10 and ER-20 scenarios: The ER-10 scenario corresponds to negative abatement costs after 2045, while the ER-20 scenario corresponds to negative abatement costs in 2050. Our model results for ER-30 scenario in both the U.S. and China's iron and steel sectors (in which larger investments are needed to decrease emissions by 30%) indicate that a longer period of time beyond 2050 would be expected for the added investment to be paid off, or become cost effective. However, as noted earlier, this conclusion highly depends on the model assumptions, e.g., technology definitions and parameter structures used for the efficient production technologies in the U.S., China, and India's iron and steel sectors.

Under the ET and EC scenarios, a portion of annual steel production of the U.S. iron and steel sector is projected to be replaced with imports from China and India, and the level of replacement increases when the emission restriction targets are higher. It is cheaper for the U.S. to import from China and India compared to investment in efficient production technologies in national steel production. In addition, price increases of China and India steel in the EC scenarios (compared to the ET scenarios) associated with investments in efficient production technologies do not make China or India steel unattractive for export to the U.S. The levels of the U.S. steel import projections are the same between commodity trading and carbon trading strategies given the same emission target, so are the production increases in China and India (due to increasing exports). Unit cost of per tonne steel production in China is the lowest among all model countries (i.e., the U.S., China, and India) with the parameter structure used in the ISEEM-IS model. Although carbon abatement costs are higher in China compared to the U.S., the sum of production cost plus carbon abatement cost is still much lower in China compared to its counterpart in the U.S. In addition, carbon abatement cost in India are negative compared to the U.S. (see Section 4.3), which makes carbon trading from India attractive for the U.S. in lieu of investing in efficiency measures in the U.S. It should be noted that this modeling result is affected by a set of parameters, such as energy prices, capital and O&M costs, material prices in modeled countries, the tariffs on imported and exported products, and transportation and fuel costs, etc. For example, in a perfect competitive market (e.g., no financial incentives or subsidies are considered), with higher tariff and transportation cost projections, the magnitudes of energy savings and carbon emission reduction from EC scenarios could become different from those of ET scenarios.

ISEEM-IS model's annual projections favor imports from China to the U.S. in the ET and EC scenarios because of the lowest unit production cost in China. With annual production increase ranging from 0.4% to 2.0% through the planning horizon, China satisfies 6.6%, 14.1%, and 22.1% of the U.S. steel demand as period averages in the ET-10/EC-10, ET-20/EC-20, and ET-30/EC-30 scenarios, respectively. With annual production increase ranging from 0.1% to 5.2%, India satisfies 1.5%, 4.7%, and 6.2% of the U.S. steel demand as period averages in the ET-10/EC-10, ET-20/EC-20, and ET-30/EC-30 scenarios, respectively. In the meanwhile, annual production shares of the U.S. in the ET and EC scenarios remain unchanged from that of the Base scenario, while annual energy consumption and emissions of the U.S. iron and steel sector decline through the planning horizon in the ET and EC scenarios compared to the Base scenario. In addition, energy and emission intensity levels are very close to those of Base-E scenario. This indicates that efficiency improvements in the ET and EC scenarios are the results of efficient production technologies that bring cost reduction to the least cost objective, as is the case in the Base-E scenario. Compared to the Base-E scenario levels, no additional efficiency investments are projected in the ET and EC scenarios. Therefore, it is clear that the U.S. iron and steel sector decreases its emissions to the scenario levels by importing the steel from China and India instead of investing in efficient production technologies and producing in the U.S. under the ET and EC scenarios. At the same time, annual energy consumption and emission levels are different between ET and EC scenarios for China's and India's iron and steel sectors, respectively. In the ET scenarios, extra annual production for export to the U.S. increases the levels of energy consumption and carbon emissions from both China and India's iron and steel sectors. This results in a net increase of total energy consumption and carbon emissions from the three countries collectively in the ET scenarios. Therefore, decreasing emissions in the U.S. iron and steel sector alone by increasing steel imports from China and India does not result in reducing net global emissions or global risks in climate change, instead it simply transfers actual production burdens to China and India where actual intensities of energy use and emissions are actually higher.

In the EC scenarios, on the other hand, even though steel production in China and India increases because of the increasing export to the U.S., annual energy consumption and CO_2 emission levels are lower than those in the Base scenario. There is an increased shift in annual production shares in China and India from BOF production to the more efficient steel production process, e.g., EAF production in China and EAF-DRI (Coal based) production in India. For example, the share of EAF production reaches to 50% in each EC scenario in China, and approximately 30%, 40%, and 50% in the EC-10, EC-20, and EC-30 scenarios, respectively, in India in 2050. The production shifts result in much lower energy intensity levels in China and India in each EC scenario; while U.S.' lowest energy intensity levels through the planning horizon remain unchanged – an indication that there are no additional investment in energy efficiency improvement in the U.S. The results from EC scenario are somewhat similar to ER scenario results.

Overall projections for both the ET and EC scenarios indicate the same changes when compared to the Base scenario. The main reason is the much lower costs of Chinese steel import and Indian steel import to the U.S. market. Particularly, the unit cost of steel import from China in the model is much lower than that of the U.S. unit production cost in both commodity trading (ET scenarios) and carbon trading (EC scenarios) scenarios. Even with additional costs associated with carbon trading, the unit cost of imported steel remains much lower than that of the U.S. domestic cost. As a result, the optimization process prefers importing from China as long as the amount of import is within the allowable import boundary.

In fact, there are many key factors that influence the optimization process (i.e., cost minimization objective), such as added costs due to transportation, tariff structure, environmental regulations pertaining to steel production and local pollutions, capital and operational expenses, raw material and energy costs, and labor costs. A cheaper production cost in China alone does not necessarily mean that the U.S. would need to import from China before achieving the maximum import limitations. The optimization process makes the decision according to all information collected from the modeled system and provides the least cost fuel-technology-production-import combination that satisfies the specified demand (with respect to minimization cost objective). For example, one can argue that the magnitude of added cost for complying with environmental regulations in the U.S. can be quite different than that of other countries (e.g., China). In this perspective, it would be useful to perform sensitivity analysis by applying different input to the ISEEM-IS model runs to further investigate the influence of model input. For discussion purpose, we assume that the magnitudes of unit production cost in China will be increased by 10%, 20% and 40% due to increased environmental regulations, and use them in the ISEEM-IS model runs while other input are held unchanged. The preliminary results indicate that an increase by 10% in unit production cost in China does not change the model output on steel trading volumes. An increase of China production cost by 20% decreases steel import of the U.S. only in the last two periods, even though the unit production cost in the U.S. is 10% lower than the China production cost through the planning horizon. An increase of China production cost by 40%, on the other hand, does change the landscape of steel trading volumes significantly reflecting the large increase in China production cost (20-30% higher than the production cost in the U.S.).

In view of the results, it should be noted that these discussions are made under a set of assumptions pertaining to the model parameters and other inputs such as the prices and availabilities of energy sources, raw materials, and technologies. For example, we observe that the U.S. steel import volume from China starts to decrease corresponding to an increase of 20% in unit production cost in China. Under a different set of model data, results may indicate different options for the U.S. iron and steel market.

7. Recommendations

The ISEEM-IS model results are affected by many assumptions related to parameters used in the model input. For example, assumptions about costs, material prices, and technology penetration rates (only for efficient production technologies) are critical factors that affect the outcomes. Our modeling analysis indicates that there is a strong correlation between domestic scrap availability, price, and shares of EAF production. In this regard, additional research on projecting the costs of domestic iron ore and scrap would be helpful, especially in China and India. In addition, alternative scrap availability scenarios can be modeled to further understand the dynamics between various parameters in the ISEEM-IS model, e.g., a sensitivity analysis focusing on the impact of scrap prices on EAF production would be helpful to understand impacts of scrap prices.

In this study, we have not explored or analyzed the sensitivity of modeling outcomes to variations in energy prices, while prices of some fuels may be critical to modeling results. For example, relatively lower prices of coking coal and coke in the China's iron and steel sector, compared to the U.S. and India, lead to much lower unit costs for steel production from China BOF process. In a perfectly competitive market structure where coking coal and coke prices in the U.S, China, and India are similar, the results can be quite different. In addition, it would also be helpful to analyze the effects of non-coking coal and natural gas prices in the India's iron and steel sector. Depending on the energy prices, dominance of EAF-DRI (Coal based) production in India could be changed. It is recommended that future study to include comprehensive sensitivity analysis with regard to variations in energy prices in each country. In addition, varying country-specific discount rates is also recommended to further update the model.

An update on autonomous energy efficiency improvement (*aeei*) rates will enhance the accuracy of the modeling outcomes. For this report, we used a generic constant *aeei* rate in the model. However, developing countries such as China and India are expected to have much higher *aeei* rates with more variations. Higher *aeei* rates in China and India, compared to the U.S., could change the model results particularly on energy intensity levels. The model results show that energy intensity of the U.S. is almost half of those in China and India in each model year in each scenario. We hypothesize that a higher *aeei* rate for the modeling could help China and India to narrow that energy intensity gap with the U.S. over time. In addition, low energy intensity levels realized in the U.S. iron and steel sector are mainly because of a more efficient iron and steel production structure (e.g., higher capacity and usage of EAF production process) in the U.S. compared to the China and India's iron and steel sectors. For example, in this study, while we adopt the projections for annual production in China according to the amount and structural limits, the ISEEM-IS model's optimizing process may seek for abandon structural limitations over time based upon cost minimization objectives. It is recommended that future modeling to consider potential impacts of varying energy efficiency improvement rates, and structural constraints in the model.

The ISEEM-IS model is a bottom-up model that relies on accurate input of cost and energy saving potential data for efficient production technologies for all countries. In this study, we relied on outcomes from the previous studies on bottom-up representations of energy efficient technologies carried out for each country, some of whose estimates was often drawn from experience or opinions of industrial experts. Our modeling results have discovered that in the case of India's steel sector, the selected efficient production technologies are projected to result in significant cost effectiveness compared to its Base scenario according to the least cost objective of the model. This projection pattern for India appears to be extremely different from those of the U.S. or China's case and would benefit from further examinations. It is recommended further analysis and study to be carried out to define the Base scenario assumptions, as well as the information on characteristics of efficient production technologies.

Current model results in this study show that the ET and EC scenarios lead to the identical changes in the U.S. iron and steel sector. Additional payments of the U.S. for energy efficiency investments in China and India in the EC scenarios do not bring any difference from the ET scenarios. This outcome is due to collective impacts by all cost items currently used in the model. As can be expected from a perfect competitive market (e.g., no financial incentives or subsidies are considered), higher unit production costs (e.g., due to tariff and transportation cost projections) will impact magnitudes of energy saving and carbon emissions differently between EC scenarios and ET scenarios. Additionally, carbon tax or pricing and environmental costs for the model countries could also be embedded into the EC scenario set requirements to observe the impact of those additional costs on the EC scenario results. Given that the ISEEM-IS model has the ability to externally define and analyze all types of cost items (such as environmental penalty implementations, subsidy implementations on energy prices, raw material prices, and capital costs, and tariffs implementation on imported and exported products, we recommend to perform additional model analysis of the impacts on emission reduction by various production costs by using different trading strategies, while productions costs can be quite different due to variations in capital and O&M costs, energy prices, raw material prices, environmental costs, tariffs on imported and exported products, transportation and fuel costs, and other regulation costs. It would be helpful to quantify and project the effects of changes in each cost item on results in trading scenarios so as to advance the understanding of key drivers in each mitigation strategy.

CO_2 emissions from the ocean freight of the trading commodities between countries were not restricted in the analysis. Currently, emission reduction in the scenarios could only be achieved in iron and steel production systems. Because ocean transportation of trading materials contributes to global emissions, there is a need for future inclusion in the analysis and modeling as a part of trading strategies. Presently the issues studied on emissions from ocean transportation are mainly on responsibility of the countries, it would be worthwhile to develop future studies on how to represent and include CO_2 emissions from ocean freight of the trading commodities through international waters.

Furthermore, the effect of technological learning associated with the efficient production technologies is not considered in the current analysis. The results show that there is a trivial additional cost (emission reduction cost) to hit the target in the ER scenario – about 1%. In fact, if technological learning is included, the total cost might actually go down. Future analysis may include the impact of technological learning on efficient production technologies.

Lastly, while this report summarizes the key development of ISEEM-IS model tailored for iron and steel industries in the U.S., China, and India, it is recommended to continuously refine the model to improve its coverage, usability, and rigors. For example, future effort can include provisions of user's manual while improving model input and assumptions, helping to widen its applications. The model can be further developed to focus on additional sectors such as cement making, which is important to both industrial and building sectors. We also expect that more regions and countries can be included in the model for regional and international studies on strategies of carbon emission reduction.

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APPENDIX A

Advanced production technologies (i.e., newer/updated versions of current production technologies) are assumed to represent the autonomously improved versions of current iron and steel production technologies listed in Table A 1. A list of efficient production technologies used in the ISEEM-IS model are given in Table C 4, Table C 5, and Table C 6 in Appendix C.

Table A 1. Supply Technologies Considered in the ISEEM-IS Model

Energy Source Supply Technologies	
1	Steam Coal Supply Technology
2	Coking Coal Supply Technology
3	Coke Supply Technology
4	Electricity Supply Technology
5	Miscellaneous Oil Supply Technology
6	Natural Gas Supply Technology
Raw Material Supply Technologies	
1	Domestic Iron Ore Supply Technology
2	Import Iron Ore Supply Technology
3	Domestic Scrap Supply Technology
4	Import Scrap Supply Technology
5	Oxygen Supply Technology

Table A 2. Current Production Technologies Considered in the ISEEM-IS Model

Current Production Technologies	
1	Blast Furnace Technology
2	BOF Casting Rolling Technology
3	BOF Casting Rolling for Export Technology
4	BOF Production Technology
5	Coke Production Technology
6	DRI (Coal based) Production Technology
7	DRI (Gas based) Production Technology
8	EAF-DRI (Coal based) Casting Rolling Technology
9	EAF-DRI (Coal based) Casting Rolling for Export Technology
10	EAF-DRI (Gas based) Casting Rolling Technology
11	EAF-DRI (Gas based) Casting Rolling for Export Technology
12	EAF Casting Rolling Technology
13	EAF Casting Rolling for Export Technology
14	EAF-DRI (Coal based) Production Technology
15	EAF-DRI (Gas based) Production Technology

16	EAF Production Technology
17	Pelletization Technology
18	Sintering Technology

Table A 3. On-site Electricity Generation Technologies Considered in the ISEEM-IS Model

Onsite Electricity Generation Technologies	
1	Natural Gas Fueled Electricity Generation Technology
2	Coal Fueled Electricity Generation Technology
3	Oil Fueled Electricity Generation Technology
4	Others Electricity Generation Technology

APPENDIX B

Appendix B provides the results of correlation and regression analysis performed to forecast future prices of all the raw materials, coking coal and coke used in the ISEEM-IS model. The correlation coefficients presented in the tables reflect the measure of linear association between two variables analyzed (middle columns). Regression analysis involves identifying the relationship between the dependent variable and independent variables. In this analysis, we apply simple linear regression.

In simple linear regression, the model used to describe the relationship between a single dependent variable y (which is the price of raw material, coking coal, or coke in our case) and a single independent variable x (which is the China steel production volume or other production volumes generated from China steel production volume in our case) is '$y = a_1x + a_0 + \mathcal{E}$' and a_0 and a_1 are referred to as the model parameters, and Ɛis a probabilistic error term that accounts for the variability in y that cannot be explained by the linear relationship with x.

Table B 1 CORRELATION COEFFICIENT Analysis between China Domestic Iron Ore Price and China Steel Production Volume

	China Domestic Iron Ore Prices [1] (2005 $/ton)	China Steel Production Volume [2] (Mtonnes)	
1995	35	95	
1996	35	101	
1997	36	109	
1998	36	115	
1999	34	124	
2000	33	129	
2001	34	152	
2002	36	182	CORRELATION COEFFICIENT = 0.9505
2003	53	222	
2004	84	283	
2005	95	353	
2006	86	419	
2007	135	489	
2008	154	501	
2009	106	531	
2010	130	560	

Data Source: (1) Metallurgical Mines'Association of China , 2012; (2) China Steel Year Book, 2011

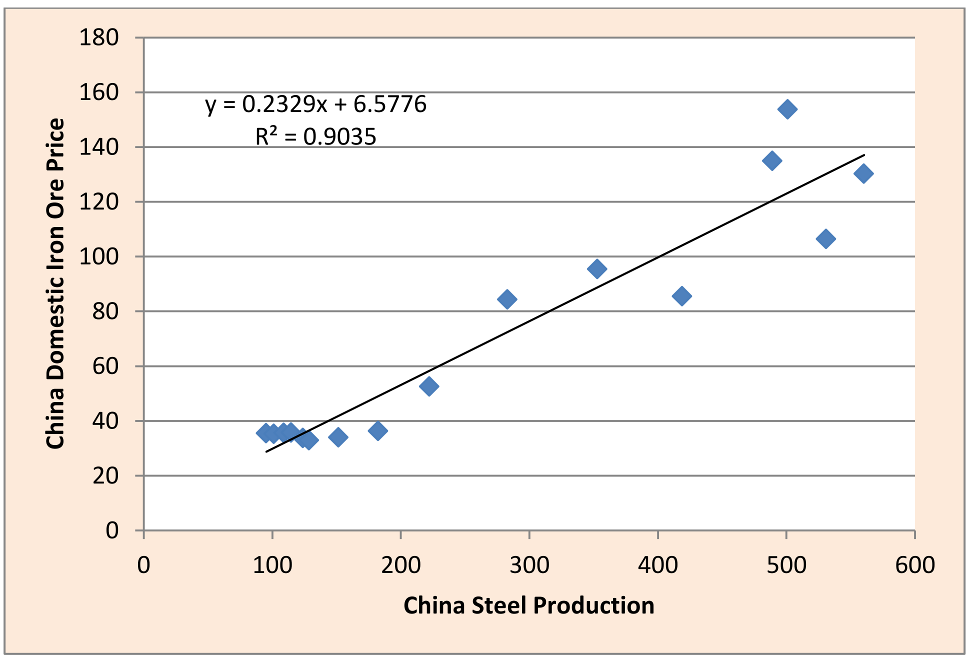

Figure B 1 Linear Regression Analysis of China Domestic Iron Ore Price and China Steel Production Volume

Table B 2 Correlation Analysis between China Import Iron Ore Price and China Steel Production Volume

	China Import Iron Ore Prices (3)	China Steel Production Volume (4)	
	(2005 $/ton)	(Mtonnes)	
1995	38	95	
1996	37	101	
1997	36	109	
1998	34	115	
1999	29	124	
2000	30	129	
2001	30	152	
2002	27	182	CORRELATION COEFFICIENT = 0.8918
2003	35	222	
2004	63	283	
2005	67	353	
2006	62	419	
2007	84	489	
2008	126	501	
2009	73	531	
2010	114	560	

Data Source: (3) China Costums, Zhang Chunxia *from CISRI, 2012; (4) China Steel Year Book, 2011*

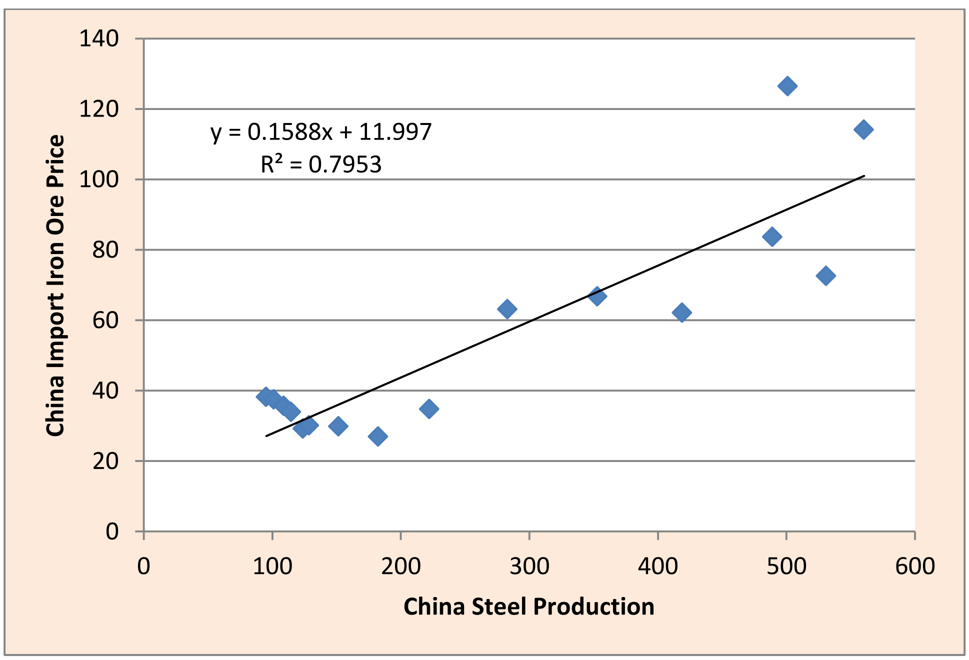

Figure B 2 Linear Regression Analysis of China Import Iron Ore Price and China Steel Production Volume

Table B 3 Correlation Analysis between India Domestic Iron Ore Price and China Steel Production Volume

	India Domestic Iron Ore Prices (5)	China Steel Production Volume (6)	
	(2005 $/ton)	(Mtonnes)	
2001	27	152	
2002	28	182	
2003	30	222	
2004	35	283	
2005	57	353	CORRELATION COEFFICIENT = 0.8906
2006	66	419	
2007	71	489	
2008	93	501	
2009	62*	531	
2010	120**	560	

*Data Source: (5) Firoz, 2008; * http://www.mining-journal.com/production-and-markets/india-iron-ore-prices-harden; ** http://www.dnaindia.com/money/report_iron-ore-prices-set-to-rise-50pct_1340497; (6) China Steel Year Book, 2011*

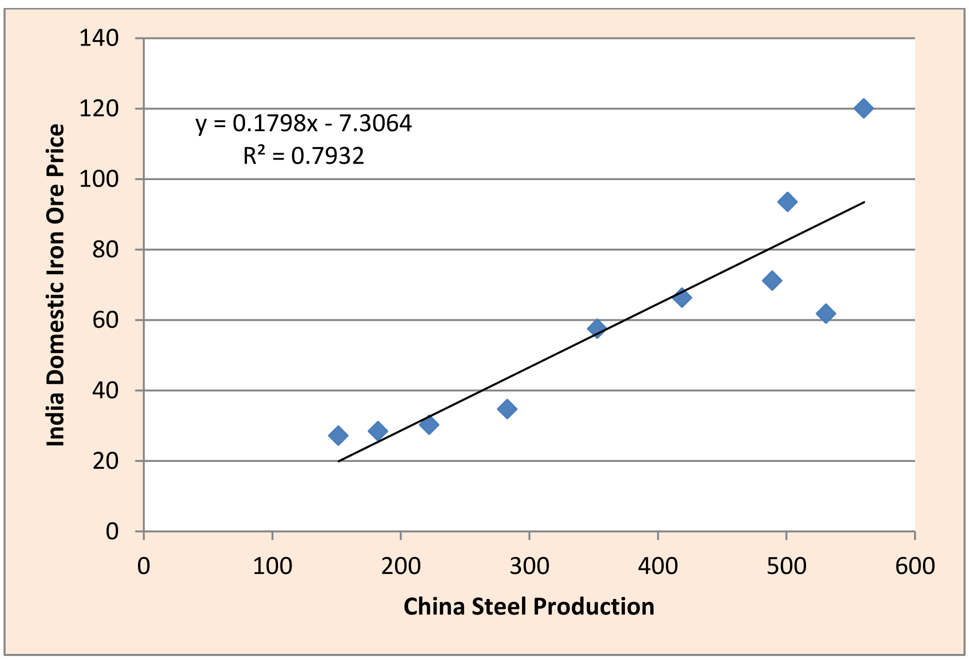

Figure B 3 Linear Regression Analysis of India Domestic Iron Ore Price and China Steel Production Volume

Table B 4 Correlation Analysis between India Import Iron Ore Price and China Steel Production Volume

	India Import Iron Ore Prices (7)	China Steel Production Volume (8)	
	(2005 $/ton)	(Mtonnes)	
1995	29	95	
1996	31	101	
1997	32	109	
1998	34	115	
1999	27	124	
2000	27	129	
2001	29	152	
2002	27	182	CORRELATION COEFFICIENT = 0.9028
2003	31	222	
2004	33	283	
2005	55	353	
2006	64	419	
2007	68	489	
2008	110	501	
2010	124*	560	

*Data Source: (7) Steel and Natural Resources Strategy Research, 2008; * http://www.dnaindia.com/money/report_iron-ore-prices-set-to-rise-50pct_1340497; (8) China Steel Year Book, 2011*

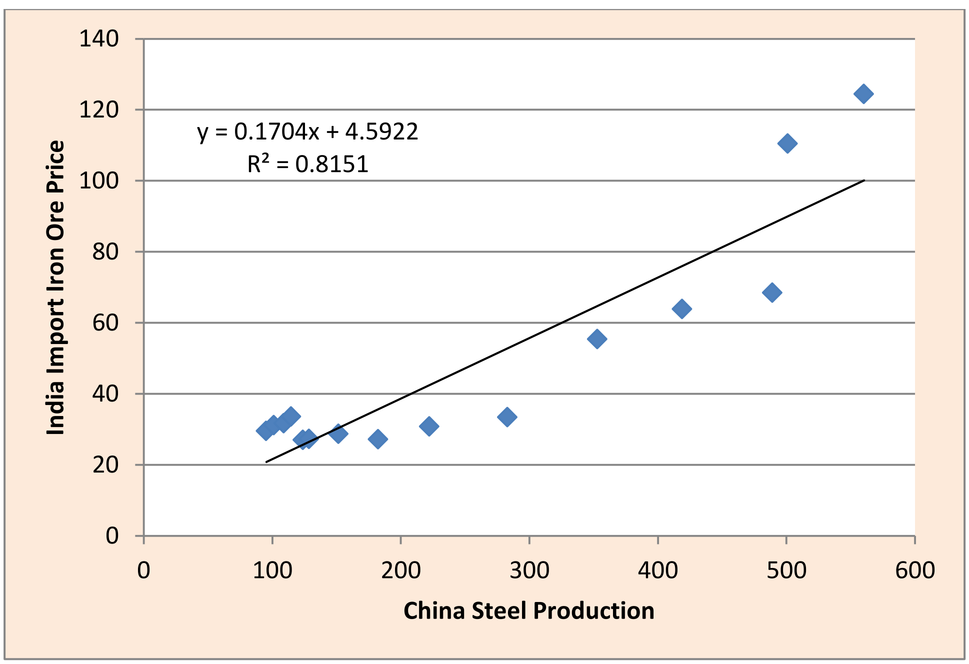

Figure B 4 Linear Regression Analysis of India Import Iron Ore Price and China Steel Production Volume

Table B 5 Correlation Analysis between the U.S. Domestic Iron Ore Price and China Steel Production Volume

	The U.S. Domestic Iron Ore Prices (9)	China Steel Production Volume (10)	
	(2005 $/ton)	(Mtonnes)	
1995	36	95	
1996	35	101	
1997	37	109	
1998	37	115	
1999	30	124	
2000	29	129	
2001	26	152	
2002	28	182	CORRELATION COEFFICIENT = 0.8987
2003	34	222	
2004	39	283	
2005	45	353	
2006	52	419	
2007	57	489	
2008	65	501	
2009	84	531	
2010	88	560	

Data Source: (9) USGS; 2012; (10) China Steel Year Book, 2011

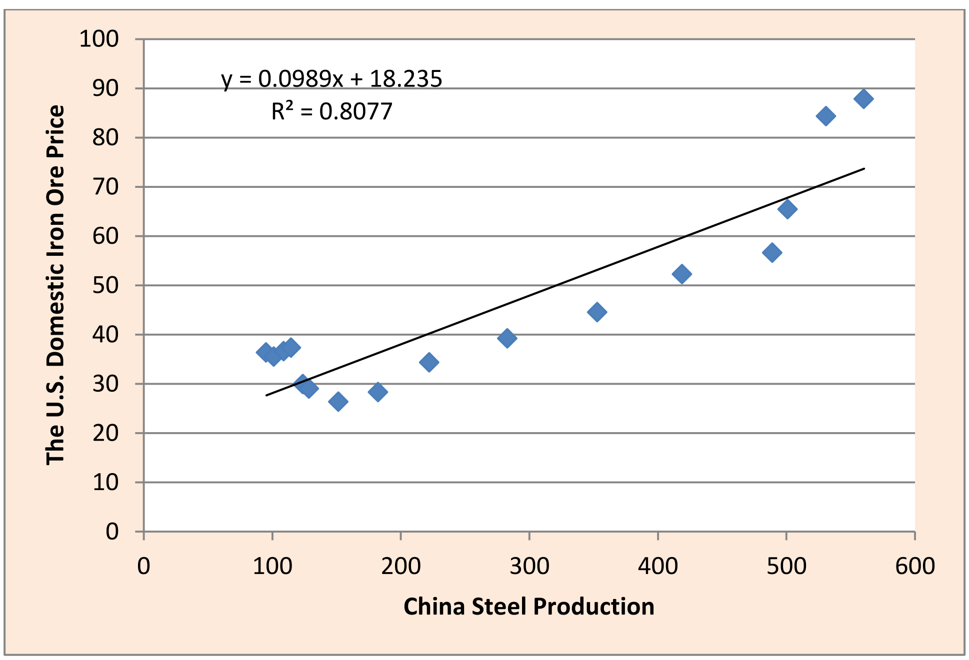

Figure B 5 Linear Regression Analysis of the U.S. Domestic Iron Ore Price and China Steel Production Volume

Table B 6 Correlation Analysis between the U.S. Import Iron Ore Price and China Steel Production Volume

	The U.S. Domestic Iron Ore Prices (11)	China Steel Production Volume (12)	
	(2005 $/ton)	(Mtonnes)	
2001	30	152	
2002	27	182	
2003	28	222	
2004	33	283	
2005	41	353	CORRELATION COEFFICIENT = 0.9066
2006	52	419	
2007	55	489	
2008	92	501	
2009	88	531	
2010	97	560	

Data Source: (11) USGS; 2012; (12) China Steel Year Book, 2011

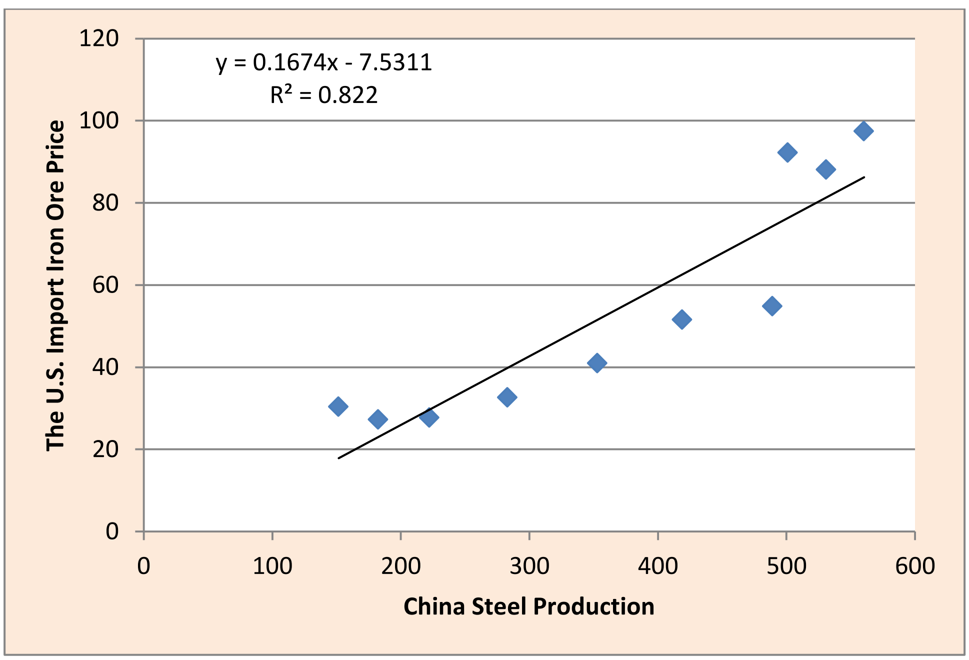

Figure B 6 Linear Regression Analysis of the U.S. Import Iron Ore Price and China Steel Production Volume

Table B 7 Correlation Analysis between China Steel Production Volume and World Steel Production Volume, World EAF Steel Production Volume, and World Scarp Usage

	China Steel Production Volume [13]	World Steel Production Volume [14]	World EAF Steel Production Volume [15]	World Scrap Usage [16]
	(Mtonnes)	(Mtonnes)	(Mtonnes)	(Mtonnes)
1995	95	752		
1996	101	750		
1997	109	799		
1998	115	777		340
1999	124	789		345
2000	129	848		385
2001	152	851	285	380
2002	182	904	305	395
2003	222	969	324	405
2004	283	1,071	353	450
2005	353	1,144	365	470
2006	419	1,247	395	500
2007	489	1,347	417	540
2008	501	1,327	410	525
2009	531	1,230	351	460
2010	560	1,412	411	520
Correlation coefficient between China Steel Production and World Steel Production = 0.9839				
Correlation coefficient between World Steel Production and World EAF Steel Production = 0.9630				
Correlation coefficient between World EAF Steel Production and World Scrap Usage = 0.9921				

Data Source: (13) China Steel Year Book, 2011; (14) World Steel Association, 2012; (15) World Steel Association, 2012; (16) Bureau of International Recycling, 2011

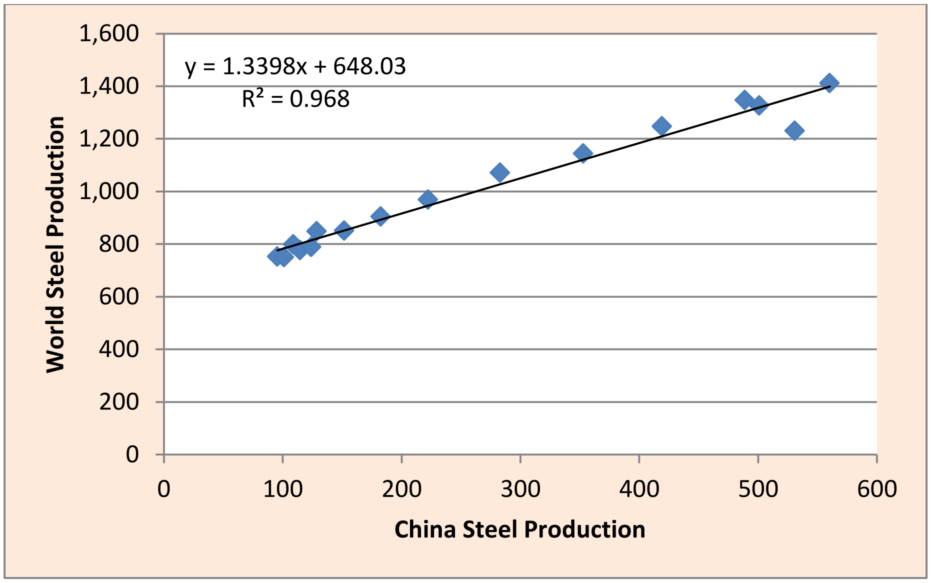

Figure B 7 Linear Regression Analysis of the China Steel Production Volume and World Steel Production Volume

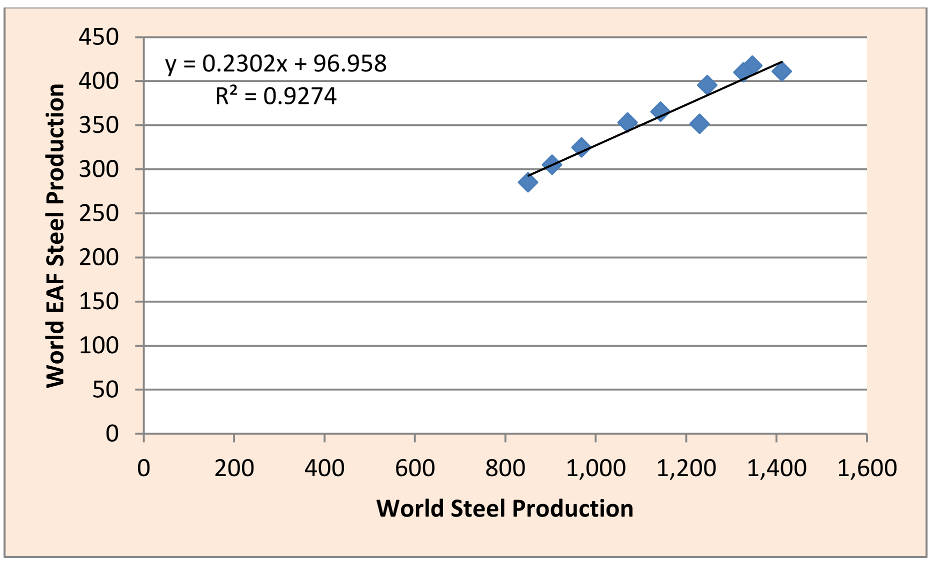

Figure B 8 Linear Regression Analysis of the World Steel Production Volume and World EAF Steel Production Volume

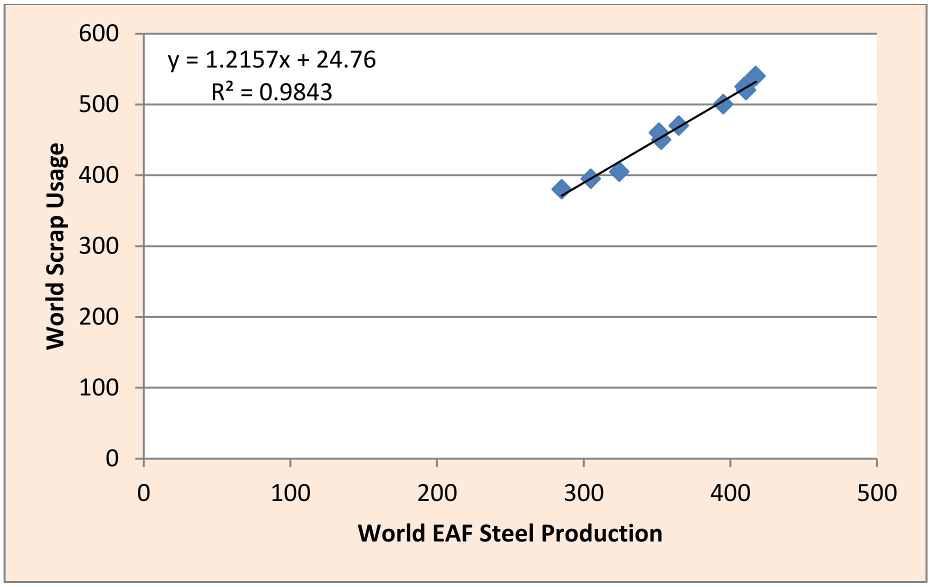

Figure B 9 Linear Regression Analysis of the World EAF Steel Production Volume and World Scrap Usage

Table B 8 Correlation Analysis between the China Domestic Scrap Price and World Scrap Usage Volume

	China Domestic Scrap Prices (17)	**World Scrap Usage** (18)	
	(2005 $/ton)	**(Mtonnes)**	
1998	209	340	
1999	128	345	
2000	97	385	
2001	130	380	
2002	142	395	
2003	123	405	
2004	201	450	**CORRELATION COEFFICIENT = 0.9554**
2005	222	470	
2006	220	500	
2007	334	540	
2008	225	525	
2009	337	460	
2010	209	520	

Data Source: (17) China Association of Metal Scrap Utilization, 2012; (18) Bureau of International Recycling, 2011

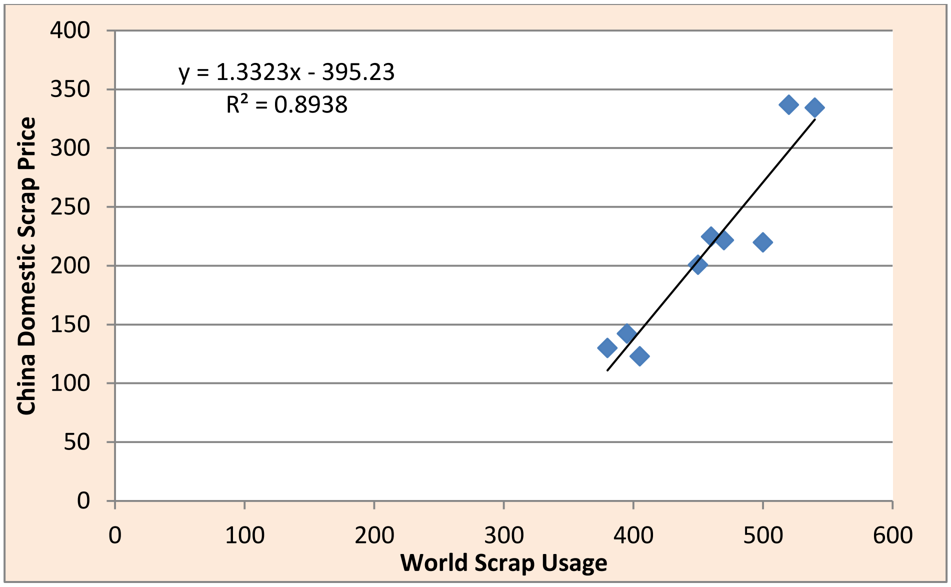

Figure B 10 Linear Regression Analysis of the China Domestic Scrap Price and World Scrap Usage Volume

Table B 9 Correlation Analysis between the China Import Scrap Price and World Steel Production Volume

	China Import Scrap Prices [19]	World Steel Production Volume [20]	
	(2005 $/ton)	(Mtonnes)	
1995	158	752	
1996	154	750	
1997	136	799	
1998	121	777	
1999	104	789	
2000	104	848	
2001	115	851	
2002	119	904	CORRELATION COEFFICIENT = 0.9198
2003	158	969	
2004	215	1,071	
2005	238	1,144	
2006	282	1,247	
2007	453	1,347	
2008	508	1,327	
2009	316	1,230	
2010	443	1,412	

Data Source: (19) China Customs, Zhang Chunxia *from CISRI, 2012; (20) World Steel Association, 2012*

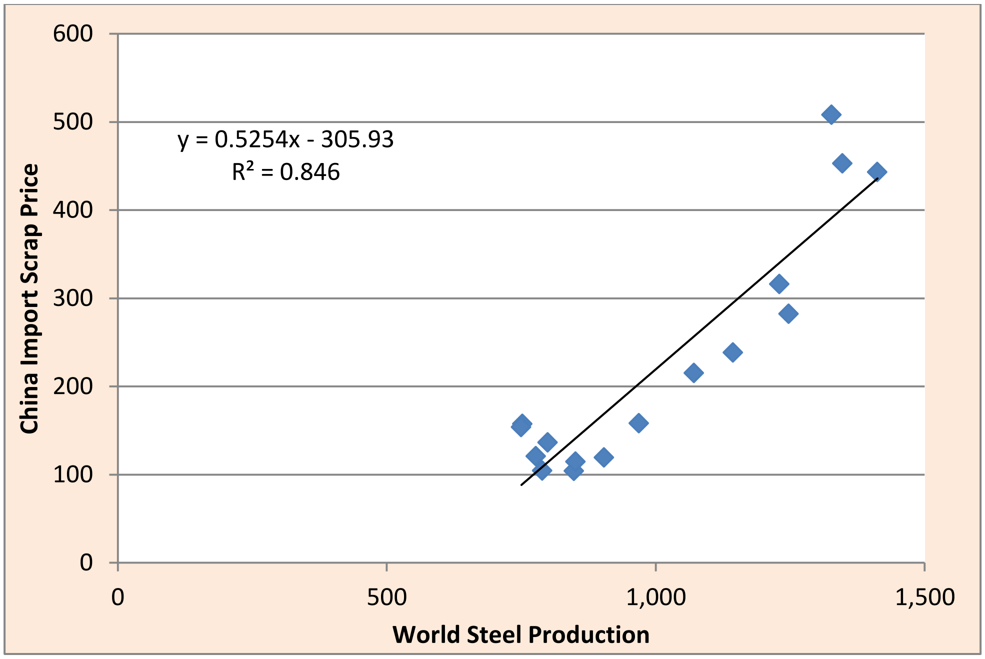

Figure B 11 Linear Regression Analysis of the China Import Scrap Price and World Steel Production Volume

Table B 10 Correlation Analysis between the U.S. Domestic Scrap Price and World Scrap Usage Volume

	The U.S. Domestic Scrap Prices (21)	World Scrap Usage (22)	
	(2005 $/ton)	(Mtonnes)	
1998	37	340	
1999	30	345	
2000	29	385	
2001	26	380	
2002	28	395	
2003	34	405	
2004	39	450	CORRELATION COEFFICIENT = 0.9274
2005	45	470	
2006	52	500	
2007	57	540	
2008	65	525	
2009	84	460	
2010	88	520	

Data Source: (21) USGS, 2012; (22) Bureau of International Recycling, 2011

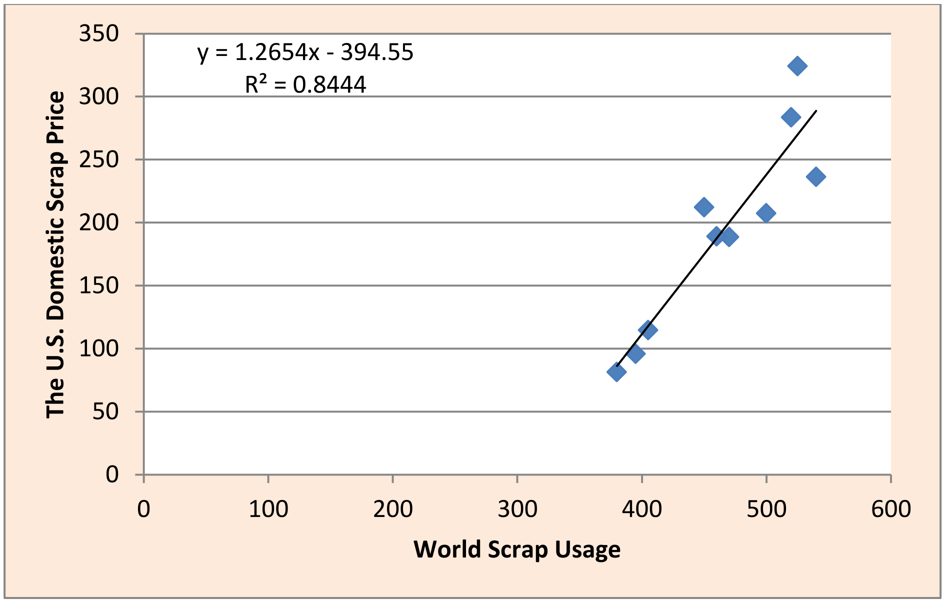

Figure B 12 Linear Regression Analysis of the U.S. Domestic Scrap Price and World Scrap Usage Volume

Table B 11 Correlation Analysis between the U.S. Import Scrap Price and World Steel Production Volume

	The U.S. Import Scrap Prices [23]	**World Steel Production Volume** [24]	
	(2005 $/ton)	**(Mtonnes)**	
1995	174	752	
1996	164	750	
1997	163	799	
1998	157	777	
1999	122	789	
2000	130	848	
2001	115	851	
2002	130	904	**CORRELATION COEFFICIENT = 0.8957**
2003	156	969	
2004	273	1,071	
2005	237	1,144	
2006	251	1,247	
2007	267	1,347	
2008	374	1,327	
2009	247	1,230	
2010	334	1,412	

Data Source: (23) USGS, 2012; (24) World Steel Association, 2012

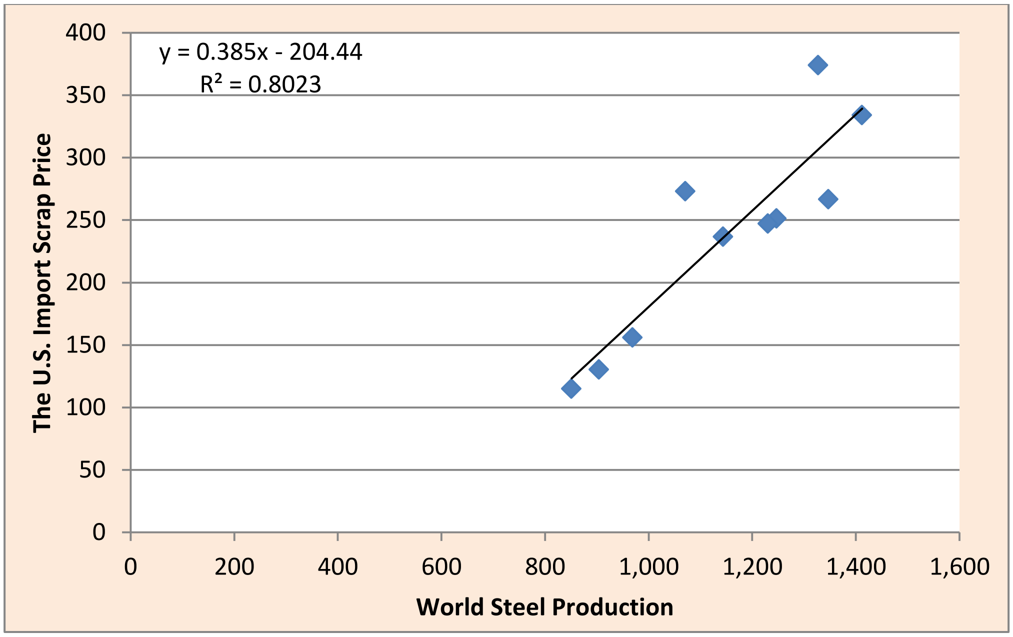

Figure B 13 Linear Regression Analysis of the U.S. Import Scrap Price and World Steel Production Volume

NOTE: Since there is no historic price information for India scrap prices, India domestic and import scrap price projections are assumed to be the same as those of China.

Table B 12 Correlation Analysis between China Coking Coal Price and China Steel Production Volume

	China Coking Coal Prices [24]	China Steel Production Volume [25]	
	(2005 $/ton)	**(Mtonnes)**	
1999	44	124	
2000	42	129	
2002	41	182	
2003	44	222	
2004	54	283	**CORRELATION COEFFICIENT = 0.9083**
2005	61	353	
2007	71	489	
2008	118	501	
2009	99	531	
2010	109	560	

Data Source: (24) IEA, 2011; BOC International, 2011; (25) China Steel Year Book, 2011

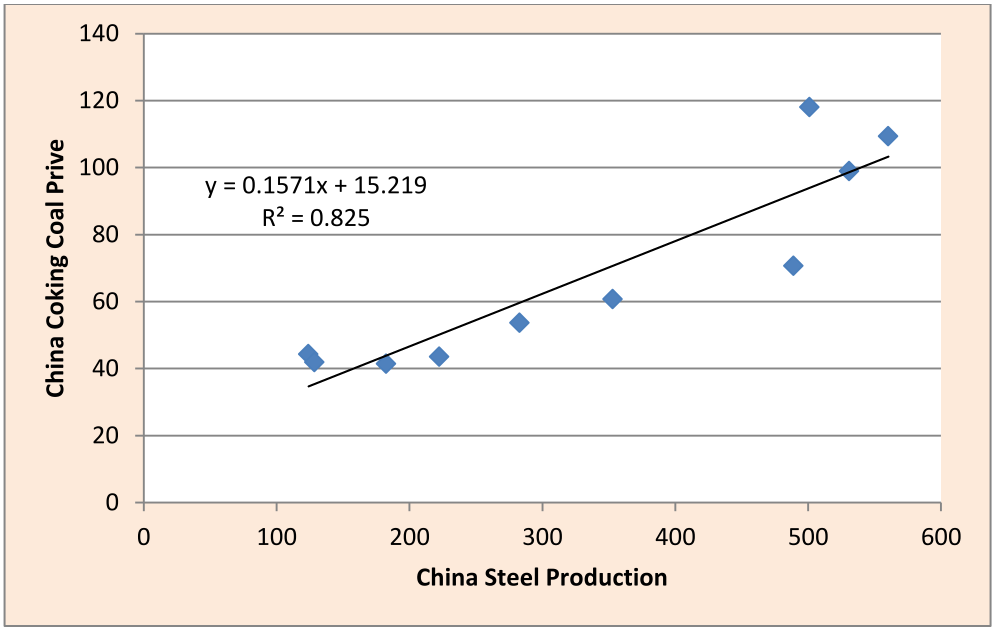

Figure B 14 Linear Regression Analysis of China Coking Coal Price and China Steel Production Volume

Table B 13 Correlation Analysis between India Coking Coal Price and China Steel Production Volume

	India Coking Coal Prices [26]	China Steel Production Volume [27]	
	(2005 $/ton)	(Mtonnes)	
1995	60	95	
1996	63	101	
1997	63	109	
1998	59	115	
1999	44	124	
2000	40	129	
2001	44	152	
2002	47	182	CORRELATION COEFFICIENT = 0.8652
2003	46	222	
2004	55	283	
2005	91	353	
2006	102	419	
2007	87	489	
2008	165	501	
2009	132	531	
2010	178	560	

Data Source: (26) IEA, 2011; Natural Resource Environment, 2010; (27) China Steel Year Book, 2011

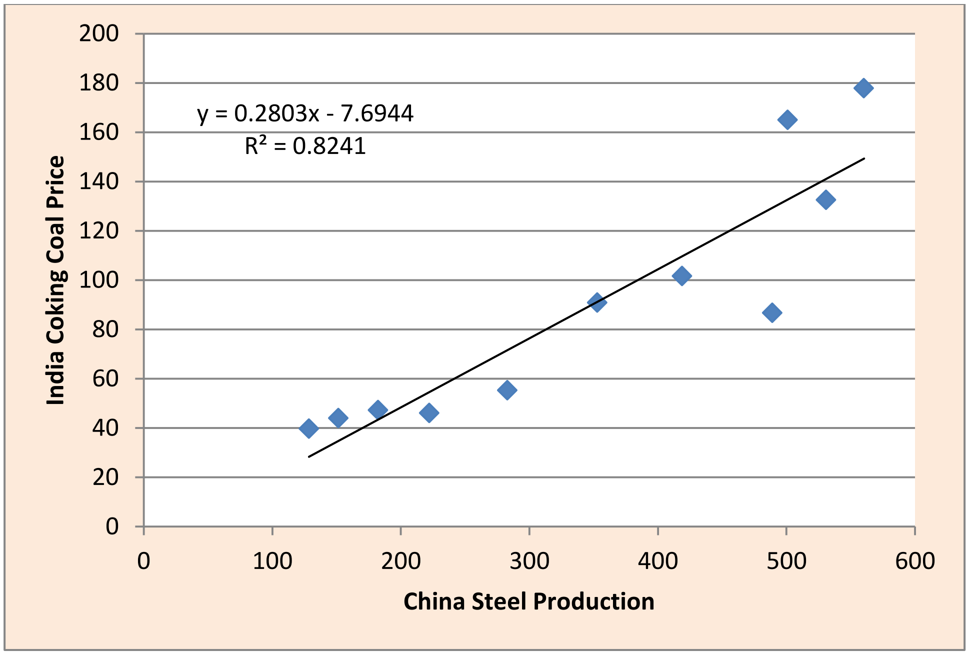

Figure B 15 Linear Regression Analysis of India Coking Coal Price and China Steel Production Volume

Table B 14 Correlation Analysis between the U.S. Coking Coal Iron Ore Price and China Steel Production Volume

	The U.S. Coking Coal Prices [28]	China Steel Production Volume [29]	
	(2005 $/ton)	(Mtonnes)	
1995	66	95	
1996	64	101	
1997	63	109	
1998	60	115	
1999	59	124	
2000	55	129	
2001	56	152	
2002	61	182	CORRELATION COEFFICIENT = 0.9154
2003	59	222	
2004	69	283	
2005	91	353	
2006	98	419	
2007	98	489	
2008	119	501	
2009	141	531	
2010	163	560	

Data Source: (28) IEA, 2011; (29) China Steel Year Book, 2011

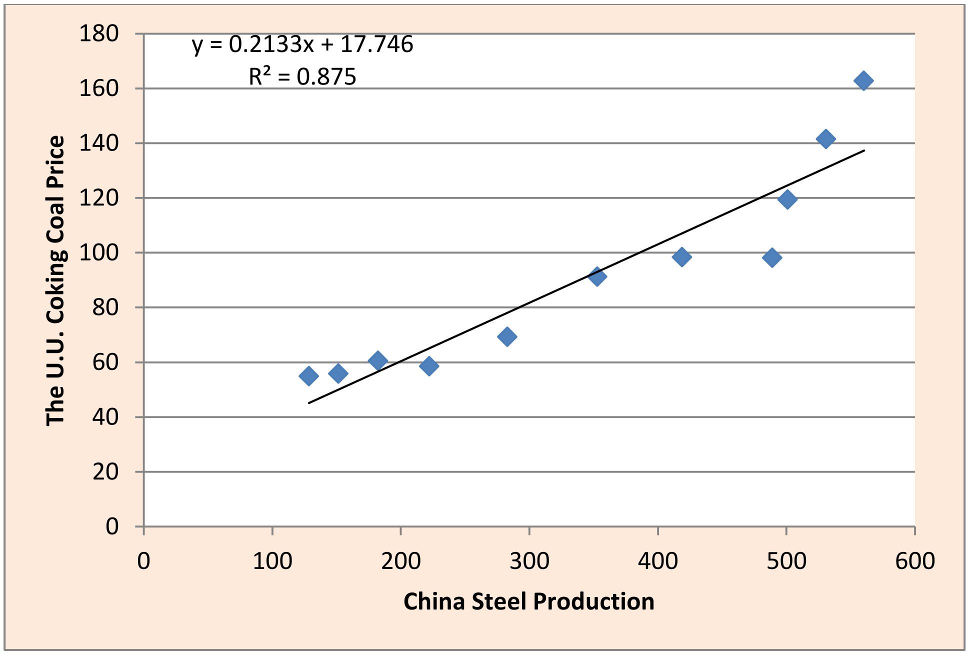

Figure B 16 Linear Regression Analysis of the U.S. Coking Coal Price and China Steel Production Volume

Table B 15 Correlations between China Coke Price and China Coking Coal Price

	China Coke Prices (30)	China Coking Coal Prices (31)	
	(2005 $/ton)	**(Mtonnes)**	
2007	169	71	
2008	292	118	**CORRELATION COEFFICIENT = 0.9066**
2009	213	99	
2010	224	109	

Data Source: (30) BOC International, 2011; (31) BOC, 2011

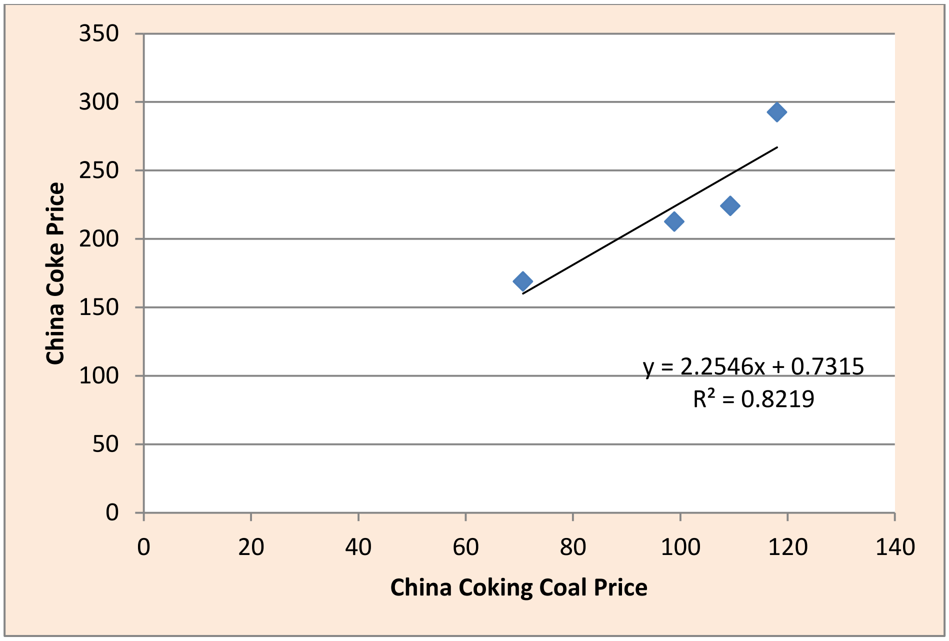

Figure B 17 Linear Regression Analysis of China Coke Price and China Coking Coal Price

Table B 16 Correlations between the International Coke Price and China Coke Export Price

	International Coke Prices* (32)	China Coke Export Prices (33)	
	(2005 $/ton)	(2005 $/ton)	
1995	86	84	
1996	90	90	
1997	93	95	
1998	85	83	
1999	78	78	
2000	59	60	
2001	74	76	
2002	72	73	CORRELATION COEFFICIENT = 0.9998
2003	87	86	
2004	154	152	
2005	326	325	
2006	195	192	
2007	145	147	
2008	237	247	
2009	511	516	

Data Source: (32) New World Resources, 2009; (33) Jones, A., 2011

** In the ISEEM-IS model, international coke prices are used as the generic prices for the imported coke that all countries are imposed.*

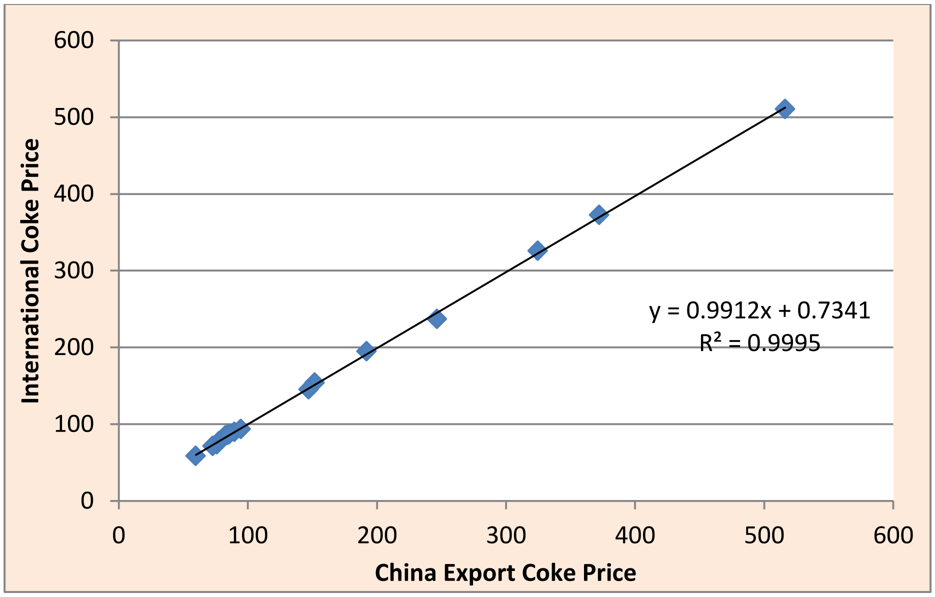

Figure B 18 Linear Regression Analysis of the International Coke Price and China Coke Export Price

NOTE: The current level of export duties (taxes) imposed on coke by Chinese government is 40% (IN-EAST, 2011). In this project, we assumed that this duty would be on through the period 2010-2050.Thus, the China domestic coke prices are increased 40% to calculate export prices.

NOTE: In the ISEEM-IS model, international coke prices are used as the generic prices for the imported coke that all countries are imposed. On the other hand, historical price series for Indian domestic and import coke are not available. The only information that we found is the 2005 and 2010 prices.

Table B 17 Coke Prices in India ($/ton)

		2005	2010
India Import Coke Prices	**($/ton)**	230	428
India Domestic Coke Prices	**($/ton)**	220	425

Data Source: UN Comtrade, 2012; CRISIL Research, 2011; http://salvanews-nishant.blogspot.com/2010/03/met-coke-prices-rise-sharply-on-higher.html, 2010.

As can be seen from Table B17, domestic and import coke prices in India are very similar in 2005 and 2010. From this point of view, we assumed that domestic and import coke prices in India are the same through the period 2010-2050. On the other hand, we assume that the U.S. iron and steel sector produces its own coke from coking coal (i.e., no domestic purchase or import of coke), since the share of offsite purchase is negligibly small. Thus, there is no price projection.

APPENDIX C

Table C 1 Investment Costs in the U.S, China, and India's iron and steel Sectors Considered in the ISEEM-IS Model (2005 $/tonne product)

	2010 - 2050 (2005 $/tonne product)	China Capital Expenditure Discount vs. the U.S.	India Capital Expenditure Discount vs. the U.S.
Sintering Plant	40.8	35%	25%
Coke Plant	209.9	35%	25%
Blast Furnace Plant	239.2	35%	25%
BOF Plant	113.4	35%	25%
DRI (Gas based) Plant	72.9	N.A.	25%
EAF Plant	91.8	10%	25%
Casting/Rolling Plant	240.0	35%	25%

Sintering plant cost from Metals Consulting International, 2011; Coke plant cost from Nill, J., 2003; Blast Furnace, BOF, DRI, EAF plant costs from IEA-ETSAP, 2010; Casting/Rolling plant cost from http://climatetechwiki.org/technology/direct-casting#Financial%20requirements%20and%20costs.

The U.S. investment costs are discounted 35% and 25% in China and India, respectively, due to low capital costs in these countries compared to the U.S. (Anderson, 2006; McKinsey&Company, 2012: IREA, 2012). Low investment costs in China and India are mostly because of low land and construction prices. On the other hand, investment costs of DRI (Coal based) plants in India are assumed 10% cheaper than DRI (Gas based) plants, since capital costs of coal-based DRI plants are the cheapest in the current structure of India's iron and steel sector (Saluja and Sengupta, 2008).

Table C 2 Fixed Costs in the U.S, China, and India's iron and steel Sectors Considered in the ISEEM-IS Model (2005 $/tonne product)

	2010 - 2050 (2005 $/tonne product)	China Fixed Cost Discount vs. the U.S.	India Fixed Cost Discount vs. the U.S.
Sintering Plant	8.3	53%	16%
Coke Plant	8.3	53%	16%
Blast Furnace Plant	8.3	53%	16%
BOF Plant	19.5	53%	16%
DRI (Gas based) Plant	4.6	53%	16%
EAF Plant	16.6	53%	16%
Casting/Rolling Plant	17.8	53%	16%

DOE , 1999; Grimond, A., 2011; www.steelonthenet.com.

Fixed costs of iron and steel plants are considered as annual payments/renting for land, taxes, and other cost items that does not change over the mid-term. It is assumed that fixed costs are proportional to land prices. Thus, China and India fixed costs are adjusted according to the average per square renting cost of the U.S., China, and India (Turner&Townsend, 2012).

Table C 3 Variable Costs in the U.S, China, and India's iron and steel Sectors Considered in the ISEEM-IS Model (2005 $/tonne product)

	2010 - 2050 (2005 $/tonne product)	China Variable Cost Discount vs. the U.S.	India Variable Cost Discount vs. the U.S.
Sintering Plant	8.6		
Coke Plant	26.2		
Blast Furnace Plant	24.4		
BOF Plant	57.5		
DRI (Gas based) Plant	11.6		
EAF Plant	41.9		
Casting/Rolling Plant	8.9		

IEA-ETSAP, 2010; Grimond, A., 2011; www.steelonthenet.com.

Variable costs of iron and steel plants are considered as labor costs, delivery, utility, and other cost items that vary based on production volumes. It is assumed that labor costs are 90% and 70% of the total variable costs in China and India, respectively. Thus, China and India variable costs are adjusted according to the average labor cost of the U.S., China, and India (Bureau of Labor Statistics, 2012).

Table C 4 Energy Savings and Costs for Energy-Efficient Technologies and Measures Applied to the U.S. Iron and steel Industry

	Secondary Steelmaking	Applied Fuel Savings (GJ/tonne crude steel)	Applied Electricity Savings (GJ/tonne crude steel)	Applied Total Retrofit Costs (US$/tonne crude steel)	Applied Annual Operating Cost Change (US$/tonne crude steel)	Lifetime of Measure	Share of total U.S. Production to which Measure is Applied
	Steelmaking Electric Arc Furnace						
1	Improved process control (neural network)	0.000	0.079	0.524	-0.552	10	55%
2	Fluegas Monitoring and Control	0.003	0.011	0.613	-0.524	15	31%
3	Transformer efficiency - UHP transformers	0.000	0.029	0.590	0.000	15	21%
4	Bottom Stirring / Stirring gas injection	0.000	0.005	0.040	-0.135	0.5	7%
5	Foamy slag	0.000	0.003	1.226	-0.221	10	12%
6	Oxy-fuel burners	-0.050	0.053	0.912	-0.342	10	19%
7	Eccentric Bottom Tapping (EBT) on existing furnace	0.000	0.002	0.098	0.000	20	3%
8	DC-Arc furnace	0.000	0.041	0.478	-0.306	30	12%
9	Scrap preheating - Tunnel furnace (CONSTEEL)	0.000	0.000	0.000	0.000	30	0%
10	FUCHS Shaft furnace	-0.086	0.093	1.287	-0.858	30	21%
11	Twin Shell w/ scrap preheating	0.000	0.009	0.368	-0.067	30	6%
12	Siemens EAF Quantum with scrap preheating	-0.064	0.116	1.716	-0.536	30	21%
13	Recover heat from waste gas	0.025	0.000	0.981	-0.098	10	49%
14	Post combustion of CO gas	0.000	0.062	1.471	-0.441	10	49%
15	Increased usage of hot metal	0.000	0.009	0.552	-0.092	10	6%
	Secondary Casting						
16	Efficient ladle preheating	0.005	0.000	0.011	0.000	10	18%
17	Proper sealing on ladle furnace preheating	0.021	0.000	0.061	0.000	10	31%
18	Near net shape casting/thin slab casting (TSC)	0.510	0.101	23.889	-5.574	20	16%
19	Use dry rolls in tunnel ovens for TSC	0.076	0.000	0.796	-0.002	20	16%

	Secondary Hot Rolling						
20	Process control in hot strip mill	0.106	0.000	0.229	0.000	10	39%
21	Recuperative burners	0.247	0.000	0.881	0.000	10	39%
22	Insulation of furnaces	0.033	0.000	1.653	0.000	10	18%
23	Ceramic wall in reheating furnace	0.106	0.000	0.705	0.000	10	39%
24	Reduce losses from furnace door opening	0.005	0.000	0.071	0.000	10	39%
25	Controlling oxygen levels and VSDs on combustion air fans	0.008	0.000	0.028	0.000	15	31%
26	Energy-efficient drives in the rolling mill	0.000	0.005	0.099	0.000	20	55%
27	Waste heat recovery from cooling water	0.014	0.000	0.282	0.025	15	39%
	General Technologies						
28	Preventative Maintenance	0.129	0.022	0.006	0.012	20	61%
29	Optimizing the steam system	0.086	0.000	0.613	0.000	20	31%
30	Increase efficiency of boilers	0.006	0.000	0.092	0.000	20	31%
31	Optimizing the air system	0.000	0.006	0.147	0.000	20	61%
32	Variable speed drive: flue gas control, pumps, fans	0.000	0.003	0.215	0.000	5	31%
33	Energy monitoring and management system	0.023	0.004	0.083	0.000	5	55%
	Integrated Steelmaking						
34	**Iron Ore Preparation (Sintering)**						
35	Sinter plant heat recovery	0.035	0.000	0.190	0.000	10	39%
36	Reduction of air leakages	0.000	0.001	0.016	-0.006	10	39%
37	Increasing bed depth	0.005	0.000	0.000	0.000	10	35%
38	Improved process control (sinter plant)	0.002	0.000	0.014	-0.013	10	35%
39	Use of waste fuels in the sinter plant	0.001	0.000	0.001	0.000	10	4%
40	Improved charging method	0.005	0.000	0.142	-0.006	10	35%
	Coke Making						
41	Coal moisture control	0.021	0.000	4.669	0.000	10	35%
42	Programmed heating - coke plant	0.018	0.000	0.022	0.000	10	35%
43	Variable speed drive coke oven gas compressors	0.001	0.000	0.029	0.000	15	35%

44	Coke dry quenching	0.152	0.000	6.669	-0.724	18	35%
	Iron Making (Blast Furnace)						
45	Pulverized coal injection to 130 kg/thm	0.054	0.000	0.490	-0.140	20	8%
46	Pulverized coal injection to 225 kg/thm	0.049	0.000	0.451	-0.073	20	10%
47	Injection of natural gas to 140 kg/thm	0.060	0.000	0.333	-0.153	20	8%
48	Injection of oil up to 130 kg/thm	0.057	0.000	0.333	-0.133	20	8%
49	Top pressure recovery turbines (wet type)	0.000	0.046	5.336	0.000	15	31%
50	Recovery of blast furnace gas	0.007	0.000	0.030	0.000	15	12%
51	Hot blast stove automation	0.074	0.000	0.060	0.000	5	23%
52	Recuperator hot blast stove	0.027	0.000	0.467	0.000	10	39%
53	Improved blast furnace control systems	0.111	0.000	0.100	0.000	5	32%
	Steelmaking **Basic Oxygen Furnace**						
54	BOF gas + sensible heat recovery	0.355	0.017	8.515	0.000	10	39%
55	Variable speed drive on ventilation fans	0.000	0.001	0.077	0.000	10	39%
	Integrated Casting						
56	Efficient ladle preheating	0.005	0.000	0.012	0.000	10	19%
57	Proper sealing on ladle furnace preheating	0.014	0.000	0.039	0.000	10	19%
58	Thin slab casting	0.223	0.044	10.445	-2.437	20	7%
59	Use dry rolls in tunnel ovens for TSC	0.048	0.000	0.503	-0.001	20	10%
	Integrated Hot Rolling						
60	Hot charging	0.042	0.000	1.044	-0.104	20	8%
61	Process control in hot strip mill	0.052	0.000	0.113	0.000	10	19%
62	Recuperative burners	0.049	0.000	0.174	0.000	10	8%
63	Insulation of furnaces	0.021	0.000	1.044	0.000	10	12%
64	Ceramic wall in reheating furnace	0.067	0.000	0.445	0.000	10	25%
65	Reduce losses from furnace door opening	0.003	0.000	0.045	0.000	10	25%
66	Controlling oxygen levels and VSDs on combustion air fans	0.005	0.000	0.017	0.000	15	19%
67	Energy-efficient drives in the rolling mill	0.000	0.002	0.035	0.000	20	19%
68	Waste heat recovery from cooling water	0.008	0.000	0.153	0.013	15	21%

	Integrated Cold Rolling and Finishing						
69	Heat recovery on the annealing line	0.085	0.003	0.764	0.000	10	29%
70	Reduced steam use in the pickling line	0.057	0.000	0.846	0.000	10	31%
71	Automated monitoring and targeting system	0.000	0.041	0.208	0.000	5	19%
	General						
72	Preventative Maintenance	0.174	0.007	0.004	0.008	20	39%
73	Optimizing the steam system	0.108	0.000	0.774	0.000	20	39%
74	Increase efficiency of boilers	0.008	0.000	0.116	0.000	20	39%
75	Optimizing the air system	0.000	0.004	0.093	0.000	20	39%
76	Energy monitoring and management system	0.031	0.001	0.052	0.000	5	35%
77	Variable speed drive: flue gas control, pumps, fans	0.000	0.002	0.135	0.000	5	19%

Table C 5 Energy Savings and Costs for Energy-Efficient Technologies and Measures Applied to the China's iron and steel Industry

No.	Technology/Measure	Sinter production capacity in base year to which the measure is applied (Mt/year)	Typical Fuel savings (GJ/t-Sinter)	Typical Electricity savings (kWh/t-Sinter)	Typical Capital cost (2010 US$/t-Sinter)	Typical Change in annual O&M cost (2010 US$/t-Sinter)	Typical lifetime of the technology (year)	Share of Sinter production capacity in base year (2010) to which measure is applied (%)
	Sintering							
1	Heat recovery from sinter cooler	688.22	0.52		4.1	-	10	90%
2	Increasing bed depth	688.22	0.01	0.06	0.0	-	10	0%
No.	**Technology/Measure**	**Coke production capacity in base year to which the measure is applied (Mt/year)**	**Fuel savings (GJ/t-Coke)**	**Electricity savings (kWh/t-Coke)**	**Capital cost (2010 US$/t-Coke)**	**Change in annual O&M cost (2010 US$/t-Coke)**	**Typical lifetime of the technology (year)**	**Share of Coke production capacity in base year (2010) to which measure is applied (%)**
	Coke Making *(within the steel industry)*							
3	Coal moisture control	123.36	0.17		71.3	-	10	95%
4	Coke dry quenching (CDQ)	123.36	1.41		85.2	0.7	18	45%
No.	**Technology/Measure**	**Pig Iron production capacity in base year to which the measure is applied (Mt/year)**	**Fuel savings (GJ/t- Pig Iron)**	**Electricity savings (kWh/t-Pig Iron)**	**Capital cost (2010 US$/t-Pig Iron)**	**Change in annual O&M cost (2010 US$/t-Pig Iron)**	**Typical lifetime of the technology (year)**	**Share of Pig Iron production capacity in base year (2010) to which measure is applied (%)**
	Iron Making – Blast Furnace							
5	Injection of pulverized coal in BF to 130 kg/t hot metal	559.72	0.77		8.7	-2.6	20	5%
6	Injection of natural gas in BF	559.72	0.37		5.9	-2.6	20	100%
7	Injection of coke oven gas in BF	559.72	0.36	18.50	5.9	-2.6	20	100%
8	Top-pressure recovery turbines (TRT)	559.72		46.00	26.7	-	15	17%
9	Recovery of blast furnace gas	559.72	0.04		0.4	-	15	94%
No.	**Technology/Measure**	**BOF crude steel production capacity in base year to which the measure is applied (Mt/year)**	**Fuel savings (GJ/t-BOF crude)**	**Electricity savings (kWh/t-BOF crude)**	**Capital cost (2010 US$/t-BOF crude)**	**Change in annual O&M cost (2010 US$/t-BOF crude)**	**Typical lifetime of the technology (year)**	**Share of BOF crude steel production capacity in base year (2010) to which measure is applied (%)**

	Steelmaking – basic oxygen furnace (BOF)							
10	Recovery of BOF gas and sensible heat	572.38	0.73		35.2	-	10	70%
No.	**Technology/Measure**	**EAF crude steel production capacity in base year to which the measure is applied (Mt/year)**	**Fuel savings (GJ/t-EAF crude)**	**Electricity savings (kWh/t-EAF crude)**	**Capital cost (2010 US$/t-EAF crude)**	**Change in annual O&M cost (2010 US$/t-EAF crude)**	**Typical lifetime of the technology (year)**	**Share of EAF crude steel production capacity in base year (2010) to which measure is applied (%)**
	Steelmaking – EAF							
11	Scrap preheating	66.31		61.00	7.6	-3.93	30	0%
No.	**Technology/Measure**	**Total crude steel production capacity in base year to which the measure is applied (Mt/year)**	**Fuel savings (GJ/t-Total crude)**	**Electricity savings (kWh/t-Total crude)**	**Capital cost (2010 US$/t-Total crude)**	**Change in annual O&M cost (2010 US$/t-Total crude)**	**Typical lifetime of the technology (year)**	**Share of Total crude steel production capacity in base year (2010) to which measure is applied (%)**
	Casting and Refining							
12	Integrated casting and rolling (Strip casting)	638.70	0.05	42.00	255.5	-27.37	20	80%
No.	**Technology/Measure**	**Hot rolled finished (HRF) steel production capacity in base year to which the measure is applied (Mt/year)**	**Fuel savings (GJ/t-HRF steel)**	**Electricity savings (kWh/t-HRF steel)**	**Capital cost (2010 US$/t-HRF steel)**	**Change in annual O&M cost (2010 US$/t-HRF steel)**	**Typical lifetime of the technology (year)**	**Share of HRF steel production capacity in base year (2010) to which measure is applied (%)**
	Hot Rolling							
13	Recuperative or regenerative burner	649.63	0.70		4.3	-	10	70%
14	Process control in hot strip mill	649.63	0.30		1.3	-	10	0%
15	Waste heat recovery from cooling water	649.63	0.04	-0.17**	1.1	0.1	15	80%
No.	**Technology/Measure**	**Cold rolled finished (CRF) steel production capacity in base year to which the measure is applied (Mt/year)**	**Fuel savings (GJ/t-CRF steel)**	**Electricity savings (kWh/t-CRF steel)**	**Capital cost (2010 US$/t-CRF steel)**	**Change in annual O&M cost (2010 US$/t-CRF steel)**	**Typical lifetime of the technology (year)**	**Share of CRF steel production capacity in base year (2010) to which measure is applied (%)**
	Cold Rolling							

No.	Technology/Measure	Total crude steel production capacity in base year to which the measure is applied (Mt/year)	Fuel savings (GJ/t-Total crude)	Electricity savings (kWh/t-Total crude)	Capital Cost (2010 US$/t-Total crude)	Change in annual O&M cost (2010 US$/t-Total crude)	Typical lifetime of the technology (year)	Share of Total crude steel production capacity in base year (2010) to which measure is applied (%)
16	Heat recovery on the annealing line	112.28	0.30	3.00	4.0	-	10	45%
17	Automated monitoring and targeting systems	112.28		60.0	1.8	-	10	45%
No.	**Technology/Measure**	**Total crude steel production capacity in base year to which the measure is applied (Mt/year)**	**Fuel savings (GJ/t-Total crude)**	**Electricity savings (kWh/t-Total crude)**	**Capital Cost (2010 US$/t-Total crude)**	**Change in annual O&M cost (2010 US$/t-Total crude)**	**Typical lifetime of the technology (year)**	**Share of Total crude steel production capacity in base year (2010) to which measure is applied (%)**
	General measures							
18	Preventative maintenance in integrated steel mills	638.70	0.43	5.56	0.01	0.03	20	60%
No.	**Technology/Measure**	**Total crude steel production capacity in base year to which the measure is applied (Mt/year)**	**Fuel savings (GJ/t-Total crude)**	**Electricity savings (kWh/t-Total crude)**	**Capital Cost (2010 US$/t-Total crude)**	**Change in annual O&M cost (2010 US$/t-Total crude)**	**Typical lifetime of the technology (year)**	**Share of Total crude steel production capacity in base year (2010) to which measure is applied (%)**
19	Preventative maintenance in EAF plants	638.70	0.09	13.89	0.01	0.03	20	60%
20	Energy monitoring and management systems in integrated steel mills	638.70	0.11	2.87	0.2	-	10	85%
21	Energy monitoring and management systems in EAF plants	638.70	0.02	2.87	0.2	-	10	85%
22	Variable speed drives for flue gas control, pumps, fans in integrated steel mills	638.70		11.11	2.2	-	10	85%
23	Cogeneration for the use of untapped coke oven gas, blast furnace gas, and basic oxygen furnace-gas in integrated steel mills	638.70	0.03	97.22	20.2	-	20	50%

source: Hasanbeigi et al. 2012.

Table C 6 Energy Savings and Costs for Energy-Efficient Technologies and Measures Applied to the India's iron and steel Industry

No.	Energy-Efficiency Measures / Technologies	Production Capacity in base year to which the measure is applied (Mt/year)	Fuel Saving (GJ/t-cl)	Electricity Savings (kWh/t-cl)	Capital Costs (2010 US$/t-cl)	Change in Annual O&M cost (2010 US$/t-cl)	Share of production capacity in base year (2010) to which measure is applied (%)
	Sintering	**as % of Sinter production**					
1	Heat recovery from sinter cooler	2	**0.52**	**N.A.**	**$ 4.12**	**$ -**	**10%**
2	Reduction of air leakage	2	**N.A.**	**3.50**	**$ 0.15**	**$ -**	**20%**
3	Increasing bed depth	2	**0.01**	**0.06**	**$ -**	**$ -**	**65%**
4	Use of waste fuel in sinter plant	2	**0.18**	**N.A.**	**$ 0.25**	**$ -**	**20%**
5	Improve charging method	2	**0.08**	**N.A.**	**$ 0.28**	**$ -**	**5%**
6	Improve ignition oven efficiency	2	**0.03**	**N.A.**	**$ -**	**$ -**	**20%**
	Coke Making	**as % of Coke production**					
7	Coal moisture control	20	**0.17**	**N.A.**	**$ 71.34**	**$ -**	**5%**
8	Programmed heating in coke oven	20	**0.17**	**N.A.**	**$ 0.33**	**$ -**	**20%**
9	Variable speed drive on coke oven gas compressors	20	**0.01**	**N.A.**	**$ 0.41**	**$ -**	**20%**
10	Coke dry quenching (CDQ)	20	**1.41**	**N.A.**	**$ 85.18**	**$ 0.7268**	**30%**
11	Next generation coke making technology (SCOPE21) (emerging technology)	20	**0.78**	**N.A.**	**$ -**	**$ -**	**0%**
	Iron Making – Blast Furnace	**as % of Pig Iron production**					
12	Injection of pulverized coal in BF to 130 kg/t hot metal	39	**0.77**	**N.A.**	**$ 8.68**	**$ (2.5665)**	**85%**
13	Injection of natural gas in BF	39	**0.37**	**N.A.**	**$ 5.92**	**$ (2.7316)**	**0%**
14	Injection of oil in BF	39	**0.58**	**N.A.**	**$ 8.68**	**$ (2.5665)**	**0%**

15	Injection of plastic waste in BF	39	**0.25**	**N.A.**	**$ 8.68**	**$ (2.5665)**	**0%**
16	Injection of coke oven gas in BF	39	**0.36**	**18.50**	**$ 5.92**	**$ -**	**0%**
17	Top-pressure recovery turbines (TRT)	39	**N.A.**	**46.00**	**$ 26.70**	**$ -**	**25%**
18	Recovery of blast furnace gas	39	**0.04**	**N.A.**	**$ 0.41**	**$ -**	**80%**
19	Improved blast furnace control	39	**0.40**	**N.A.**	**$ 0.73**	**$ -**	**0%**
20	Slag heat recovery (emerging technology)	39	**0.35**	**N.A.**	**$ -**	**$ -**	**0%**
21	Preheating of fuel for hot blast stove	39	**0.30**	**N.A.**	**$ -**	**$ -**	**20%**
22	Improvement of combustion in hot blast stove	39	**0.04**	**N.A.**	**$ -**	**$ -**	**40%**
23	Improved hot blast stove control	39	**0.37**	**N.A.**	**$ 0.49**	**$ -**	**40%**
	Steelmaking – basic oxygen furnace (BOF)	**as % of BOF crude steel production**					
24	Recovery of BOF gas and sensible heat	26	**0.73**	**N.A.**	**$ 35.21**	**$ -**	**70%**
25	Variable speed drive on ventilation fans	26	**N.A.**	**1.00**	**$ 0.25**	**$ -**	**65%**
26	Control system for oxygen supply to BOF process	26	**N.A.**	**0.56**	**$ -**	**$ -**	**75%**
27	Programmed and efficient ladle heating	26	**0.03**	**N.A.**	**$ -**	**$ -**	**70%**
	Steelmaking – EAF	**as % of EAF crude steel production**					
28	Converting the furnace operation to ultra-high power (UHP) (Increasing the size of transformers)	41	**N.A.**	**17.00**	**$ 10.85**	**$ -**	**20%**
29	Adjustable speed drives (ASDs) on flue gas fans	41	**N.A.**	**16.50**	**$ 2.51**	**$ -**	**20%**
30	Oxy-fuel burners/lancing	41	**N.A.**	**17.00**	**$ 6.11**	**$ (5.3508)**	**20%**
31	Post-combustion of flue gases	41	**N.A.**	**44.10**	**$ -**	**$ -**	**20%**
32	Improving process control in EAF	41	**0.28**	**30.87**	**$ 1.73**	**$ (1.3102)**	**20%**
33	Refractories using engineered particles	41	**N.A.**	**11.00**	**$ -**	**$ -**	**20%**
34	Direct current (DC) arc furnace	41	**N.A.**	**22.05**	**$ 5.56**	**$ (3.7105)**	**20%**

35	Scrap preheating	41	**N.A.**	**61.00**	**$ 7.62**	**$ (3.9306)**	**20%**
36	Plastic waste and used tire injection in EAF (emerging technology)	41	**N.A.**	**N.A.**	**$ -**	**$ -**	**0%**
37	Airtight operation (emerging technology)	41	**N.A.**	**N.A.**	**$ -**	**$ -**	**20%**
38	Bottom stirring/gas injection	41	**N.A.**	**18.00**	**$ 0.98**	**$ (4.8385)**	**20%**
39	Contiarc Furnace (emerging technology)	41	**N.A.**	**N.A.**	**$ -**	**$ (15.3989)**	**20%**
40	Comelt Furnace (emerging technology)	41	**N.A.**	**N.A.**	**$ 4.89**	**$ (11.7917)**	**20%**
	Casting and Refining	**as % of total crude steel production**					
41	Integrated casting and rolling (Strip casting)	67	**0.05**	**42.00**	**$ 255.51**	**$ (27.3655)**	**10%**
42	Efficient Ladle preheating	67	**0.02**	**N.A.**	**$ 0.09**	**$ -**	**25%**
	Shaping	**as % of finished steel production**					
43	Use of energy-efficient motors	68	**N.A.**	**4.00**	**$ -**	**$ -**	**20%**
44	Installation of lubrication system	68	**N.A.**	**4.00**	**$ -**	**$ -**	**20%**
	Hot Rolling	**as % of Hot rolled finished steel production**					
45	Recuperative or regenerative burner	64	**0.70**	**N.A.**	**$ 4.25**	**$ -**	**30%**
46	Flameless oxyfuel burners	64	**0.77**	**-6.12**	**$ 3.10**	**$ 0.4620**	**20%**
47	Controlling oxygen levels and variable speed drives on combustion air fans	64	**0.33**	**N.A.**	**$ 0.75**	**$ -**	**40%**
48	Insulation of reheat furnaces	64	**0.16**	**N.A.**	**$ 14.43**	**$ -**	**20%**
49	Hot charging	64	**0.65**	**N.A.**	**$ 18.83**	**$ (1.5067)**	**20%**
50	Process control in hot strip mill	64	**0.30**	**N.A.**	**$ 1.28**	**$ -**	**80%**
51	Heat recovery to the product	64	**N.A.**	**N.A.**	**$ -**	**$ -**	**20%**
52	Waste heat recovery from cooling water	64	**0.04**	**-0.17**	**$ 1.06**	**$ 0.0997**	**0%**
53	Walking beam furnace for reheating	64	**N.A.**	**N.A.**	**$ -**	**$ -**	**0%**
	Cold Rolling	**as % of cold rolled finished steel production**					

54	Continuous annealing	4	**0.20**	**-20.00**	**$ 529.56**	**$ -**	**70%**
55	Heat recovery on the annealing line	4	**0.30**	**3.00**	**$ 4.04**	**$ -**	**0%**
56	Reduced steam use in the acid pickling line	4	**0.01**	**N.A.**	**$ 4.11**	**$ -**	**0%**
57	Automated monitoring and targeting systems	4	**N.A.**	**60.00**	**$ 1.81**	**$ -**	**0%**
	General measures	**as % of total crude steel production**					
58	Preventative maintenance in integrated steel mills	68	**0.43**	**5.56**	**$ 0.01**	**$ 0.0273**	**60%**
59	Preventative maintenance in EAF plants	68	**0.09**	**13.89**	**$ 0.01**	**$ 0.0273**	**60%**
60	Energy monitoring and management systems in integrated steel mills	68	**0.11**	**2.78**	**$ 0.20**	**$ -**	**0%**
61	Energy monitoring and management systems in EAF plants	68	**0.02**	**2.78**	**$ 0.20**	**$ -**	**0%**
62	Variable speed drives for flue gas control, pumps, fans in integrated steel mills	68	**N.A.**	**11.11**	**$ 2.18**	**$ -**	**60%**
63	Variable speed drives for flue gas control, pumps, fans in EAF plants	68	**N.A.**	**N.A.**	**$ 2.18**	**$ -**	**30%**
64	Cogeneration for the use of untapped coke oven gas, blast furnace gas, and basic oxygen furnace-gas in integrated steel mills	68	**0.03**	**97.22**	**$ 20.20**	**$ -**	**50%**
	DRI Production	**as % of DRI production**					
65	Use of iron ore pellets in DRI kiln	26	**1.44**	**N.A.**	**$ 117.44**	**$ -**	**20%**
66	Install VVFD on kiln cooler drives	26	**1.44**	**N.A.**	**$ 8.76**	**$ -**	**20%**
67	Properly sized blowers	26	**5.63**	**N.A.**	**$ 8.03**	**$ -**	**20%**

source: Morrow et al. 2012.

Appendix D (to be a separate document of the report)