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Author

Morrow III, William R.

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William R. Morrow III, Ali Hasanbeigi, Jayant Sathaye, Tengfang Xu

Energy Analysis and Environmental Impacts Department,
Environmental Energy Technologies Division,
Lawrence Berkeley National Laboratory,
Berkeley, CA USA

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Principal Investigator: Tengfang Xu

Prepared by

William R. Morrow III

Ali Hasanbeigi

Jayant Sathaye

Tengfang Xu

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

Berkeley, CA

Prepared for

Eric Smith

Climate Economics Branch

Climate Change Division

US Environmental Protection Agency

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Abstract

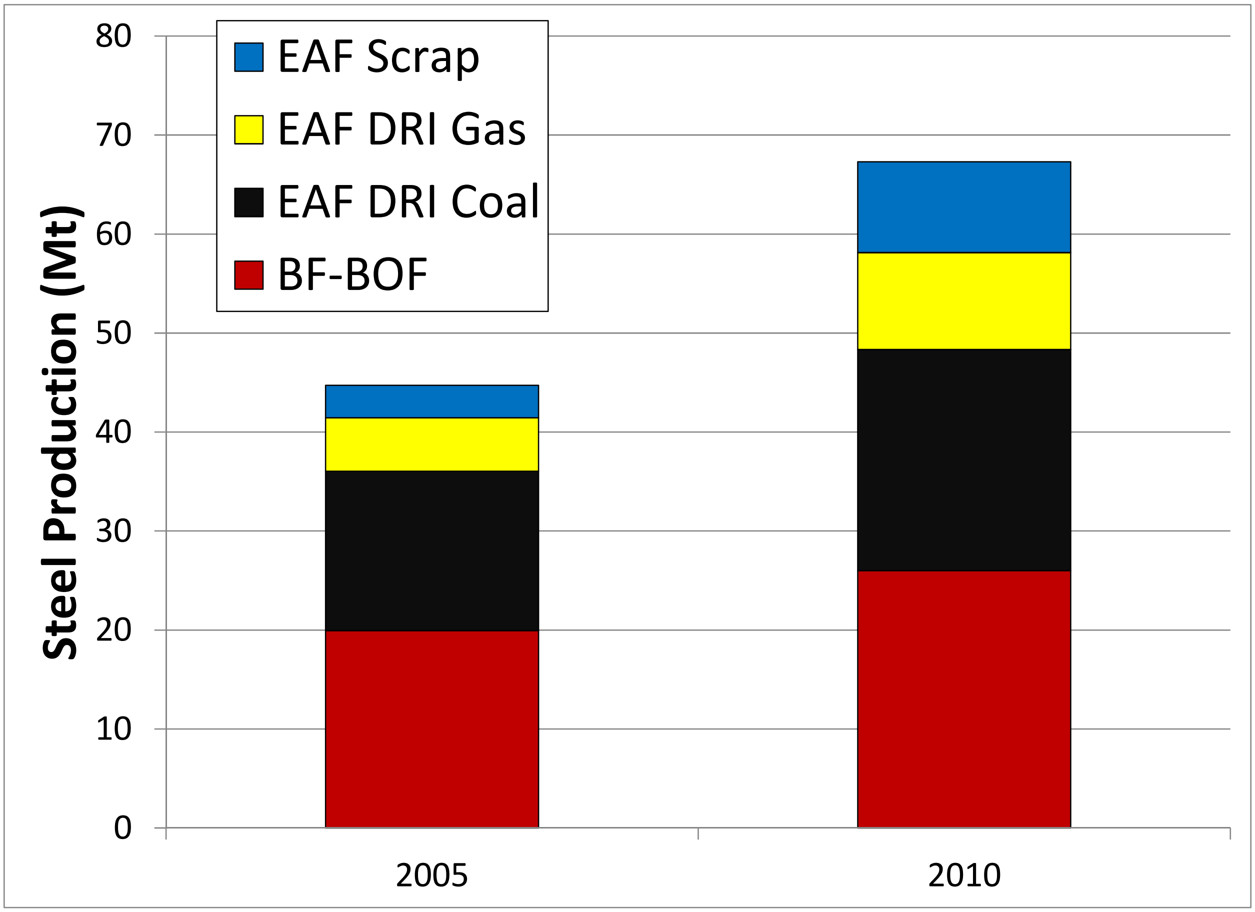
India's 2010 annual crude steel production was 68 Mt which accounted for nearly five percent of the world's annual steel production in the same year. In 2007, roughly 1600 PJ were consumed by India's iron and steel industry to produce 53 Mt of steel. We identified and analyzed 25 energy efficiency technologies and measures applicable to the processes in the Indian iron and steel industry. The Conservation Supply Curve (CSC) used in this study is an analytical tool that captures both the engineering and the economic perspectives of energy conservation. Using a bottom-up electricity CSC model and compared to an electricity price forecast the cumulative plant-level cost-effective electricity savings potential for the Indian iron and steel industry for 2010-2030 is estimated to be 66 TWh, and the cumulative plant-level technical electricity saving potential is only slightly greater than 66 TWh for the same period. The primary energy related CO_2 emissions reduction associated with cost-effective electricity savings is 65 Mt CO_2. Compared to a fuel price forecast, an estimated cumulative cost-effective fuel savings potential of 768 PJ with associated CO_2 emission reduction of 67 Mt CO_2 during 2010-2030 is possible. In addition, a sensitivity analysis with respect to the discount rate used is conducted to assess the effect of changes in this parameter on the results. The result of this study gives a comprehensive and easy to understand perspective to the Indian iron and steel industry and policy makers about the energy efficiency potential and its associated cost.

Contents

1. Introduction

1.1 Indian Iron and Steel Industry Overview

India's iron and steel sector is the fourth largest national iron and steel sector following China, Japan, and the United States (WSA, 2011). The 68 million metric tonnes (Mt) of Iron and Steel produced in India in 2010[1] was produced from a total capacity of 75 Mt (IndiaStat, 2012a). India's iron and steel industry produced 53 Mt in 2006 and consumed roughly 1,600 PJ of energy (EIA, 2011a), an estimated 17% of which was electricity. India's iron and steel production is dominated by two processes: blast furnace – basic oxygen furnaces (BF-BOF), and electric arc furnaces (EAF) supplied by either scrap or direct reduction iron (DRI) feedstocks. Figure 1 shows the capacity share of each (WSA, 2011) with a breakdown of EAF by feedstock (GOI, 2011). Although some natural gas fired DRI capacity operates in India, the relative higher cost of natural gas and limited availability compared to coal has resulted in the dominance of coal-based DRI. This trend is expected to continue because India had relatively abundant domestic coal supplies but imports a significant portion of its natural gas consumption.



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[1] India data is reported using the Hindu calendar which is March through February. For simplification, the dominant year (March through December) is the year used in this report.

Figure 1. Indian Iron and Steel Production by Process Type (WAS 2011, GOI 2011)

India's iron and steel sector is expected to expand by 2030, the timeframe of this analysis. By 2030 India's iron and steel sector is anticipated to produce between 200 and 242 Mt per year (IEA 2011a). We use the lower growth assumption, but note that using the higher growth assumption simply increases the benefits, or energy savings potential, in proportion to the relative higher demand to lower demand but does not change the cost effectiveness of measures. See Appendix 1 for the demand forecast used in this analysis.

This report is unique for India as it provides a detailed analysis of energy efficiency improvement opportunities for the majority of Indian steel industry. This report presents an assessment of the potential for energy saving in the Indian steel industry using a technology-level, bottom-up approach and estimates the cost associated with this potential. We use the concept of a "Conservation Supply Curve (CSC)" (Meier 1982) to construct a bottom-up model in order to capture the cost-effective potential as well as the technical potential for energy efficiency improvements and CO_2 emission reductions. These results can guide policy makers in designing better sector-specific energy efficiency policy programs.

2. Methodology

2.1. Data Collection

The data collection in this report draws upon work done by Lawrence Berkeley National Laboratory (LBNL) on the assessment of energy efficiency and CO_2 emission reduction potentials of the Iron and Steel industry in the U.S. and in China (Worrell et al. 1999; Xu et al. 2010; Worrell et al. 2010) and energy intensity calculation for Chinese and the U.S. steel industry (Hasanbeigi et al. 2011), as well as other references. Because we could not obtain Indian domestic technology information (e.g. energy saving, cost, etc.) for the energy efficiency measures/technologies, the analysis in this report is done based on international technologies only. International technologies are defined in our study as technologies that are manufactured outside of India. The data on the energy saving, cost, lifetime, and other details on each technology were obtained from these LBNL reports, which are based on case-studies around the world (Worrell et al. 1999 and 2010).

Many of the international energy-efficient technologies examined in LBNL publications and reports are used in this analysis because other studies on energy efficiency in the iron and steel industry do not provide consistent and comprehensive data on energy savings, cost, and lifetime of different technologies. Information on some of the technologies examined, however, is presented in other studies (e.g. APP 2010; EIPPCB 2012; NEDO 2008). Furthermore, the methodology used for this analysis, i.e. construction of the energy CSC and abatement cost curve, is also used by LBNL for the various industries in the U.S. (Worrell et al. 1999, Sathaye et. al. 2010, Xu et. al. 2010, 2011, 2013a&b).

The year 2010 was defined as the base year since it was the last year for which the data was available from the World Steel Association statistics. The historic national level data for the production of different products and processes in India's iron and steel industry was obtained from World Steel Association (WSA, 2011; WSA 2001; and WSA, 2000). Forecasts for Indian iron and steel process and product outputs are taken from the International Energy Agency's *Energy Transition for Industry: India and the Global Context* (IEA, 2011a). See Appendix 1 for time-series forecasts used in the analysis.

We worked closely with Indian experts of the CSTEP (Center for Study of Science, Technology, and Policy), to develop high-level estimates for the adoption rates of measures within India's current iron and steel sector as a whole. CSTEP have worked closely with India's iron and steel industry and the Indian government in the development of the PAT (Perform, Achieve, Trade) program designed to reduce energy consumption in key Indian industrial sectors, including the iron and steel sector.

2.2. Conversion Factors and Assumptions

Roughly 82% of India's electricity was generated from fossil fuels in 2011 (GOI 2012a). India's fossil fuel generation capacity is primarily domestically sourced coal based which has a lower average heat rate due to the poor energy density of India's coal than many non-domestic coals. India's national average net heat rate for fossil fuel-fired power generation was 10.5 MJ/kWh in 2011 (GOI, 2012b). India's 2009 national average electricity system transmission and distribution (T&D) losses of 25.4% (GOI 2012c) are used for the analysis. A conversion factor of 2.9 is used to convert electricity to primary fossil fuel. The conversion factor combines the percentage of fossil fueled power, the average heat rate of thermal plants, and the T&D losses. The CO_2 emission factor for grid electricity was 0.79 kg CO_2/kWh in 2012 (GOI, 2012b). Although the electricity savings are reported as finial electricity (electricity used by the iron and steel sector), due to T&D losses, saving a kWh of electricity at the final use, or plant level, saves more than 0.79 kg of CO_2 from grid-level electricity generation. Thus, the primary energy related electricity CO_2 emissions factor used in this analysis is 0.99 kg CO_2/kWh which includes T&D losses of 25.4%. The primary energy related CO_2 emission factor for electricity is held constant through 2030 as fossil-fueled thermal power plants are forecasted to remain the dominating power generation technology through this time period (GOI 2000) (see Appendix 2).

India's Iron and Steel industry 2010 fuels use is estimated to be coal (42%), coking coal (34%) natural gas (12%), miscellaneous oil (9%), and coke gas (3%). A weighted average emissions factor based on IPCC emissions factors for the 2010 fuel mix (IPCC 2006) of 86.5 tCO_2/TJ is used for calculating CO_2 emissions from energy consumption. The emission factor is assumed to be unchanged during the study period as the fuel mix is held constant out to 2030.

The variation between state-based electricity prices averaged across all customer classes is quite substantial ranging from 52 – 103 US$/MWh in 2010 (GOI 2012a). The industrial sector's national average price was 114 US$/MWh in 2010 (GOI, 2012a). The national average industrial price is used as the electricity price in the base year. Historic (2000-2009) average industry fuel price trends are used to estimate the 2010 base year values of $1.66 (coal), $2.82 (coke, and coke gas), $4.43 (natural gas), and $14.22 (miscellaneous oil), all US$/GJ (IEA 2012). A weighted average fuels price of 3.52 US$/GJ is used in the base year and future price escalation rates, based on historic real energy price trends, are used to estimate future energy prices for the study period (the following real escalation rates based on IEA data (IEA 2012) from 2000 2010 are used: 3.8% for electricity; and 5.6% coal; 6.2% for coke, coke oven gas, natural gas, and coke gas; 11.5% for miscellaneous oil). These prices are in constant dollars. The 2011 average exchange rate of 45.73 Rupees/US$ is used to convert reported costs in Indian Rupees to U.S. dollars (US$) (The World Bank 2012). Then, we used the same discount rate that we used to calculate the NPV of the future capital costs, to calculate the present value of the future energy prices in constant dollars in the base year. Finally, we calculated the discounted average unit price of electricity and coal used in electricity and fuel CSCs, respectively.

Future energy prices (i.e. prices in 2010-2030) determine the cost-effectiveness of energy efficiency measure implementations over the analysis period and are treated the same as future capital and operation and maintenance (O&M) non-energy costs over the study period by discounting them to a present value using the same discount rate as applied to future capital and non-energy O&M costs. This consistent treatment represents the benefit-cost decision from the Iron and Steel industry perspective. If future energy prices are not treated the same as capital and O&M costs (i.e., not discounted to present value using the same discount rate), then the cost effective results could be misinterpreted.

2.3. Energy Conservation Supply Curve Modeling

A bottom-up model based on the CSC concept was developed in order to estimate the cost effectiveness and technical potential for efficiency improvements and CO_2 emission reduction in India's Iron and Steel industry. The CSC approach, first introduced by Art Rosenfeld and his colleagues at LBNL, is an analytical tool that captures both the engineering and the economic perspectives of energy conservation. The curve shows the energy conservation potential as a function of the marginal Cost of Conserved Energy and has been used in various studies to assess energy efficiency potentials in different economic sectors and industries (Sathaye et al. 2010, Xu et al. 2010, 2011, 2013a&b, Koomey et al. 1990, Levine and Meier 1999, Lutsey 2008, Hasanbeigi 2010). Recently, McKinsey & Company (2008) also developed GHG abatement cost curves for different countries using the CSC concept. The CSC can be developed for a plant, a group of plants, an industry, or for the entire economic sector.

The work presented in this chapter is a unique study of India as it provides a detailed analysis of energy-efficiency improvement opportunities in the entire Indian Iron and Steel industry.

The Cost of Conserved Energy (CCE) required for constructing the CSC can be calculated as shown in Equation 1:

$$\mathrm{CCE} = \frac{\sum_{n=1}^{N} \frac{(ACC + \Delta\, AO\&M)_n}{(1+d)^n}}{\sum_{n=1}^{N} (Annual\ Energy\ Saving)_n} = \frac{\text{NPV (Annual Costs)}}{\text{Sum (Annual Energy Saving)}} \qquad \text{(Equation 1)}$$

Where:
CCE = Cost of Conserved Energy
ACC = Annualized Capital Costs
Δ AO&M = Change in Annual Operations and Maintenance Non-energy Cost
n= year – measure lifetime
N = time horizon of the analysis period
d = discount rate

The annualized capital cost can be calculated from Equation 2:

Annualized capital cost = Capital Cost*(d/ (1-(1+d)$^{-n}$)   (Equation 2)

Where:
d = discount rate
n = lifetime of the energy efficiency measure

After calculating the Cost of Conserved Energy for all energy-efficiency measures separately, the measures were ranked in ascending order of their Cost of Conserved Energy to construct the Energy CSC, and measures were applied in cascading fashion to avoid “double counting” of savings between measures. In an Energy CSC, an energy price line is determined. The energy price line is the net present value of energy prices escalated through over the analysis period as shown in equation 3. All measures that fall below the energy price line are considered “cost-effective”. Furthermore, the CSC also shows the total technical potential for electricity or fuel savings accumulated from all the applicable measures. On the curve, the width of each measure (plotted on the x-axis) represents the energy saved by that measure in a year or during the period for which the analysis is conducted. The height (plotted on the y-axis) shows the measure’s CCE calculated as explained above.

$$\text{Energy Price Line} = \sum_{t=1}^{T} \frac{P \times (1+E)^t}{(1+d)^t \times T} \qquad \text{(Equation 3)}$$

Where:
P = base year energy price
E = energy price escalation rate
d = discount rate
t = analysis time frame

The methodology used for the analysis consists of five main steps as follows:

1. Establish 2010 as the base year for energy, material use, and production in the iron and steel industry. The base year is also used to calculate the costs in constant base year dollar. The study period for which the CSC was developed is 2010-2030. Thus, the implementation of the measures starts in 2010. This is different from some other studies such Sathaye et al. (2010) where the application of energy efficiency technologies and the cost-effectiveness is assessed only for the base year.
2. Develop a list of commercially available energy-efficiency technologies and measures in the iron and steel industry to include in the construction of the conservation supply curves. We assumed that the energy efficiency measures are mutually exclusive and there is no interaction between them. Twenty-five energy efficiency measures/technologies are used in this study based on their applicability to the Indian iron and steel industry as well as the significant energy saving that can be achieved by implementing them.
3. Determine the potential application of energy-efficiency technologies and measures in the Indian iron and steel industry in the base year based on an estimate of their current adoption in India's existing iron and steel industry. Basing their current adoption on India's iron and steel industry is simply a starting point for this analysis because detailed information on the Indian industry was not available. We assumed 70% of the existing potential for energy efficiency measures will be realized by the end of 2030 (3.5% per year in each year (starting after the 2010 base year between 2011 and 2030 for an additive total of 70% of remaining potential by 2030) (except for injection of coke oven gas in blast furnace which we assume 40% remaining potential by 2030 because we are also account for injection of pulverized coal in the blast furnace), with a linear deployment rate assumed between the start year (2010) and end year (2030).
4. Obtain forecast data for iron and steel demand up to 2030. The adoption rate explained in step 3 was based on the base year's production capacity. However, there will be new capacity installed by 2030 to meet increased demand. Additionally, there will be plant retirements in the existing capacity that will be replaced with new capacity. To define the potential application of the measures to the new production capacity, we used the "new capacity with EE implementation" indicator. By defining this indicator, we take into consideration how much of the new capacity will have already implemented the energy efficiency measures from the start and how much potential will still exist in each subsequent year. We apply the same adoption assumptions to the retired and replaced capacity as we do to the new capacity.
5. Construct an Electricity Conservation Supply Curve (ECSC) and a Fuel Conservation Supply Curve (FCSC) separately in order to capture the accumulated cost effective and total technical savings potential due to electricity and fuel efficiency improvements in the iron and steel industry from 2010 to 2030. For this purpose, the Cost of Conserved Electricity (CCE) and Cost of Conserved Fuel (CCF) were calculated separately for respective technologies in order to construct the CSCs. After calculating the CCE or CCF

for all energy-efficiency measures, we rank the measures in ascending order of CCE or CCF to construct an ECSC and a FCSC, respectively. Two separate curves for electricity and fuel are constructed because the cost-effectiveness of each energy-efficiency measure is highly dependent on the price of energy. Since average electricity and fuel prices are different and because many technologies save either solely electricity or fuel, it is appropriate to separate electricity and fuel saving measures. Hence, the ECSC with discounted average unit price of electricity only plots technologies that save electrical energy while the FCSC with discounted average unit price of fuel only plots technologies that save fuel.

An important aspect of the CSCs is the methodology that was used to determine how energy efficiency measures are implemented. An illustrative graph is used below to explain the underlying basis for the implementation of each energy efficiency measure in the model (Figure 2).

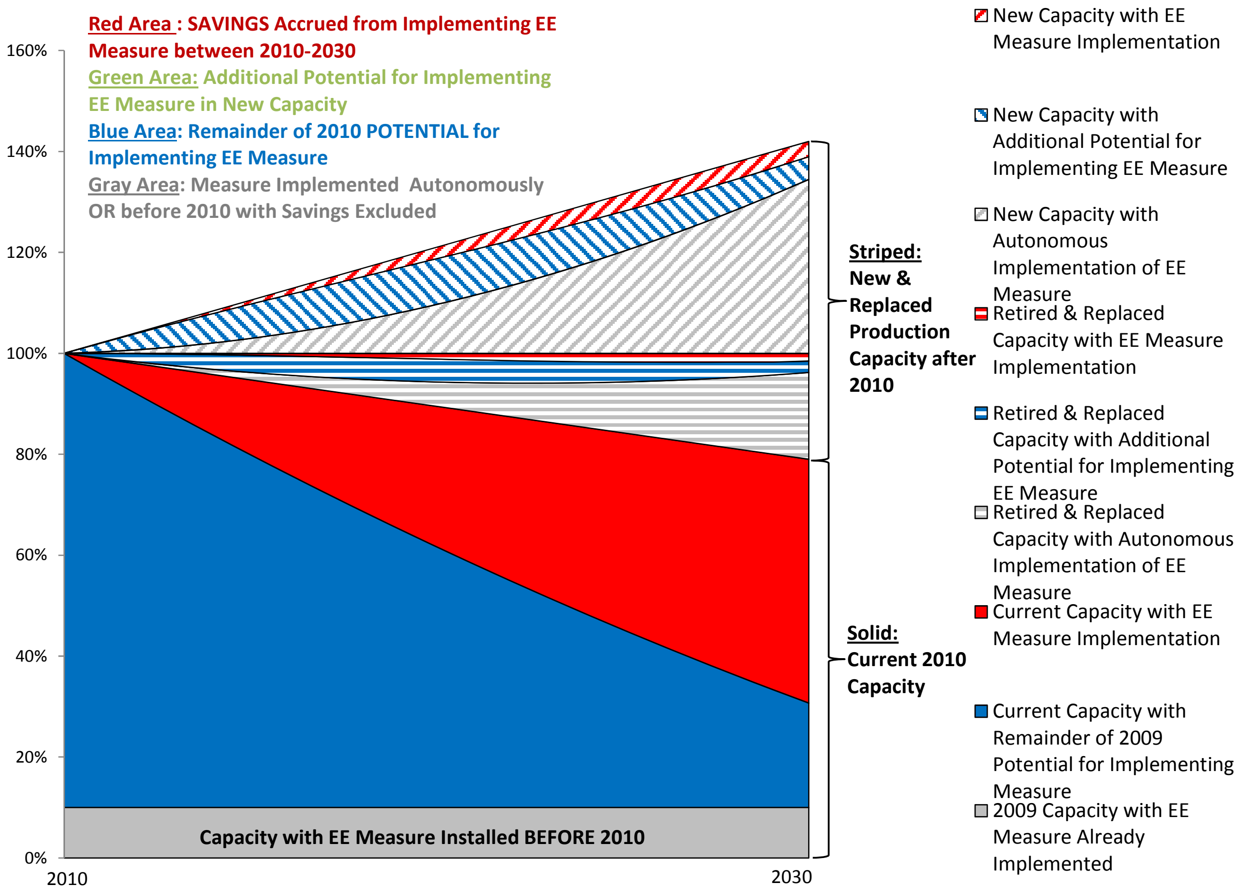

Figure 1. Illustration of Methodology for Determining Implementation of Energy Efficiency Measures from 2010 to 2030

Note: This graph is only for illustrative purposes

Based on estimates of adoption rate of energy efficiency measures in the base year (i.e., 2010) as shown in Table 1, we can calculate the remaining potential for adoption of efficiency measures in the existing capacity in the base year. We first estimate how much of the existing capacity should be retired and replaced with new capacity based on historic capacity expansions and the assumption that Iron and Steel plants last 30 years (IEA 2011b). This is shown in the figure as "Retired and Replacement". For the remaining existing potential we assumed 70% adoption will be reached by 2030 (i.e., 70% / (2030-2010) = 3.5% per year) for almost all measures. We developed a linear line which serves as the slope for the new implementation of the measure in each year between 2010 and 2030. We can then calculate the proportion of current capacity where savings are achieved through the implementation of each efficiency measure after the end of 2010, i.e. beginning of 2011 through the end of 2030 (solid red area in Figure 2).

In addition, industrial production capacity may grow between 2010 and 2030. To determine the implementation potential of efficiency measures in the new additional capacity, we did the following. First, we used estimated production capacity growth from (IEA, 2011a) and assumed that a certain proportion of the new capacity will adopt the efficiency measures autonomously each year. We assume that the new capacity in 2011 autonomously adopts measures to the same ratio that current capacity has adopted measures in 2010. Then we assume that new production capacity stock out to 2030 autonomously adopts energy efficiency measures at the incremental rate of 4% of the remaining potential each year (reflecting a continuation of India's aggressive implementation of energy efficiency measures (gray angular striped area in Figure 2)). Since the autonomous implementation of the measure in some of the new capacity will occur regardless of new policies, the savings potential of the autonomous implementation is excluded from the supply curves calculation. Second, the new capacity with additional potential for implementing the efficiency measures (not captured in autonomous improvement) is determined for each year (blue angular striped area in Figure 2). We assumed that a certain portion of the new capacity with additional potential for implementing the efficiency measures adopts the measures each year (2% per year between 2010 and 2030, for a total of 40% implementation by 2030) (the red angular striped area in Figure 2). We treat the *retired and replacement* capacity the same as new capacity expansions by assuming the same rates for autonomous adoption of energy efficiency measures and adoption rates within the additional potential for implementing the efficiency measures (the horizontal striped area in Figure 2). Because the *new capacity* and *retired and replaced* capacity are both calculated as the product of growth rates and the adoption rates, the resulting wedges are not always straight lines (e.g., gray stripped areas – both horizontal and angular). To sum up, the red solid and red stripped areas in Figure 2 is the total source of energy saving potentials captured on the supply curves.

Although the CSC methodology is a good screening tool for evaluating the potentials of energy-efficiency measures, the actual energy savings potential and cost of each energy-efficiency measure and technology may vary and depend on various conditions such as raw material quality, technology provider, production capacity, plant size, final product quality and byproducts, time of the analysis, and other factors. Moreover, it should be noted that some energy efficiency measures also provide additional productivity and environmental benefits which are difficult and sometimes impossible to quantify. However, including quantified estimates of other non-energy benefits could further reduce the CCE values for the energy-efficiency measures (Worrell et al. 2003; Lung et al. 2005; Xu et al. 2010, 2013a&b; Sathaye et al. 2010). In this study, we include only O&M benefits when treating other non-energy benefits in the analysis.

It should be noted that there are other approaches for developing conservations supply curves. For a review of these, as well as a discussion of some of the key differences and driving components and variable of single-year versus time horizon (the approach used in this analysis) methodologies, see (Hasanbeigi 2012).

2.4. Discount Rate

In this study, a real discount rate of 15% was assumed for the analysis. However, the choice of the discount rate depends on the purpose and approach of the analysis (prescriptive versus descriptive) used. A prescriptive approach (also known as social perspective) uses lower discount rates (4% to 10%), especially for long-term issues like climate change or public sector projects (Worrell et al. 2004). Low discount rates have the advantage of treating future generations more equally to current generations; thus may less favor the relatively certain, near-term effects over more uncertain, long-term effects (NEPO/DANCED, 1998).

A descriptive approach (or private-sector or industry perspective), however, uses relatively high discount rates between 10% and 30% in order to reflect the existence of barriers to energy efficiency investments in industrial sectors (Worrell et al. 2004, Sathaye et al. 2010; Xu et al. 2010, 2011, 2013a&b). These barriers include perceived risk, lack of information, management concerns about production and other issues, capital constraints, opportunity cost, and preference for short payback periods and high internal rates of return (Bernstein et al. 2007 and Worrell et al. 2000). Hence, the 15% discount rate used for these analyses is close to the higher end of discount rates from a social perspective and the lower end of the discount rates from private-sector or industry perspective.

3. Technologies and Measures to Reduce Energy and CO_2 Emissions for the Iron and Steel Industry

Based on previous analysis (Hasanbeige et al. 2012), 25 energy-efficiency measures were identified most relevant to the iron and steel industry in terms of applicability as well as the significance of the energy saving that can be achieved by implementing them. Descriptions of these 25 measures can be at Worrell et al. (2010). Current adoption rates are estimated based on the work of CSTEP in developing plant-specific Specific Energy Consumption benchmarks for use in the PAT program as described above. Table 1 presents data related to the production capacity in each step of the iron and steel production process in India. It also presents the energy savings, capital costs, and change in annual operation and maintenance (O&M) cost, and potential application share of the respective production for each energy-efficiency technology and measure when applied to India’s iron and steel industry. The potential application share of the respective production is based on expert estimates in collaboration with CSTEP.

Table 1. Energy Savings and Costs for Energy-Efficient Technologies and Measures Applied to the 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/tcs)	Electricity Savings (kWh/tcs)	Capital Costs (2010 US$/tcs)	Change in Annual O&M cost (2010 US$/tcs)	Share of production capacity in base year (2010) to which measure is applicable (%) *
	Sintering						**as % of Sinter production**
1	Heat recovery from sinter cooler	2	0.52	N.A.	4.12	0.00	90%
2	Increasing bed depth	2	0.01	0.06	0.00	0.00	25%
	Coke Making						**as % of Coke production**
3	Coal moisture control	20	0.17	N.A.	71.34	0.00	95%
4	Coke dry quenching (CDQ)	20	1.41	N.A.	85.18	1.33	70%
	Iron Making – Blast Furnace						**as % of Pig Iron production**
5	Injection of pulverized coal in BF to 130 kg/t hot metal	39	0.77	N.A.	8.68	-3.84	10%
6	Injection of coke oven gas in BF	39	0.36	18.50	5.92	0.00	98%
7	Top-pressure recovery turbines (TRT)	39	N.A.	46.00	26.70	0.00	75%

No.	Energy-Efficiency Measures / Technologies	Production Capacity in base year to which the measure is applied (Mt/year)	Fuel Saving (GJ/tcs)	Electricity Savings (kWh/tcs)	Capital Costs (2010 US$/tcs)	Change in Annual O&M cost (2010 US$/tcs)	Share of production capacity in base year (2010) to which measure is applicable (%) *
8	Recovery of blast furnace gas	39	0.04	N.A.	0.41	0.00	60%
	Iron Making - DRI						**as % of DRI production**
9	Use of iron ore pellets in DRI kiln	26	1.44	N.A.	212.30	0.00	80%
10	Install VVFD on kiln cooler drives	26	N.A.	1.60	8.76	0.00	80%
11	Properly sized blowers	26	N.A.	5.63	8.03	0.00	80%
	Steelmaking – basic oxygen furnace (BOF)						**as % of BOF crude steel production**
12	Recovery of BOF gas and sensible heat	26	0.73	N.A.	35.21	0.00	60%
	Steelmaking – EAF						**as % of EAF crude steel production**
13	Scrap preheating	41	N.A.	61.00	7.62	-6.09	80%
	Casting and Refining						**as % of total crude steel**

No.	Energy-Efficiency Measures / Technologies	Production Capacity in base year to which the measure is applied (Mt/year)	Fuel Saving (GJ/tcs)	Electricity Savings (kWh/tcs)	Capital Costs (2010 US$/tcs)	Change in Annual O&M cost (2010 US$/tcs)	Share of production capacity in base year (2010) to which measure is applicable (%) *
							production
14	Integrated casting and rolling (Strip casting)	67	0.05	42.00	255.51	-42.37	85%
	Hot Rolling						**as % of Hot rolled finished steel production**
15	Recuperative or regenerative burner	64	0.70	N.A.	4.25	0.00	60%
16	Process control in hot strip mill	64	0.30	N.A.	1.28	0.00	20%
17	Waste heat recovery from cooling water	64	0.04	-0.17	1.06	0.18	95%
	Cold Rolling						**as % of cold rolled finished steel production**
18	Heat recovery on the annealing line	4	0.30	3.00	4.04	0.00	90%
19	Automated monitoring and targeting systems	4	N.A.	60.00	1.81	0.00	50%

No.	Energy-Efficiency Measures / Technologies	Production Capacity in base year to which the measure is applied (Mt/year)	Fuel Saving (GJ/tcs)	Electricity Savings (kWh/tcs)	Capital Costs (2010 US$/tcs)	Change in Annual O&M cost (2010 US$/tcs)	Share of production capacity in base year (2010) to which measure is applicable (%) *
	General measures						**as % of total crude steel production**
20	Preventative maintenance in integrated steel mills	68	0.43	5.56	0.01	0.05	40%
21	Preventative maintenance in EAF plants	68	0.09	13.89	0.01	0.05	40%
22	Energy monitoring and management systems in integrated steel mills	68	0.11	2.78	0.20	0.00	95%
23	Energy monitoring and management systems in EAF plants	68	0.02	2.78	0.20	0.00	95%
24	Variable speed drives for flue gas control, pumps, fans in integrated steel mills	68	N.A.	11.11	2.18	0.00	70%
25	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	0.00	50%

* The share of production capacity in base year (2010) to which the measure is **applicable** is different than the share of production capacity in the base year to which the measure is **applied**. The method for determining the application rates of the measures are described in detail in the methodology section with Figure 2 as an illustration.

4. Results and Discussions

Based on the methodology explained above and the information from Table 2, the FCSC and ECSC were constructed separately to estimate the cost-effective and total technical potential for electricity and fuel efficiency improvement in the Indian iron and steel industry from 2010 to 2030. In addition, the CO_2 emission reduction potential from implementing efficiency measures was also calculated. Seventeen of 25 energy-efficiency measures are fuel-saving measures that are included in FCSC and 8 are electricity-saving measures used to derive the ECSC.

However, it should be noted that there are some technologies such as preventative maintenance in integrated and EAF steel mills, energy monitoring and management systems in integrated and EAF steel mills, cogeneration, heat recovery on the annealing line, waste heat recovery from cooling water, flameless oxy-fuel burners, integrated casting and rolling (Strip casting), and injection of natural gas in BF that either save both electricity and fuels, or increase electricity consumption as a result of saving fuel. These technologies with fuel savings accounting for a larger portion of their total primary energy savings are included in the FCSC with exception for cogeneration and integrated casting and rolling for which the electricity saving has a larger share of total primary energy saving; thus these two measures are included in ECSC.

4.1. Fuel Conservation Supply Curve for the Iron and Steel Industry

Seventeen energy-efficiency measures were used to construct the FCSC. Figure 3 shows that twelve energy-efficiency measures fall below the discounted average unit price of fuel in the iron and steel industry from 2010 to 2030 (1.6 US$/GJ), indicating that the CCF is less than the discounted average unit price of fuel for these measures. In other words, the cost of investing in these twelve energy-efficiency measures to save one GJ of energy in the period of 2010 - 2030 is less than purchasing one GJ of fuel at the given price. The other efficiency measures (grey area in Table 2) are technically applicable but are not cost-effective; thus, their implementation may require financial incentives beyond energy savings alone. Figure 4 shows the annual cost-effective fuel and fuel-based CO_2 saving including the electricity grid generator-level fuels and CO_2 emissions from the measures that have both fuel and electricity savings identified in Table 2.

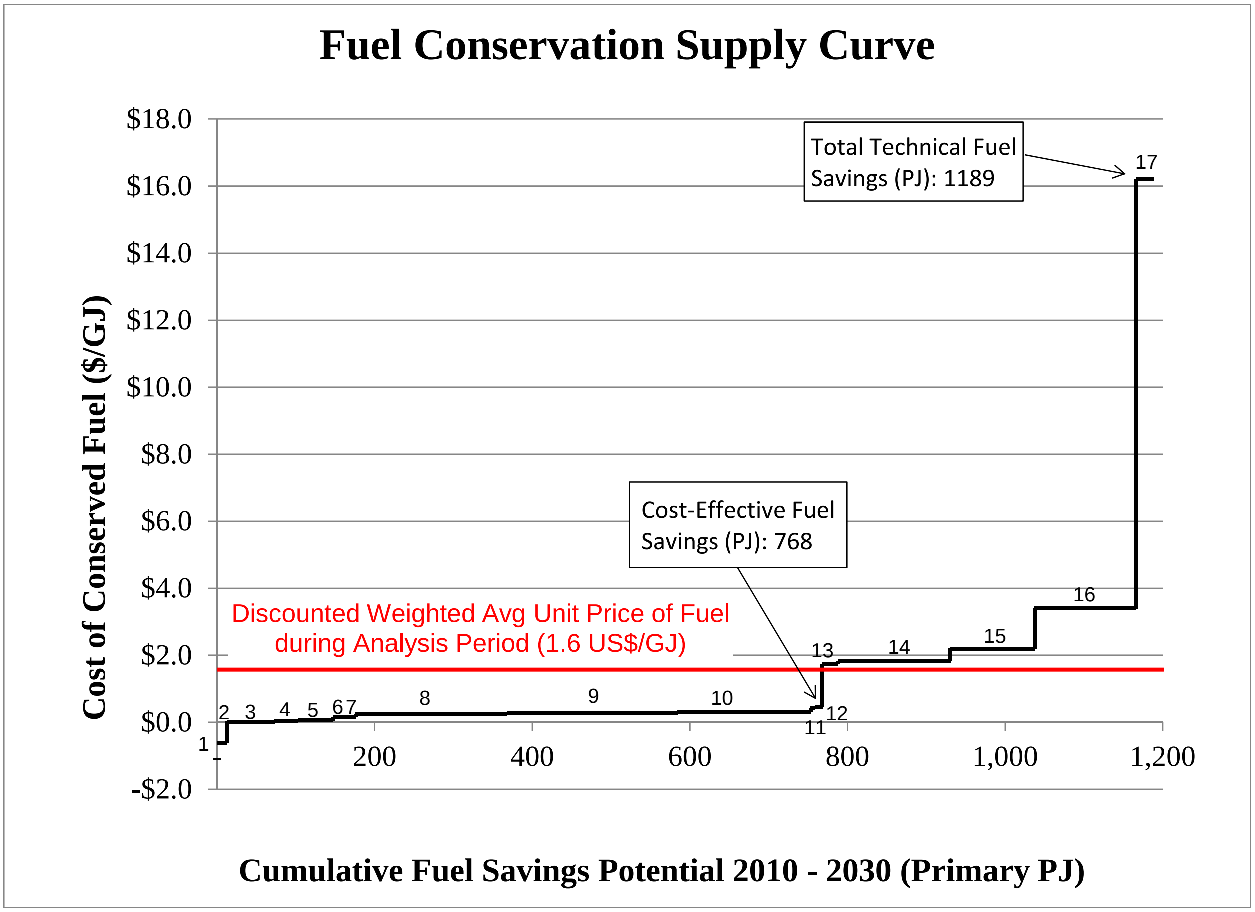

Figure 3. 2010-2030 FCSC for the Iron and Steel industry in India

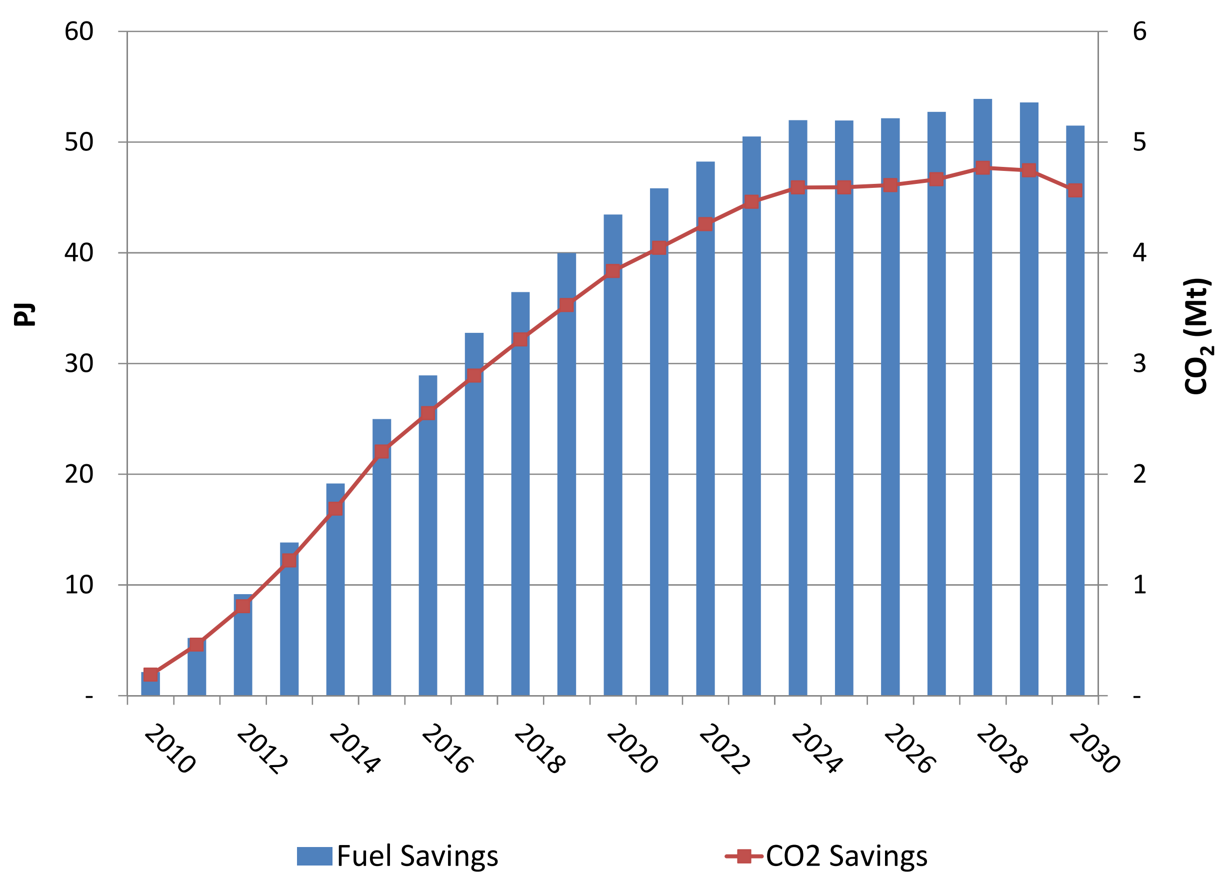

Figure 4. 2010-2030 Cost-Effective Fuel and Fuel-Base CO_2 Emissions Savings for the Iron and Steel industry in India for measures identified in Table 2

Table 2 presents the fuel efficiency measures applicable to the iron and steel industry ranked by their CCF. The fuel savings and CO_2 emission reduction achieved by each measure is also shown. Injection of pulverized coal in BF and increasing bed depth are the two most cost-effective measures (although increasing bed depth only contributes a modest contribution to the fuel savings). The highest fuel saving during 2010-2030 is achieved by recuperative or regenerative burner in hot rolling followed by injection of coke oven gas in blast furnaces and heat recovery from sinter cooler. Table 3 shows the cumulative cost-effective and the total technical potential for energy saving and CO_2 emission reduction from 2010 to 2030 as calculated by the model.

Table 2. Fuel Efficiency Measures for the Iron and Steel industry in India Ranked by Cost of Conserved Fuel (CCF)

CCF Rank	Energy-Efficiency Measures / Technologies *	Fuel Savings (PJ)	Cost of Conserved Fuel (US$/GJ-saved)	CO2 Emissions Reduction (Mt CO_2)

CCF Rank	Energy-Efficiency Measures / Technologies *	Fuel Savings (PJ)	Cost of Conserved Fuel (US$/GJ-saved)	CO2 Emissions Reduction (Mt CO_2)
1	Injection of pulverized coal in BF to 130 kg/t hot metal	12.7	-0.62	1.1
2	Increasing bed depth **	0.6	0.00	0.1
3	Preventative maintenance in integrated steel mills **	52.6	0.02	5.2
4	Preventative maintenance in EAF plants **	11.0	0.04	2.6
5	Energy monitoring and management systems in integrated steel mills **	35.5	0.05	4
6	Energy monitoring and management systems in EAF plants **	6.4	0.15	1.4
7	Process control in hot strip mill	12.4	0.16	1.1
8	Recuperative or regenerative burner	191.7	0.23	16.6
9	Injection of coke oven gas in BF **	139.6	0.28	19.2
10	Heat recovery from sinter cooler	168.9	0.31	14.6
11	Recovery of blast furnace gas	5.2	0.43	0.5
12	Heat recovery on the annealing line **	9.0	0.46	0.9
13	Waste heat recovery from cooling water **	20.7	1.75	1.7
14	Recovery of BOF gas and sensible heat	142.4	1.83	12.3
15	Coke dry quenching (CDQ)	106.9	2.20	9.2
16	Use of iron ore pellets in DRI kiln	128.9	3.40	11.1
17	Coal moisture control	22.6	16.20	2

* The descriptions of these 17 measures can be found at Worrell et al. (2008, 2010).

** For these measures, the share of fuel saving is more than that of electricity saving; thus, these measures are included as fuel saving measures on the FCSC. The national average power generation efficiency is used to convert electricity to fuel saving and the national electricity grid generator-level CO_2 emissions factor is used to calculate electric grid CO_2 savings.

Table 3. Cost-Effective and Total Technical Potential for Fuel Savings and the Associated CO_2 Emission Reduction in the Iron and Steel Industry in India during 2010-2030

	Cumulative Fuel Savings Potential (PJ)		Cumulative CO_2 Emissions Reduction (Mt CO_2)	
	Cost-Effective	Technical	Cost-Effective	Technical
Cumulative Saving Potential During 2010-2030	768	1189	67	104

Note: Numbers are rounded.

4.2. Electricity Conservation Supply Curve for the Iron and Steel Industry

For the iron and steel industry, eight energy-efficiency measures are included in the ECSC. Figure 5 and Table 4 show that seven out of eight energy-efficiency measures on ECSC fall below the discounted average unit price of electricity during the period of 2010-2030 (43.1 US$/MWh). Therefore, the CCE for these seven measures is less than the discounted average electricity price during the study period. In other words, these measures can be considered cost-effective as the cost of investing in these seven energy-efficiency measures to save one MWh of electricity is less than purchasing one MWh of electricity at the discounted average 2010-2030 unit price of electricity. Figure 6 shows the annual cost-effective final electricity, or plant-level electricity, and electricity grid generator-level CO_2 emissions from the measures identified in Table 4.

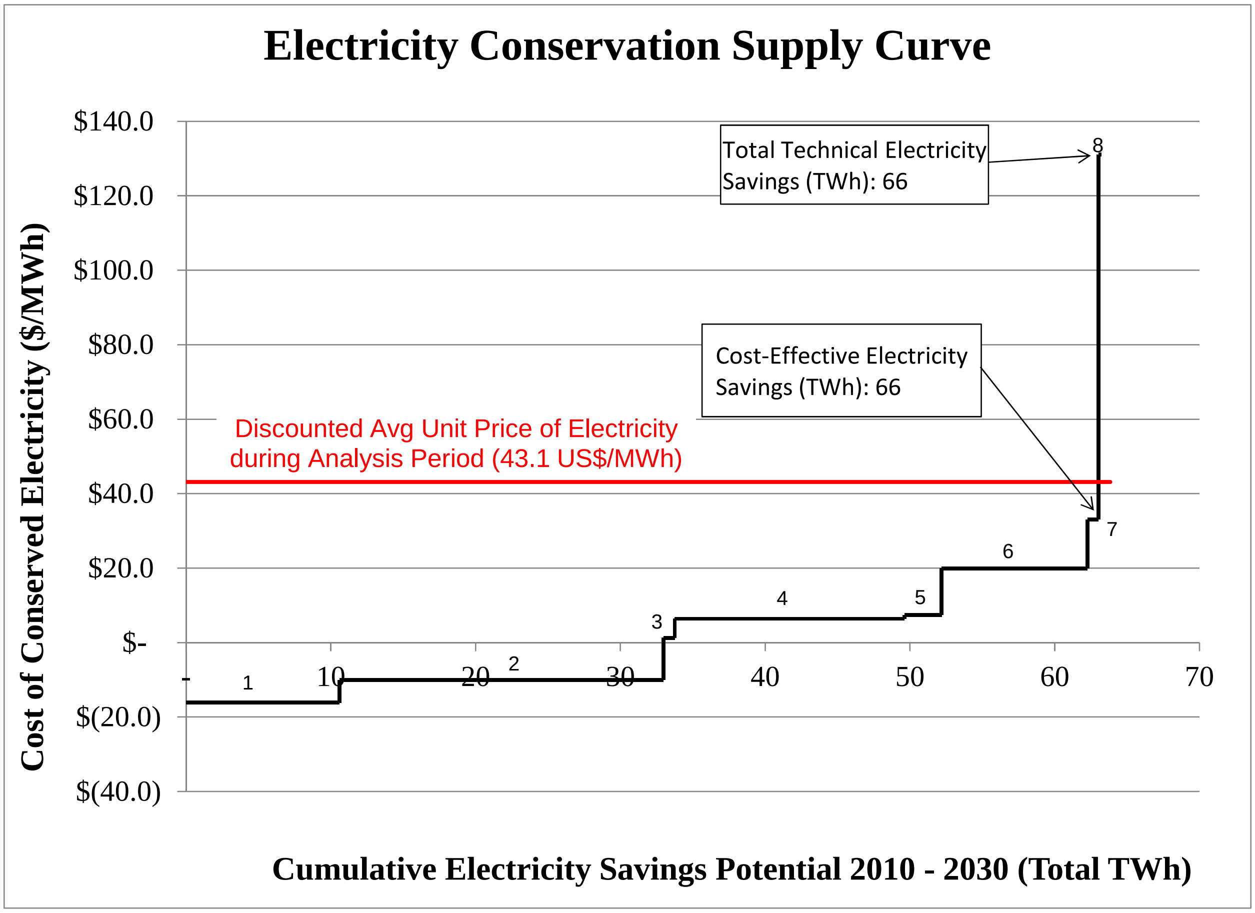

Figure 5. 2010-2030 ECSC for the Iron and Steel Industry in India (Final Electricity)

The three most cost-effective measures are scrap preheating in EAF plants, integrated casting and rolling, and automated monitoring and targeting systems in cold rolling. The largest electricity saving potential is from integrated casting and rolling followed by cogeneration (ranked 4 on the curve). Installing variable voltage or frequency drives (VVFD) on kiln cooler drives is the only measure that is not cost effective to implement (ranked 8 on the curve). Table 5 shows the cumulative cost-effective and the total technical potential savings for plant-level electricity and electricity grid generator-level CO_2 emissions from the measures identified in Table 4 for 2010-20300.

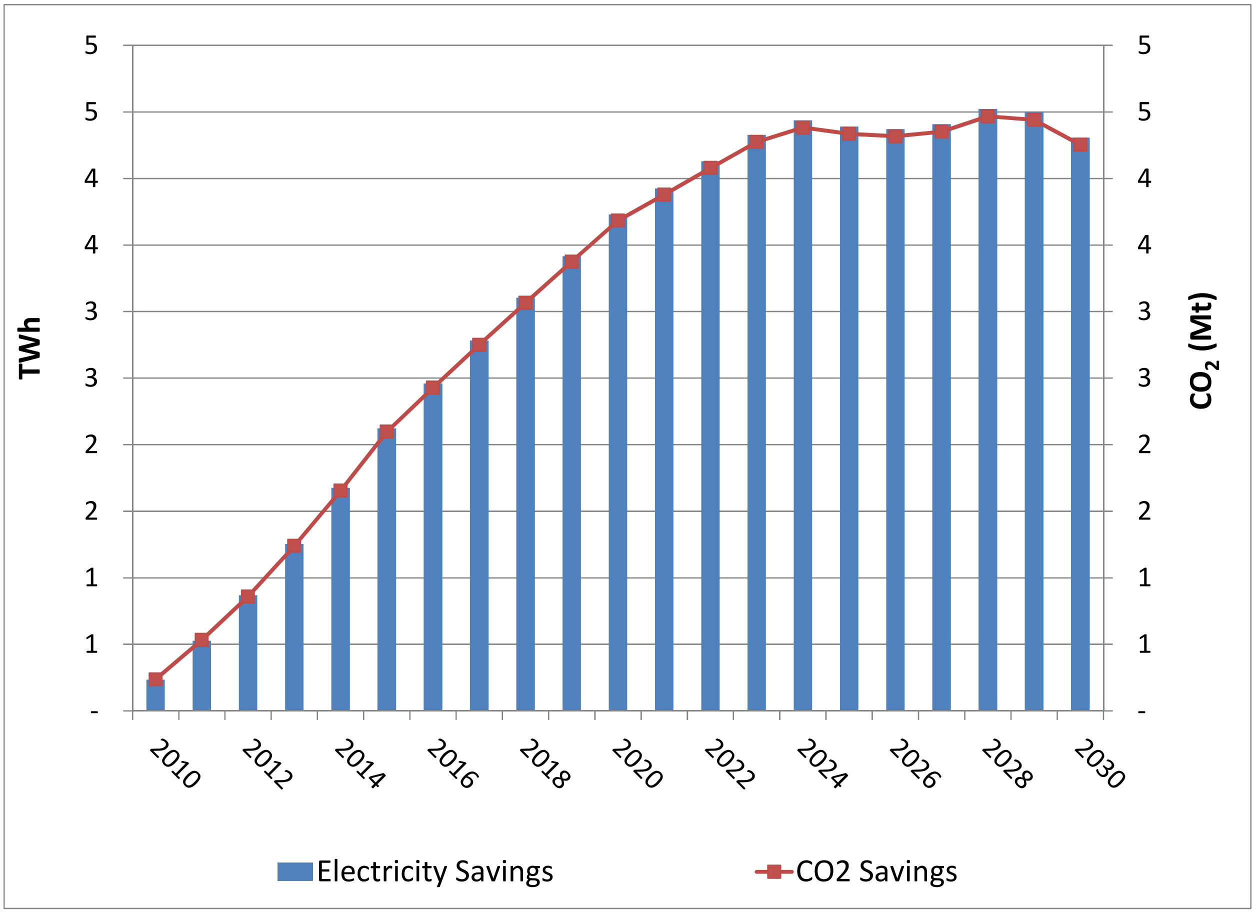

Figure 6. 2010-2030 Cost-effective Electricity and Electricity-Base CO$_2$ Emissions Savings for the Iron and Steel industry in India for the measures identified in Table 5

Table 4. Electricity Efficiency Measures for the Iron and Steel industry in India Ranked by Cost of Conserved Electricity (CCE)

CCE Rank	Energy-Efficiency Measures / Technologies *	Electricity Savings (TWh) **	Cost of Conserved Electricity (US$/kWh-saved)	CO$_2$ Emissions Reduction (Mt CO$_2$) †
1	Scrap preheating	10.6	-16.16	10.5
2	Integrated casting and rolling (Strip casting) ‡	24.9	-10.06	24.5
3	Automated monitoring and targeting systems	0.8	1.25	0.8
4	Cogeneration for the use of untapped coke oven gas, blast furnace gas, and basic oxygen furnace-gas in integrated steel mills ‡	15.9	6.40	15.7
5	Variable speed drives for flue gas control, pumps, fans in integrated steel mills	2.6	7.38	2.5
6	Top-pressure recovery turbines (TRT)	10.1	19.97	10

7	Properly sized blowers	0.7	33.06	0.7
8	Install VVFD on kiln cooler drives	0.2	131.10	0.2

* The descriptions of these 8 measures can be found at Worrell et al. (2008, 2010).

** Electricity results are final electricity, not primary electricity (electricity grid generator level), and therefor exclude transmission and distribution losses.

† CO_2 results are primary energy related (electricity grid generator level) and therefor included transmission and distribution losses.

‡ For these measures, the share of electricity saving is more than that of fuel saving; thus, this measure is included as an electricity saving measures on the ECSC. To convert fuel saving by this measure to electricity saving, the national average power generation efficiency is used.

Table 5. Cost-Effective and Total Technical Potential for Electricity Saving and CO_2 Emission Reduction in the Iron and Steel Industry in India during 2010-2030

	Cumulative Electricity Savings Potential (TWh) *		Cumulative CO_2 Emissions Reduction (Mt CO_2) **	
	Cost-Effective	Technical	Cost-Effective	Technical
Cumulative Saving Potential During 2010-2030	66	66	65	65

Note: Numbers are rounded.

* Electricity results are final electricity, not primary electricity (electricity grid generator level), and therefor exclude transmission and distribution losses.

** CO_2 results are primary energy related (electricity grid generator level) and therefor included transmission and distribution losses.

4.2. Sensitivity Analysis

In the previous sections, the cost-effective and technical energy-efficiency improvement potentials for India’s Iron and Steel industry were presented and discussed. Since the discount rate used in the analysis plays an important role in the analysis and results of energy-efficiency potentials, it is important and relevant to see how changes in this parameter can influence the cost effectiveness of the potentials. Hence, a discount rate sensitivity analysis is performed and the results are discussed below.

We conducted the sensitivity analysis for the discount rates of 5%, 13%, 17%, and 30%. As discussed previously in section 2.4. Discount Rate, A discount rate of 5% represents a societal perspective, while a discount rate of 30% represents an industry perspective capturing various non-monetary barriers to implementation. Discount rates of 13% and 17% are very close to the 15% discount rate used in the base case. Because some plants may use slightly different discount rate than 15% for their investment decision making, we assess the effect of the minor changes in the discount rate.

Table 6 shows how changes in the discount rate can affect the cost-effective energy-saving potentials and their associated CO_2 emission reduction potentials while keeping the other parameters constant (i.e. electricity and fuel prices, investment cost of the measures, and energy saving of the measures). It shows that, for this specific study, the cost-effective fuel savings increase only when the discount rate is at 5%. The cost-effective electricity savings change between discount rates of 17% and 30% (i.e., 66 TWh at and below 17%, and 41 TWh at 30%).

Table 6. Sensitivity Analysis for the Cost-Effective Electricity and Fuel Saving Potentials and CO_2 Emission Reduction in Indian Iron and Steel Industry during 2010-2030 with Different Discount Rates Keeping Other Parameters Constant

Discount Rate (%)	Electricity		Fuel	
	Cost-Effective Savings (TWh) **	Cost-effective CO2 emission reduction (MtCO2) ***	Cost-effective saving (PJ)	Cost-effective CO2 emission reduction (MtCO2)
D.R. = 5	66	65	1,038	90
D.R. = 13	66	65	768	67
D.R. = 15 *	66	65	768	67
D.R. = 17	66	65	768	67
D.R. = 30	41	40	768	67

*: The discount rate = 15% is the base scenario which is used in the main analysis presented in previous sections.

** Electricity results are final electricity, or plant-level, not the electricity grid generator-level, and therefor exclude transmission and distribution losses.

*** CO_2 results are at the electricity grid generator-level and therefor included transmission and distribution losses.

In general, for this specific study, results are not very sensitive to discount rates. The total technical energy saving and CO_2 emission potentials (X-axis) do not change with the variation of the discount rate. The discount rate is applied to both the measure investments and the unit price of energy that determines cost-effectiveness. Therefore, the affect that the discount rates has on the CSC tends to move the curve up or down along the Y axis (the cost axis) and it also moves the discounted unit cost of energy up or down the Y axis. Thus, discount rate effect tends to cancel out leaving the analysis results largely insensitive to changes in the discount rates.

5. Conclusions

Given the importance of India’s Iron and Steel industry as one of the highest energy-consuming and CO_2-emitting industry, this study aims to understand the potential for energy-efficiency improvement and CO_2 emission reduction using a bottom-up model. Specifically, bottom-up Energy Conservation Supply Curves (i.e. ECSC and FCSC) were constructed for the Indian Iron and Steel industry to estimate the savings potential and costs of energy-efficiency improvements by taking into account the costs and energy savings of different technologies.

We analyzed 25 energy efficiency technologies and measures for the Iron and Steel industry. Using a bottom-up CSC models, the cumulative cost-effective and technical electricity and fuel savings as well as the CO_2 emissions reduction potentials for the Indian Iron and Steel industry for 2010-2030 are estimated. Between now and 2030, the cumulative fuels saving potential less than half the current annual total iron and steel sector fuel consumptions and the electricity savings potential is slightly less than the industry's current annual electricity consumption.

When looking at CSCs and trying to interpret the results, one should pay attention to the method and formulas used in the development of the curves in addition to the assumptions used such as the discount rate, energy prices, period of the analysis, measure adoption rates, cost of technologies and their energy saving, etc. Finally, the approach used in this study and the model developed can be viewed as a screening tool to help policymakers understand the savings potential of energy-efficiency measures and design appropriate policies to capture the identified savings. However, energy-saving potentials and the cost of energy-efficiency measures and technologies will vary according to regional- and plant-specific conditions. This study shows that in India's case, an efficiency gap is relatively small as many of the identified cost-effective opportunities for energy efficiency improvement have already been adopted within the relatively new and efficient industry. The gap that does exist is a result of various obstacles to adoption, especially non-monetary barriers in the Iron and Steel industry, and suggests that effective energy efficiency policies and programs are needed to realize cost-effective energy savings and emission reduction potential.

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Appendixes

Appendix 1. Time Dependent Key Model Inputs

Time Dependent Key Model Inputs	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Emissions Factors																					
CO2 Emission factor for grid electricity (tonne CO2/MWh)	1.02	1.02	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
CO2 Emission factor for fuel (tonne CO2/TJ)	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5
Industry Capacity (Mt)																					
Sintering	32	41	50	60	69	79	81	82	84	86	88	90	91	93	95	97	99	100	102	104	106
Coke Making	20	24	29	33	38	42	43	44	45	46	47	48	48	49	50	51	52	53	53	54	55
Iron Making – Blast Furnace	39	50	62	73	85	96	98	100	102	105	107	109	111	113	115	117	119	122	124	126	128
Iron Making – Direct-reduced Iron	26	29	32	35	37	40	43	45	48	50	53	56	58	61	63	66	69	71	74	76	79
Steelmaking – basic oxygen furnace (BOF)	26	40	54	68	82	96	98	100	102	105	107	109	111	113	115	117	119	122	124	126	128
Steelmaking – EAF	41	40	39	38	36	35	37	40	42	45	47	50	52	55	57	60	62	65	67	70	72
Casting and Refining	67	80	93	106	118	131	136	140	145	149	154	159	163	168	172	177	182	186	191	195	200
Shaping	68	80	93	106	118	131	136	140	145	149	154	159	163	168	172	177	182	186	191	195	200
Hot Rolling	64	75	87	99	111	123	128	132	136	141	145	149	154	158	162	167	171	175	180	184	188
Cold Rolling	4	5	5	6	7	8	8	8	8	9	9	9	9	10	10	10	11	11	11	11	12

Source: IEA 2011a, GOI 2012b

Appendix 2. Annual Results

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Fuel Savings (PJ)	2.13	5.21	9.16	13.84	19.16	25.00	28.94	32.77	36.46	39.99	43.46	45.82	48.23	50.52	51.98	51.96	52.16	52.73	53.89	53.59	51.48
Fuel Related CO$_2$ Savings (Mt)	0.19	0.46	0.81	1.22	1.69	2.20	2.55	2.89	3.22	3.53	3.83	4.04	4.26	4.46	4.59	4.59	4.61	4.66	4.77	4.74	4.56
Electricity Savings (TWh)	0.23	0.53	0.87	1.25	1.68	2.12	2.46	2.78	3.10	3.42	3.73	3.93	4.13	4.33	4.44	4.39	4.37	4.41	4.52	4.50	4.31
Electricity Related CO$_2$ Savings (Mt)	0.24	0.53	0.86	1.24	1.65	2.10	2.43	2.75	3.07	3.38	3.68	3.88	4.08	4.27	4.38	4.34	4.32	4.35	4.47	4.44	4.25