A Study of Energy Efficiency in the Indian Iron and Steel Industry

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SHAKTI
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Preface

There is a well-defined correlation between the production of iron and steel and a country's industrial and economic growth, at least during the initial growth years. India is no exception to this relationship. In fact this relationship should be much more pronounced considering that the country has large reserves of iron ore and a tradition of iron and steel making for many decades.

The annual production of iron and steel in India is around 80 million tonnes and it consumes over 46 Mtoe of energy contributing about 6 percent of the National Greenhouse Gas emission. Globally, this industry is an efficient one and in a few stages of iron making the efficiency touches almost theoretical levels. In spite of this, energy consumption at some of the Indian plants is 50 percent higher than the global best practice.

There can be a number of options for improving energy efficiency. Such innovations include capturing and reusing by-product gases for heat and for generating electricity. There are also substitutions in the choice of raw materials. These include pulverised coal and medium quality iron ore with natural gas or electricity substituting for coking coal. Europe has become the leader for working with such innovations. In a programme identified as ULCOS (Ultra Low Carbon-dioxide Steel), European manufacturers are experimenting with a number of options including electrolysis, and natural gas as the reducing agent. There is a need for India to invest in such transformative technologies. These have the potential to reduce the greenhouse gas emissions by almost fifty percent! Recycling steel scrap has the potential to reduce the use of iron ore. In the US over 60 percent of steel comes from melting scrap metal reducing capital costs for building blast furnaces.

India's annual per capita consumption of steel is still modest and if the country has to multiply its consumption from 57 to near 200 kilograms, it must build more steel plants that use low energy and low carbon technologies. This CSTEP report, sponsored by the Shakti Foundation and encouraged by Bureau of Energy Efficiency suggests options for making this core industry energy efficient with minimum greenhouse gas emissions. Dr. S.S Krishnan provided the leadership to this project, and many thanks are due to him and his colleagues. In the coming years we propose to take this area for further studies to identify transformative opportunities in technologies.

V.S. Arunachalam
Chairman, CSTEP, Bangalore

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ENERGY IS LIFE ऊर्जा दक्षता ब्यूरो
(भारत सरकार, विद्युत मंत्रालय)
BUREAU OF ENERGY EFFICIENCY
CONSERVE IT (Government of India, Ministry of Power)

अजय माथुर, पीएच.डी
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Director General

Foreword

The Indian iron & steel sector has seen a steady increase in the addition of steel-making capacity over the years. Crude steel production in India has shown a sustained rise since 2004, and the Indian industry is now the 4th largest crude steel producer in the world. Steel production in India was about 120 MTPA in 2012, and is expected to reach 275 MTPA by 2020 which could make India the second largest steel producer in the world.

The iron & steel sector is one of the most energy intensive sectors in India. On an average, iron & steel plants spend about 20-40% of their total manufacturing cost to meet their energy demands. In fact, energy cost is considered as a major factor in the pricing and competitiveness of steel.

The energy consumption of steelmaking depends on a number of factors, including the production route, type of iron ore and coal used, the steel product mix, operation control technology, and material efficiency. In spite of this diversity, the sector has a well-deserved reputation for technological intervention to promote energy efficiency. The PAT programme has provided a further stimulus for advanced interventions for enhancing energy efficiency, and spurred the need to identify priority interventions. This analysis, based on energy efficiency modeling of this sector, would be very helpful in assessing the potential and the technological interventions for the successful implementation of energy efficiency programmes.

I congratulate CSTEP on this work, which is technologically detailed and reader friendly. I would like to compliment Dr. S. S. Krishnan and his team for their hard work which has made this modeling possible. I am sure that this would be of great use to the industry, and could become the basis for unit-specific models through which energy efficiency performance and interventions could be mapped.

(Ajay Mathur)

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The support and encouragement from Dr. V.S. Arunachalam, Chairman, and Dr. Anshu Bharadwaj, Executive Director of CSTEP is immensely appreciated. We are especially grateful to our advisors Dr Ramakrishnan N., Dr. N. Balasubramanian and former advisor Dr. R. Krishnan for their valuable suggestions and inputs on a continuous basis, their diligent review and invaluable feedback. We thank Dr. K.C. Bellarmine, Chief Financial Officer, for support on project management and deliverables.

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Executive Summary

The National Action Plan on Climate Change (NAPCC) released by the Honourable Prime Minister seeks to promote sustainable development through increased use of clean technologies. NAPCC has a mission specifically dedicated to energy efficiency – National Mission on Enhanced Energy Efficiency (NMEEE). Perform, Achieve and Trade (PAT), one of the flagship programs under NMEEE was launched and implemented by the Bureau of Energy Efficiency (BEE) to issue energy efficiency norms to energy intensive manufacturing units. As of now BEE has identified 478 such units, notified as Designated Consumers (DCs) under eight energy intensive sectors. About 67 Iron and Steel DCs have annual energy consumption of 30,000 tonnes oil equivalent (toe) or above. These DCs together consumed an average of about 25.33 Million toe (Mtoe) and the apportioned energy reduction targets for them equivalent to 1.48 Mtoe have to be reached by 2014-15.

The objective of this study has been to model the Energy Efficiency (EE) of the Indian iron and steel industry, in the context of the diversity and the challenges in operating conditions, in order to provide analysis and insights for the successful implementation of PAT.

This sector contributes around 3% to the Gross Domestic Product (GDP). The average consumption of steel during 2011-12 was 70.92Mt (59kg per capita). The production of crude steel capacity has grown to 89.29 Mt at 8% (CGAR) annually. The projected estimates of crude steel production and capacity by 2020 is expected to reach 136Mt with per capita consumption of 90kg. There are three major process routes in steel making- 45% steel is produced by Blast Furnace –Basic Oxygen Furnace (BF-BOF) route; 24% and 31% by electrical furnace such as Arc furnace and Induction furnace routes respectively.

In 2009, India's total final energy consumption was 449.27 Mtoe; the residential and industrial sectors consuming 38% and 30% respectively. Iron and steel production involves highly energy intensive processes. The sector contributes to about 6.2% of the national Green House Gas (GHG) emissions. The sector consumed about 33.69Mtoe or 25% of the total industrial energy consumption.

There is huge potential in improving energy efficiency in the Iron and Steel Industry irrespective of limitations in the availability and quality of iron ore and coking coal. In India, the average primary Specific Energy Consumption (SEC) from selected major steel plants was 27.3 GJ/tcs. The globally, the Best Available Technology (BAT) has a benchmark of primary SEC of 16.4 GJ/tcs through BF-BOF route, 19.3 GJ/tcs by the smelt reduction (COREX)-BOF route, 19.1 GJ/tcs through coal based DRI-EAF route and 15.9 GJ/tcs from gas based DRI-EAF route in 2009. Additionally, energy cost is a major component of the manufacturing cost and ranges between 40-60% in a typical iron and steel plant.

In 2007, GHG emissions from various sectors in India were 1904.73 $MtCO_2$, amongst which 38% (719.31 $MtCO_2$) and 22% (412.55 $MtCO_2$) were from power and industry sector respectively. The Indian Iron & Steel sector contributed to about 117.32 $MtCO_2$ (28.4% of the industrial sector). In this context, India announced a voluntary 20-25 per cent carbon emission intensity reduction by 2020 on the 2005 levels, ahead of the UNFCCC's COP15 summit held in Copenhagen. The Government of India, in 2010, announced its intent to reduce the carbon intensity in 2020 by 25% as compared to 2005 levels. This could possibly be accomplished by improved processes, adoption of energy efficient technologies and measures, and renewable energy options.

Engineering Modeling and Economic Analysis

The research showcases eight case studies of sample plants employing different iron and steel manufacturing processes, product mix, production and energy consumed. Scenarios were developed considering six different actual SEC reductions by the sample DCs to highlight the performance of these plants during the three year PAT cycle. The total energy consumed and annual energy savings were calculated and compared. The outcome of the analysis is to provide valuable insights to personnel and senior management to evaluate their performance with set targets and the actual performance of the plant in both energy and monetary units.

Economic analysis of energy efficiency interventions was performed. Investments for different types of energy efficient interventions along with the corresponding annual savings were used to calculate the payback period, net present value and internal rate of return.

Two kinds of models were developed for blast furnace and basic oxygen furnace processes, one through stoichiometric analysis and another with the computer based simulation software – ASPEN Plus. This tool models the thermodynamic reactions and provides a mass and energy balance estimate for the process. This model has been used to understand the energy and emissions intensity of these processes under variations in quality of iron ore and coal. The results from the computation modeling tools are preliminary; however they provide a basis for further modeling.

There are several breakthrough ULCOS technologies which were deployed around the world and in India as well such the Coke Dry Quenching and Top Recovery Turbine among others. Technologies which could have a significant impact on improving energy efficiency a few years into the future is the use of hydrogen or electrolysis for reducing or extracting iron from the ore. SAIL has drafted plans to improve the performance of its five ISPs with an emphasis on technology upgradation and research and development at centres such as the Research and Development Centre for Iron and Steel, at Ranchi.

Barriers and Challenges: Policy Suggestions

The Indian iron and steel industry has been working consistently and contributing to the infrastructure development and economic growth of the country in the face of several barriers and challenges. Some of these can be summarized as follows:

- Availability of raw materials such as ores and coal resources
- Supply chain and associated infrastructure (roadways and railways)
- Variation in the international prices
- Land acquisition and grant of environment clearance
- Techno-economics, and production efficiency benchmark in compliance with international standards
- Sustaining in a competitive environment due to global trade agreements
- Reckonable restrictions and high tariff barriers

To overcome these challenges, suitable economic policy framework needs to be formulated to facilitate continuous technology advancements and adoption of energy saving measures with specific national policy mechanisms such as PAT.

The periodic economic crunch that has led to an increase in domestic and imported coal price, has affected the growth and performance targets of the industry. In addition, fluctuating demand profiles of specific product types, high transportation costs and variations in freight charges impacts the sector as a whole.

The Indian Steel industry will need to adopt suitable economic policy and investment framework to facilitate continuous upgradation to best available technology which will result in reduction in the energy consumption. This report studies the potential improvements in energy efficiency for the sector and showcases the environmental and economic benefits of implementing various measures. The study could be used as a guidance tool for the industry in the PAT mechanism.

Outline of the Report

The report begins with an overview of the Iron and Steel Industry in the context of its importance to Indian economy and introduces the objective of this study. The status of the industry by production, energy consumption and emissions are discussed with projections. Additionally, a quick outline of Iron & Steel manufacturing process chain is explained.

The core technical research activity is augmented in the second chapter. The detailed stoichiometric process model and computer based simulation (ASPEN) model of various sub processes and its results are discussed. This chapter examines the electrical and thermal SEC of the sub-processes. The variation in operating parameters at major equipment across the different sub-processes of the sample plants over a sample time period is also examined.

The PAT methodology of estimating SEC is outlined in the third chapter followed by its application in eight sample plants from the Integrated Steel Plant (ISP) and Sponge Iron (SI) sub-sectors. Both simple and normalised baseline Gate-to-Gate G2G SECs are estimated and a summary table comparing the two indicators is provided.

Levers to improve Energy Efficiency (EE) across the different sub processes, with respective technology up-gradation options, are illustrated in the fourth chapter. Several energy efficiency measures were evaluated based on financial parameters viz. Payback period, Net Present Value (NPV) and Internal Rate of Return (IRR). Other EE options such as Waste Heat Recovery (WHR), and Alternative Fuel Resources (AFR) are also discussed.

An interesting study of manufacturing units under the energy efficiency norms are discussed in the chapter five 'PAT Focussed Scenario Analysis'. The chapter analyses and showcases the potential performance of DCs under different SEC reduction scenarios. The plant specific economic impact and the energy savings for different scenarios have been estimated. Simulations visualising the behavior of sample plants in the first cycle of PAT have been conducted to provide insights for planning the plants PAT focused upgradation by the DCs.

Lastly, challenges and policies in the context of PAT are discussed along with environmental pollution norms, financing to meet EE goals, guidelines for Monitoring and Validation, and ISO 50001 (Energy Management Standard) description. The report concludes with a summary of the study, highlighting some of the key findings.

Contents

List of Tables

List of Figures

1. Introduction

Indian industrial sectors such as Iron & Steel and Cement manufacture products for equitable growth but at the same time consume huge amounts of energy. India's total final energy consumption was estimated at 449.27Mtoe of which the industrial sectors consumed about 30%. The Iron & Steel sector is one of the most energy intensive manufacturing industries, consuming about 25% of the total industrial energy consumption (1). The total GHG emissions in India were assessed at 1904.73 $MtCO_2$, and 38% (719.31 $MtCO_2$) and 22% (412.55 $MtCO_2$) were from electricity generation and industry sectors respectively. The Indian Iron and Steel sector contributed to about 117.32 $MtCO_2$ or 6.2% (2).

Figure 1 shows the sectoral share of total industrial energy consumption in India and the world. Among the major industries the Iron and Steel sector is among the most energy intensive. Globally, the sector consumes almost 21% of total industrial energy consumption.

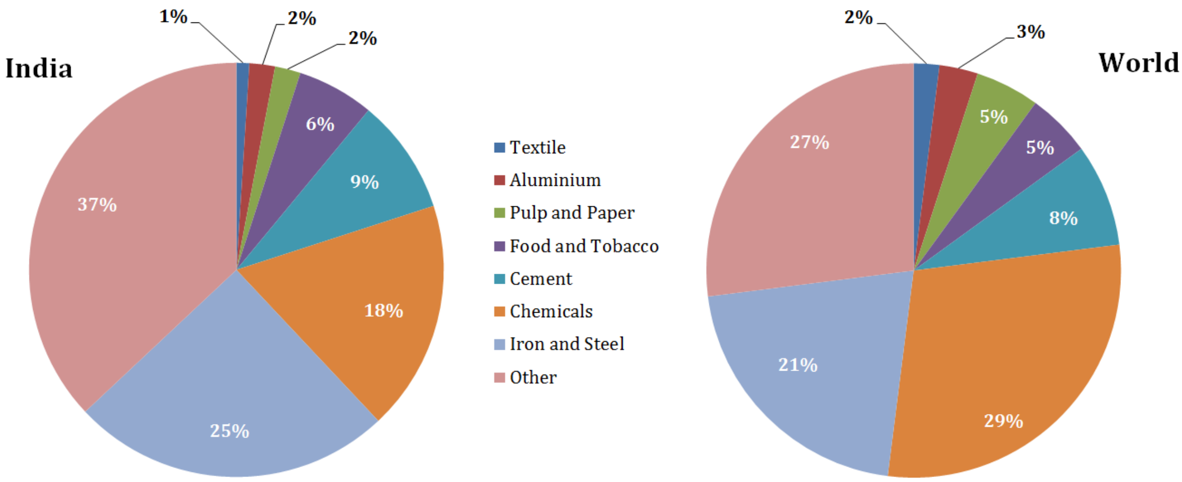


Figure 1: Sectoral energy consumption (2009), India (150Mtoe) and World (3019 Mtoe)

The Indian Iron and Steel industry is vital to the nation's development efforts and to support the required rapid economic growth. Steel finds its application in a wide range of sectors such as automobile, power, machine goods, and infrastructure. Energy efficiency and low carbon growth have emerged as key pathways to reduce the nation's energy intensity and emissions intensity. The industry has taken several initiatives to conserve energy at each sub process by adopting best technologies and innovative process operations or the usage of alternate materials.

The Bureau of Energy Efficiency (BEE) under the Ministry of Power (MoP) has been entrusted with the responsibility of implementing various strategic policy mechanisms specifically to enhance the energy efficiency. The National Steel Policy has been framed by the Ministry of Steel, Government of India for long-term objectives of improving production, consumption, quality and techno-economic efficiency, environmental and social sustainability. The Central Pollution Control Board (CPCB) has set norms for permissible emissions and other hazardous pollutants from several industrial sectors.

The Indian industrial sectors have worked hard amidst several challenges in the development of the Indian economy. The industry needs to be supported with rigorous research and development studies focusing on technology, economics and policy aspects. The research findings will be disseminated among industries, policy making bodies, financial institutions and related stakeholders to enable them to contribute to the development of a globally competitive industry by enhancing energy efficiency while increasing environmental sustainability.

1.1 Energy Efficiency Legislative Framework

This section of the report highlights some of the existing legislations and policies with respect to energy efficiency measures in the Iron and Steel industry.

- **National Mission on Enhanced Energy Efficiency (NMEEE)**

The National Mission on Enhanced Energy Efficiency (NMEEE) is one of the eight missions under the National Action Plan on Climate Change (NAPCC). The mission provides measures and actions to unlock the energy efficiency potential in various sectors of the economy.

The key initiatives under the NMEEE are:

- Perform, Achieve and Trade (PAT) – A market based mechanism to enhance cost-effectiveness of improvements in energy efficiency in energy-intensive large industries and facilities, through certification of energy savings that could be traded.

- Market Transformation for Energy Efficiency (MTEE) – Accelerating the shift to energy efficient appliances in designated sectors through innovative measures to make the products more affordable.

- Energy Efficiency Financing Platform (EEFP) – Creating mechanisms that would help finance demand side management programmes in all sectors by capturing future energy savings.

- Framework for Energy Efficient Economic Development (FEEED) – Developing physical instruments to promote energy efficiency.

- **Energy Conservation Act**

The Energy Conservation (EC) Act 2001 contains provisions to specify energy consumption standards for notified equipment and appliances, and to direct mandatory display of labels on them (3). It empowers the government to prohibit manufacture, sale, purchase and import of notified equipment and appliances not conforming to energy consumption standards. Notification of energy intensive industries and commercial buildings as Designated Consumers (DCs) is one of the salient features of this Act. Furthermore, the government is authorised to establish and prescribe energy consumption norms and standards for DCs. DCs are required to appoint energy managers and to conduct periodic energy audits in order to increase the efficient utilisation of energy.

- **Bureau of Energy Efficiency (BEE)**

Under the provisions of the Act, the Bureau of Energy Efficiency (BEE), Ministry of Power, Government of India, was established in March, 2002, to develop policy and strategies, and has been entrusted with the responsibility of implementing various mechanisms under the EC Act 2001.

- **PAT Mechanism**

PAT is a market-based mechanism to incentivise improvements in energy efficiency in energy intensive large industries. Energy Saving Certificates (ESCs) are given to DCs who are able to reduce their SEC beyond the specified target. The mechanism is being implemented in compliance with the EC Act 2001, situational analyses of DCs and consideration of the national energy saving goals.

ESCs earned by one DC can be traded on platforms with other DCs. DCs who find it difficult to comply with the whole or a part of their targets can purchase these ESCs. The PAT methodology involves setting up a baseline SEC for a DC, and providing a norm or target for reducing it over a three year time period. It also includes processes for data collection, data verification, and to verify the SEC of each DC in the baseline year and target year. In the target year ESCs will be issued to eligible DCs.

Table 1 below shows the sectors and the number of DCs which are currently in the first PAT cycle which was notified on March 30, 2012. These sectors account for about 220 Mtoe of energy consumption, which is about 49% of the total energy consumed in 2007-08 (3).

- **Designated Consumers (DCs)**

DCs in the Iron and Steel industry are plants that consume more than 30,000 tonnes of oil equivalent of energy per annum. The estimated list has 67 DCs in the Iron and Steel Sector.

Table 1: Minimum annual energy consumption and estimated number of DCs (3)

SECTOR	Minimum annual energy consumption for the DC (tonnes of oil equivalent - toe)	No. of DCs
Cement	30,000	85
Iron and Steel	30,000	67
Aluminium	7,500	10
Fertiliser	30,000	29
Pulp and Paper	30,000	31
Textiles	3,000	90
Chlor-Alkali	12,000	22
Thermal Power Plants	30,000	144

- **National Steel Policy**

The steel sector is one of the important sectors which drive the country's economic growth. Countries have strongly relied on domestic steel production during their journey towards economic development. The National Steel Policy 2012 aims to attract investment in Indian steel sector from both domestic and foreign sources to reach the ambitious goal of crude steel production capacity of 300 Mt with a production level of 275 Mt by 2025-26. One more objective is to ensure easy availability of inputs and necessary infrastructure to achieve a projected ambitious production level (4). The key goals of NSP 2012 are depicted in Table 2 and Table 3.

Table 2: Raw Material Requirement at 7 and 8% GDP

Raw Material Requirement		
At 7% GDP	**2016-17**	**2025-26**
Iron Ore	203	392
Coking Coal	89	173
Non-coking coal	27.8	66.2
PCI	4.5	9
Met Coke(including captive)	67.4	89.2
At 8% GDP	**2016-17**	**2025-26**
Iron Ore	215.4	452
Coking Coal	94.2	200
Non-coking coal	30.4	78
PCI	4.8	10.4
Met Coke(Including Captive)	72.5	153.9

Table 3: Parametric goal towards 2025-26 from the existing level

Parameter/Area	Unit	Existing Level	Strategic Goal/Projection by 2025-26
Specific Energy Consumption	GCal/tcs	6.3	4.5
CO_2 emissions	T CO2/tcs	2.5	2.0
Material Efficiency	%	93.5	98.0
Specific Make up Water Consumption (Works excluding power plant)	T/tcs	3.3	2.0
Utilization of BOF slag	%	30	100
Share of continuous cast production	%	70.0	95.0
BF Productivity	T/m3/Day	1.9	2.8
BOF productivity	No. of Heats/ Converter/year	7800	12000
R&D expenditure/turnover	%	0.2	1.5

1.2 Objective

The objective of the study is to generate a technology and policy focussed assessment for the Indian I&S sector and to provide support to the industry and BEE in the implementation of the Perform Achieve Trade (PAT) mechanism. The study focuses on the following key aspects:

- Study the present state of the I&S sector
- Sub-process specific technical models to study the process behaviour with varied inputs
- Policy focused study of sample plants and techno-economic analysis of their performance in the PAT mechanism
- Highlight the key Polices and Challenges

1.3 Background

- ***Status of Indian Iron and Steel Sector***

Globally, the Indian Iron and steel sector is the fourth largest crude steel producer and expected to become second largest in near future. World crude steel production during 2012 was estimated to 1547.8 Million tonnes, China at the top with 716 Mt followed by Japan, USA and India (Figure 2). The sector is the leading direct reduced iron (DRI) or Sponge iron producer in the world. The average consumption of steel in India during 2011-12 was 70.92 Mt (59kg per capita). The production capacity of crude steel has grown to 89.29 Mt at 8 % (CGAR) (5). About 3% of the Gross Domestic Product is the contribution from this sector. Figure 3 illustrates the historical crude steel production in comparison with annual capacity. The trend indicates that the sector has observed a steady performance with capacity utilisation between 85-90%.

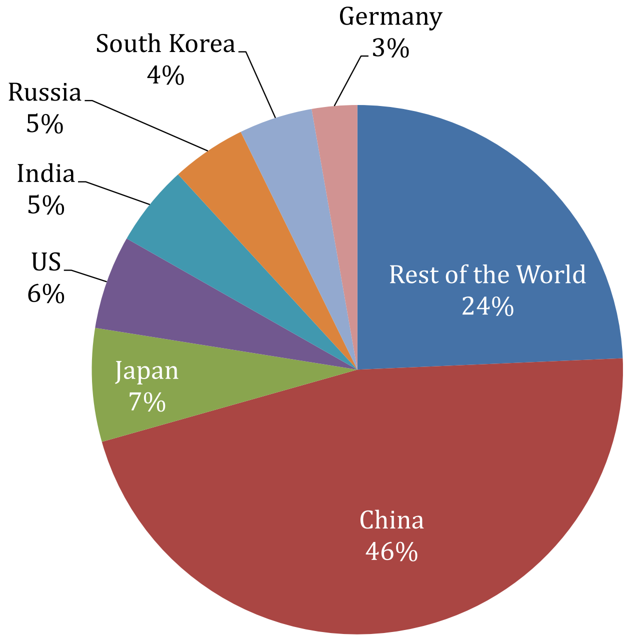


Figure 2: World Crude Steel Production in 2012 (4)

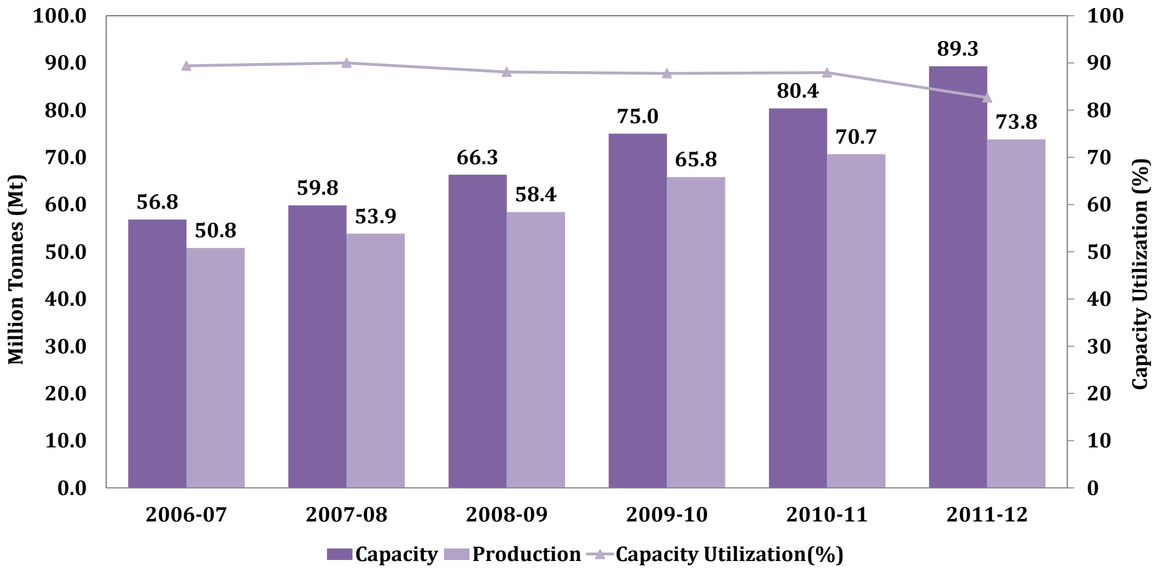


Figure 3: India's crude steel production, capacity and Capacity utilization (**production number for 2011-12 was provisional)*

The XIIth Five Year Plan (FYP) working group report for the steel industry envisaged 9% GDP annually and projected that the demand for steel could have an annual growth of 10.3% by 2016-17 (6). The National Steel Policy (NSP) 2012 considers a growth of 7.8% (CGAR) and a projected demand of 202 Mt by 2025-26. In order to meet the production demand, the capacity of the industry could need an expansion to 244Mt (7).

Figure 4 illustrates the projection estimates at 8% CGAR till 2020. The industry could reach production levels of 136 Mt with a capacity of 165 Mt. During 2011-12, the per capita consumption was about 59 kg and is estimated to grow at 6% annually while the national population is estimated to grow by 1.1%. The projected domestic consumption and the total demand are estimated at 130 Mt and 139 Mt of crude steel respectively by 2020 and are illustrated in Figure 5.

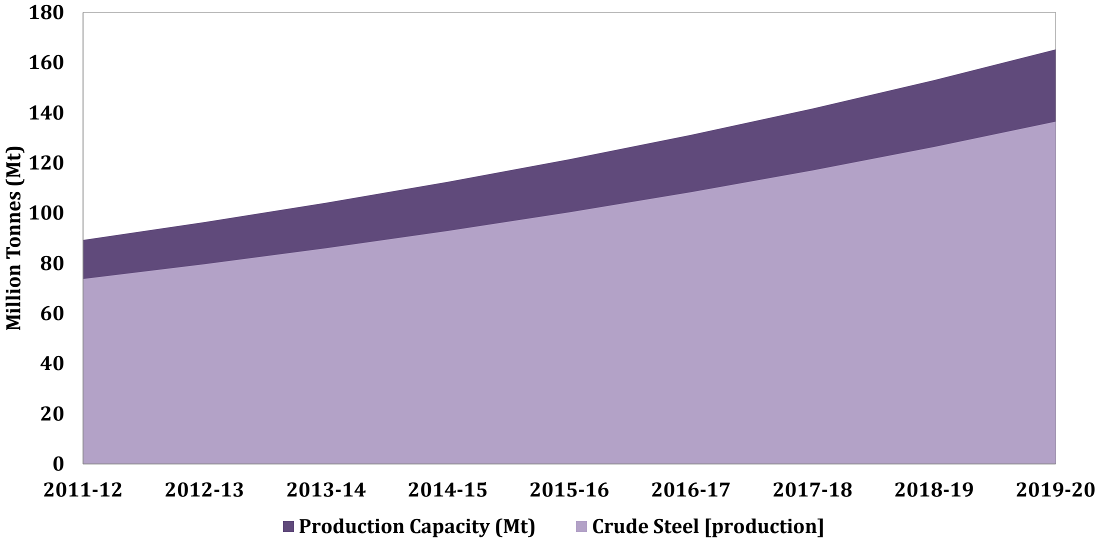


Figure 4: Projected capacity and production (2011-2020)

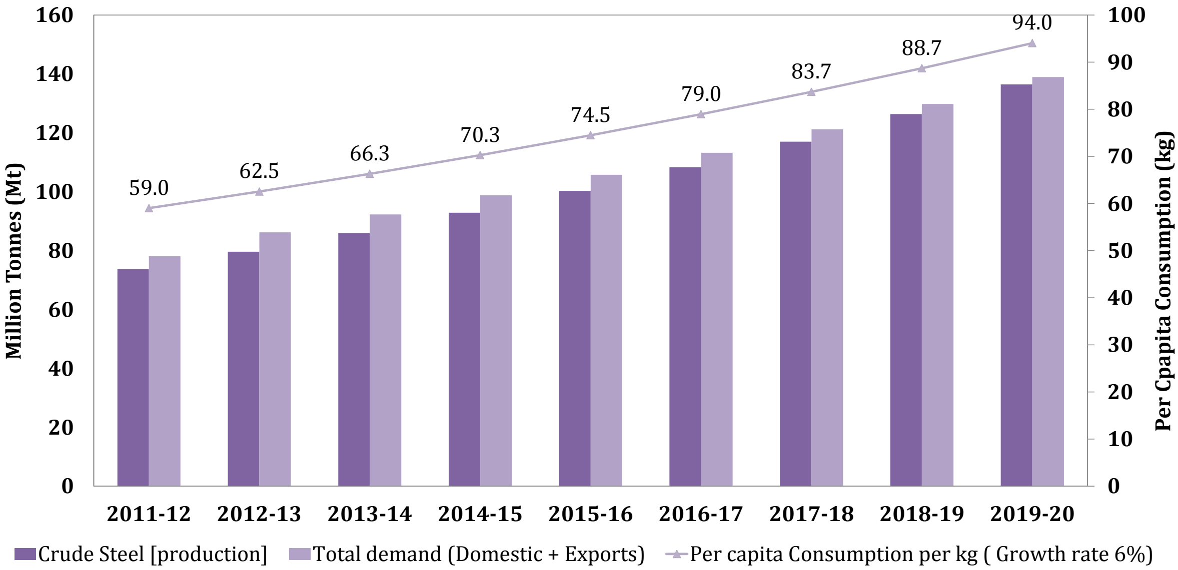


Figure 5: Crude steel production, demand in contrast with per capita consumption

1.4 Energy Consumption

- ***Review of Energy Efficiency in Iron and Steel Plants***

Reduction of hematite and magnetite ores to iron and thereafter to steel involves highly energy intensive processes. Coal, electricity and natural gas are most widely used energy sources in this sector. The efficiency of steelmaking varies with the kind of production route, type of iron ore and coal used, the steel product mix, operation control technology, and material efficiency. The iron and steel sector follows three major process routes in steel making. About 45% steel is produced by Blast Furnace – Basic Oxygen Furnace route, 24% and 31% by electrical furnace such as Arc furnace and Induction furnace routes respectively (8). It is observed that the blast furnace process is an energy intensive process and 48% of the total energy input in the BF-BOF route is used in blast furnace operations. Typically, the larger plants utilize the BF-BOF route while smaller plants have DRI-EAF, mini blast furnace and induction furnace processes.

The sub process wise energy consumption associated with the best available techniques in steel production is shown in Figure 6. The Best Available Technology (BAT) (9) indicates the SEC of 16.4 GJ/tcs through BF-BOF route, 19.3 GJ/tcs by the smelt reduction (COREX)-BOF route, 19.0 GJ/tcs through coal based DRI-EAF route and 15.9 GJ/tcs in the gas based DRI-EAF route in 2009 (Table 4). In India, the average SEC from selected major steel plants was 27.3 GJ/t of crude steel. When compared to the best available technology, the current technology has an energy saving potential of about 35% without adjusting for variations in major operating parameters.

Table 4: SEC by different process routes (9)

<table>
<tr><th colspan="2">Process</th><th>BF-BOF (GJ/tcs)</th><th>Smelt Reduction-BOF (GJ/tcs)</th><th>Coal based DRI-EAF (GJ/tcs)</th><th>Gas based DRI-EAF (GJ/tcs)</th></tr>
<tr><td rowspan="3">Material Processing</td><td>Sintering</td><td>2.1</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Pelletizing</td><td>-</td><td>0.8</td><td>0.8</td><td>0.8</td></tr>
<tr><td>Coking</td><td>1.0</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">Iron Making</td><td>BF</td><td>11.8</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Smelt Reduction</td><td>-</td><td>17.0</td><td>-</td><td>-</td></tr>
<tr><td>DRI</td><td>-</td><td>-</td><td>12.6</td><td>9.5</td></tr>
<tr><td rowspan="4">Steel Making</td><td>BOF</td><td>1.0</td><td>1.0</td><td>-</td><td>-</td></tr>
<tr><td>EAF</td><td>-</td><td>-</td><td>5.6</td><td>5.6</td></tr>
<tr><td>Refining</td><td>0.4</td><td>0.4</td><td>-</td><td>-</td></tr>
<tr><td>Continuous Casting</td><td>0.1</td><td>0.1</td><td>0.1</td><td>0.1</td></tr>
<tr><td>Total</td><td></td><td>16.4</td><td>19.3</td><td>19.0</td><td>15.9</td></tr>
</table>

Historically, the SEC of I&S sectors have shown a significant improvement during 1998-2008 when it declined by >15% (10). Presently, the SEC of the large plants in the ISP sector is estimated to be about 6.3 GCal/tcs (4) and this could reduce to 5.81 GCal/tcs by 2020. Accordingly the projected energy requirements increase from 46.4 to 79.3 million toe for the same period due to the increased production. Figure 7 illustrates the projected energy intensity and consumption till 2020.

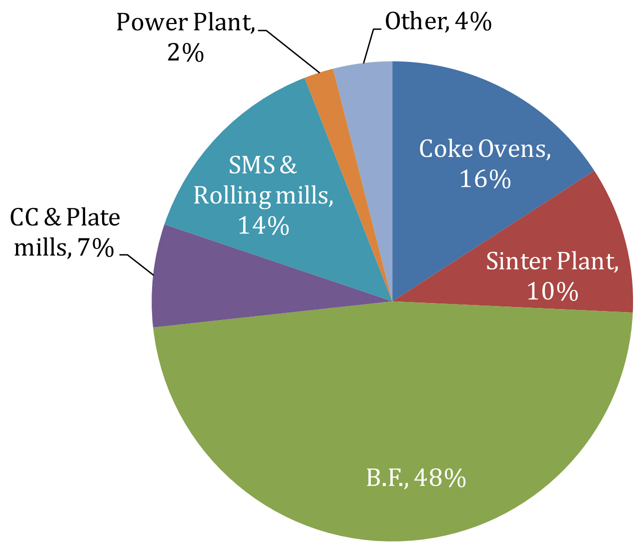


Figure 6: BF-BOF energy distribution in a typical integrated iron and steel plant (11)

Electrical energy is one of the major components, which largely supports the Electric Furnace, machinery operations, drives, fans, lighting and other process supported systems. Among the three major process routes in steel making, 24% and 31% utilise electrical furnaces such as Arc furnace and Induction furnace routes respectively. The power required by the steel industry is estimated to increase to 16,000 MW in 2025-26 from around 8200MW in 2016-17 (7). Electrical furnaces melt the charged materials to produce specialised steel using electrical energy. A variety of steels are manufactured through electrical furnaces. Reducing the burning losses of iron and readily oxidising the alloying elements are other advantages of electrical furnaces (12).

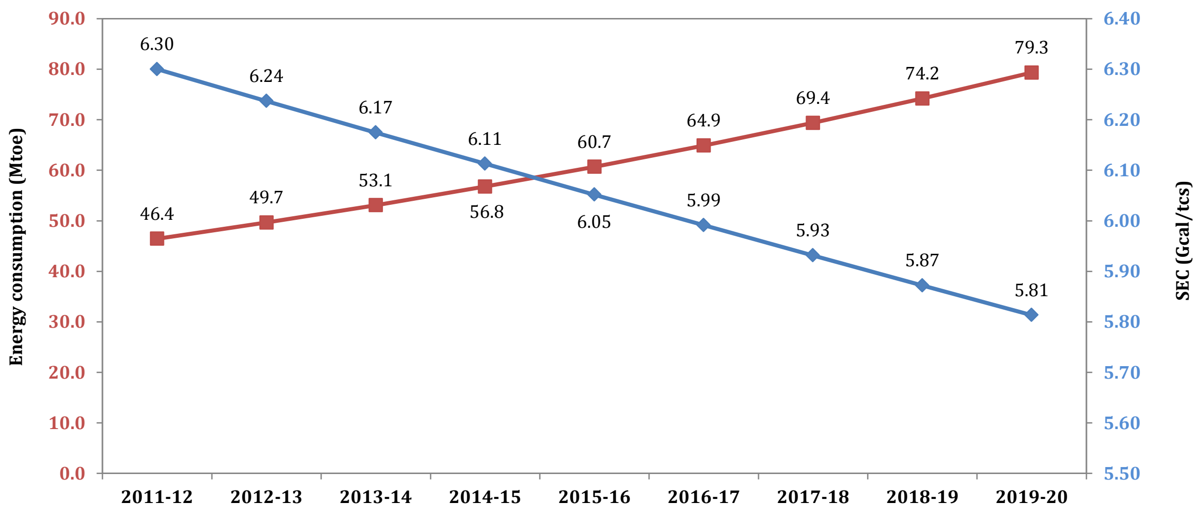


Figure 7: Projected Energy Consumption and Energy Intensity

Submerged arc furnaces are largely employed in manufacture of ferro alloys. India produces approximately 3 Mt with a capacity of 5 Mt. Ferro alloys are basically constituted of iron, inclusive of proportion of fusible materials which give certain specific properties of steel.

The performance of the domestic Ferro Alloy sector has been in line with the Indian and global steel industry. According to Indian Ferro Alloy Production Association IFAPA, the Industry's present capacity is around 5.15 Mt (13). SEC of various types of Ferro Alloys which are largely manufactured in India is summarized in Table 5. A 15.5% growth rate was observed during 2010-11 (14). The FA sector could require an estimated 16600GWh by 2017-18. Figure 8 below shows the projection until 2017-18.

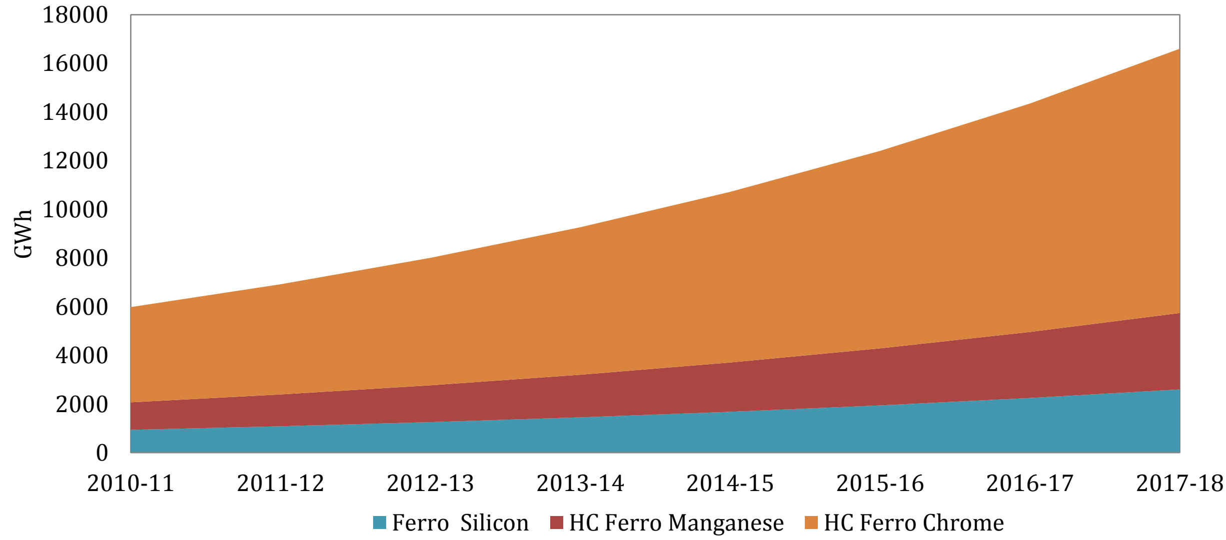


Figure 8: Projected energy consumption of Ferro Alloy in India

Table 5: SEC of Ferro Alloys (15)

	(FeSi)	(SiMn)	(FeMn)	(FeCr)
Specific Power (kWh/T)	8000	4000	2900	3800
% of Power in total cost	65	50	45	45

1.5 Emission in Iron and Steel Industry

Figure 9 illustrates the share of emission intensity for each sub processes in iron and steel manufacturing. The emission intensive stages are in iron making, where the sintering stage accounts for about 0.3-0.4 t-CO_2 and the blast furnace intensity range is between 0.7-1.1 t-CO_2 to produce new steel using the best technology (16).

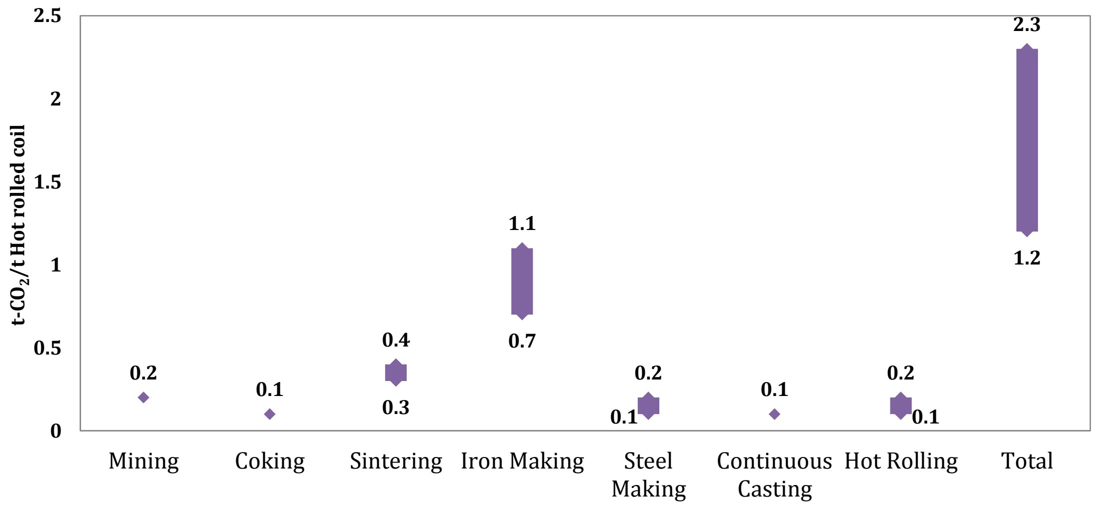


Figure 9: CO_2 Emissions Share within an Integrated Steel Plant (91)

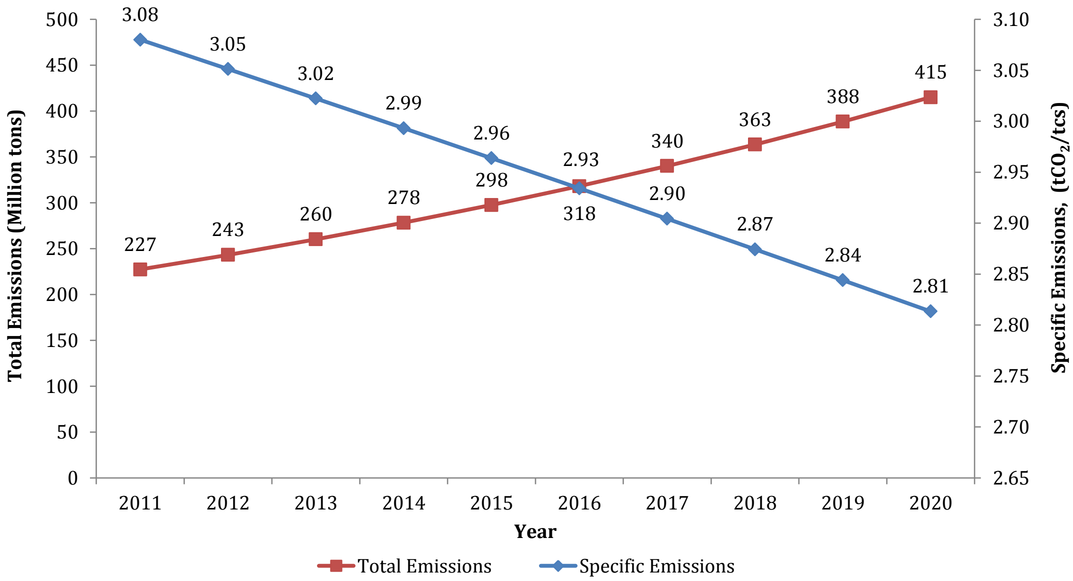


Figure 10: Total and Specific Emission of Indian Iron and Steel Industry

The specific emission of the Indian Iron and steel Industry between 2011 and 2020 is projected in Figure 10. It is observed that the specific emission will also undergo significant reduction from current level of 3.08 tCO_2/tcs to 2.81 tCO_2/tcs. The total emissions could increase from 227 to 415 Mt CO_2.

1.6 Iron and Steel Production Process

The steel making process is a multi-stage process and yields a large number of by-products. Steel can be produced either from iron or steel scrap. The process involves complex heterogeneous reactions, high temperature operations, gas and solid handling systems along with solid transport systems. There are several technologies available with variations in the operating conditions and process for making iron and steel.

Most of the crude steel/steel products in India are produced by Integrated Steel Plants (ISP) using Direct Reducing Iron (DRI) – Electric Arc Furnace (EAF) process. India is the largest producer of DRI in the world. There exists other process of steel making including the Induction Furnace (IF) which is used mostly in secondary steel making process and Submerged Arc Furnace (SAF) for making Ferro-alloys (Figure 11).

The process of steel making in ISP involves sinter plant, coke ovens, blast furnace section, basic oxygen furnace, finishing section. Iron ore fines along with blast furnace dust and fuel are sintered to specified size in sinter plant. The sinter along with fluxing agent and lump ore is fed into the blast furnace as a feed material. The coke from the coke ovens is used as a fuel and reducing agent in the blast furnace along with other auxiliary fuels. The feed undergoes transformational changes in the blast furnace to yield hot metal at a high temperature.

Hot metal in the liquid form is discharged from the blast furnace into the ladles, and is sent to the steel making section. The steel making section involves basic oxygen furnace, where the hot metal along with scrap is further refined to yield liquid crude steel. The crude steel is then processed in the finishing section to make final desired products.

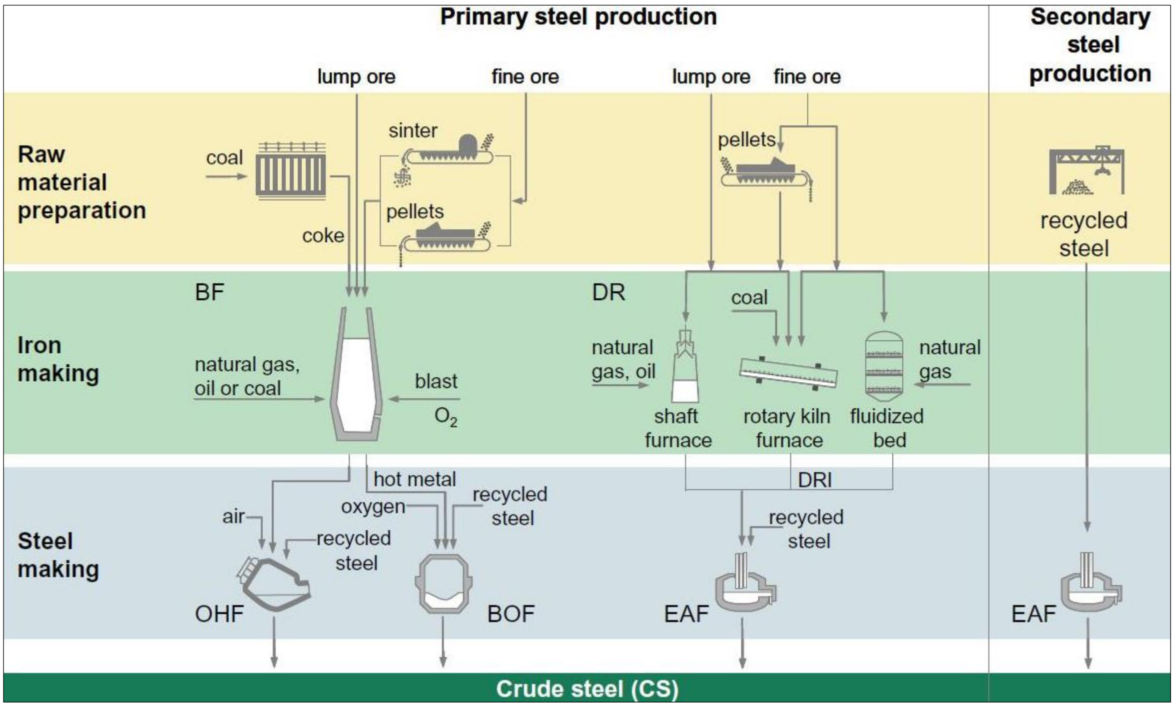


Figure 11 Iron and Steel Production Process routes (17)

Sinter Plant

Sintering is a process of agglomeration to agglomerate iron ore fines into useful blast furnace burden material. Sintering provides several advantages such as: enables the use of iron ore fines, coke breeze, metallurgical wastes, lime and, dolomite for hot metal production, improves reducibility and other high temperature properties, improves blast furnace productivity and quality of hot metal.

Globally, more than 70% of hot metal is produced through the sinter plant?. In India, approximately 50% of hot metal is produced using sinter feed.

Iron ore fines (-10 mm), coke breeze (-3 mm), lime tonnes & dolomite fines (-3mm) and other metallurgical wastes are the raw materials used in the process (25). These are mixed with water in a mixing drum and the mixture is loaded on sinter machine. The mixture is ignited at 1200^{o}C and a high temperature combustion zone is created in the charge bed. Finished sinter cake is crushed and cooled and dispatched to blast furnace section.

Coking Plant

Coking coals undergo a transformation into plastic state at around 350^{o}-400^{o} C during carbonisation. Then it swells and then re-solidifies at around 500^{o}-550^{o} C to give semi-coke and then coke. The main reactions involved in the process of coke making are condensation and pyrolysis. Coals should have a certain degree of maturity, good rheological properties, wide range of fluidity and low inerts to produce good quality coke (25).

Blast Furnace (BF)

A blast furnace is used to reduce and physically convert iron oxides into liquid iron called hot metal. The blast furnace is a tall structure, steel stack lined with refractory brick, where iron ore, coke and limestones are dumped on the top, and preheated air is blown at the bottom. A typical modern blast furnace operates continuously for months or years at a time, with coke, ore, and flux being charged in the top, air/blast being blown through numerous tuyeres near the bottom, and molten iron and slag being tapped out of tap holes at the bottom. (27).

Iron oxides enter the blast furnace plant either in the form of raw ore, pellets or sinter. The ore is mainly composed of Hematite (Fe_2O_3) or Magnetite (Fe_3O_4) with other impurities. The ore is calcined (roasted) before charging, so that the iron in it is entirely in the form of Fe_2O_3 (ferric oxide, hematite). The fundamental reactions in the blast furnace are the reduction of hematite by CO (carbon monoxide), first to Fe_3O_4 (ferrosoferric oxide, magnetite), then to FeO (ferrous oxide, wustite) both proceed between 400 – 700^{0}C, and finally to metallic iron which occurs between 700 – 1000^{0}C.

Basic Oxygen Furnace (BOF)

Basic Oxygen Furnace (BOF) is a steel making furnace and is also known as Basic Oxygen Process/LD process and is the most powerful and effective steel making method. The molten pig iron and steel scrap converts into steel due to oxidizing action of vertically blown oxygen at supersonic speed through lance on to the surface of the molten hot metal. Due to the simplicity and flexibility of the process, BOF steel making has replaced the existing open hearth furnaces.

The refractory lining of basic oxygen furnaces work is exposed to severe conditions of high temperature and oxidizing atmosphere. The materials used for refractory bricks for lining basic oxygen furnaces are made of either resin bonded magnesite or tar bonded mixtures of magnesite (MgO) and burnt lime (CaO).

The basic oxygen furnace uses pig iron impurities (carbon, silicon, manganese and phosphorous) as fuel to maintain the desired temperature. The heat evolved by the combustion of the iron and its impurities serves the heat requirement of the process.

Finishing Section

Crude steel from the steel making process is casted to make specific shape and size steel products in finishing section. This process purely involves unit and mechanical operations to make specific products. The casting process involves either ingot casting to make ingots or continuous casting to make blooms, slabs, and billets.

Continuous casting also known as strand casting is used in manufacturing industry to cast a continuous length of metal. Molten metal is cast through a mold which provides two dimensional profiles to the metal. Molten metal is poured into a tundish, which is a container that is located above the mold. This particular casting operation uses the force of gravity to fill the mold and to help move along the continuous metal casting.

Mini Blast Furnace (MBF)

Mini Blast Furnace (MBF) is a miniature scale of operation of the actual Blast Furnace and is characterised by simplicity and economy. It is ideal for small-scale operation and the products resemble the conventional blast furnace products in quality.

The advantage of the system is the usage of high ash content (27 – 40%) metallurgical cokes. The high slag volume to be handled in the system requires special hearth design and lowers the hot metal temperature. These systems normally suffer from poor thermal and chemical efficiency and have high environmental impact Table 6 provides a comparison between the conventional blast furnace and mini blast furnace.

Table 6: Comparison of Conventional BF and Mini BF (35)

Parameter	Conventional Blast Furnace	Mini Blast Furnace
Size	Greater than 350 m^3	175 – 350 m^3
Ore/Sinter	Ore agglomeration is required to certain extent	Lump ore is used in this process
Coke	High grade coke is required with size above 25/30 mm	Premium or low grade coke can be used
Performance	Productivity and lower coke rate	Reasonably good productivity and high coke rate
Cold Blast	High blast pressure (up to 5 bar) is used which require powerful turbo blowers	Blast pressure of about 1.5 bar max will be used and can be generated by centrifugal fans
Blast Preheating	Hot blast temperatures up to 1200^{0}C will be used which will be generated by hot stoves	Metallic blast preheater with hot blast temperature of 800^{0}C is sufficient for the operation
Charging System	Bell less top is desirable	Rotary hopper with double bell system is used
Instrumentation	The system is equipped with wide range of monitoring devices	Low level of instrumentation is sufficient for normal operation
Investment	High specific investment	Low specific investment
Construction time	30 months	15 months.

Direct Reducing Iron (DRI)

Direct reduction is a process of converting iron ore to iron using a reducing agent at temperatures lower than the melting point of ore. The product with high content of metallic iron is called Direct Reduced Iron (DRI). There are two processes for DRI manufacturing, i.e. coal based and gas based processes.

Coal based DRI process requires non-coking coal as reducing agent which is available in plenty in India. The raw material consists of iron ore, coal and dolomite with proper size charged into the rotary kiln with the help of a conveyor. The coal is divided into two equal parts; one portion of coal is with raw material stream and the other portion is fed from the discharge end. Dolomite acts as a fluxing agent to produce slag. Hot sponge iron is discharged at the discharge end and sponge iron is separated using magnetic separator.

In the gas based DRI process, gas is used as a reducing agent and fuel instead of coke. India has adopted two gas based technologies namely MIDREX and HYL-3.However, due to a limitation of natural gas availability; these technologies have not found wide acceptability.

Electric Arc Furnace (EAF)

Manufacturing steel also utilise electrical furnace equipment such as arc furnace and induction furnace. One the key advantage of involving this process is to achieve all grades of steel and melting of scraps. The process is divided into four phases: meltdown, oxidizing, composition and temperature adjustment and tapping.

The meltdown period starts after the furnace is charged with scrap and the charge is completely melted. It is an expensive process because of a high rate of energy and electrode consumption.

During oxidizing period phosphorus, silicon, manganese, carbon and iron are oxidized. Almost all silicon in the metal oxidizes to SiO_2 and enters into slag. The oxygen required is injected through side lances and excess carbon reacts with oxygen to form carbon monoxide gas that bubbles out of the steel. This causes stirring of the charge to make composition and temperature more uniform.

During tapping period, the furnace is tilted to transfer the melt to ladle after raising the electrodes. Steel is often refined further to reduce oxygen and sulphur content. The slag also acts as a medium for the transfer of oxygen to the slag-metal interface, shields the arc from atmosphere, protects the refractory from the arc and provides an insulation blanket to minimize heat losses from the melt.

Another variety of the electrical furnace is the submerged arc furnace; Ferro Alloys are largely produced from sub merged arc furnaces. The key parameters governing the efficiency of the SAF are the Furnace design, Electrode spacing, Taping time (time for removal of mass of melt), and transformers efficiency.

Induction Furnace (IF)

Induction furnace is electrical melting processing equipment with an induction heating system. The system contains a crucible surrounded by induction coils and the whole assembly is firmly confined with refractive materials. Induction furnace has few important parameters which govern the performance of the equipment,

- Furnace design - Large and spacious design encourage the operations with loading and un loading of materials
- Furnace refractory materials - Good refractive materials with high temperature tolerant, ability to reduce the heat loss.
- Holding time - More the holding time, higher the energy consumption
- Scheduling of operations – Induction furnace operates in batch process, timing between batches needs to be optimized. This has a vital effect on energy intensity

2. Process Modeling and Analysis

2.1 Blast Furnace

The study has developed a model to estimate the energy consumption of a blast furnace and assess its SEC. Blast furnace is one of the energy intensive processes of the integrated steel plants. Coal is used as a primary reducing agent in the process, which is also high possession of carbon. Carbon enters into the system and it is released into the environment in the form or CO_2. As the energy consumption increases equivalently CO_2 emissions increases. There has been rigorous research across industry and academia towards improvement in the operation techniques and to mitigate emissions (18) (19). A group of researchers from France have used the ASPEN model to examine the carbon dioxide emissions reduction potential based on Life Cycle Assessment (LCA) methodology (20).

Our study has utilised two methods of estimating the material and energy balance of a blast furnace system. A comprehensive spread sheet model and software simulation model have been chosen for this purpose. The models have ensured several stoichiometric reactions involved in the process. Indian ores and coal properties are used as input factors in order to analyse the effect on blast furnace performance. The purpose of considering two types of models is to compare their results.

2.1.2 *Stoichiometric* spread sheet model

Model Description and Assumption

The calculation and modeling approach is based on per unit production of hot metal, considering all possible stoichiometric reactions that take place in the blast furnace reactor along with heats of reactions. The ultimate SEC of the system is calculated based on the total energy consumed in the process divided by the production of the process. Following are the list of assumptions considered:

- Ratio of direct and indirect reduction of iron ore and sinter is taken as 0.6 and above.
- Carbon monoxide is the only reductant used for the indirect reduction of iron ore and sinter and hydrogen generated was not participating in the reduction reaction was assumed.
- Total energy input split into the outlet streams.
- Carbon is the reducing agent in the direct reduction reaction.
- Process operating at steady state conditions
- Molar ration of CO/CO_2 in the blast furnace gas is assumed ≥ 1 for stable operation

Input Parameters

The model was simulated with variation of different parameters to analyse the system performance. The parameters varied in the model are:

- Pulverised coal rate was varied from 0 to 150 kg/thm
- Sinter composition
- Ore composition
- Coal composition at particular ore and sinter composition

Coal specifications taken from different geological locations and Ore and Sinter compositions are broadly explained through Table 7 and Table 8. Low grade and high grade ore are referred to as O_2 and O_3.

Table 7: Ore and Sinter Composition in wt % (21)

Component	Ore_1	Ore_2	Ore_3		$Sinter_1$	$Sinter_2$	$Sinter_3$
Symbol	O_1	O_2	O_3		S_1	S_1	S_3
Fe_2O_3	95.22	95.6	88.65		69.36	68.2	68.64
FeO	0	0	0		10.92	11.15	11.19
SiO_2	1.13	1.57	3.5		5.81	6.15	5.88
Al_2O_3	1.49	0.83	3.0		2.2	2.16	2.29
CaO	0	0	0		9.32	9.96	9.72
MgO	0	0	0		2.24	2.26	2.18
MnO	2.155	2.0	4.86		0.15	0.12	0.1

Table 8: Different Coal Compositions in wt% (22)

Component	West Australia	Ranigunj	West Bokaro	Talchar
Moisture	2.0	3.5	1.86	6.37
C	60.3	60.2	52.3	40.56
O	8.2	7.1	4.9	9.0
N	1.1	1.8	1.23	0.93
S	0.5	0.3	0.41	0.38
H	4.8	4.2	3.3	2.76
Ash	22.9	22.9	36.0	40.0
Heating Value (kcal/kg)	5454	4280	4098	3910

Reactions and Equations

The stoichiometric reactions considered for the modeling exercise is listed below along with corresponding heats of reactions:

$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2$ ΔH = -52800 kJ/kg-mol

$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2$ ΔH = -11020*4.184 kJ/kg-mol

$2Fe_3O_4 + CO = 6FeO + CO_2$ ΔH = 36300 kJ/kg-mol

$FeO + CO = Fe + CO_2$ ΔH = -17300 kJ/kg-mol

$SiO_2 + 2C = Si + 2CO$ *ΔH = 1862*1000 kJ/kg-mol*

$MnO + C = Mn + CO$ ΔH = 269*1000 kJ/kg-mol

$C + O_2 = 2CO$ ΔH = -110.6*1000 kJ/kg-mol

$C + O_2 = CO_2$ ΔH = -393.7*1000 kJ/kg-mol

$C + CO_2 = 2CO$ ΔH = 173.6*1000 kJ/kg-mol

$H_2O + C = CO + H_2$ ΔH = 131.3*1000 kJ/kg-mol

$FeO + C = Fe + CO$ ΔH = -140.1*1000 kJ/kg-mol

$Al_2O_3 + CaO + SiO_2 = CaO.Al_2O_3.SiO_2$ ΔH = -102712.3 kJ/kg-mol

$CaO + SiO_2 = CaO.SiO_2$ ΔH = -88725 kJ/kg-mol

$MgO + SiO_2 = MgO.SiO_2$ ΔH = -63139 kJ/kg-mol

$CaCO_3 = CaO + CO_2$ ΔH = 179*1000 kJ/kg-mol

$FeS + C + CaO = CaS + CO_2 + Fe$ ΔH = 145.6*1000 kJ/kg-mol

$P_2O_5 + 5C = 2P + 5CO$ ΔH = 979*1000 kJ/kg-mol

$\dot{m}_{sinter} + \dot{m}_{ore} + \dot{m}_{flux} + \dot{m}_{hot\ blast} = \dot{m}_{hot\ metal} + \dot{m}_{slag} + \dot{m}_{gas}$

$\dot{m}_{carbon\ in\ coke} + \dot{m}_{carbon\ in\ coal} = \dot{m}_{carbon\ in\ hot\ metal} + \dot{m}_{carbon\ in\ gas} + \dot{m}_{carbon\ in\ coke} + \dot{m}_{carbon\ for\ combustion} + \dot{m}_{carbon\ for\ reduction}$

Where ṁ = mass flow rate

$\Sigma Hi_{,tuyere\ injectants} + \Sigma Hi_{,\ coke} + \Sigma Hi_{,\ sinter} + \Sigma Hi_{,flux} + \Sigma Hi_{,hot\ blast} + \Delta H_{combustion} + \Delta H_{exothermic} = \Sigma Hci_{,\ Hot\ metal} + \Sigma Hci_{,\ slag} + \Sigma Hi_{,gas} + \Delta H_{endothermic} + \Delta H_{losses}$

Where, H_i is Enthalpy of the i component in kJ/kg

ΔH = Heat of reactions in kJ/kg
H_{ci} = Enthalpy of the liquid components i.e. summation of sensible heat and latent heat of fusion of component i

Expected Output from the Model

The model is designed to calculate the following:

- Overall and constituent balance in the system
- Coke rate, pulverised coal rate and air blast rate required for the particular input rate
- Effect of the variation of different input rates and composition on the fuel rate requirement
- Total carbon requirement of the system.
- Identify the participation of the carbon in different reactions
- The direct and indirect reduction ratio of the ore.
- Estimate the SEC of the system
- Effect of the different parameters variation on the SEC
- Identify the ore that can be reduced for a particular fuel rate.
- Net input energy available for the reactions
- Amount of carbon lost in the hot metal
- Heating value of the blast furnace gas
- Fusion energy of the solid particles

Validation of Models

The results from the models are validated by applying the input parameters discussed above with the available plant performance data. Three different sample plants are considered in this assessment termed as P1, P2 and P3. The SEC difference between model results and reported values are appearing in the range of +/- 5%.

2.1.3 *ASPEN Plus® Process Model*

ASPEN PLUS® simulator is the commercial software largely used for simulation of processes, study the material and energy flows, equipment design, and perform sensitivity analysis. It can also be used to find the feasibility of new processes. The software is capable of solving basic governing equations to get material and energy balances of the process.

The model was constructed considering the process into different constant temperature zones in the Iron making. This section discusses modeling techniques followed in the application. The ASPEN PLUS is a process simulator which uses in-built unit operations and unit specific models to solve basic governing equations behind the process. The output from the simulator has different product flow rates, compositions and enthalpy values of each stream. SEC of the process estimated is based on the energy balance of the system. The process model considerations for different operations while developing process flow sheet are shown below Table 9.

Table 9: ASPEN PLUS Process Models

Model	Purpose
Mixer	It is used to mix different streams to make single stream.
Rstoic	To perform the basic calculations of the reacting system based on given stoichiometric reactions and extent of the reactions.
Rgibbs	To perform the basic calculations of the reacting system based on Gibbs free energy minimization of the system.
SSplit	To separate the solid and gas phases.
Sep	To split the stream into fractions based on input split factor.
Fan	It is used to input the cold blast to the hot stove.
FSplit	It is used to split the total flow into fractions.
Compr	To compress the gas to high pressure.
HeatX	To heat up the cold blast to make the hot blast.

Ore and sinter composition used in the model is provided in Table 10. The iron ore is assumed as hematite (Fe_2O_3) type and lime ($CaCO_3$) as fluxing material. The hot blast enters the furnace at 900^0C with composition of O_2 – 21% and N_2 – 79% by moles.

Table 11 provides the composition of coke used in the model, a high ash content coal composition is provided in Table 12.

Table 10: Ore and Sinter Composition (23)

Component	Fe_2O_3	FeO	SiO_2	Al_2O_3	CaO	MgO	MnO	FeS	P_2O_5	Total
Sinter (%wt)	67.84	11.03	6.11	2.75	9.88	2.29	0.1	-	-	100
Lump ore (%wt)	95.6	-	1.57	0.83	-	-	2	-	-	100
Ore (%wt)	94.65	-	2.5	2.5	-	-	0.15	0.05	0.15	100

Table 11: Coke Composition (23)

No.	Parameters	Typical Specifications (% wt)
1	Moisture	1
2	Ash	12
3	VM*	1.5
4	Sulphur	0.8
5	FC*	85 min
6	Size	20-80 mm

*VM=Volatile Matter; FC=Fixed Carbon

Table 12: Coal Ultimate Composition

Component	% (wt)
Carbon	67.1
Oxygen	10.7
Nitrogen	1.1
Sulphur	1.3
Hydrogen	4.8
Ash	14.9
Chlorine	0.1
Total	100

Model Results

The output of the blast furnace model with only iron ore input is provided in Table 13. The computed SEC of the blast furnace system with lump ore input alone is estimated at 14.289 GJ/tonnes of hot metal.

Table 13: Model result: One ton of hot metal basis with lump ore

HM (kg/h)	1000
Sinter (kg/h)	0
Lump Ore (kg/h)	1413
Flux Agent (kg/h)	81
Nut Coke Injection (kg/h)	0
PCI (kg/h)	0
Coke (kg/h)	500
Air Blast (m^3/h)	1000
O_2 (m^3/h)	15
SEC (GJ/thm)	14.289

Case study: Sinter as a feed material along with the lump ore as input

The model was simulated was simulated with three different iron ore compositions at a particular sinter composition to find the coke rate and blast rate for one tonne hot metal production. The sample calculation of the material and heat balance calculation with one particular ore (Ore_1) and sinter1 combination is depicted below (Figure 12 and Figure 13). The computed SEC of the blast furnace system with lump ore input alone is 13.74 GJ/tonne of hot metal.

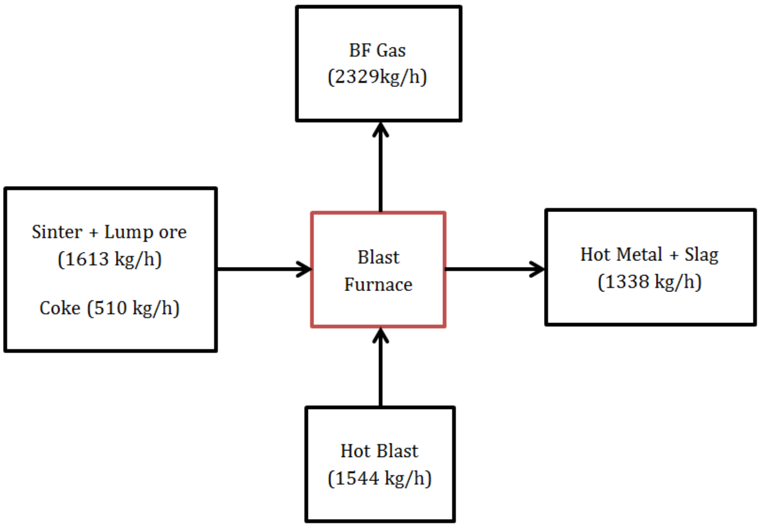


Figure 12: Material Balance of the BF with Coke Input

Energy In	
Item	MJ/h
Coke	10608.5
Nut coke	1127.6
PCI	0
Ore	0
Sinter	0
Hot Blast	2010.5
Total	13746.6

Blast Furnace

Energy Out	
Item	MJ/h
BF Gas	468.5
Heat absorbed by reactions	2839
Hot Metal	1045
Slag	582
Heat content of reductant	3754
Carbon content of hot metal	828
Loss/unaccountable	4230
Total	13746.6

Figure 13: Energy Balance of Blast Furnace with Coke Input

Case study: Fractional replacement of coke with pulverised coal as fuel input

In this case, 1 kg of coke was replaced with 1 kg of Pulverised Coal Injection (PCI). The simulations were carried out with PCI rate up to 150 kg per ton of hot metal. The sample calculation of the material and heat balance calculation with one particular ore and sinter combination is depicted below (Figure 14 and Figure 15). The computed SEC of the blast furnace system with lump ore input alone is at a level of 13.51 GJ/tonne of hot metal. It can be observed from the depicted data that pulverised coal injection reduces the SEC of the blast furnace.

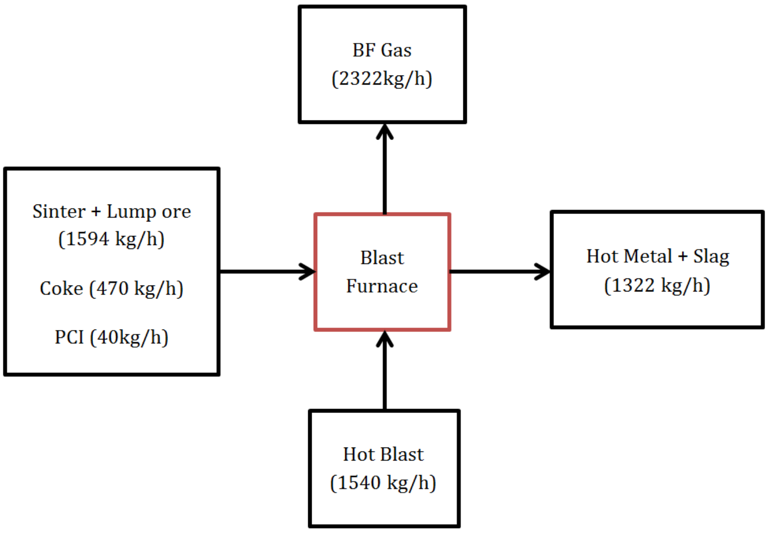


Figure 14: Material Balance of Blast Furnace with Coke and PCI Input

Energy In	
Item	MJ/h
Coke	9688
Nut coke	1128
PCI	686
Ore	0
Sinter	0
Hot Blast	2010
Total	13512

Blast Furnace

Energy Out	
Item	MJ/h
BF Gas	470
Heat absorbed by reactions	2705
Hot Metal	1047
Slag	596
Heat content of reductant	3628
Carbon content of hot metal	828
Loss/unaccountable	4237
Total	13512

Figure 15: Energy Balance of Blast Furnace with Coke and PCI Input

ASPEN Results

The material and energy balances from the process model simulation for coking plant processes is illustrated in Table 14. It is found that the thermal SEC, which is calculated, based on energy balance for Coking Plant is at 2.5 GJ/ ton of coal.

Table 14: Coking Plant Material and Energy Balance

Input			Output		
Material (kg/h)		Energy (GJ/h)	Material (kg/h)		Energy (GJ/h)
Dry Coal	4545	11	Dry Coal	0	0
Gas	0	0	Gas	1429	2
Coke	0	0	Coke	3000	6
Tar	0	0	Tar	122	1
Water	2273	0	Water	2273	
Electricity	0	0	Unaccountable	0	2.8
Total	6818	11	Total	6824	11
SEC		2.5 GJ/t of coal			

The results from the process simulator for the blast furnace is described in Table 15 and the corresponding outlet stream composition from different sub-processes is given in Table 16 and Table 17. The SEC calculated from the energy balance of the model is around 17.2 GJ/ ton of hot metal. The iron content of the hot metal is found to be 94% (w/w) and the slag has high CaO content. Sensitivity analysis of the models considered also performed with different input variable like iron ore, coke and coal compositions. BF gas has equal mole ratio of carbon monoxide (CO) and carbon dioxide (CO_2) with high mole percent of nitrogen (N_2) and carries 2458 GJ/h of input energy.

Table 15: BF Material and Energy Balance

Input			Output		
Material (kg/h)		Energy (GJ/h)	Material (kg/h)		Energy (GJ/h)
Coke	184952	5545	Hot Metal	357587	870
Sinter	437885	0	Slag	126833	
Lump Ore	146800	0	BF Gas	929967	2458
Hot Blast	626377	592			
Oxygen	7766	7	Energy Unaccountable	0	2808
Nitrogen	10617	10			
Total	1414397	6136	Total	1414387	6136
SEC		17.2 GJ/thm			

Table 16: BF Solid Stream Flows

Component	Kg/h		% wt	
	Hot Metal	Slag	Hot Metal	Slag
C	14011	0	4	0
Fe	334489	0	94	0
FeO	1296	5185	0.4	4
Fe2O3	5643	0	2	0
CaO	0	43260	0	34
P2O5	0	2	0	0
Al2O3	0	13260	0	10
SiO2	0	25861	0	20
Si	1494	0	0.4	0
Mn	653	0	0.2	0
Ash	0	26707	0	21
MnO	0	2530	0	2
MgO	0	10027	0	8
Total	357587	126833	100	100
Energy (GJ/h)	870			

Table 17: BF Gas Stream Flows

Component	Kg/h	Kmol/h	%mol
O2	12353	386	1.3
N2	491100	17539	58.8
CO	164866	5888	19.7
CO2	258885	5884	19.7
S	829	26	0.1

Component	Kg/h	Kmol/h	%mol
H2O	1480	82	0.3
SO2	414	6	0.0
H2	41	21	0.1
Total	929967	29832	100
Energy (GJ/h)	2458		

Blast furnace performance by Ore, Sinter and Coal variations

- From the results, it is observed that the performance of the blast furnace is affected by the increased rate of pulverised coal injection which is flowing at fixed carbon rate. Western Australian coal was also used in this assessment with different ore and sinter compositions as discussed in the earlier section.

- Effect on energy intensity as indicated in Figure 16, the SEC of the low grade ore i.e. O_3 is higher than the high grade ore i.e. O_2 for any sinter compositions and pulverised coal injection rate. It is inferred that the low grade ore will have high gangue to treat and consumes more energy. The SEC is in the range of 13.55 GJ/thm and 13.75 GJ/thm.

- The blast furnace gas calorific value decreases with increased ore and sinter quality due to more reductant consumption to reduce more ore and sinter at any considered pulverised coal injection rates. The variations can be observed from Figure 16.

- Carbon monoxide rate is slightly decreasing and carbon dioxide rate is slightly increasing with increased ore and sinter quality due to higher reductant consumption of the higher quality ore and sinter input at any pulverised coal injection rate.

- Hot metal production rate is higher for the ore and sinter combination of O_2S_1 and the value decreases with lowering quality of ore and sinter. The variations can be observed in Figure 16.

- The blast furnace gas volume increases with increased pulverised coal injection rate due to increased carbon dioxide and hydrogen production rate at any ore and sinter combination and can be observed in Figure 16.

- Slag rate increases with increasing pulverised coal injection rate for different ore and sinter compositions. The low grade ore i.e. O_3 will produce more slag than high grade ore i.e. O_2. The hot metal production rate increases with increased sinter and ore quality. These variations can be visualised in Figure 17

- The carbon monoxide is slightly lower and carbon dioxide is slightly higher for the ore and sinter of O_2S_1 at any pulverised coal injection rates. The carbon monoxide rate decreases and carbon dioxide rate increases with increased pulverised coal injection rate at any ore and sinter combination.

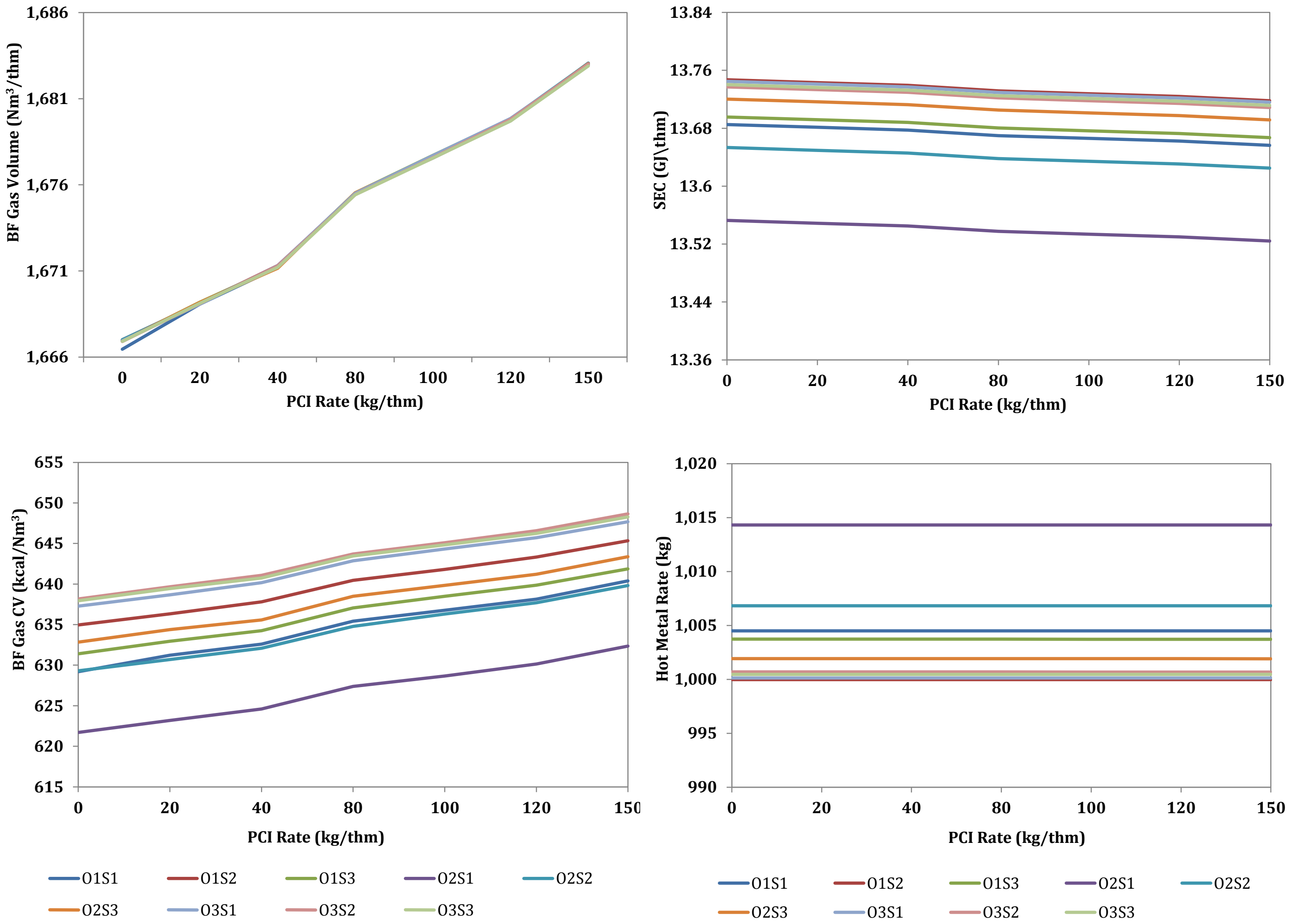


Figure 16: Gas Volume, SEC, BF Gas CV and Hot Metal Rate variation with PCI input rate

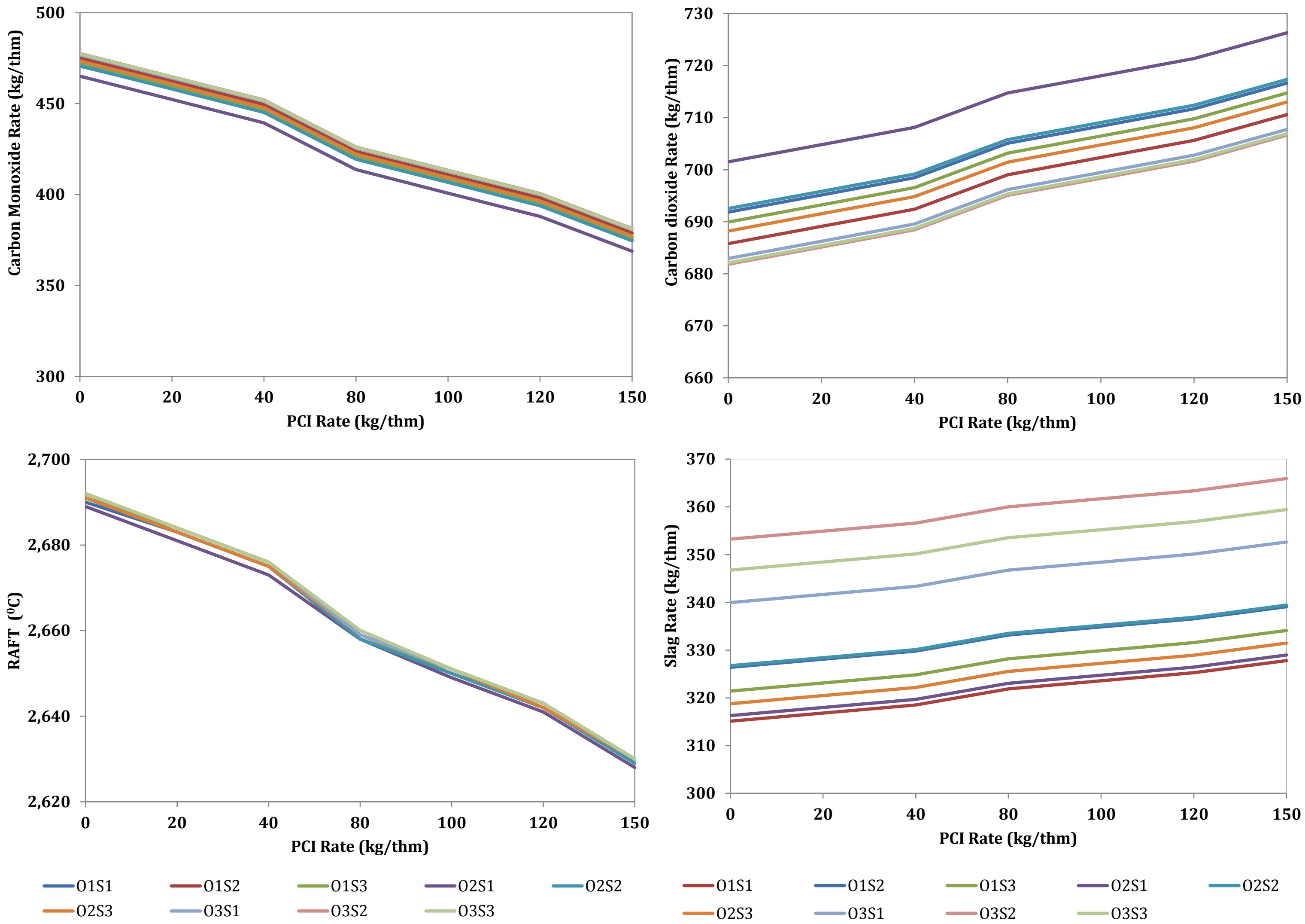


Figure 17: CO, CO_2, RAFT and Slag Rate variation with PCI Rate

The variation of the different parameters with coal type for a particular ore and sinter combination is depicted below. It can be observed in Figure 18 that the blast furnace gas volume and calorific values decrease with decreasing coal quality due to increased impurity and decreased carbon input rates.

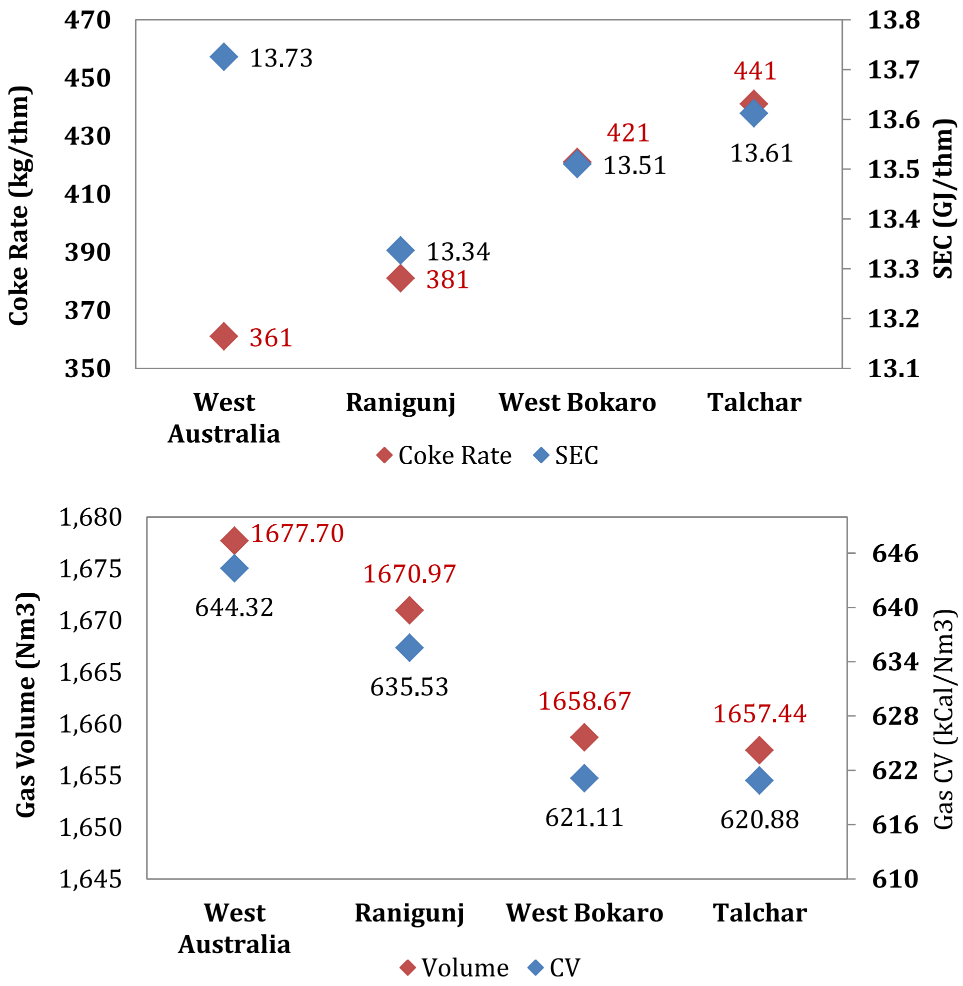


Figure 18: Parametric analysis on coal type and its effect on SEC

SEC initially decreases and then increases due to higher calorific value of the high quality coal which is more or less equal to the calorific value of the coke considered. The coke rate increases with decreased coal quality due to lower replacement ratio and has to be used due to reduced performance with decreasing coal quality. The same was depicted in Figure 19.

It can be observed in Figure 19 that the pulverised coal injection rate decreases with decreasing coal quality at the same performance level of the blast furnace due to reduced reductant and increased gangue input rate.

It was found from the simulation that the total carbon rate increases with decreased coal quality and the same is depicted in Figure 19. The replacement ratio is defined as the ratio between pulverised coal injection rate and coke rate. The replacement rate of coke with pulverised coal decreases with decreasing coal quality for the fixed performance of the blast furnace.

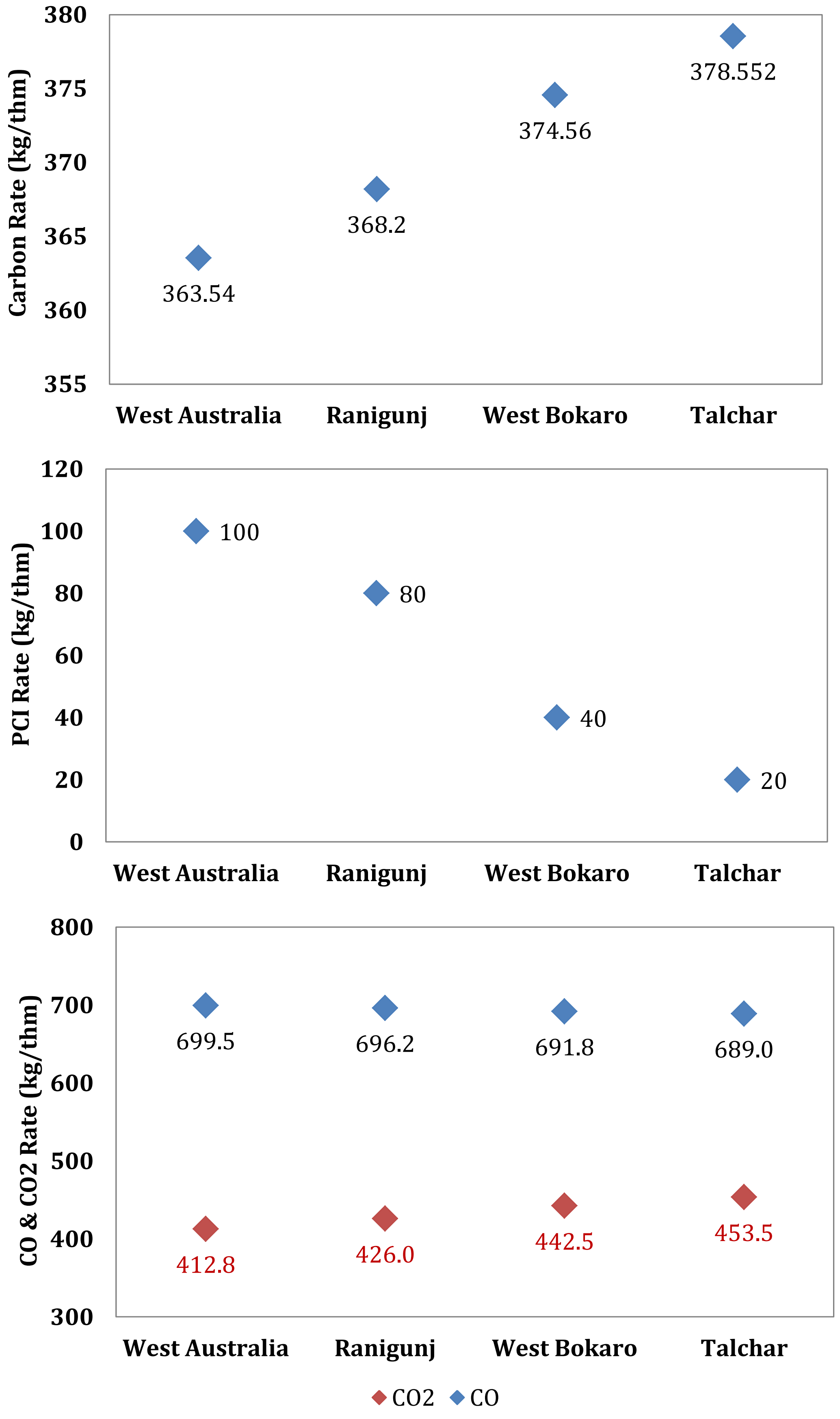


Figure 19: BF Performance with Coal Type

The comparison of simulation results with different plants (P1, P2 and P3) blast furnace data with high ore and particular sinter composition is depicted below. The variation of blast furnace gas volume of different plants with different coal types can be observed in Figure 20.

The SEC of different plant blast furnaces is found to be increasing with decreasing coal quality and is depicted in Figure 20. This is obvious because of the reduction in carbon content of the coal with coal quality and the high quality coal which will have higher heating value which requires lower input or higher replacement ratio.

The coke rate of different plants with decreasing coal quality was found to be increasing and is depicted in Figure 21. Similarly the carbon rate for different coal qualities for different plants is depicted in Figure 21. The carbon rate's increasing trend is observed with decreasing coal quality for different plants.

The variation of CO and CO_2 for different plants with different coal inputs is illustrated in Figure 21. It is observed that the values are varying with plant type and the variation trend is similar with all coal types.

Conclusion

The conclusion from the modeling exercise is summarised below:

- The best combination of the ore and sinter needs to be used to minimise the energy consumption of the process. Iron content of the ore is low means improved sinter quality is necessary for the operation.

Increased PCI rate is recommended to minimise the coke consumption as well as energy consumption. The optimised PCI rate depends on coal quality for stable operations.

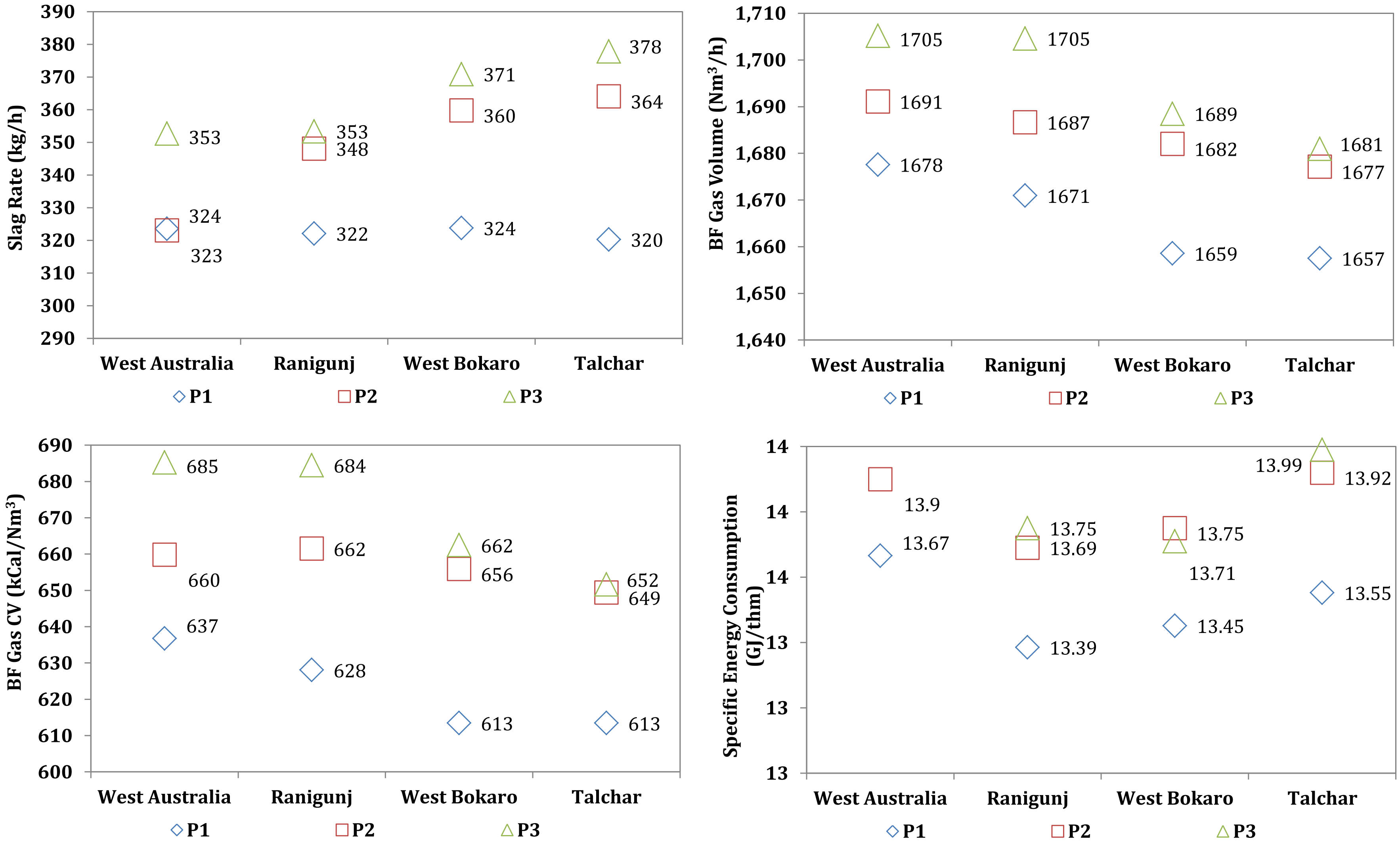


Figure 20: Slag Rate, Gas Volume, Gas CV and SEC variation with Plant Type

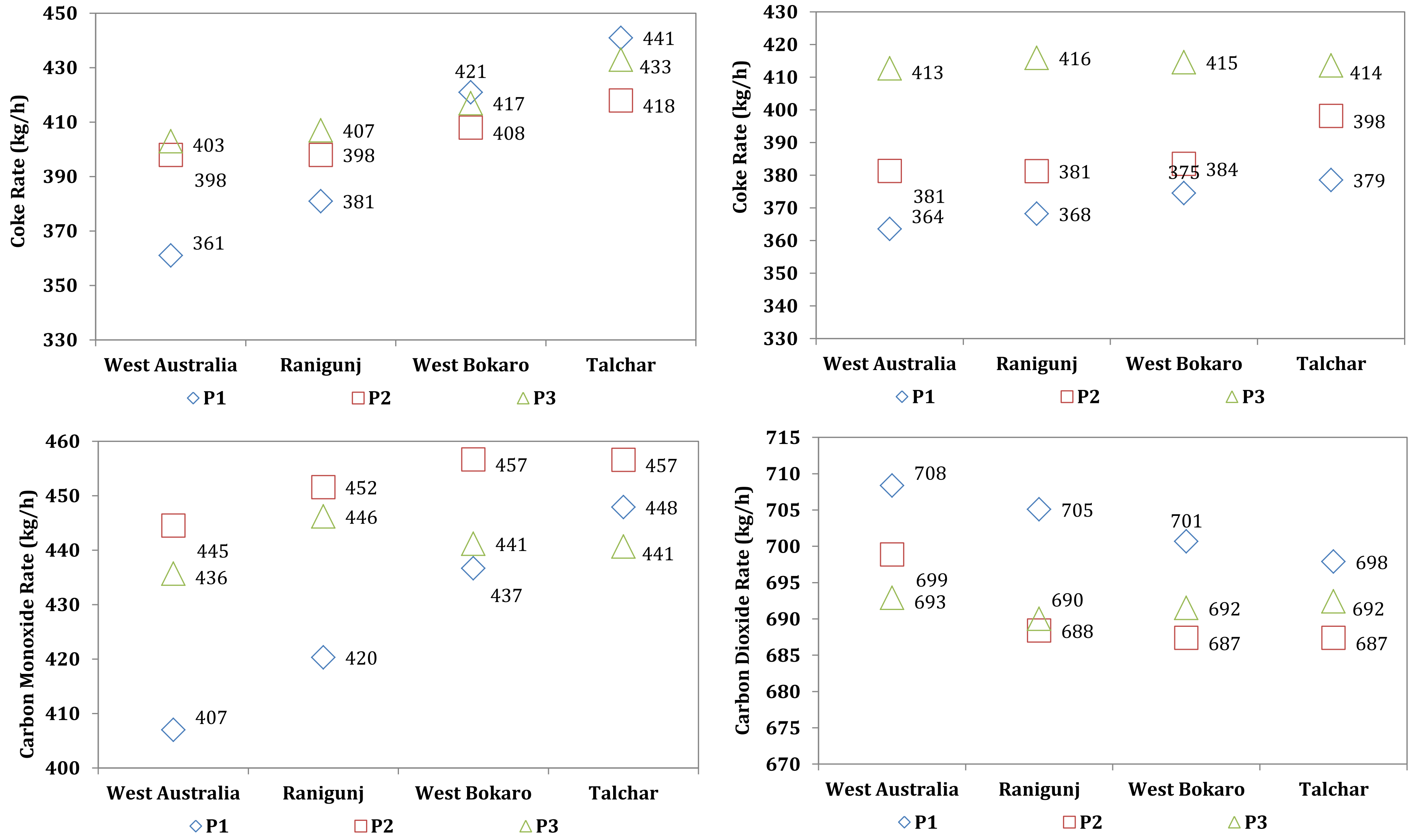


Figure 21: Coke Rate, CO, CO_2 and Carbon Rate variation with Plant Type

2.2 Hot Stove

The hot stove model is to calculate the fuel rate required to heat the cold blast to a specified temperature. The fractional replacement of the fossil fuel with BF outlet gas is also examined in the process.

Model Description

Hot stove is the heat exchanging equipment which will be used to make hot blast i.e. heated air required for the operation of blast furnace. Stove has a refractory brick chamber, heated initially by combusting the fuel or fuel and blast furnace gas/coke oven gas mixture. The energy will be stored in the refractory bricks. Counter current cold air is then circulated through the refractory brick chamber, thus heating the air. The model was developed based on several stoichiometric reactions involved in the process and basic material and heat balance principles. Natural gas and blast furnace gas are fuel types used in modeling hot stove. The efficiency of the system is assumed to be 85%.

The calculation of Raceway Adiabatic Flame Temperature (RAFT) is a very useful tool for furnace control. The method used to calculate the RAFT in the present model is given below:

$$\text{Flame Temperature} = (\Sigma Hi,_{\text{tuyere injectants}} + \Delta H_{\text{combustion}} + \Delta H_{\text{cracking}} + H_{\text{blast}}) \ / \ \Sigma Cp,j_{T=FT}$$

Where:

$\Sigma Hi,_{\text{tuyere injectants}}$ = Sensible enthalpy of all tuyere injectants

$\Delta H_{\text{combustion}}$ = Enthalpy of combustion for $C + \frac{1}{2}O_2 \rightarrow CO$

$\Delta H_{\text{cracking}}$ = Enthalpy of cracking of $H_2O \rightarrow H_2 + \frac{1}{2}O_2$

H_{blast} = Enthalpy of air blast at blast temperature

$\Sigma Cp,j_{T=FT}$ = Heat capacity of all raceway gas at flame temperature.

The input natural gas and BF gas composition is depicted in Table 18.

Table 18: Natural Gas and BF Gas Composition

Component	% mol		
	Natural Gas		BF Gas
CH_4	70 - 90	80.9	0.00
C_2H_6	0 - 20	10	0.00
CO_2	0 - 8	4	19.59
O_2	0 - 0.2	0.1	0.88
N_2	0 - 5	2.5	57.46
H_2S	0 - 5	2.5	0.00
H_2	0	0	0.43
CO	0	0	21.57
H_2O	0	0	0.07
Total		100	100

Output of the Model

The objective from the model is to calculate,

- Fuel/fuel mixture and air requirement for the specific hot blast rate requirement
- Adiabatic flame temperatures of the flue gas (i.e. the maximum temperature attainable during combustion under adiabatic conditions)
- Flue gas composition and flue gas temperature
- The RAFT of the blast furnace (based on the heat balance across the burner)

Results

The sample material balance calculated from the model over the hot stove is depicted below.

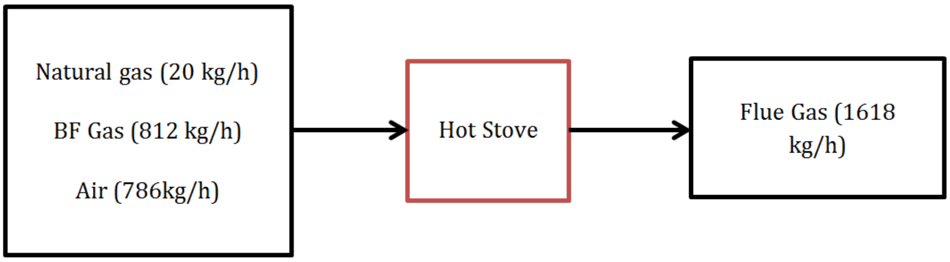


Figure 22: Material Balance across Hot Stove

Hot Stove Performance by Fuel Type

This model was simulated by varying blast furnace gas input and oxidant requirement at one particular natural gas input rate to supply the desired energy. The same was repeated at different natural gas input rates and the results are depicted Figure 24 below. The variation of adiabatic flame temperature and flue gas temperature with natural gas flow rate is depicted in Figure 23. It can be observed from this that the adiabatic flame temperature decreases initially as the natural gas flow rate increases because of the increased high specific heat components flow rate and the change in the behaviour starts when the fuel is replaced with natural gas alone. The flue gas temperature was increasing initially because of the excess energy released due to natural gas combustion and the change in behaviour starts when the fuel is replaced with natural gas alone due to increased inert inflow with oxidant.

The variation of different fuel rates with natural gas flow rate is depicted in Figure 23. The blast furnace gas required to be combusted decreases as the natural gas flow rate increases and becomes zero when the total fuel is replaced with natural gas. The oxidant required to combust the fuel to supply the necessary energy to heat up the air is found to be decreasing with increasing natural gas flow rate. The replacement rate blast furnace gas with natural gas is quite low because of the high calorific value of the natural gas.

The oxidant rate i.e. air required to combust the fuel was found to be decreasing due to reduction in the total fuel to be combusted and the same is depicted in Figure 24.

Conclusion

The BF gas which will have reasonable calorific value needs to be used in the hot stove as a heating media along with fossil fuel to minimise the energy consumption.

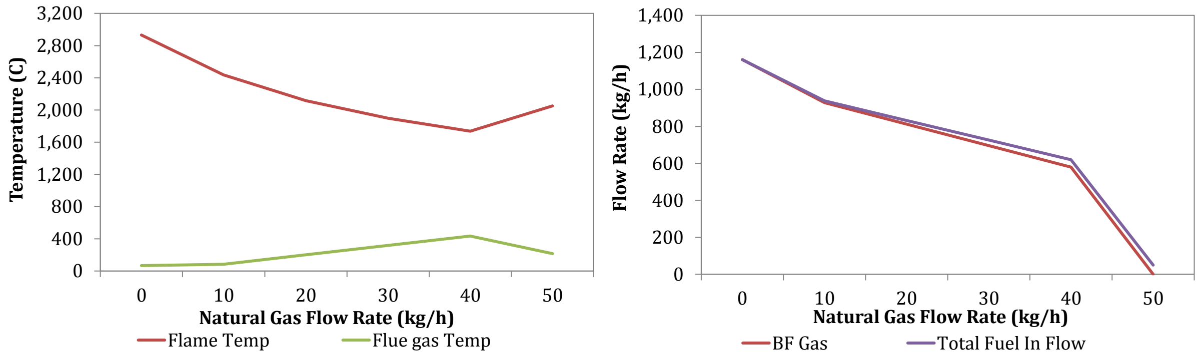


Figure 23: Hot Stove Performance with Mixed Fuel Injection

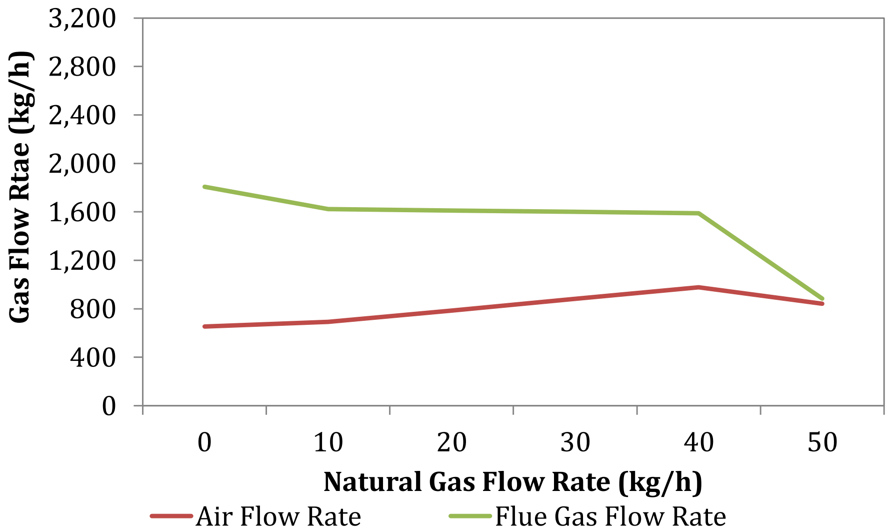


Figure 24: Hot Stove Performance with Mixed Fuel Injection

2.3 Basic Oxygen Furnace (BOF)

Model Description and Inputs

The BOF model rationalises the effect on energy consumption due to variation in the input material. Materials such as scrap, lime, dolomite and oxygen are used as input, and nitrogen as inert and coolant during the process. The scrap compositions used in the analysis is depicted in Table 19 and different types of scraps will have different compositions of the elements as mentioned accordingly. The iron content present in the scrap is higher than any other element. The scrap named HMS-1 is the scrap from used rail and the one named as Heavy Melt is the low carbon steel scrap. The material and energy balance model of the BOF is shown below (Figure 25 and Figure 26).

Table 19: Different Scrap Compositions (24)

Element	Composition (%wt)			
	Scrap-1	HMS-1	Heavy Melt	Briquetted Turnings
Cu	0.2	0	0.25	0.21
Cr	0.2	0	0.15	0
Ni	0.2	0	0.15	0.03

Element	Composition (%wt)			
	Scrap-1	HMS-1	Heavy Melt	Briquetted Turnings
Mo	0.05	0	0.06	0.12
Sn	0.02	0	0	0
P	0.04	0.035	0.05	0.02
Mn	1.65	0.825	0	0.42
Pb	0.02	0	0	0
S	0.06	0.04	0.05	0.03
C	1.1	0.67	0	1.6
Si	0.35	0.29	0.2	0.78
C	1.1	0.674	0	1.6
Si	0.35	0.29	0.2	0.78
Fe	96.11	98.14	99.09	96.79
Total	100	100	100	100

Reactions and Equations

The possible reactions are presented below: (square brackets [ ] - signify solution in steel, round brackets ( ) - in slag, curly brackets {} - in gas stream).

$CaCO_3 = CaO + CO_2$ ΔH = 400 Kcal/kg-$CaCO_3$

$[Fe] + 1/2\ O_2 = (FeO)$ ΔH = -900 Kcal/kg-FeO

$[Si] + \{O_2\} = SiO_2$ ΔH = -7460 Kcal/kg-Si

$[Mn] + \frac{1}{2}\{O_2\} = (MnO)$ ΔH = -1680 Kcal/kg-Mn

$2[P] + \frac{1}{2}\{O_2\} = (P_2O_5)$ ΔH = -6000 Kcal/kg-P

$2[C] + \frac{1}{2}\{O_2\} = (CO)$ ΔH = -2200 Kcal/kg-C

$\{CO\} + \frac{1}{2}\{O_2\} = \{CO_2\}$ ΔH = -2415 Kcal/kg-CO

$Fe_2O_3 = 2Fe + \frac{3}{2}O_2$ ΔH = 1230 Kcal/kg-Fe_2O_3

$S + \frac{1}{2}O_2 = SO_2$ ΔH = 1230 Kcal/kg-S

Output

BOF model calculates the following,

- Excess energy available or energy deficient of the system
- Hot metal required to produce unit crude steel
- SEC
- BOF Gas composition and energy

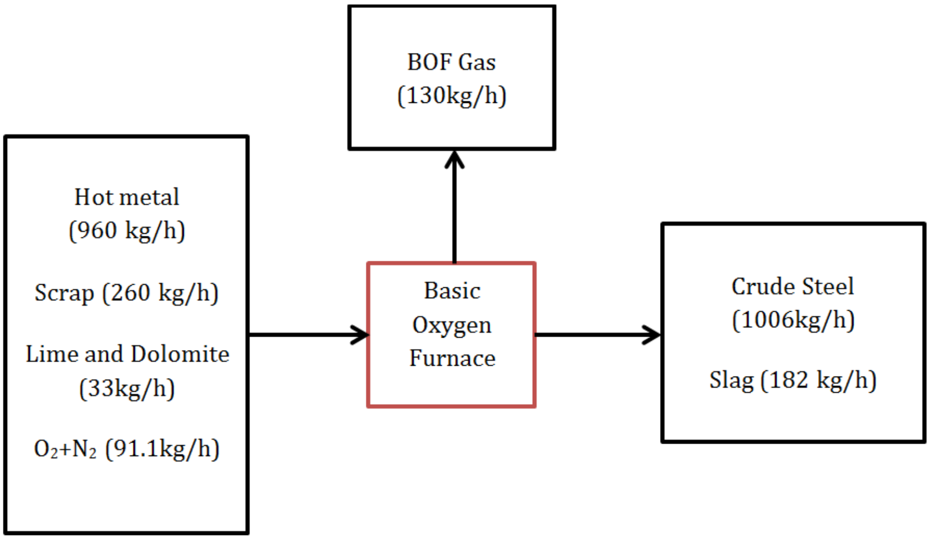


Figure 25: BOF Material Balance

Energy In	
Item	**MJ/h**
Hot Metal	931
Scrap	0
Lime	0
Dolomite	0
Oxygen	0
Nitrogen	0
Heat released by reactions	1334
Total	2265

Basic Oxygen Furnace

Energy Out	
Item	**MJ/h**
BOF Gas	28
Heat absorbed by reactions	338
Crude Steel	915
Slag	271
Carbon content of hot metal	105
Loss/unaccountable	662
Total	2265

Figure 26: Energy Balance – BOF

ASPEN Results

Overall input and output of the model has estimated 94% crude steel conversion efficiency by mass and other released as BOF Gas. The results from the process simulator for the basic oxygen furnace is described in Table 20 and the corresponding outlet stream composition from different sub-processes is given in Table 21 and Table 22. The SEC calculated from the energy balance of the model is around 0.8 GJ/ ton of crude steel. The iron content of the crude steel is found to be 99.98% (w/w) and the slag has high CaO content. BOF gas has higher carbon dioxide (CO_2) content than any other gas and carries 272 GJ/h of input energy.

Table 20: BOF Material and Energy Balance

Input			Output		
Material (kg/h)		Energy (GJ/h)	Material (kg/h)		Energy (GJ/h)
Hot Metal	357569	296	Crude Steel	436635	330
Scrap	96921	4	Slag	8729	
Lime	7962	-	BOF Gas	53714	272
Dolomite	2769	-			
Oxygen	33230	0.152	Energy Unaccountable	-	117
Nitrogen	692	0.0036			
Electricity	-	35			
Total	499143	335	Total	499079.8	719
SEC		0.8 GJ/tcs			

Table 21: BOF Solid Stream Flows

Component	Kg/h		% wt	
	CS	Slag	CS	Slag
C	-	-	-	-
Fe	436561	-	99.98	-
FeO	-	-	-	-
S	75	-	0.02	-
CaO	-	5301	-	61
P_2O_5	-	405	-	5
SiO_2	-	491	-	6
Si	-	-	-	-
Mn	-	-	-	-
MnO	-	1925	-	22
MgO	-	608	-	7
Total	436636	8730	100	100
Energy (GJ/h)	330			

Table 22: BOF Gas Stream Flows

Component	**Kg/h**	**Kmol/h**	**%mol**
O_2	0.005	-	-
N_2	1294	46	3.1
CO	19301	680	45.6
CO_2	33390	759	50.9
SO_2	414	6	0.4
Total	54128	1491	100
Energy (GJ/h)	272		

BOF performance by scrap type and hot metal temperature-capitalisation issue

The model was simulated with different input parameters and it also chronicled the effect on system performance with variation in the inputs. The hot metal input temperature is varied to observe the effect of hot metal energy on net energy available. The increase in hot metal inlet temperature increase will lead to increase in the net energy available for the process and the same is depicted in Figure 27. The reduction in hot inlet metal temperature will lead to increase in auxiliary energy input.

The variation of the basic oxygen furnace gas volume and calorific values are depicted in Figure 28 as a function of scrap type. It can be observed from the plot that the gas volume and calorific values decreases with increased scrap quality based on iron content alone.

The slag rate decreases initially because of the reduction in gangue of the scrap and then increases because of the reduced scrap quality and the same is depicted in Figure 28.

It can be observed from Figure 28 that the basic oxygen gas rate i.e. carbon monoxide and carbon dioxide decreases slightly with increased scrap quality and then increases due to low scrap quality.

The SEC of the basic oxygen furnace decreases with increased scrap quality and then increases because of the high gangue content of the scrap. The same can be observed in Figure 28.

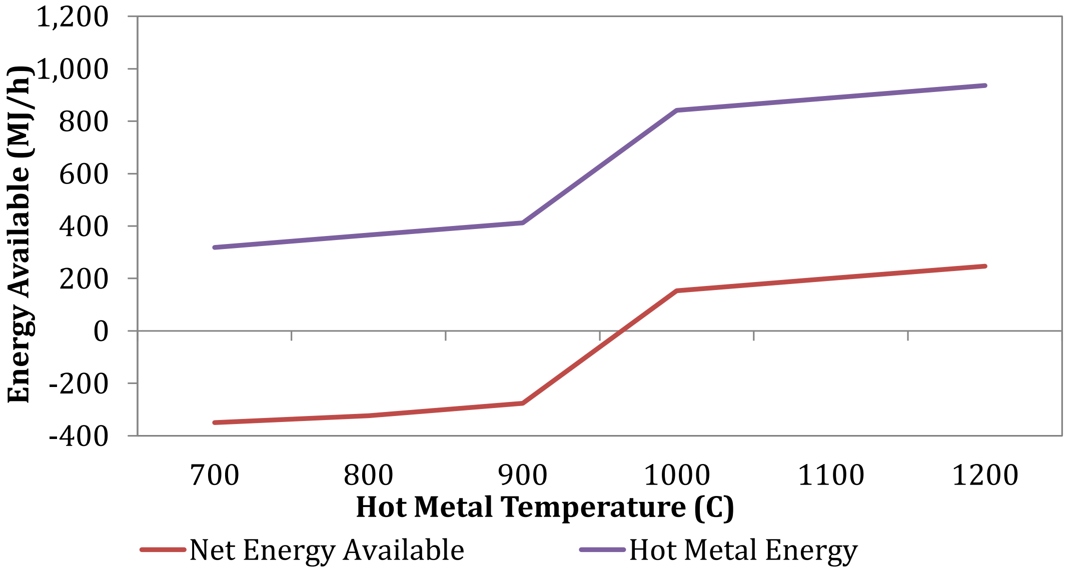


Figure 27: Hot Metal Energy Availability Variation with Temperature

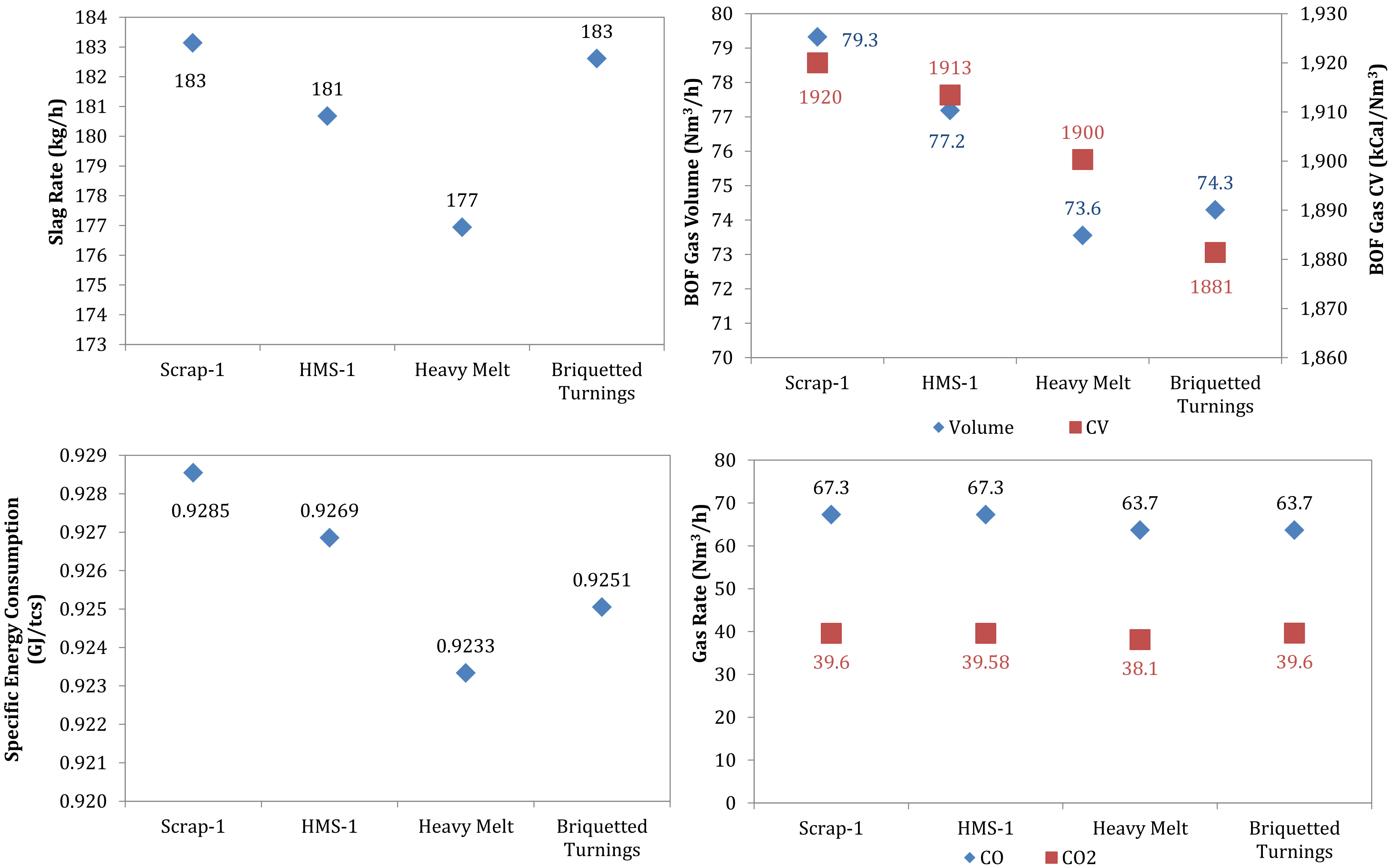


Figure 28: BOF Performance with Scrap Type

Conclusion

SEC and slag rate variation with scrap type is marginal under consideration. The hot metal energy availability will greatly affected by the hot metal inlet temperature and subsequent energy consumption.

2.4 Coal Based DRI Process

The DRI process involves reduction of iron ore to sponge iron, the technology incorporates rotary kiln supported by coal based fuel inputs. In this technology material and energy flows counter current. The model developed considered possible reactions in the DRI kiln. The objective of this particular equipment model estimates the material and energy balance of the system in producing one ton of sponge iron.

Based on exhaust gas temperature and ore preheating conditions, four alternative routes were analysed for sponge iron production as shown in Table 23. The ore and air pre-heating is considered in alternative IV but not in other alternative processes. The exhaust gas temperature range taken in this model are between 700-1200^{0}C. The composition of different types of coals is shown in Table 24. The % of carbon is highest in Raniganj (C1) and lowest in Singrauli (C4).

Table 23: Alternatives considered for calculation and boundary conditions (25)

	Preheating					Recirculation	
	Ore	^{0}C	Air	Mean air ^{0}C	Exhaust gas ^{0}C	Char	Char quantity (kg/t DRI)
Alternative-I	No	25	No	25	1200	No	0
Alternative-II	No	25	No	25	1000	No	0
Alternative-III	No	25	No	25	800	No	0
Alternative-IV (Optimised process)	Yes	664	Yes	400	700	Yes	200

Table 24: Composition of different coals

Coal composition	Raniganj, C1	West Bokaro, C2	Wardha valley, C3	Singrauli, C4
C	60.2	52.3	46.4	39.27
H	4.2	3.3	2.9	2.88
O	7.1	4.9	9.3	9.18
S	0.3	0.41	0.41	0.5
N	1.8	1.23	1.16	0.92
H_2O(free)	1.7	0	6	6.48
H_2O(combined)	1.8	1.8	1.8	1.8
Ash	22.9	36	32	39

Case Study: DRI Performance by Different Ore Type and Coal Types

- ***Use of ore type 1 (Ore_1)***

Figure 29 shows the total coal required for various alternatives of sponge iron production. It is observed that alternate IV requires the least amount of coal compared to other routes. This is mainly due to the char recirculation in alternate IV.

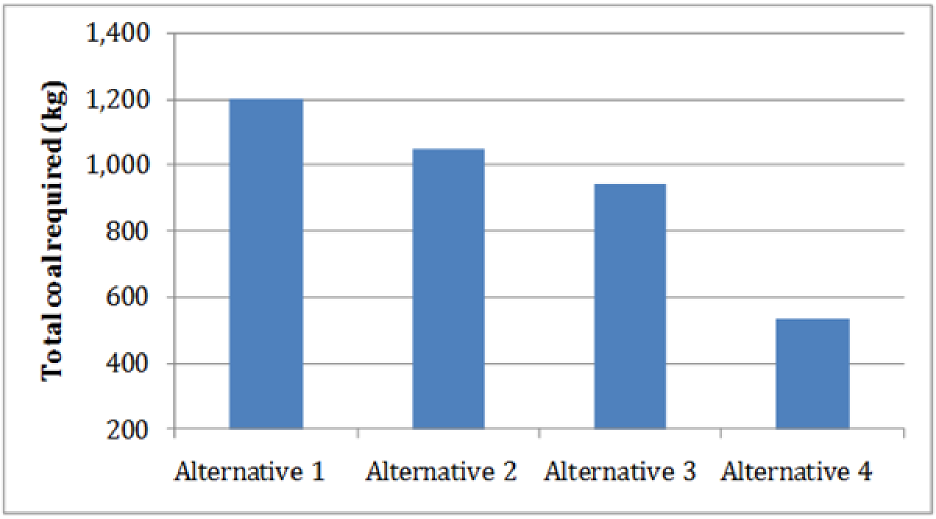


Figure 29: Total coal required for different alternatives

Figure 30 shows the amount of iron ore reduced for different types of coals. From the figure, it is observed that the amount of iron ore reduced increases with the % carbon in coal.

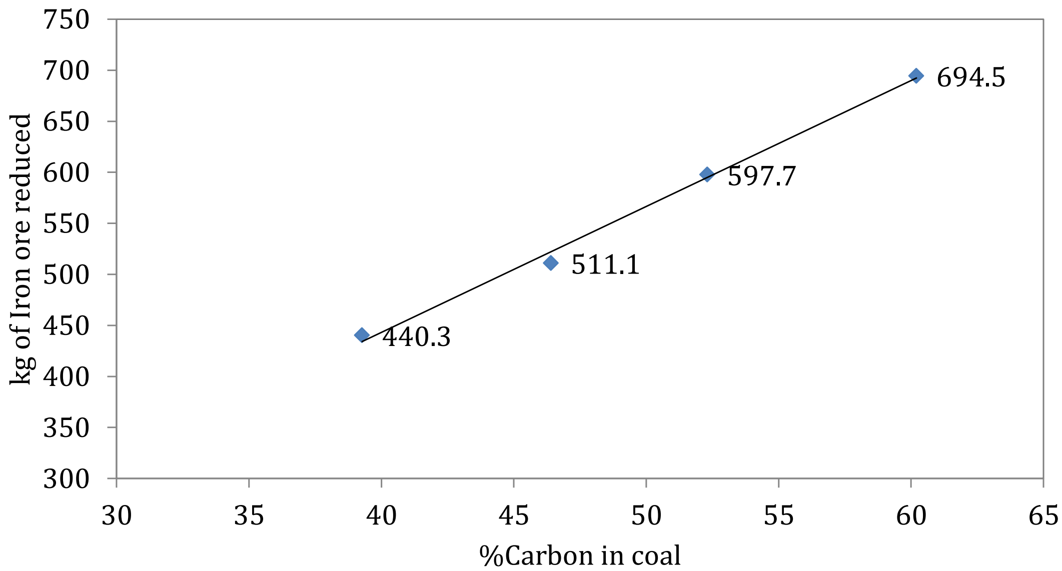
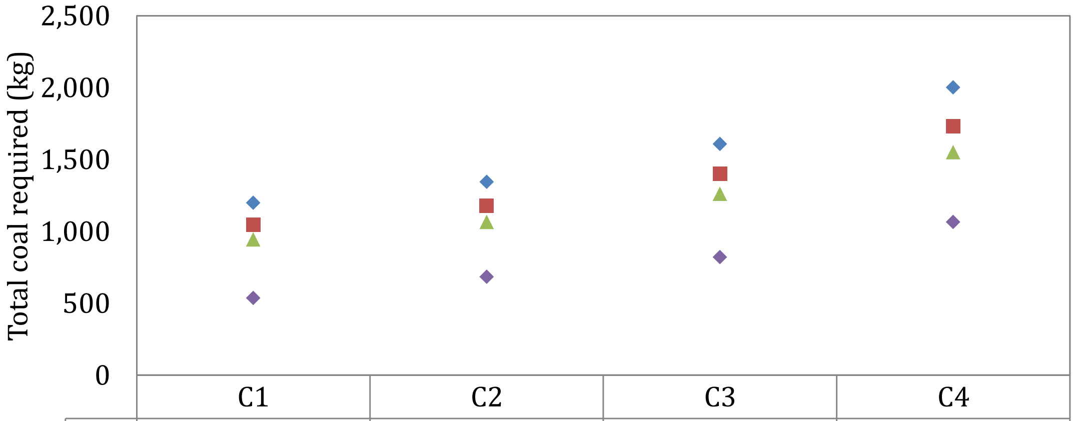


Figure 30: Iron ore reduced vs. %carbon in coal

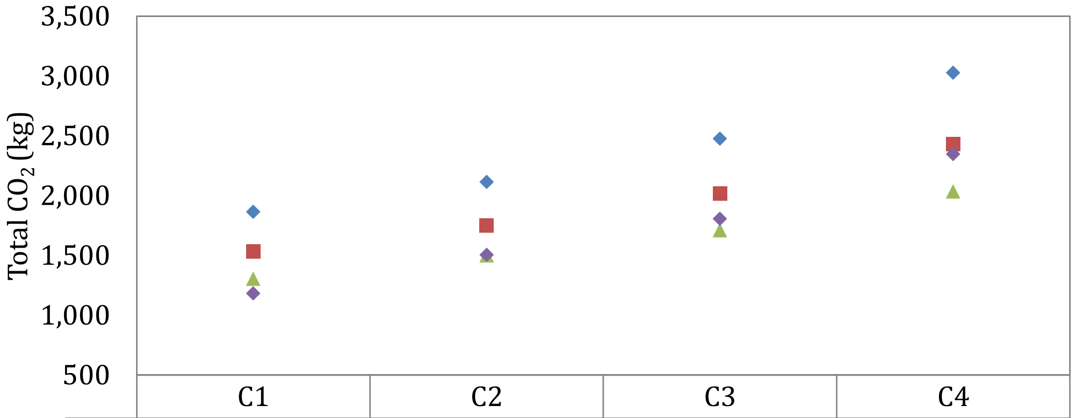
This model was analysed for different iron ore and coal combinations and the results are shown in the following sections. Figure 31 shows the coal required for the four alternatives of sponge iron production. It is observed that A4 requires less amount of coal compared to other alternatives due to char recirculation.



	C1	C2	C3	C4
A1	1,198.2	1,344.3	1,608.2	2,001.6
A2	1,046.8	1,178.2	1,400.3	1,730.8
A3	944.0	1,065.2	1,260.9	1,550.4
A4	537.0	684.0	820.4	1,066.1

Figure 31: Coal required for different alternatives for iron ore$_1$

The emissions are calculated after subtracting the char quantity from the total coal used in the process, except for A4. The emissions trend is similar to coal consumption trend. Figure 32 shows the CO_2 emission from the four alternatives of sponge iron production

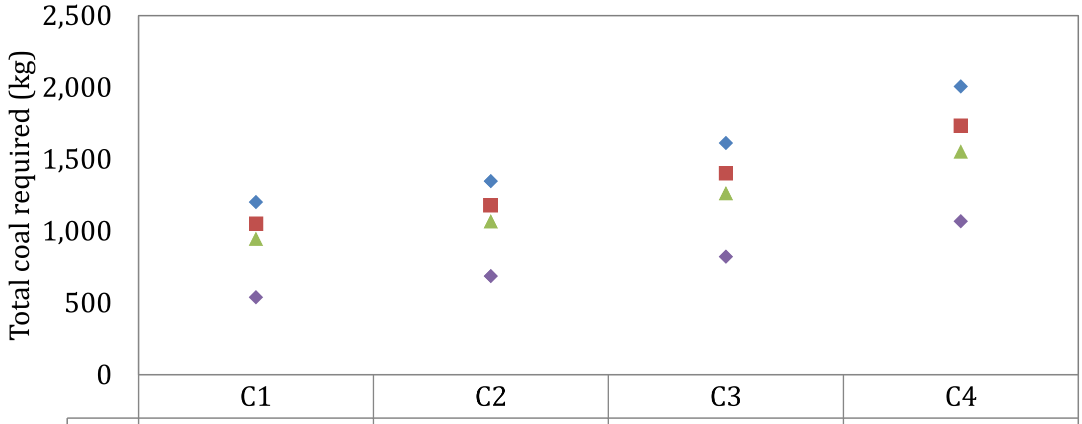


	C1	C2	C3	C4
A1	1,863.3	2,113.9	2,474.7	3,027.7
A2	1,530.1	1,748.5	2,017.5	2,431.9
A3	1,304.0	1,499.8	1,710.7	2,035.1
A4	1,181.3	1,504.7	1,804.9	2,345.5

Figure 32: Total CO_2 emissions for different coals and for iron ore$_1$

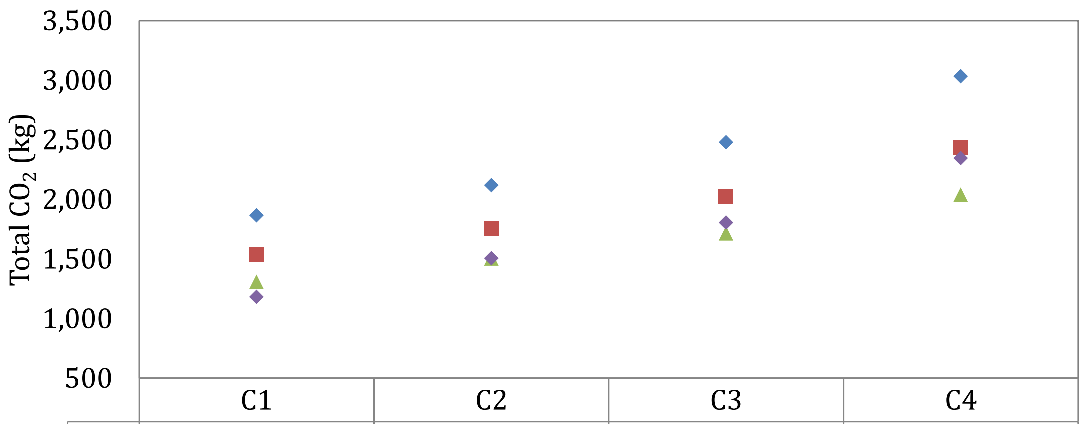
- ***Use of ore type 2 (Ore$_2$)***

Figure 33 and Figure 34 show the total coal required in the kiln and corresponding emissions for different alternatives of sponge iron production using ore$_2$.



	C1	C2	C3	C4
A1	1,199.7	1,346.1	1,610.2	2,004.0
A2	1,048.1	1,179.8	1,402.2	1,733.0
A3	945.3	1,066.7	1,262.6	1,552.4
A4	537.0	684.0	820.4	1,066.1

Figure 33: Coal required for different alternatives for iron ore$_2$

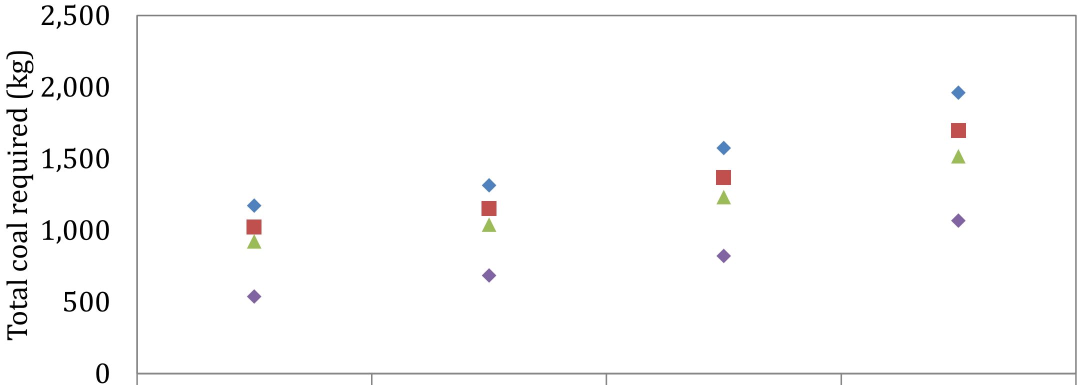


	C1	C2	C3	C4
A1	1,866.5	2,117.7	2,479.1	3,032.8
A2	1,533.1	1,752.0	2,021.5	2,436.6
A3	1,306.9	1,503.1	1,714.5	2,039.5
A4	1,181.3	1,504.7	1,804.9	2,345.5

Figure 34: Total CO_2 emissions for different coals and for iron ore$_2$

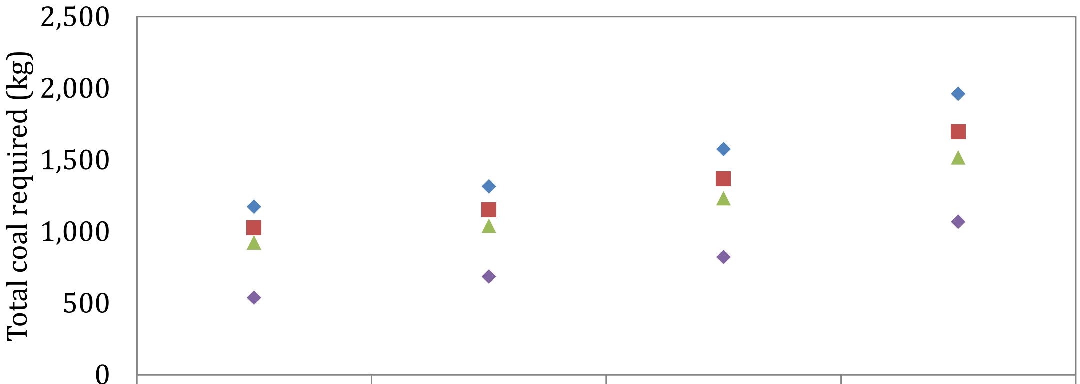
- ***Use of ore type 3 (Ore₃)***

Figure 35 and Figure 36 show the total coal required in the kiln and corresponding emissions for different alternatives of sponge iron production using ore_3.



	C1	C2	C3	C4
A1	1,172.4	1,314.2	1,573.4	1,961.4
A2	1,023.0	1,150.5	1,368.4	1,693.9
A3	921.7	1,039.2	1,230.9	1,515.8
A4	537.0	684.0	820.4	1,066.1

Figure 35: Coal required for different alternatives for iron ore_3



	C1	C2	C3	C4
A1	1,172.4	1,314.2	1,573.4	1,961.4
A2	1,023.0	1,150.5	1,368.4	1,693.9
A3	921.7	1,039.2	1,230.9	1,515.8
A4	537.0	684.0	820.4	1,066.1

Figure 36: Total CO_2 emissions for different coals for iron ore_3

2.5 Analysis of Electrical Furnaces in Steel Making

After iron is extracted through thermal process, these energy intensive electrical furnaces is used to produce some of the specialised steel and steel products. There are three major variants of steel making through electrical technology such as Electrical Arc Furnace (EAF), Induction Furnace (IF) and submerged arc furnace (SAF). Recycling of scraps is largely incorporated in these processes. Each process facility could be standalone units or integrated along the complete ore to steel making process chain.

2.5.2 Electric Arc Furnaces (EAF)

An energy balance model was simulated with different types of scrap and the results are shown in the following section. Figure 37 shows the EAF gas volume and calorific value of gas for different types of scraps.

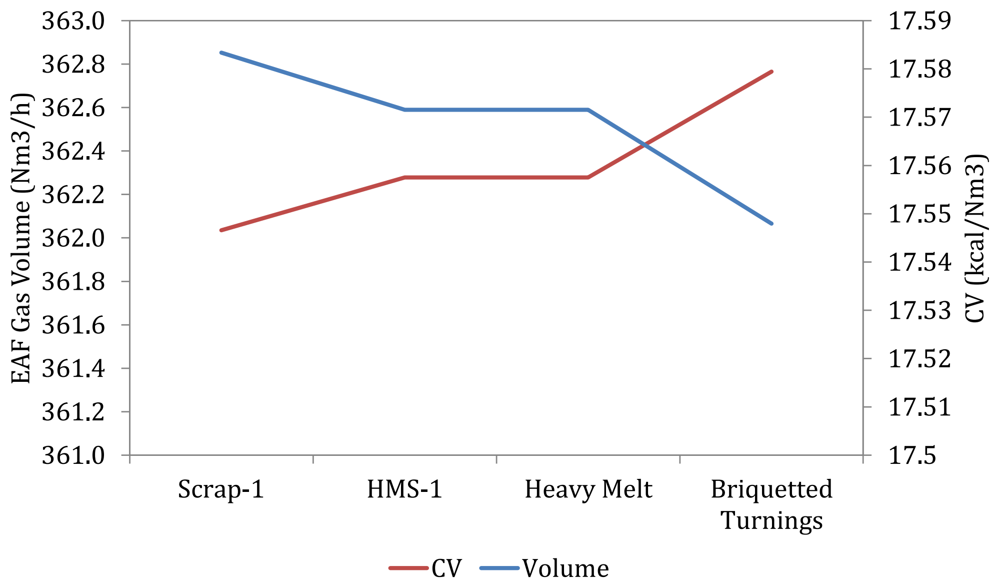


Figure 37: EAF gas volume and CV vs. scrap type

Figure 38 shows the slag rate for different scraps. It is observed that the slag rate is more for the briquetted turnings because of its high impurity/gangue.

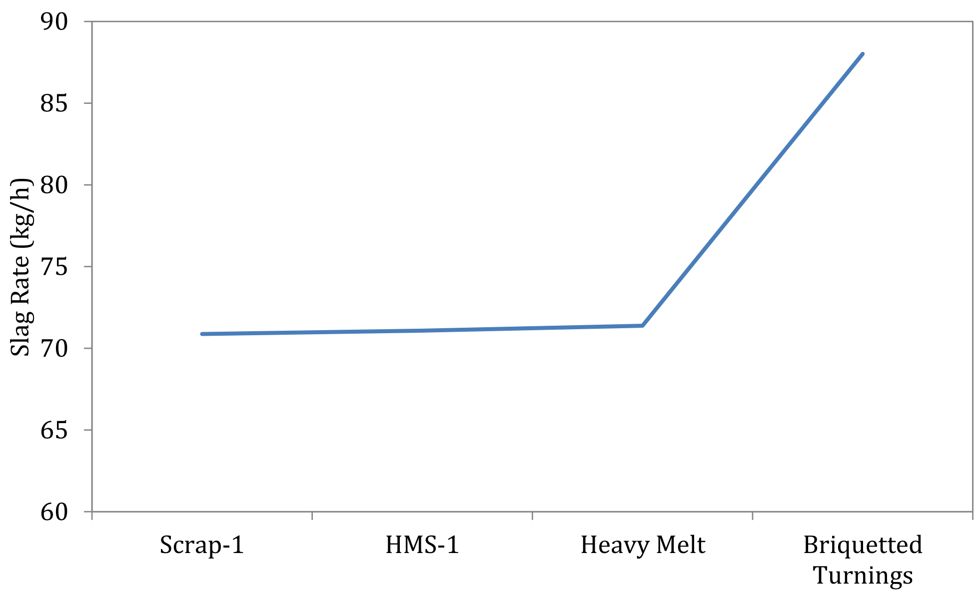


Figure 38: Slag rate vs. scrap type

The gas rate and SEC of different scrap types are shown in Figure 39 and Figure 40 respectively.

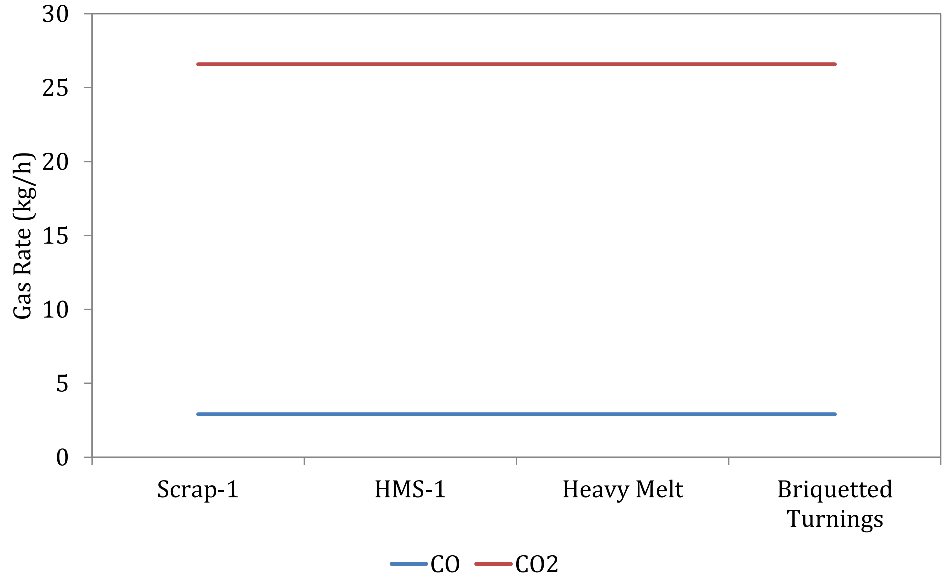


Figure 39: Gas rate vs. scrap type

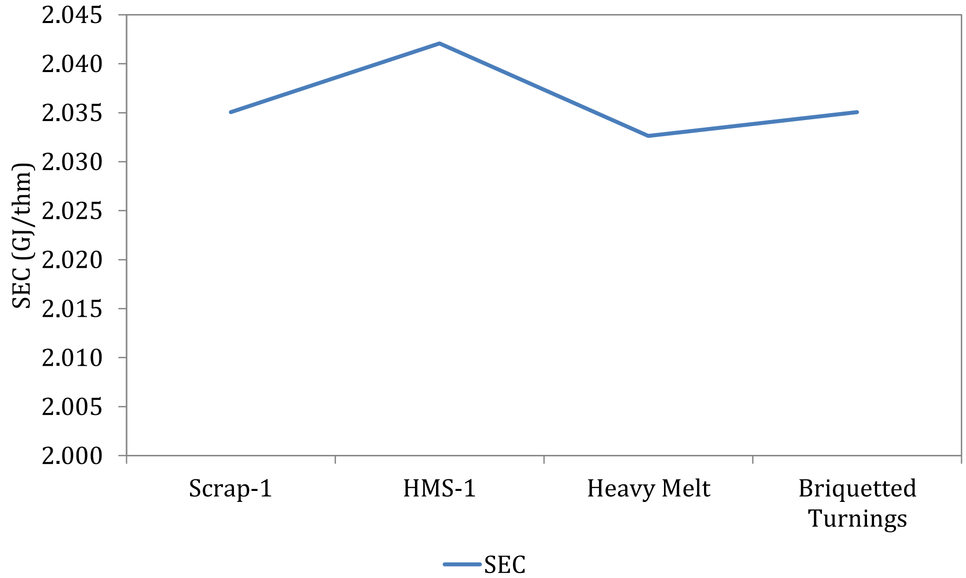


Figure 40: SEC of different scrap types

2.5.3 Induction Melting furnace (IMF)

Performance of induction furnace with varying capacity and input voltage is discussed in this section. It is observed the SEC varies as capacity increases. Figure 41 illustrates the variation of SEC with the increasing capacity of the furnace from 0.25 to 4 tonnes as the input voltage is regulated (26).

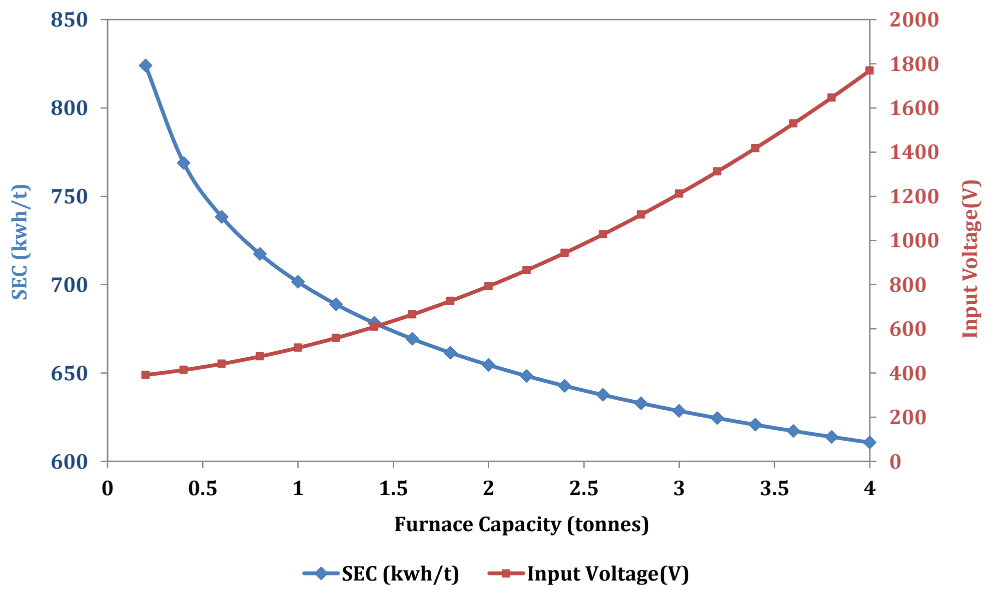


Figure 41: Energy consumption behaviour with increasing furnace capacity and input voltage

Another parameter is the water consumption. A one ton capacity furnace requires water flow rate of 10 t/hr. and doubles as the capacity increases. Figure 42 shows the variation in the water flow rate as the capacity increases in comparison with the melting rate.

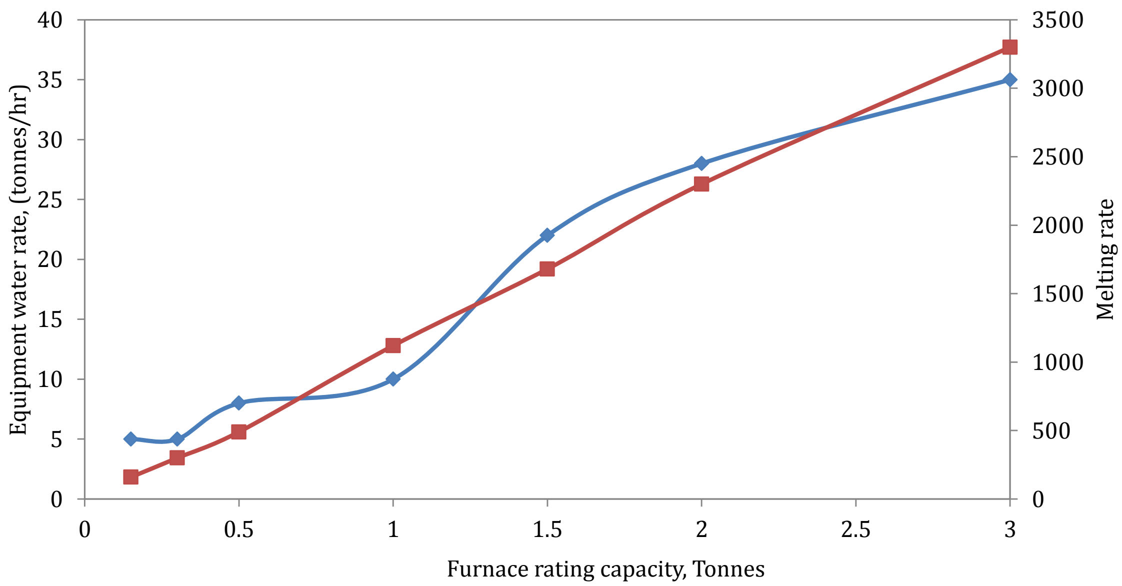


Figure 42: Furnace performance on melting rate and water consumption rate with increasing capacity of furnace

2.5.4 Submerged Arc Furnace (SAF)

A model SAF was built to study its performance with furnace initial temperature of 15°C, mass of steel to melt of 2.5 t and operating with a furnace efficiency of 70%. Melting time is one of the desired performing characteristics of a furnace; the study reviewed how the melting time has its effects on current drawn and transformers capacity.

- ***Current Drawn vs. Melting Time***

As the current drawn is increased, the power requirement increases and correspondingly the melting time reduce (Figure 43).

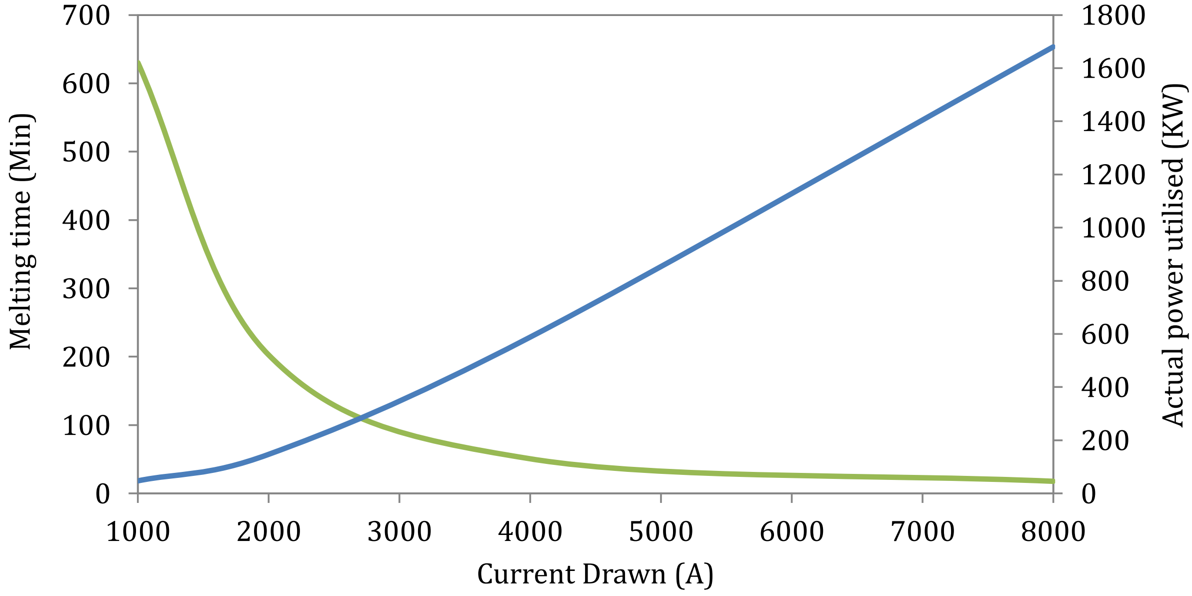


Figure 43: Performance of the furnace with respect to melting time and power utilised with increasing current drawn from the transformer

- ***Transformer Capacity vs. Mass of Melt***

Alternatively, the transformer capacity requirement to melt 1 t of steel with furnace efficiency of 70% is estimated to be about 260 kVA; as the capacity increases the transformer capacity is also increased to support the system. Figure 44 illustrates the estimated average transformer capacity required to melt steel for a range of capacities.

Sensitivity analysis: Estimation of transformer capacity requirements with the increasing efficiency of the equipment.

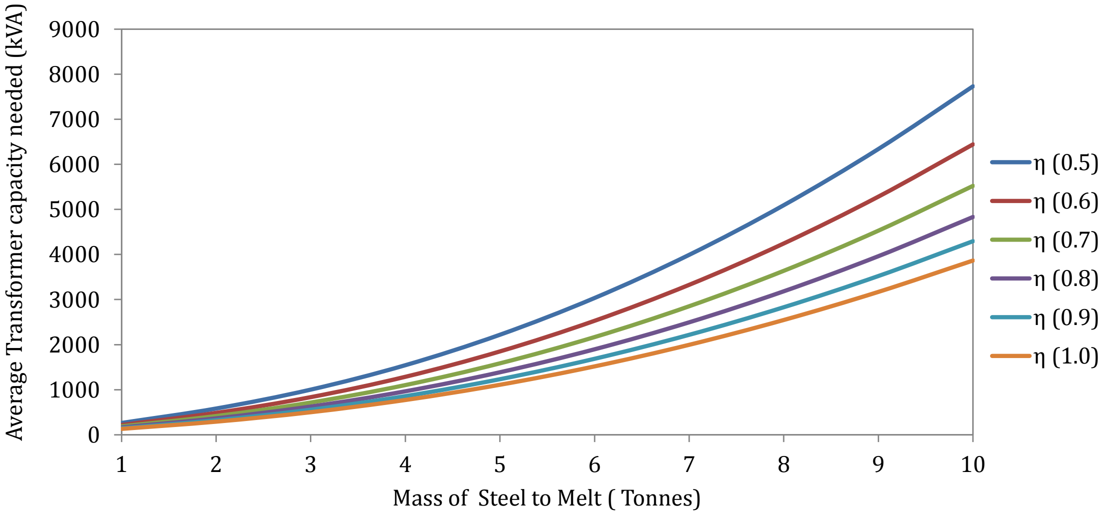


Figure 44: Sensitivity analysis for estimating the transformer capacity

Figure 44 shows the results of sensitivity analysis and it is observed that the typical transformers capacity requirement to melt 1tonne of steel is of the range of 260 kVA to 150 kVA with increasing furnace efficiency from 50-100%. Efficiency also impacts energy consumption; for the base case the energy consumption ranges between 200-1980 kWh with melting mass from 1-10 tonnes respectively. Figure 45 illustrates the power utilised by the furnace.

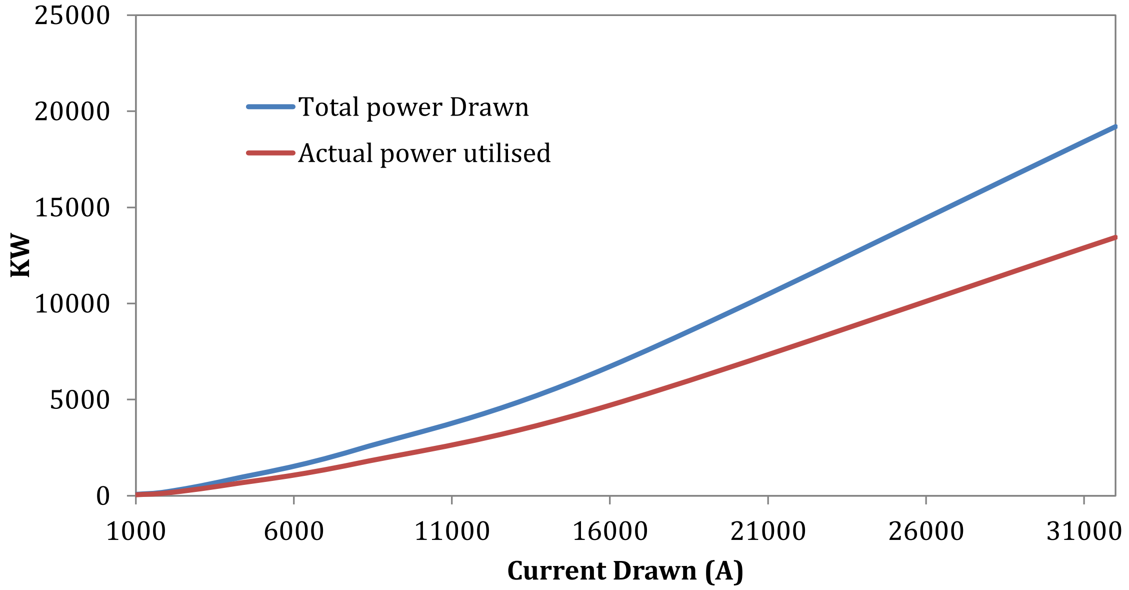


Figure 45: Actual power utilised vs. Power Drawn

- ***Effect of Preheating the Furnace on SEC***

Large amounts of energy could be saved if the equipment is preheated. Figure 46 illustrates effect on SEC if the equipment is preheated. The melting of steel takes place in three stages: melting, continuous melting and holding. The pre-heated charge is at 500℃, and the preheated equipment is started with room temperature. About 120 kWh/t of saving could be achieved if the IF is operated with preheating on first melt and about 160 kWh/t on continuous melting. The melting time improves by pre-heating the equipment as shown in Figure 47 (27).

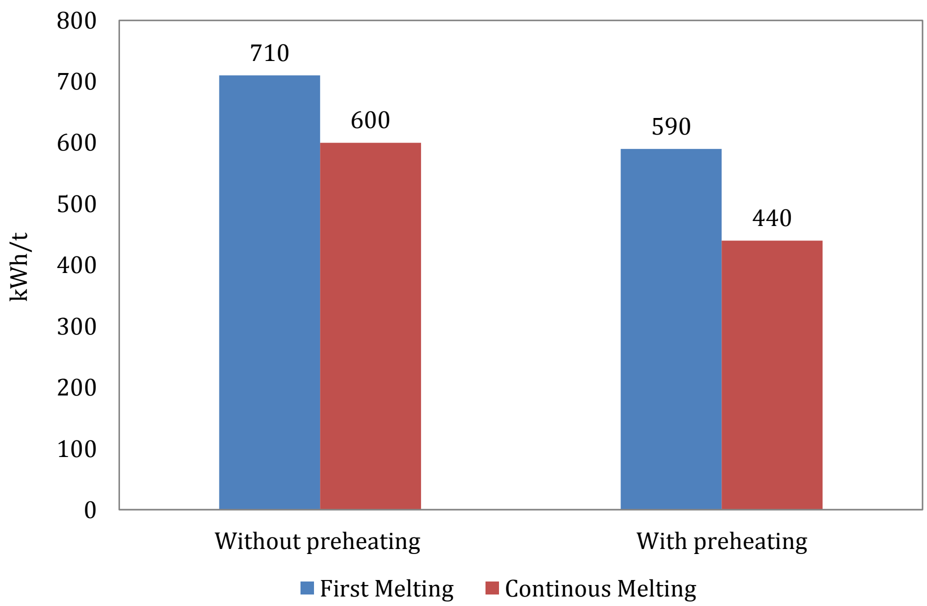


Figure 46: Comparison of equipment with and without preheating

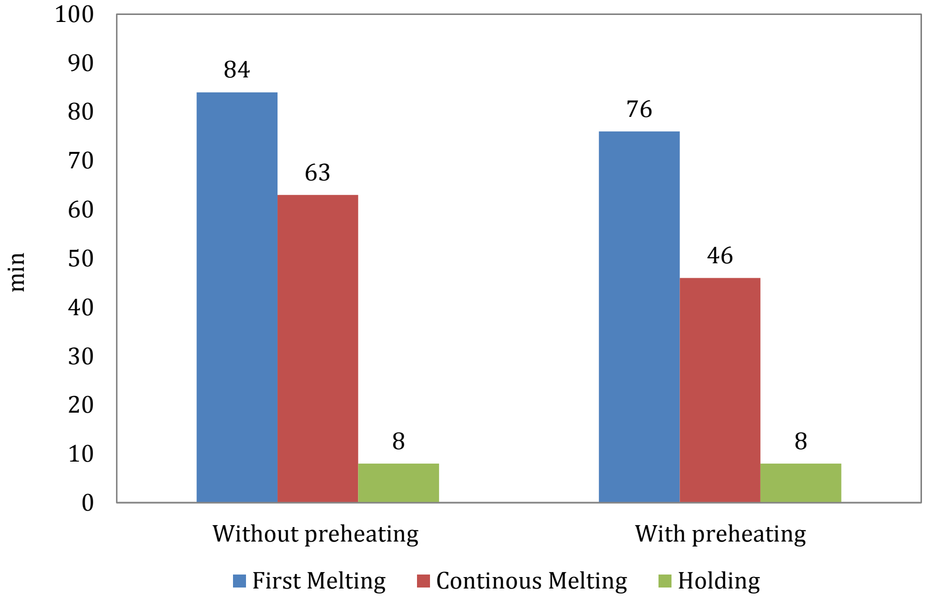


Figure 47: Review of melting time for equipment with and without preheating

3. PAT Methodology and Application in Sample Plants

3.1 Baseline SEC Computation

PAT follows a Gate to Gate (G2G) approach for establishing the baseline SEC. G2G refers to the physical boundary of an iron and steel plant and the processes within it. A DC's baseline energy could be calculated taking into consideration the average thermal and electrical energy for three years. The ratio of total energy consumption of crude steel production gives a simple measure of the SEC.

$$\text{Specific Energy Consumption (kCal}/tcs) = \frac{\text{Energy Consumption (MkCal)}}{\text{Production (Mt)}}$$

Note: In the formula above, energy consumption can be defined as the total energy from all sources that is used for process heating and electrical power consumption. Energy generated from waste may not be considered, if the waste has been generated from the initial fuel inputs to the plant.

An accurate estimation of the baseline SEC value is an important step in the PAT methodology. Each DC is dynamic in nature and its performance depends on the technology incorporated and business demand. The baseline SEC could be computed considering the average performance of the last three years as it captures variations in manufacturing practices and operating conditions.

However, variation in product mix (such as blooms, billets, rods, flats, wires, rails, wheel and axle), DC's with CPP vis. a vis. without-CPP and DC's trading intermediate products or supplying varying shares of electrical energy to the grid are some of the key factors that need to be considered while establishing the baseline SEC. Normalisation of the baseline SEC may be required in order to increase the robustness in the presence of variations in certain operating conditions.

3.2 Variations in Plant Operating Conditions

A simple calculation of the baseline SEC gives a broad indication of the energy intensity of a plant. However, it is necessary that a robust calculation of the baseline SEC be designed in order to reduce the impact of variations in plant operating conditions. Such normalisation factors may be considered based on a few significant plant operating parameters.

1. **Captive Power Plant (CPP)**
   Major steel industries and plants may have a CPP and may also export surplus power to the grid. When there is a change in the share of power that is exported then the baseline SEC of the plant may undergo variations.

2. **Performance factors**

   SEC – Electrical:

   Electricity energy is required for different sub-processes such as electrical furnaces, drive mechanism for feeders, conveyors, DRI rotary kiln, and other supporting devices. The total electrical SEC of a plant includes casting, rolling, and other secondary steel making sections and plant utilities are situated within the boundary, but excludes power supply to the colony.

SEC – Thermal:

Thermal energy is intensely utilised during the reduction of iron ore both in blast furnace and direct reduced iron. The thermal energy consumption is based on the total quantity of fuel used and the gross calorific values of the fuels used in the plant. The thermal SEC is the energy (GCal) required to produce one unit of pig iron or steel as applicable.

3.3 Normalised Baseline SEC

Normalisation in the calculation of gate-to-gate SEC for Steel industry is challenging. The simple methodology as described earlier does not account for variations in plant specific factors such as variation in product mix, export and import of pig iron, crude steel, steel scraps and export and import of power. There is a need to include normalization factors and conversion factors to improve the robustness of SEC.

$$Normalized\ baseline\ SEC = f[Simple\ baseline\ SEC, normalization\ factor(s)]$$

3.4 Application of methodology in Integrated Steel Plant (ISP)

The baseline methodology is applied to four sample integrated steel plants and the analysis is illustrated below. The sub process-wise energy balance comparison of four different ISP's is depicted in Figure 48. Marginal variation in energy consumption of most of the sub processes is observed in Figure 48. Blast furnace process consumes more energy than any other sub process; in the range of 3.124 to 3.375 GCal/tcs. Total SEC of the considered ISP's is in the range of 6.864 to 7.075 GCal/tcs.

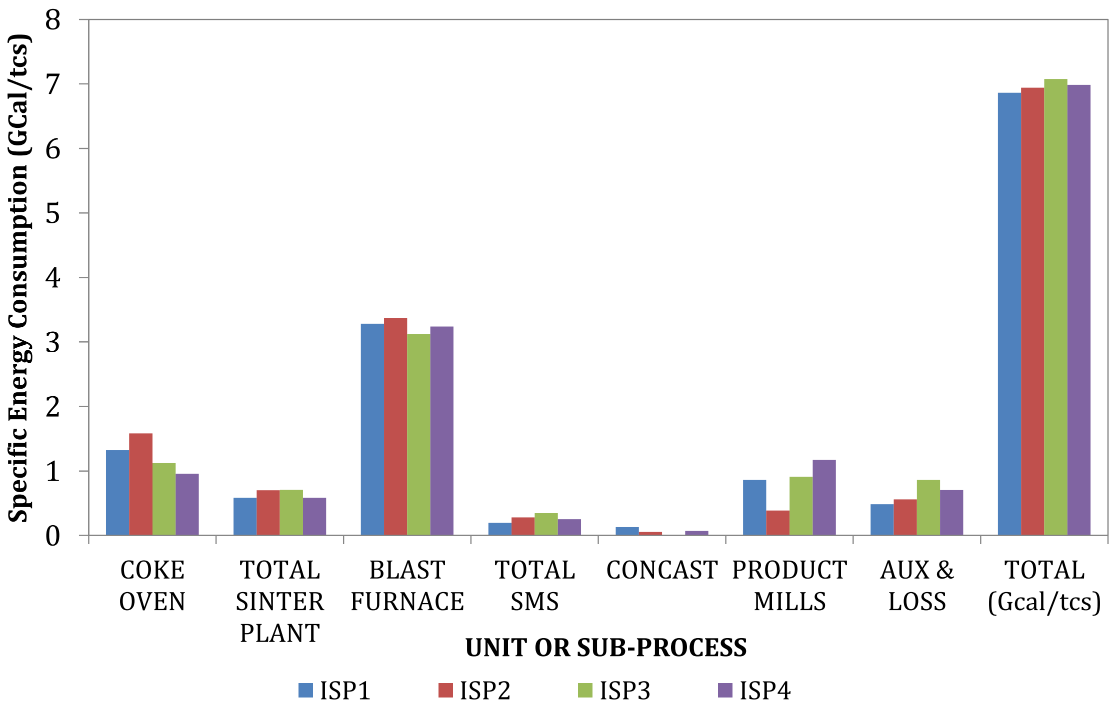


Figure 48: Energy Balance Comparison for Sample ISP Plants

The comparison of ISP SEC and associated specific CO_2 emissions is depicted in Figure 49. The SEC and associated specific CO_2 emissions are different for different ISPs due to variation in technology and other parameter variations. The SEC for ISP3 is 7.075 GCal/tcs, which is higher than any other plant. Similarly the specific CO_2 emission is higher from ISP4 than any other plant, which is 3.148 tonnes/tcs.

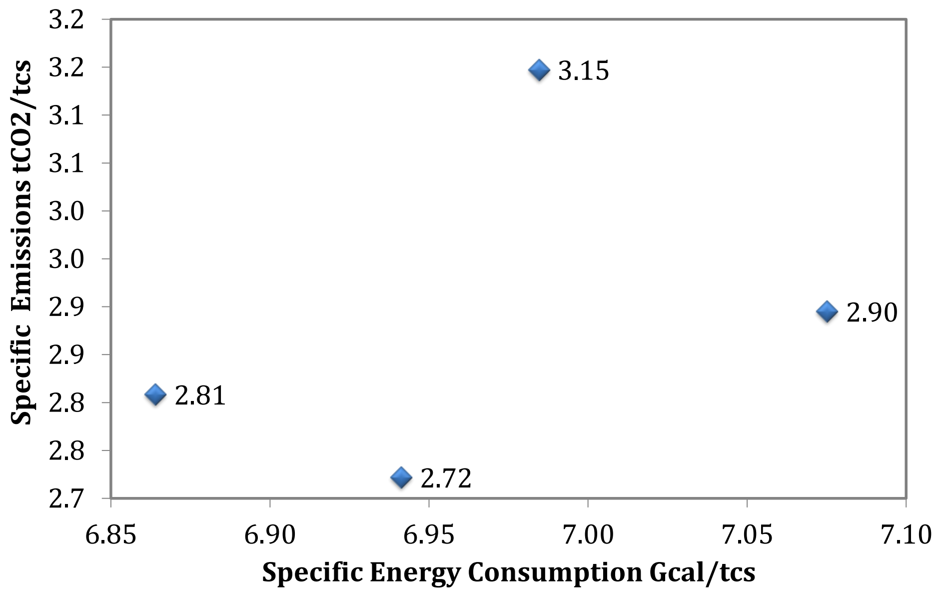


Figure 49: Comparisons of ISP Energy and Emission for Sample ISP Plants

A comparison of direct specific emissions and total specific emissions in terms of CO_2 from sample integrated steel plants is compared in Figure 50. The direct specific CO_2 emissions are higher in the case of ISP2, whereas the total specific CO_2emissions are highest for ISP4.

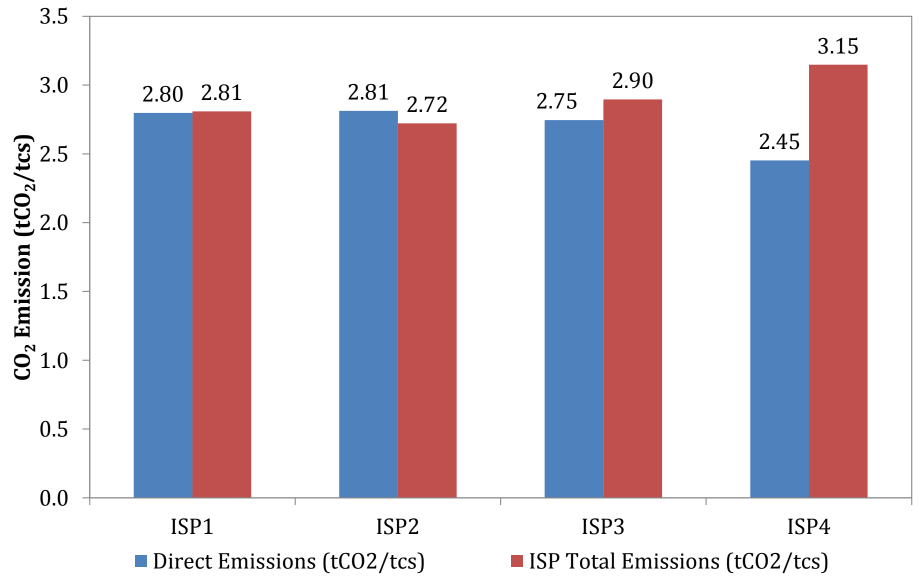


Figure 50: CO_2 Emission Comparison of Sample ISP Plants

The overall and selected sub processes SEC for different ISP is compared in Figure 51. The SEC up to hot metal stage is highest for ISP2, which is at 5.655 GCal/tcs. The SEC for steel making &

concast section is highest for ISP3 (0.34 GCal/tcs) and the SEC for rolling section is highest in case of ISP4 and is 1.174 GCal/tcs.

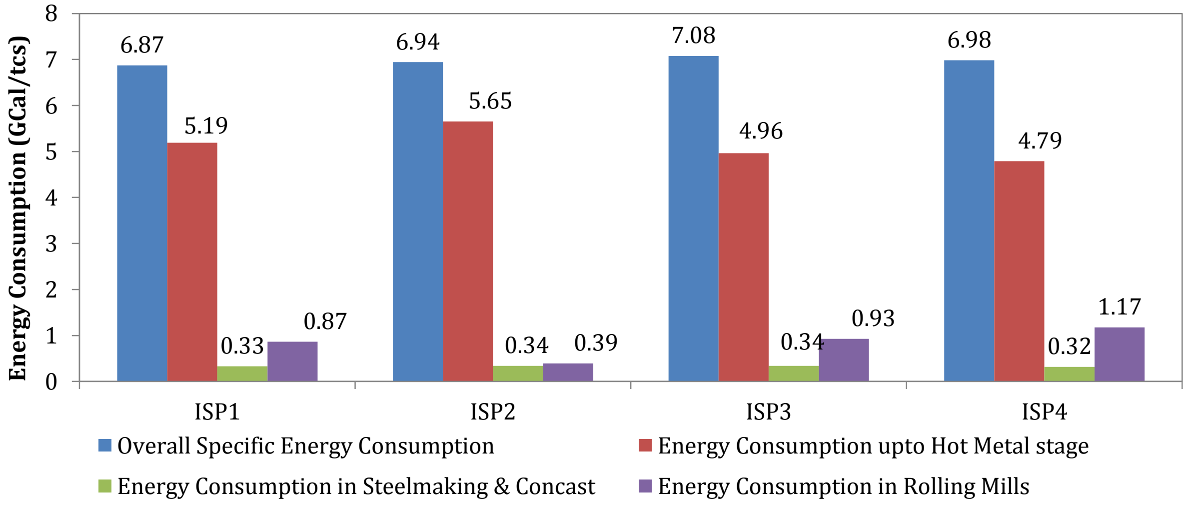


Figure 51: Specific Energy Consumption --- Comparison of Major Units for Sample ISP plants

The coke gas yield from different ISP's considered is depicted in Figure 52 and the values range from 298.3 to 323.3 Nm^3/ton of coal.

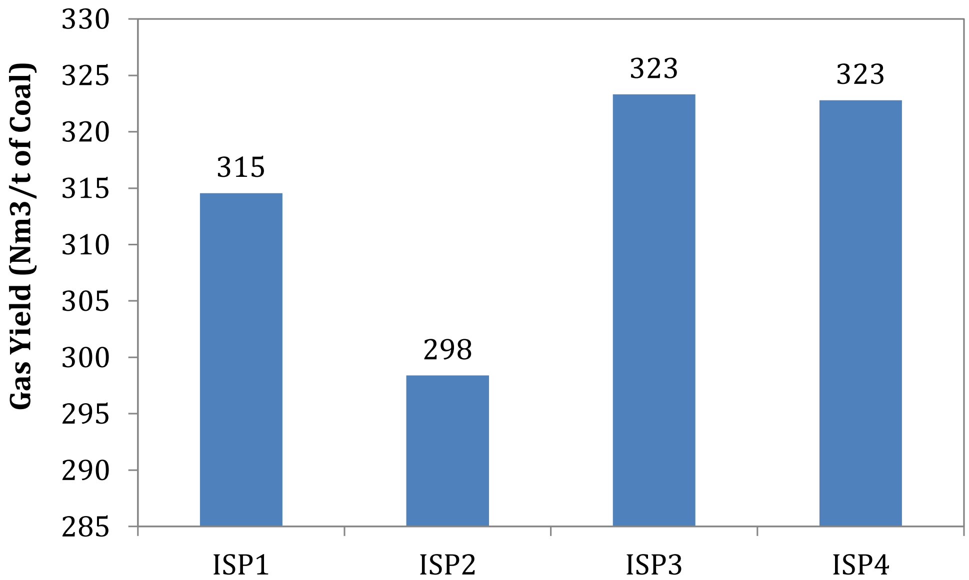


Figure 52: Coke Oven Gas Yield (At actual CV) for Sample ISP Plants

The coke yields of coke ovens from different steel plants can be observed in Figure 53. The values are in the range of 67.5 to 71.3%. The coke yield from coke oven is higher for ISP1 when compared to other plants.

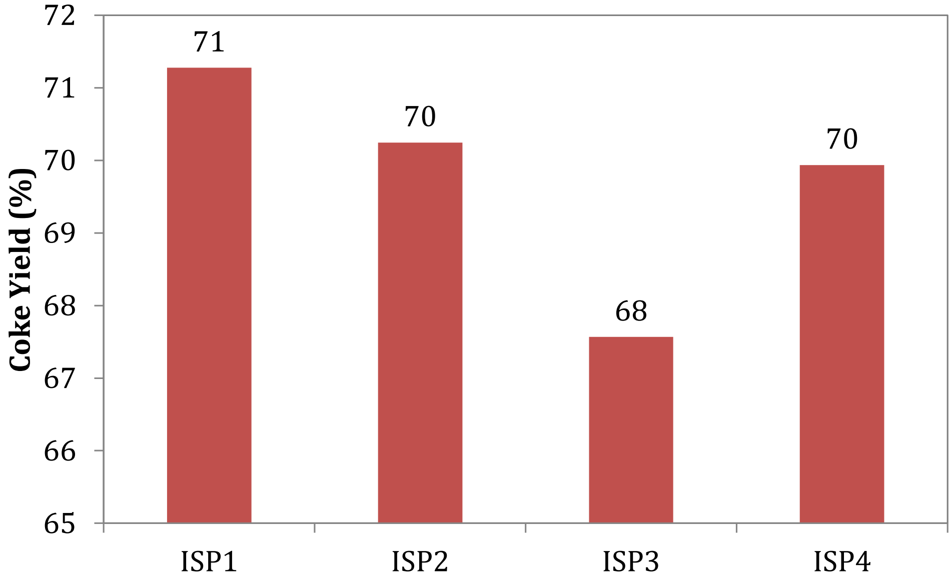


Figure 53: Coke Oven Yield for Sample ISP Plants

The fuel consumption rate in blast furnace of different ISP's considered is depicted in Figure 54 and it varies from 565 to 572 kg/thm. The fuel consumption rate for ISP2 is 565 kg/thm and is lowest due to efficient operational techniques or technological upgrade.

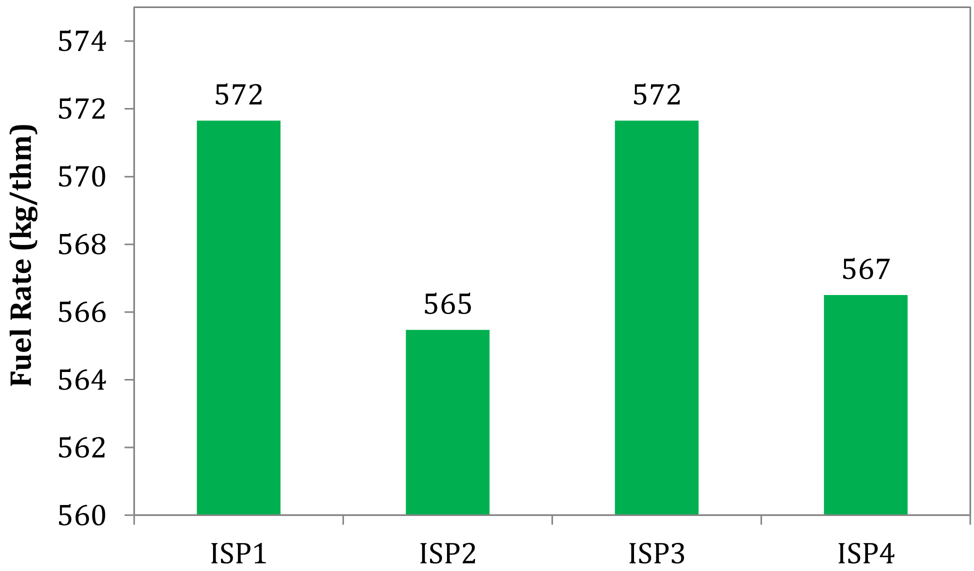


Figure 54: Blast Furnace Fuel Rate for Sample ISP Plants

The LD gas recovery rate from different ISP's considered is depicted in Figure 55 and it varies from 45.3 to 86.5Nm³/tcs. The gas recovery rate for ISP3 is 86.5 Nm³/tcs, which is highest.

Figure 55: LD Gas Recovery for Sample ISP Plants

The specific gross hot metal consumption rate for different ISP's is illustrated in Figure 56 and it varies from 1058 to 1116 kg/tcs. The value for ISP4 is 1117 kg/tcs, is higher than other plants.

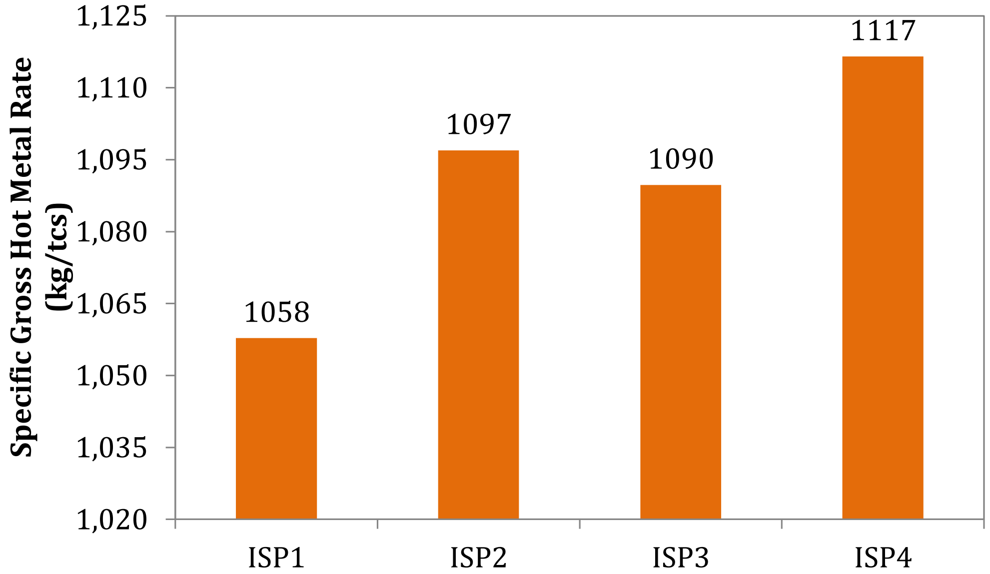


Figure 56: Specific Gross Hot Metal Consumption for Sample ISP Plants

The variation of specific heat consumption rate of coke ovens with plant type is depicted in Figure 57 and it varies from 0.617 to 0.771 GCal/ton of dry coal. The value is observed to be higher for ISP1; this may be due to variation in coal quality, moisture content, and inefficient operation.

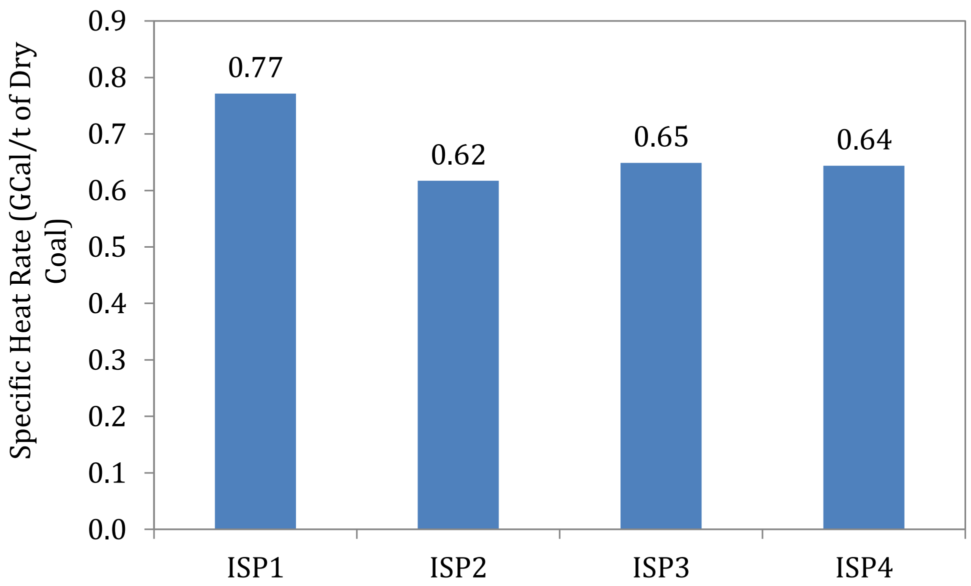


Figure 57: Specific Heat Consumption in Coke Oven for Sample ISP Plants

The variation of specific heat consumption rate of sinter plant with plant type is shown in Figure 58 and it varies from 0.024 to 0.039 GCal/ton of pellet. The value is observed to be higher for ISP4; this may be due to variation in ore quality, moisture content, and inefficient operation.

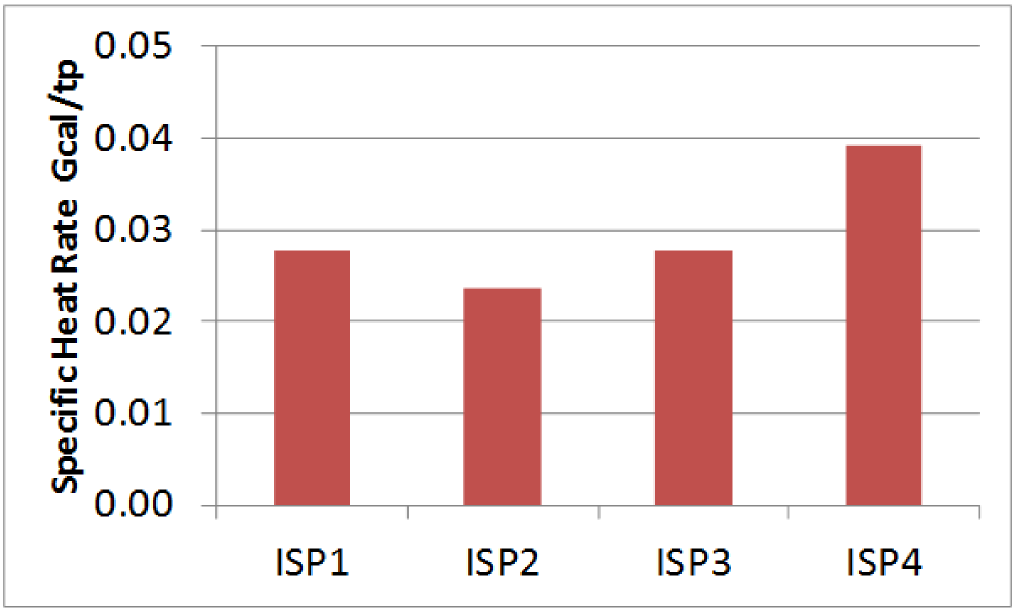


Figure 58: Specific Heat Rate in Sinter Plant for Sample ISP Plants

The variation of specific heat consumption rate of blast furnace hot stove with plant type is depicted in Figure 59 and it varies from 0.513 to 0.663 GCal/thm. The value is observed to be higher for ISP4. This may be due to variation in cold blast moisture content, flow rate and inefficient operation.

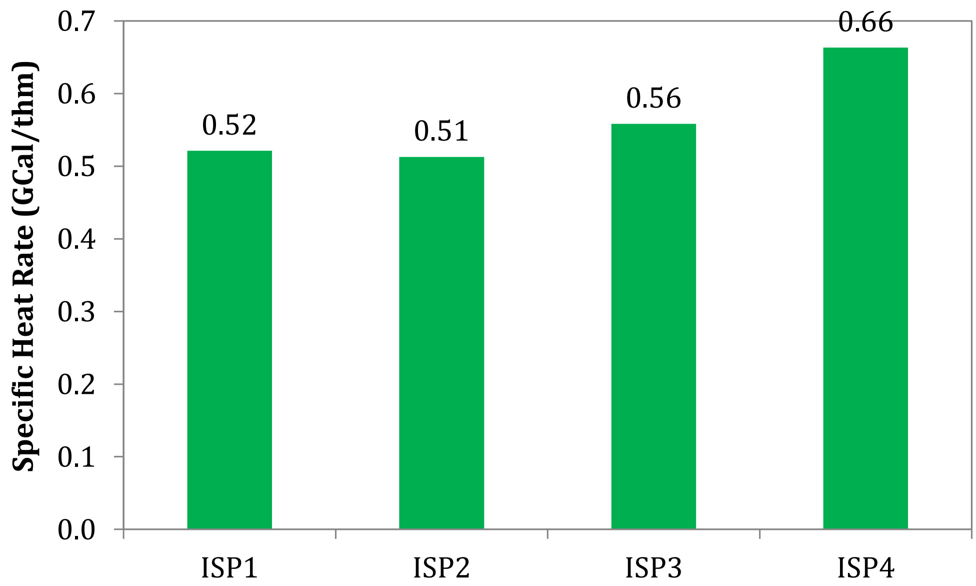


Figure 59: Specific Heat Rate in BF Hot Stove for Sample ISP Plants

The variation of specific heat consumption rate of hot mill with plant type can be observed from Figure 60 and it varies from 0.356 to 0.719 GCal/ton of input. The value is observed to be higher for ISP1. This may be due to variation in capacity and operational variables.

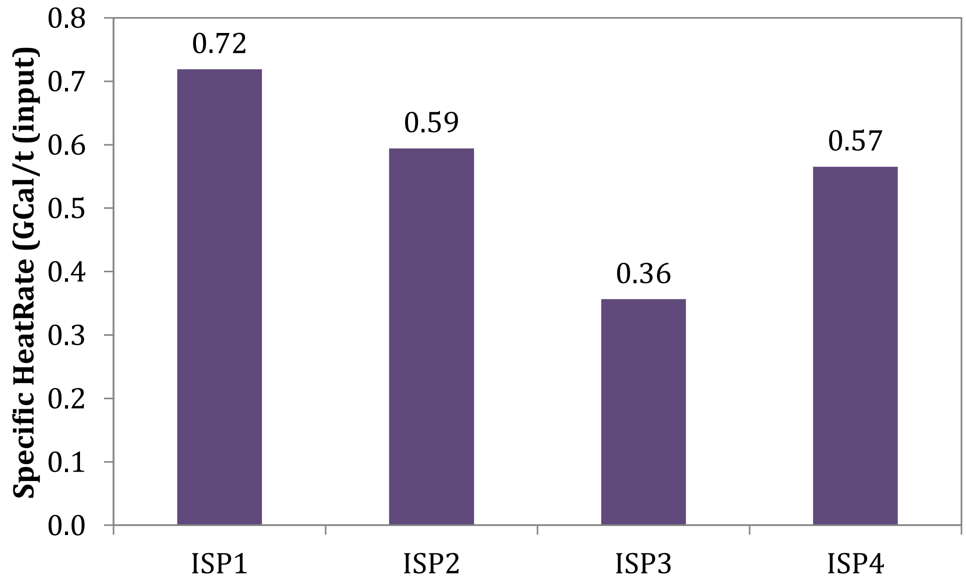


Figure 60: Specific Heat Consumption in Hot Mill for Sample ISP Plants

The variation of steam consumption rate of coke ovens with plant type is illustrated in Figure 61 and it varies from 243 to 325 kg/t of gross coke. The value is observed to be higher for ISP3.

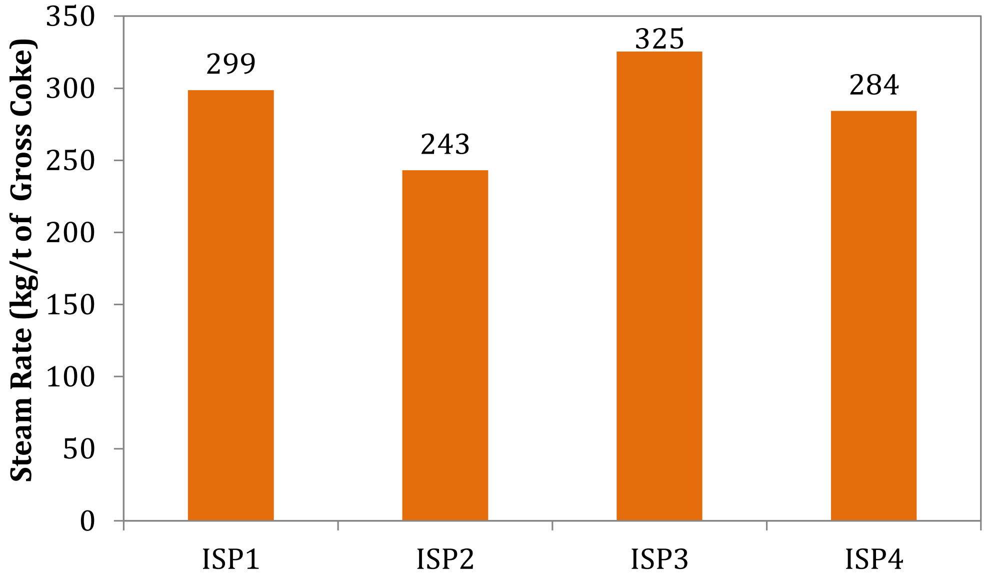


Figure 61: Steam Used in Coke Oven for Sample ISP Plants

The variation of steam consumption rate of blast furnace with plant type is illustrated in Figure 62 and it varies from 486 to 663 kg/thm. The value is observed to be higher for ISP4.

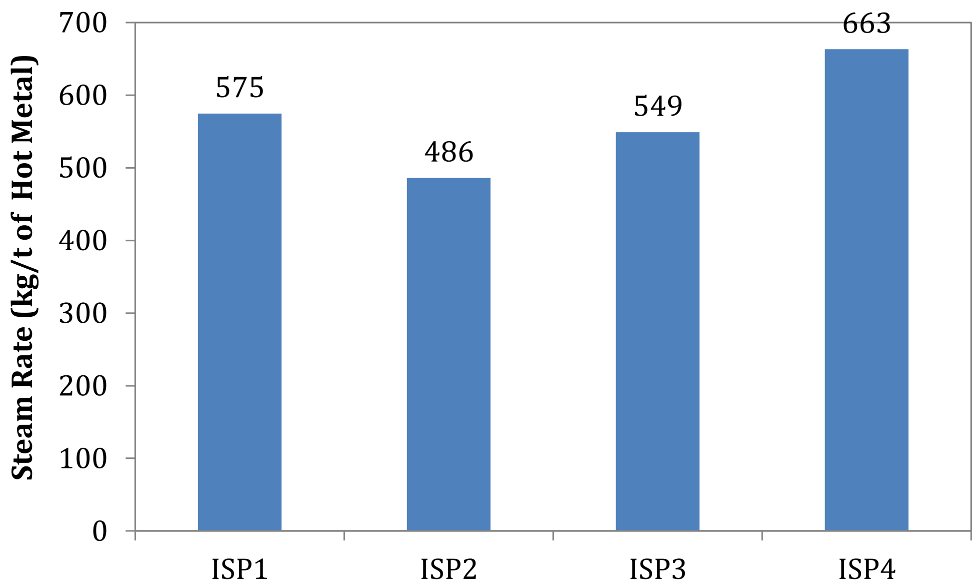


Figure 62: Steam Consumption Rate in Blast Furnace for Sample ISP Plants

The variation of total energy input rate of integrated steel plant with plant type is illustrated in Figure 63 and it varies from 14.451 to 41.52 million GCal. The value is observed to be higher for ISP1. This may be due to variation in the capacity of the plant, adopted technology and operational variables.

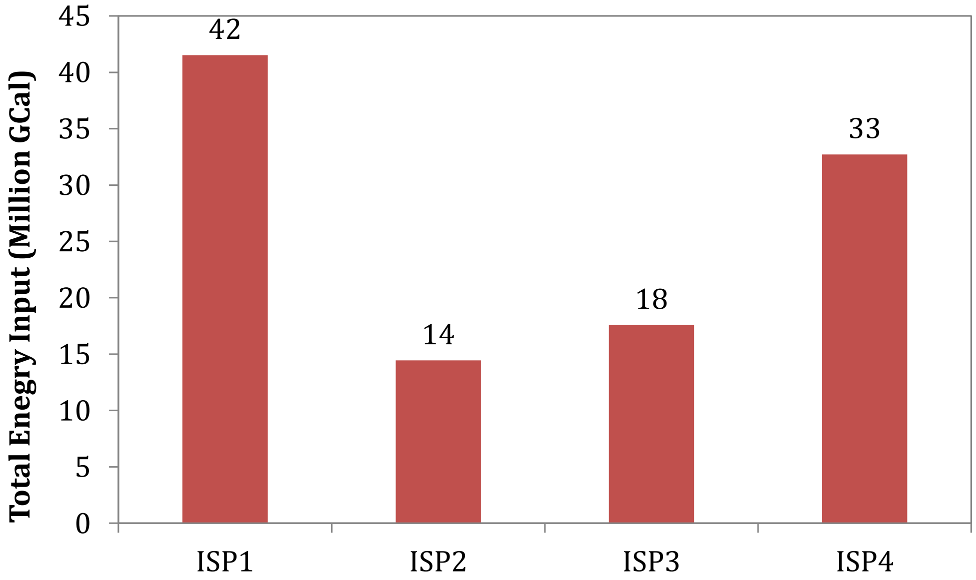


Figure 63: Total Energy Input for Sample ISP Plants

The variation of crude steel production and hot metal production with plant type is described in Figure 64. The crude steel production rate varies from 2.02 to 5.5 Mt and hot metal production rate varies from 2.2 to 5.88 Mt. The value is observed to be higher for ISP1 and it is 5.5 Mt of crude steel and 5.88 Mt of hot metal. This may be due to variation in capacity of plant and adopted technology.

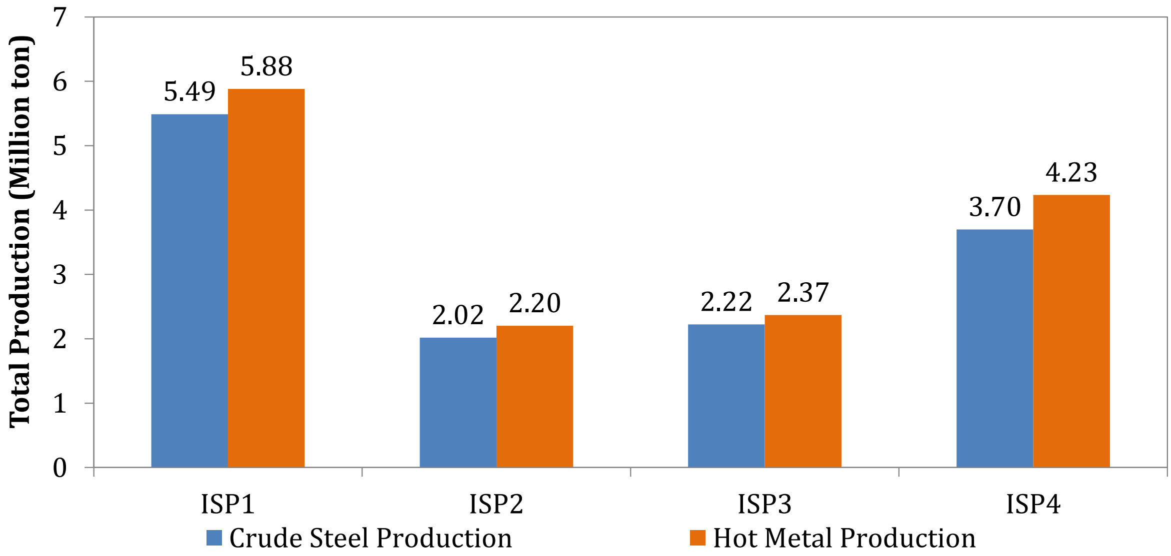


Figure 64: Crude Steel and Hot Metal Production Comparison for Sample ISP Plants

3.5 Application of methodology in DRI Based Plants

Four sponge Iron (SI1, SI2, SI3 and SI4) plants with different installed capacity and SI production are being considered for an analysis with baseline methodology. Figure 65 shows the annual sponge iron production across sample plants. The production varies from 61000 tonnes (SI1) to 200,000 tonnes (SI4).

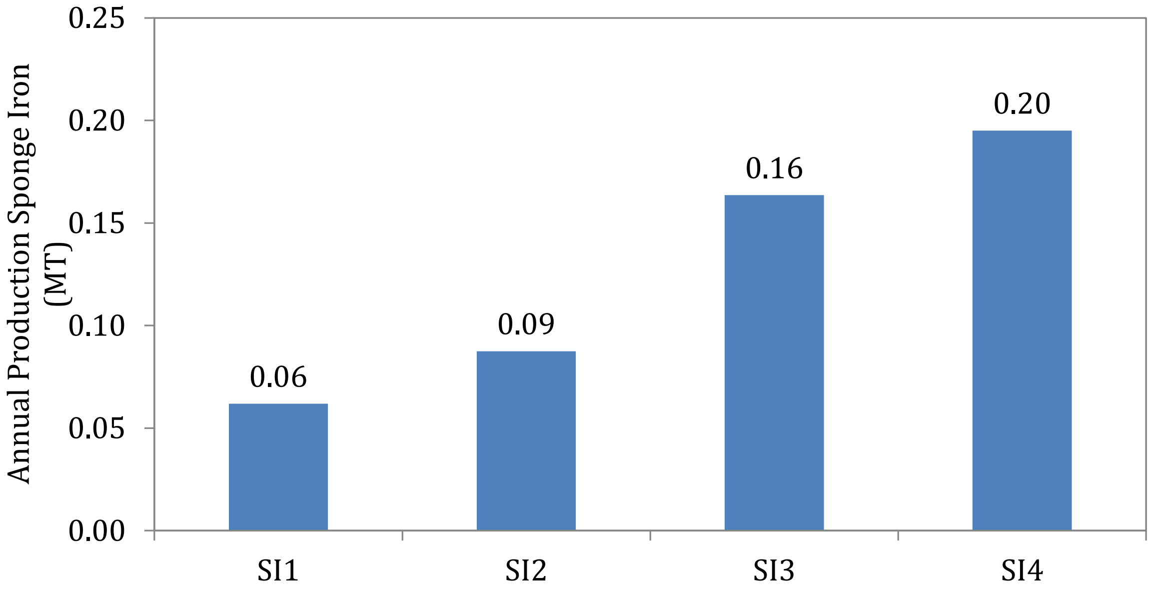


Figure 65: Annual sponge iron production for sample SI plants

The comparison of thermal energy consumption among different sample plants is depicted in Figure 66. The thermal energy consumption ranges from 0.8M GCal to 1.7 M GCal. This is mainly due to variation in capacity, raw material composition and vintage of the plant.

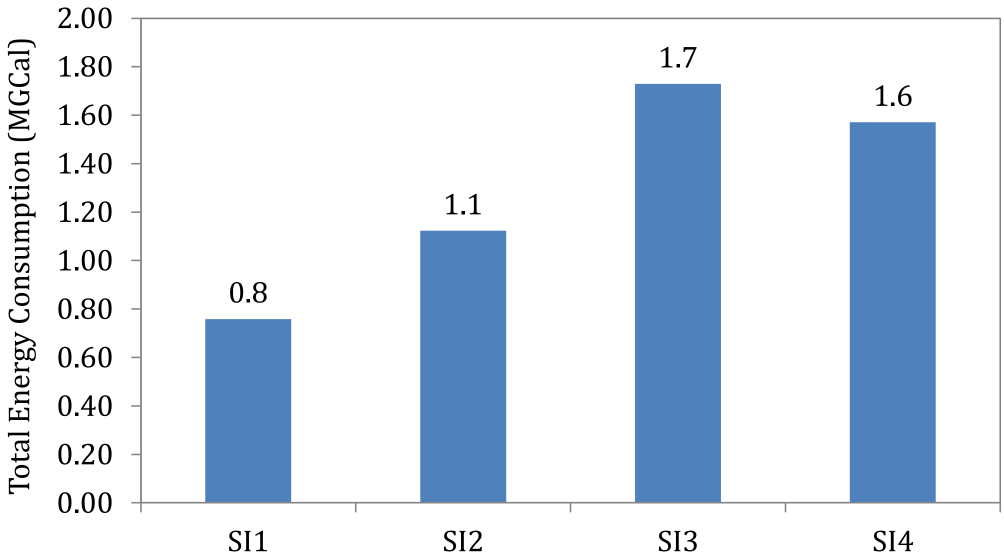


Figure 66: Thermal energy consumption across sample SI plants

Figure 67 shows the comparison of steel production across different plants. The steel production ranges from 30000 tonnes to 139,000 tonnes. This may be due to the export of sponge iron and scrap utilization in the Steel Melting Shops (SMS).

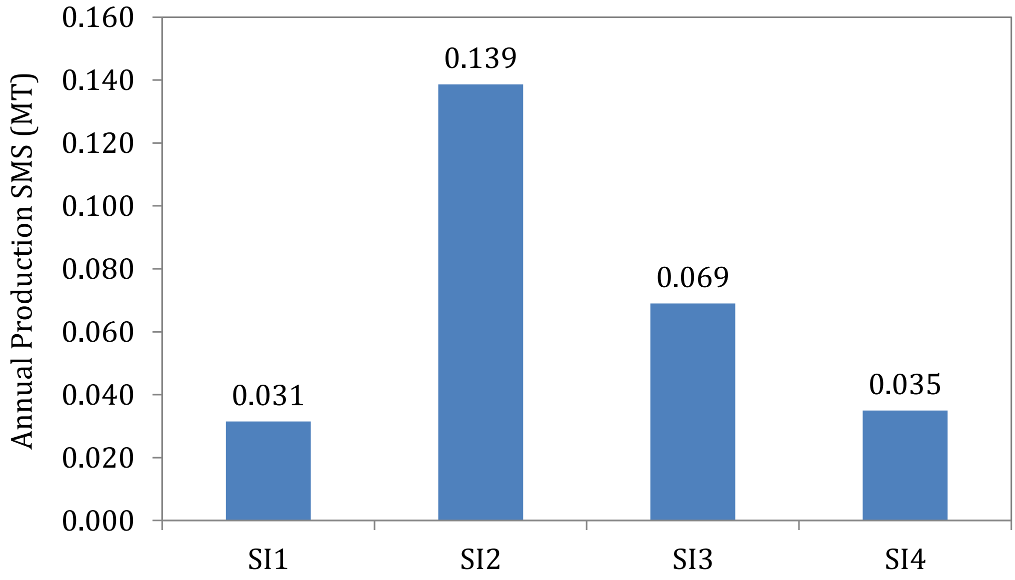


Figure 67: Steel production across sample SI plants

Figure 68 and Figure 69 show the comparison of purchased electricity and electricity exported to grid for different sample plants. The excess electricity from waste heat recovery system or CPP is usually exported to grid. It is observed that SI3 is neither purchasing electricity from grid nor exporting electricity to grid.

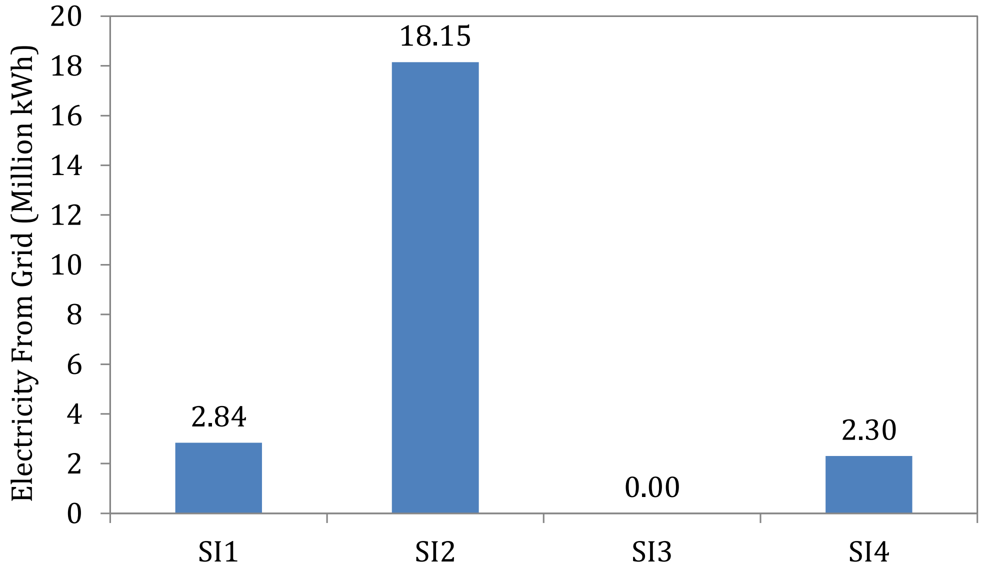


Figure 68: Purchased electricity from grid for sample SI plants

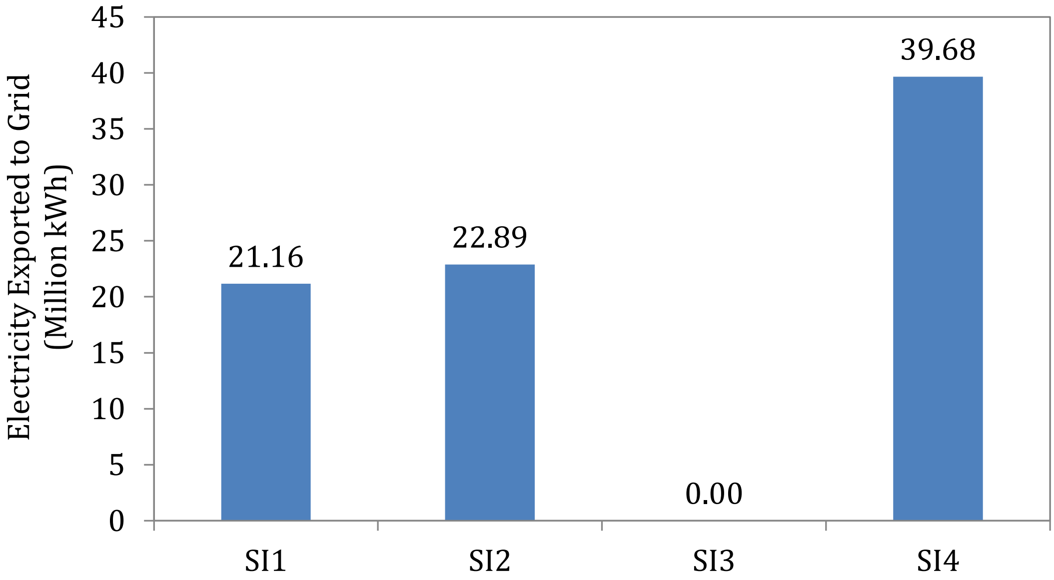


Figure 69: Electricity exported to grid for sample SI plants

Figure 70 shows the electrical SEC of Steel Melting Shops (SMS) across different plants and it varies from 800-1400 kWh/t steel. This may be due to variation in capacity, vintage and operational variables.

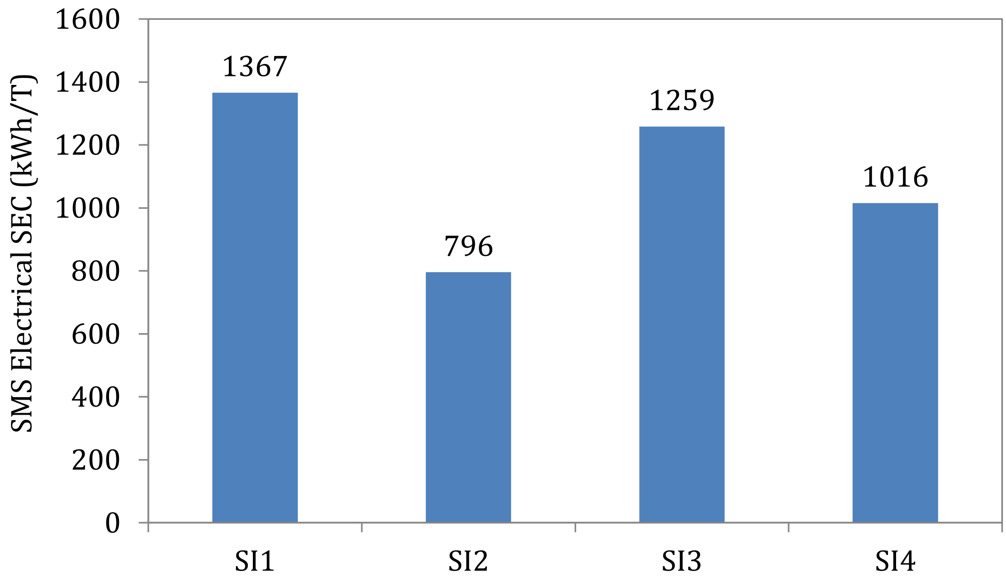


Figure 70: Electrical SEC of SMS across sample SI plants

Figure 71 shows the Gross Calorific value (GCV) of different coals being used across plants. The GCV varies from 4100-5600 kCal/kg coal.

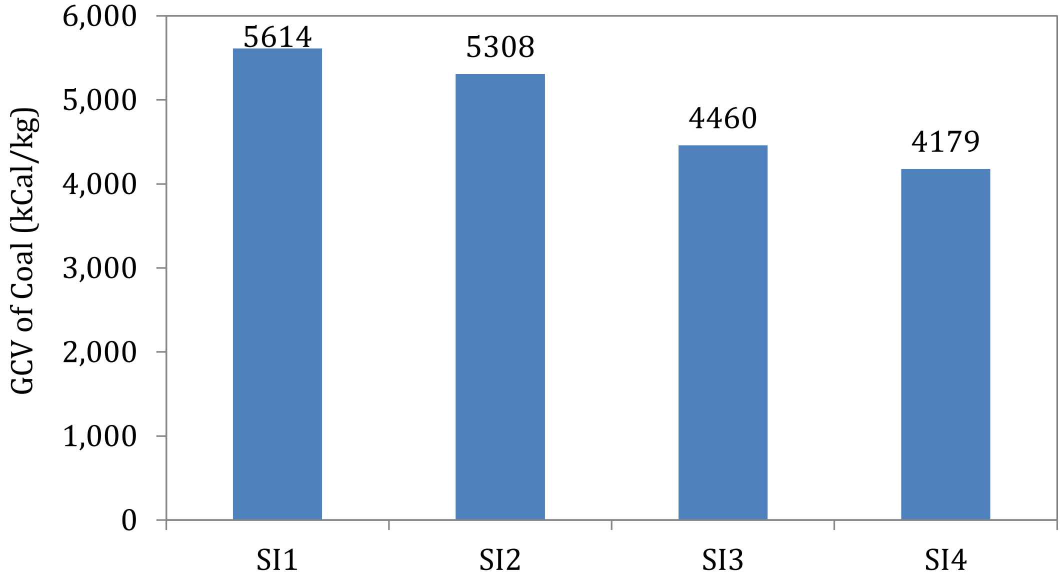


Figure 71: Gross Calorific Value (GCV) of different coals for sample SI plants

Figure 72, Figure 73 and Figure 74 show the comparative performance of four plants. The overall SEC of the sample plants is in the range of 7.58-7.86 GCal/t steel. The total electrical SEC up to sponge iron making ranges from 77-135 kWh/t of sponge iron. The total SEC up to sponge iron making is in the range of 6.33-8.0 GCal/t sponge iron with normalization adjustments.

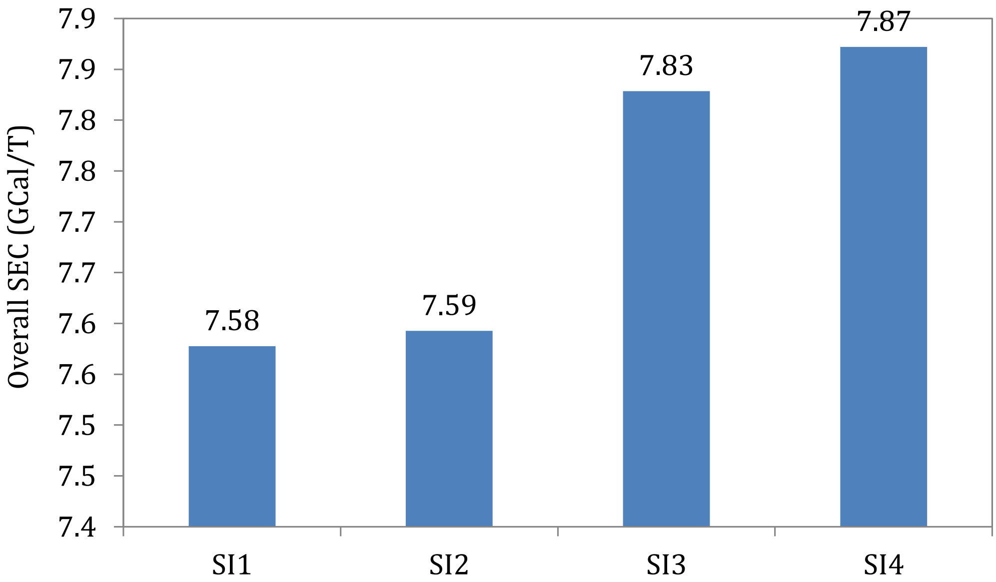


Figure 72: Specific Energy Consumption of different sample SI plants

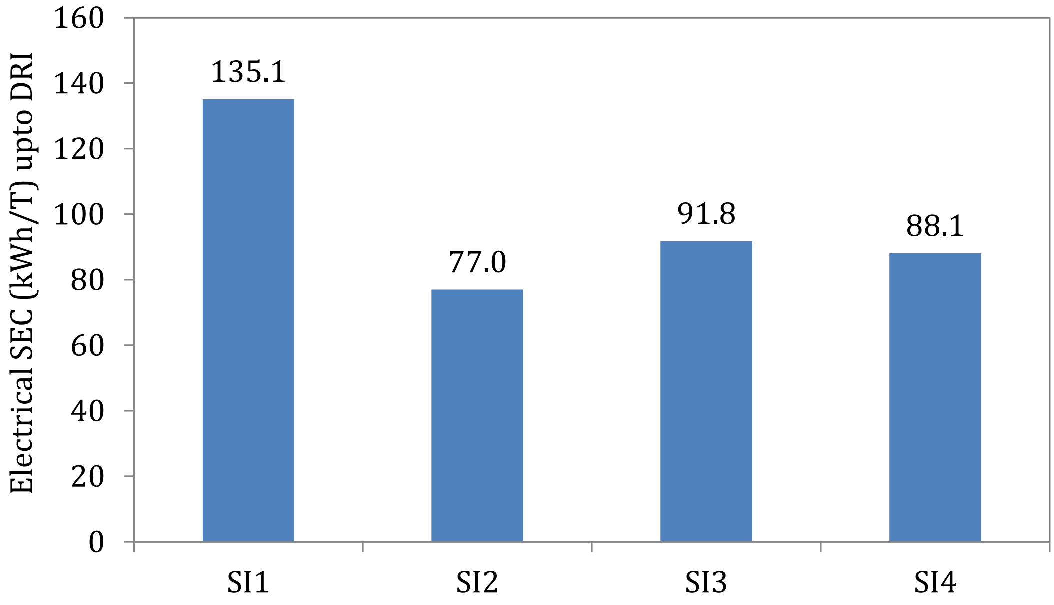


Figure 73: Electrical SEC of sponge iron making for sample SI plants

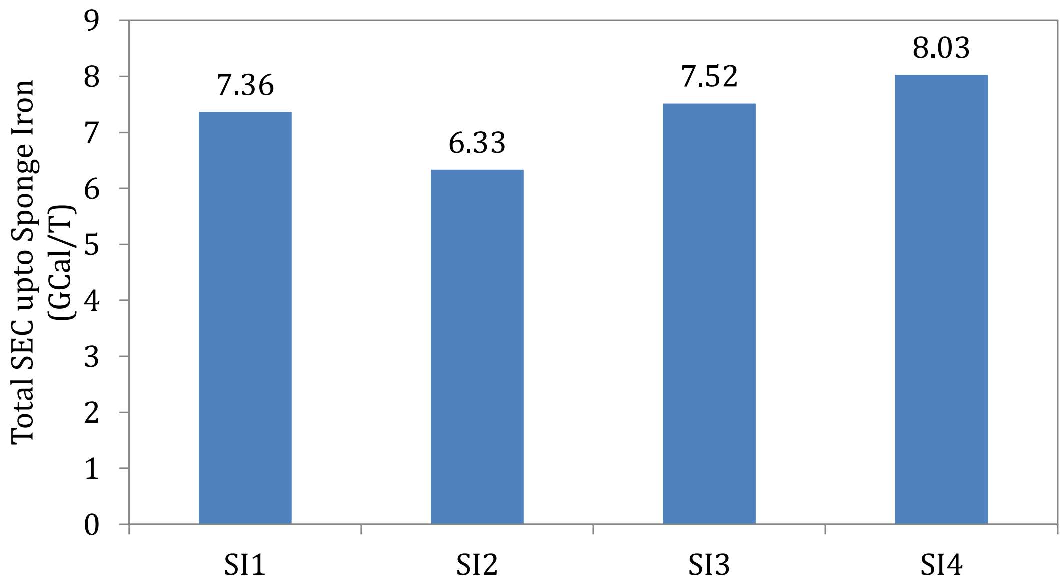


Figure 74: Total SEC up to sponge iron across sample SI plants

4. Levers to Improve EE in an Iron and Steel Plant

There are several measures that are available to improve EE in the iron and steel industry. Many of these measures are listed and analysed from the economic perspective of a typical plant. In the case of the iron and steel industry, the two EE measures that have been exemplified in this analysis are: injection of pulverised coal in Blast Furnace (BF), and variable speed drive on Coke Over Gas compressors. The investments required to implement each EE measure have been taken from Energy Efficiency Analysis and Greenhouse Gas Emission Reduction (EAGER) Tool for the Iron and Steel Industry developed by LBNL (28)

4.1 NPV and IRR of EE options

The study examined several energy efficiency measures for which the Net Present Value (NPV) and Internal Rate of Return (IRR) were calculated. The following were assumed for the analysis:

1) Discount rate of 10%
2) Corporate tax rate of 30% with a surcharge of 3%
3) End of Life (EoL) of 10 years
4) Minimum Alternate Tax (MAT) of 18% and carry forward of MAT credits as applicable u/s 115JAA of the IT Act, 1961
5) Carry forward of operating losses as applicable under the provisions of IT Act, 1961
6) Book depreciation by engaging straight line method
7) Income tax depreciation at 80% and 20% for the first and second years, respectively.

The Present Value (PV) of each year's net profit is calculated using the following formula:

$$Present\ value(PV) = \frac{Net\ Profit_i}{(1+r)^n}$$

Where,

i = year at which the net profit was achieved

r = discount rate

n = Number of years to the EoL

High efficiency preheater fans and Star delta star starters are two case studies reported in this study.

- ***Case Study 1 – Variable Speed Drive on Coke Oven Gas Compressors***

Coke oven gas is generated at low pressures and is pressurised for transport in the internal gas grid. However, coke oven gas flows vary over time due to the coking reactions. Variable speed drives on coke oven compressors can therefore be installed to reduce compression energy. For an initial investment of Rs. 6.051 million, the corresponding annual energy savings are Rs. 7.629

million. The IRR is 97.48% and the payback period is 0.8 years. These calculations are shown in Table 25.The present value of annual energy savings is shown in Figure 75. We observe that higher depreciation rates (in the first two years) result in larger annual savings in the first two years. Further, the steep decrease in the present value (in the later years) can be explained by the higher discount rate employed in the analysis.

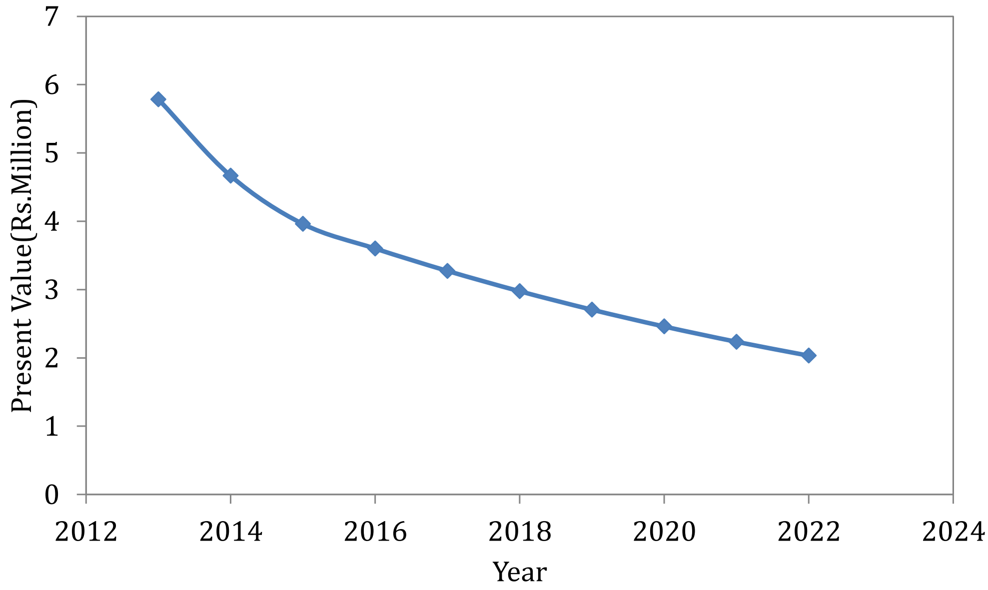


Figure 75: Present value of annual energy savings for variable speed drive

Table 25 : Annual energy savings for Variable Speed Drive on Coke Oven Gas Compressors

Variable speed drive on coke oven gas compressors

All figures in Millions of Indian Rupees

				Income Tax Depreciation	
Annual Savings	7.629	Payback	0.8 years	Depreciation Rate - First Year	80%
Investment	6.051	Life of Equipment	10 years	Depreciation Rate - Second Year	20%
Discount Rate	10%				

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Income		7.629	7.629	7.629	7.629	7.629	7.629	7.629	7.629	7.629	7.629
Expenses		-									
EBITDA		7.629	7.629	7.629	7.629	7.629	7.629	7.629	7.629	7.629	7.629
Book Profit											
Depreciation (Straight Line Method)		0.6051	0.6051	0.6051	0.6051	0.6051	0.6051	0.6051	0.6051	0.6051	0.6051
Profit Before Tax (PBT)		7.0238	7.0238	7.0238	7.0238	7.0238	7.0238	7.0238	7.0238	7.0238	7.0238
IT Profit											
Deprecation (Written Down Value)		4.8408	1.2102	-	-	-	-	-	-	-	-
PBT		2.7881	6.4187	7.6289	7.6289	7.6289	7.6289	7.6289	7.6289	7.6289	7.6289
Tax (@Normal rate)	**30.90%**	0.8615	1.9834	2.3573	2.3573	2.3573	2.3573	2.3573	2.3573	2.3573	2.3573
MAT Credit											
Calculated Tax		0.8615	1.9834	2.3573	2.3573	2.3573	2.3573	2.3573	2.3573	2.3573	2.3573
Tax (@ MAT rate)	**18.00%**	1.264	1.264	1.264	1.264	1.264	1.264	1.264	1.264	1.264	1.264
Effective Tax		1.2643	1.9834	2.3573	2.3573	2.3573	2.3573	2.3573	2.3573	2.3573	2.3573
Profit After Tax (PAT)	-6.051	6.365	5.646	5.272	5.272	5.272	5.272	5.272	5.272	5.272	5.272

IRR	**97.48%**
NPV	**27.643**

- **Case Study 2 – Injection of Coke Oven Gas in BF**

In most steel plants, coke oven gas is produced as a by-product when coal is heated in the absence of oxygen to drive volatile matter. Around 40% of the coke oven gas is used as fuel in the coke oven. The remaining gas is used to fuel equipment such as boilers. Since the remaining gas constitutes to about 60%, this measure provides an opportunity to inject coke oven gas in blast furnace. The investment required to inject coke oven gas in blast furnace is around Rs. 231.53 million with corresponding annual energy savings of Rs. 183.30 million. The IRR is 60.17% with a payback period of 1.26 years. These calculations are shown in Table 26. The present value of annual energy savings is shown in Figure 76.

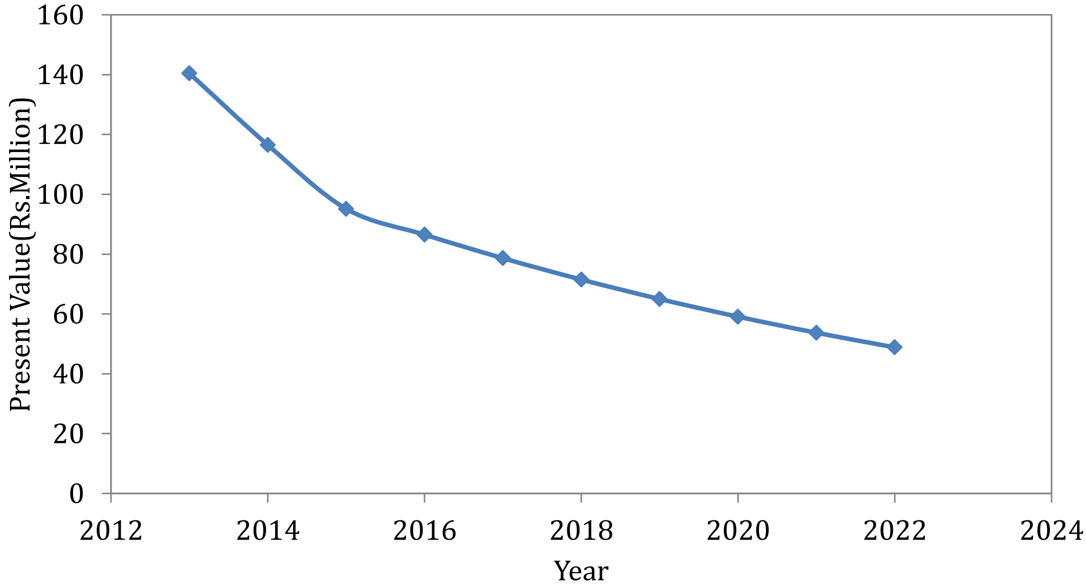


Figure 76: Present value of annual energy savings for Injection of coke oven gas in BF

Table 26 : Annual energy savings for Injection of Coke Oven Gas in BF

Injection of coke oven gas in BF

All figures in Millions of Indian Rupees

Annual Savings	183.30	Payback	1.263171924 years	Income Tax Depreciation	
Investment	231.53	Life of Equipment	10 years	Depreciation Rate - First Year	80%
Discount Rate	10%			Depreciation Rate - Second Year	20%

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Income		183.296	183.296	183.296	183.296	183.296	183.296	183.296	183.296	183.296	183.296
Expenses		-									
EBITDA		183.296	183.296	183.296	183.296	183.296	183.296	183.296	183.296	183.296	183.296
Book Profit											
Depreciation (Straight Line Method)		23.153	23.153	23.153	23.153	23.153	23.153	23.153	23.153	23.153	23.153
Profit Before Tax (PBT)		160.142	160.142	160.142	160.142	160.142	160.142	160.142	160.142	160.142	160.142
IT Profit											
Deprecation (Written Down Value)		185.227	46.307	-	-	-	-	-	-	-	-
PBT		-1.931	136.989	183.296	183.296	183.296	183.296	183.296	183.296	183.296	183.296
Tax (@Normal rate)	30.90%	-0.597	42.330	56.638	56.638	56.638	56.638	56.638	56.638	56.638	56.638
MAT Credit											
Calculated Tax		-0.597	42.330	56.638	56.638	56.638	56.638	56.638	56.638	56.638	56.638
Tax (@ MAT rate)	18.00%	28.826	28.826	28.826	28.826	28.826	28.826	28.826	28.826	28.826	28.826
Effective Tax		28.826	42.330	56.638	56.638	56.638	56.638	56.638	56.638	56.638	56.638
Profit After Tax (PAT)	-231.53	154.470	140.966	126.657	126.657	126.657	126.657	126.657	126.657	126.657	126.657

IRR	60.17%
NPV	583.83

Table 27: Consolidated list of EE measures

Measure ID	Sub process	Measure Undertaken	Payback Period	Net Present Value(NPV)	Internal Rate of Return(IRR)	Investment	Annual Savings
			Years	Rs Millions	%	Rs Millions	Rs Millions
EM1	Sintering	Heat recovery from sinter cooler	1.6	250.395	49.892%	129.659	81.74
EM2		Reduction of Air Leakage	0.3	68.356	313.488%	4.32	16.76
EM3		Use of Waste Fuel in Sinter Plant	0.3	134.836	311.328%	8.64	32.70
EM4		Improved Charging Method	2.6	33.369	27.218%	43.22	16.35
EM5	Coke Making	Programmed hearing in coke oven	0.3	61.861	280.781%	4.03	15.26
EM6		Variable speed drive on coke oven gas compressors	0.8	27.643	97.484%	6.05	7.63
EM7		Coke Dry Quenching (CDQ)	0.9	3796.760	83.902%	1008.46	1068.04
EM8	Iron Making - Blast Furnace (BF)	Injection of pulverized coal in BF	2.3	366.954	32.228%	360.16	155.69
EM9		Injection of natural gas in BF	3.0	123.652	22.098%	231.53	77.85
EM10		Injection of Oil in BF	3.1	173.017	20.953%	360.16	116.77
EM11		Injection of coke oven gas in BF	1.3	583.830	60.174%	231.53	183.30
EM12		Top-pressure recovery turbines (TRT)	3.9	214.412	14.994%	1029.04	262.20
EM13		Recovery of Blast Furnace Gas	2.0	19.842	37.281%	15.44	7.78
EM14		Improved Blast Furnace Control	0.3	314.828	247.398%	25.73	77.85
EM15		Improved Hot Blast Stove Control	0.2	319.346	368.966%	15.44	77.85
EM16	Steel Making - Basic Oxygen Furnace (BOF)	Recovery of BOF gas and sensible heat	3.7	85.073	15.356%	375.33	100.38
EM17		Variable speed drive on ventilation fans	0.8	15.405	99.010%	3.41	4.20
EM18		Efficient Ladle preheating	0.4	12.384	231.147%	1.02	2.87
EM19	Steel Making - Electric Arc Furnace	Converting the furnace operation to ultra-high power (UHP) (Increasing the size of transformers)	1.0	250.034	78.164%	72.37	71.40
EM20		Adjustable Speed Drives (ASDs) on flue gas fans	10.0	273.033	267.553%	17.44	69.30
EM21		Oxy-fuel burners/lancing	0.6	273.340	135.641%	41.86	71.40
EM22		Improving process control in EAF	0.1	730.226	1248.811%	11.34	172.80
EM23		Direct Current (DC) arc furnace	0.4	370.923	219.069%	34.01	92.82
EM24		Scrap Preheating	0.2	1058.872	434.224%	47.96	256.20
EM25		Bottom Stirring/gas injection	0.1	319.266	1183.587%	5.23	75.60

4.2 Results

Different EE measures have been taken into consideration for the financial analysis of the iron and steel industry. Various case studies involving different EE measures for the different processes are considered here. The measures are presented with their corresponding investment, payback and annual savings. The Internal Rate of Return (IRR) and Net Profit Value (NPV) are also calculated.

The highest initial investment is for the installation of Top-pressure Recovery Turbines (TRT) (around Rs. 1029.04 million). The highest NPV was for changing the coke making process to Coke Dry Quenching (CDQ) with Rs. 3796.76 million and corresponding annual energy savings of Rs. 1068.04 million. Improving process control in an Electric Arc Furnace (EAF) while making steel led to the highest IRR (1248.81%) with the lowest payback period of 0.1 years. The complete financial analyses are depicted in Table 27and Figure 77 to Figure 79. These serve as a valuable tool to policy makers and industry operations personnel and senior management to weigh the options and implement EE measures in the iron and steel industry.

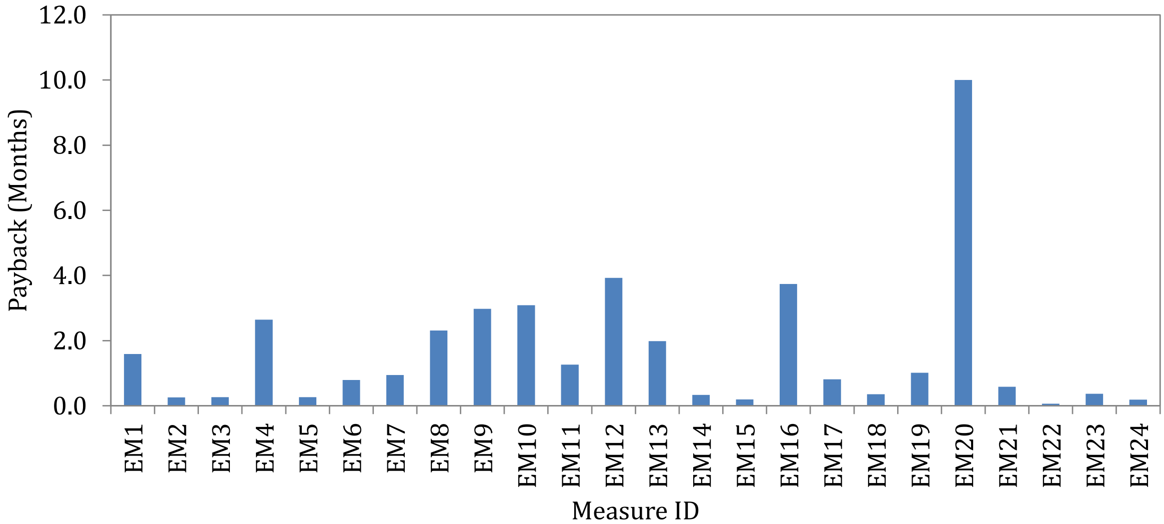


Figure 77; Payback period of different EE measures

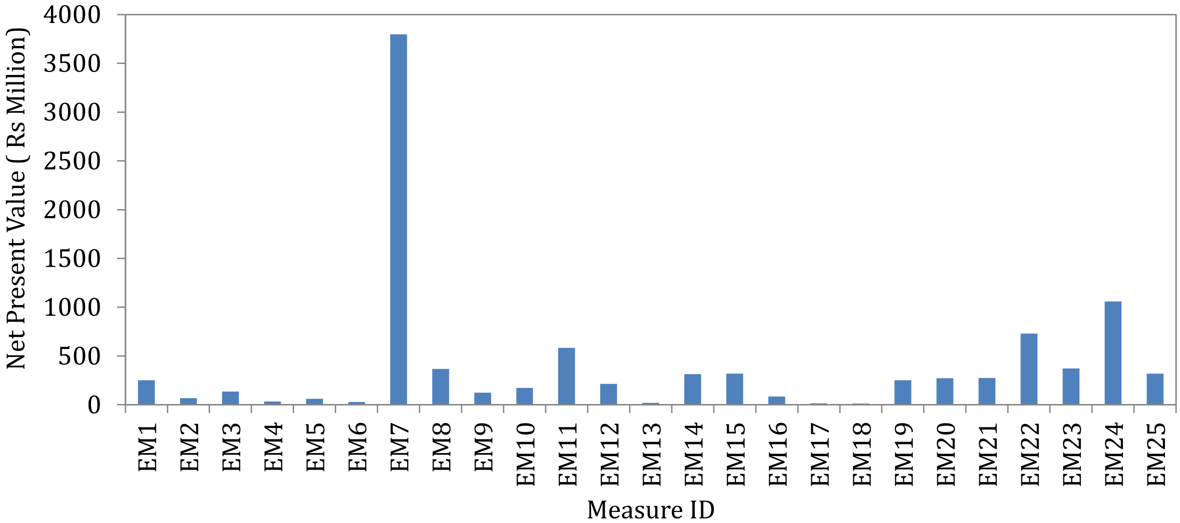


Figure 78: NPV of EE measures

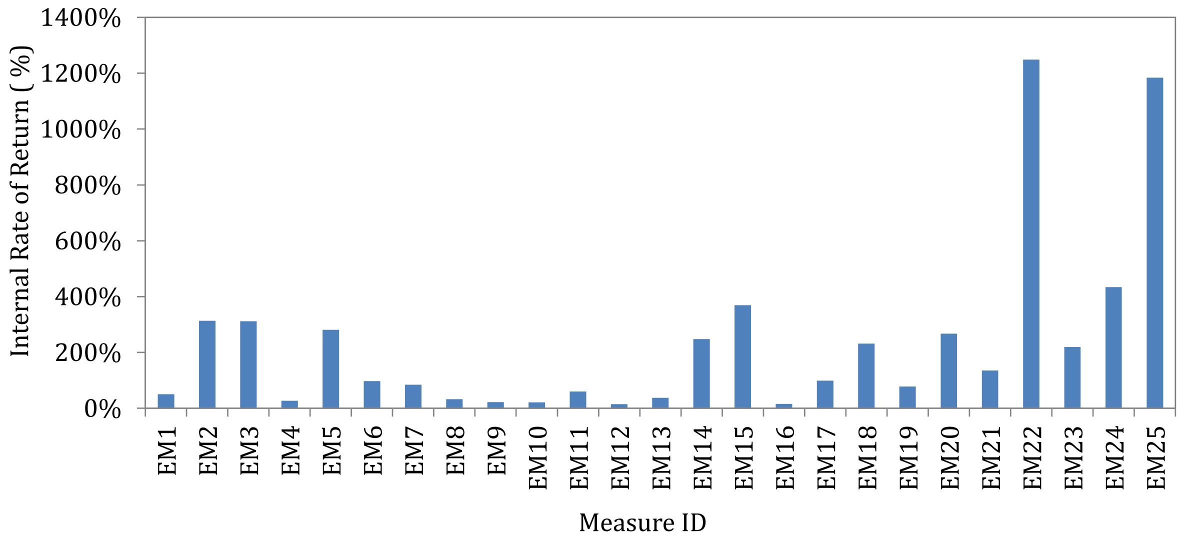


Figure 79: IRR of EE measures

4.3 Marginal Abatement Cost of EE Options

Marginal Abatement Cost curves are constructed for several EE options in iron and steel industry to estimate the cost of reducing emissions over the established timeframe. The methodology is described below. .

A standard DC is taken as the baseline model for a particular sector. In this DC, all the processes are considered to be business as usual with no energy efficiency measures implemented. The energy consumed in each process is calculated and the resulting emissions (from thermal and electricity) are computed. One energy efficiency measure is taken into consideration in one process. When this measure is implemented, the new SEC is calculated throughout the lifetime of the new equipment installed. The resultant emissions are calculated based on this. The difference between the baseline scenario and the energy efficient scenario over the lifetime is the total amount of GHG emissions saved owing to the measure implemented. The cost of implementation of the measure, discounted over the lifetime and taking into account the operation and maintenance costs, gives the present value of the measure. Dividing this cost by the emissions saved over the lifetime gives us the marginal abatement cost of the particular measure.

Consider one process in the baseline scenario which will need to be changed to implement an EE measure – EM1

- Emission factor of fuel used (coal in case of electricity) – EF ($kgCO_2/kWh$)
- SEC in baseline scenario - SEC_b (kWh/t)
- Specific Emission Intensity (SEI) in baseline scenario - $SEI_b = SEC_b * EF$ ($kgCO_2/t$)
- Cost of EE equipment – IV (Rs)
- SEC in EE scenario – SEC_{ee} (kWh/t)

- SEI in EE scenario – SEI_{ee}= SEC_{ee}* EF ($kgCO_2/t$)

Lifetime of equipment is assumed based on the sub process where it is installed. For instance, measures pertaining to fans are assumed to work for 8 years, while compressors and motor related measures run for about 10 years.

- Discount rate (DR) = 10%
- Annual production (AP) = 1 MT
- Discounted electricity price in year *i*- DE_i= Present Electricity Price/ (1+DR/100) ^i
- Cost of Electricity in Baseline scenario (CE_b) = AP*10^6* SEC_b* DE_i(Rs)
- Cost of Electricity in EE scenario (CE_{ee}) = AP*10^6* SEC_{ee}* DE_i(Rs)
- Total expenditure on electricity in Baseline scenario (TE_b) = $\sum_{i=1}^{30} CE_{bi}$ (Rs)
- Total expenditure on electricity in EE scenario (TE_{ee}) = $\sum_{i=1}^{30} CE_{eei}$ + IV (Rs)
- Negative savings over lifetime (SV) = TE_{ee} - TE_b (Rs)
- Total emission savings over lifetime (ESV) = AP*10^6*(SEI_b - SEI_{ee})*30/1000 (tCO_2)
- MAC = SV/ESV (Rs/ tCO_2)

The MAC curve is depicted in Figure 80. It shows the MAC curves of selective measures implemented in industries across the globe. In this analysis, the lifetime of measures deployed to construct the MAC curve ranges between 5 and 30 years (29) this tool links the cost of installing EE measures to the resultant emissions that are saved and is extremely useful for policy makers and industry management to make sound and well informed decisions on implementing EE measures.

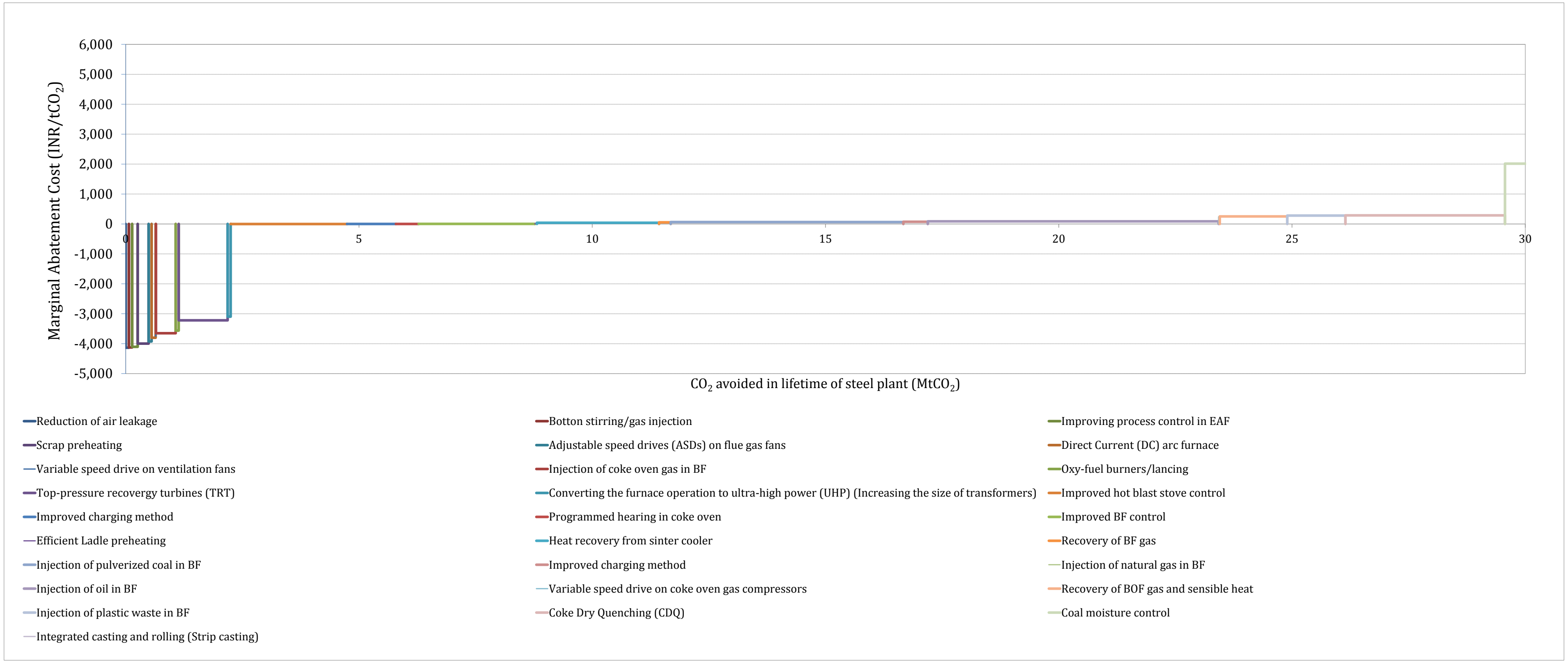


Figure 80: MAC curve for EE options in Iron and Steel Industry

4.4 Waste Heat Recovery Options

Waste heat recovery options for an integrated steel plant are described in Table 28 per ton of rolled steel (trs). The energy value accounts for the quality of energy, higher temperature being suited for energy generation. The sensible heat accounts for low temperature steam as the main target for heat recovery. The energy values are projected on the basis of per ton of rolled steel production. The values suggest a significant energy recovery potential for sinter plants.

Table 28: Waste Heat Recovery Options for ISP (65)

Process	Energy (GJ/trs)		Temperature (^{0}C)	Status
	Sensible Heat	Exergy		
Coke oven				
Hot coke	0.24	0.14	1100	Commercial
Coke oven gas	0.24	0.12	850	Stopped
Sinter Plant				
Cooler gas	0.97	0.28	100-350	Commercial
Exhaust gas	0.23	0.12	100-350	Commercial
Blast Furnace				
Hot stove	0.82	0.33	250-400	Commercial
Slag	0.39	0.26	1500	Stopped
Basic Oxygen Furnace				
Gas	0.19	0.12	1600	Commercial
Slag	0.02	0.01	1600	Stopped
Casting				
Cast steel slab	1.39	1.06	700	Commercial
Reheating furnace	1.04	0.62	700	Commercial
Total	5.53	3.06		

The total sensible heat recovery possible from ISP is 5.53 GJ/trs out of which 4.88 GJ/trs is commercially practiced. The possible saturated steam generation with the available waste heat is illustrated in Table 29. As the steam pressure increases, the amount of steam generated decreases due to increase in boiling point and steam enthalpy. The boiler efficiency assumed for the calculations is 90%. The steam can be utilised in the process wherever required.

Table 29: Possible Saturated Steam Generation

Pressure (bar)	Boiling point (^{0}C)	Amount of steam (kg)
2	120.23	1622.88
3	133.54	1611.94
3.5	138.87	1607.83
5	151.85	1598.52

WHR Boilers (WHRB) can be installed at coke oven and hot stove exit points. Waste heat can be utilised in the following ways:

1. Power – Steam Rankine Cycle
2. Power – Organic Rankine Cycle
3. Integration with Captive Power Plant

The exhaust gases emanating from different sections of an ISP are at a high temperature. The enthalpy of the exhaust gases can be utilised to supplement the heat requirements of the steel plant.

The exhaust gases from different processes are made to pass through heat exchangers to generate steam. The steam generated from each section is collected and used to run a turbine to generate electricity.

The following are the technologies available for producing power from exhaust gases of an iron and steel plant.

- Rankine Cycle
- Organic Rankine Cycle
- Kalina Cycle

The potential for WHR from different sections together is in the range of 12 - 56 MW depending on the capacity of the plant.

4.4.2.1 WHR Potential of a Model Plant

The basis for model plant calculations is taken as 2 Mt per annum (MTPA) and the other considerations and outputs are illustrated in Table 30 and for DRI plant it was considered as 33,000 tonnes of sponge iron production per annum. Medium pressure (5 bars) steam generation was considered as one option for waste heat recovery and power as other option. Out of the waste recovery options considered for model plant, coking plant has highest potential in terms of power which is 11.8 MW and 46.2 tonnes/h of steam generation potential. In case of DRI plant the power potential from waste heat is 1.13 MW.

Table 30: Model Plant Sample Calculations

Item	Coking Plant	BOF Plant	DRI Plant
Material	Coke	Hot Metal	Iron ore
Material flow rate (tonnes/h)	154	254	7.5
Gas exit temperature (^{0}C)	850	1600	1000
Gas flow rate (Nm^3/h)	67777	18940	24000
Gas exit temperature from waste heat recovery system (^{0}C)	220	220	220
Energy available (GJ/h)	141	12.41	16.9
Boiler Efficiency (%)	90	90	90
Power Cycle Efficiency (%)	30	30	30
Steam flow rate (tons/h)	46.2	4.1	5.5
Power Potential (MW)	11.8	1.03	1.13

5. PAT Focussed Scenario Analysis

The likely scenarios for sample integrated steel plants and sponge iron plants are studied in this chapter. It is assumed that each plant has a certain baseline SEC and is required to reduce its SEC by a specific percentage. It would be useful for the energy managers, operation personnel and the senior management to have a detailed analysis of the possible scenarios that are likely to occur. These scenarios can be used to better understand the impact of the required SEC reduction in the context of the various choices that are available to a plant. The calculations include an estimation of the amount of energy that a plant is required to have saved in three years. It is assumed that a plant may be able to reduce its SEC beyond the given norm or may not be able to reduce its SEC sufficiently in order to achieve the norm. In case a plant exceeds the given norms it would have saved energy beyond what is required while there would be an energy savings shortfall otherwise. In both cases the likely cost of the energy savings or shortfall is estimated based on low-cost and high-cost scenarios.

5.1 PAT Focused Scenarios for Sample Integrated Steel Plants

Scenario analyses for selected plants (ISP1 – ISP4) based on the reduction target percentage are shown in Table 31. Savings are calculated based on the Baseline (BL) SEC and target SEC. Their corresponding energy savings or shortfalls are computed for two cost scenarios.

Table 31: Baseline data, SEC reduction target and estimated cost for sample ISP plants

PERFORMANCE ASSESSMENT		ISP 1	ISP 2	ISP 3	ISP 4
Baseline Production - BL Prod	Mt	5.49	2.02	2.22	3.70
Baseline Energy - BL Energy	10^6 Million kCal	37.70	14.01	15.73	25.82
Baseline SEC - BL SEC	GCal/tcs	6.867	6.937	7.070	6.982
SEC Reduction Target	%	-5			
Target SEC	GCal/tcs	6.523	6.590	6.716	6.633

Each scenario is synthesised with the following structure:

- BL Energy: The energy consumed by the plant during the baseline year.
- Actual SEC Reduction Percentage: A set of actual reduction percentage is assumed for every plant: -7,-5,-3, 0, 3 and 5.
- Actual SEC: The actual SEC is computed based on the baseline SEC and the set of actual SEC reduction percentage.
- Actual Energy at BL Production: Actual Energy at BL Production is calculated by multiplying the above calculated Actual SEC and Baseline Production.

$$Actual\ Energy\ at\ BL\ Production = Actual\ SEC\ \times BL\ Production$$

- Target Energy at BL Production: Target Energy at BL Production is calculated by multiplying the target SEC and Baseline Production.

$$Target\ Energy\ at\ BL\ Production = Target\ SEC\ \times BL\ Production$$

- Energy saved at BL Production: Energy saved at BL Production is the difference between Actual Energy at BL Production and Baseline Energy

$$Energy\ saved\ at\ BL\ Production = BL\ Energy - Actual\ Energy\ at\ BL\ Production$$

- Energy saved beyond target: The difference between actual energy at BL production and target energy at BL production is calculated as energy saved beyond target.

$$Energy\ saved\ beyond\ Target = Target\ Energy\ at\ BL\ Production - Actual\ Energy\ at\ BL\ Production$$

- Low Cost Scenario
  - Savings at BL Production: The savings at BL Production, in rupees, is calculated by multiplying the energy saved at BL Production by low cost assumption of energy price.

$$Savings\ at\ BL\ Production\ in\ LC\ Scenario = Energy\ Saved\ at\ BL\ Prod \times low\ cost\ price\ of\ energ$$

  - Savings beyond target: The savings beyond target, in rupees, is calculated by multiplying the energy saved beyond target by low cost assumption of energy price.

$$Savings\ beyond\ target\ in\ LC\ Scenario = Energy\ Saved\ beyond\ target \times low\ cost\ price\ of\ energy$$

- High Cost Scenario
  - Savings at BL Production: The savings at BL Production, in rupees, is calculated by multiplying the energy saved at BL Production by high cost assumption of energy price.

$$Savings\ at\ BL\ Production\ in\ HC\ Scenario = Energy\ Saved\ at\ BL\ Prod \times high\ cost\ price\ of\ energy$$

  - Savings beyond target: The savings beyond target, in rupees, is calculated by multiplying the energy saved beyond target by high cost assumption of energy price.

$$Savings\ beyond\ target\ in\ HC\ Scenario = Energy\ Saved\ beyond\ target \times high\ cost\ price\ of\ energy$$

5.2 Results of Scenario Analysis for ISPs

The results of scenario analysis on the sample plants are shown in this section. The scenarios I-VI imply an actual SEC reduction percentage of -7,-5,-3, 0, 3, 5 respectively. Based on these scenarios the energy saved by a plant when compared to the baseline energy consumption is estimated. In addition the energy saved by a plant beyond the required target SEC at the end of a PAT cycle is estimated. The estimate of the value of the energy savings in monetary terms is done by considering two cost scenarios as described earlier.

The results are shown later in this section and provide a guidance for the implication of different SEC performance of the sample plants at the end of the first PAT cycle. Such analysis would be very helpful to Iron and steel plant operators and senior management to make informed decisions regarding the implementation of the various EE measures and options in a specific plant.

It is observed that the various plants save energy compared to the baseline in the scenarios in which the actual SEC is lower than the baseline SEC. However, for a plant to save energy beyond the targeted energy consumption, it is necessary for a plant to decrease its actual SEC lower than the target SEC. Therefore it is observed from the results that there is a shortfall in energy savings beyond the target in both energy and monetary units in scenarios where the actual SEC is higher than the target SEC. Such a shortfall provides an indication of the potential that needs to be exploited by plants in order to achieve maximum benefits under a mechanism such as PAT.

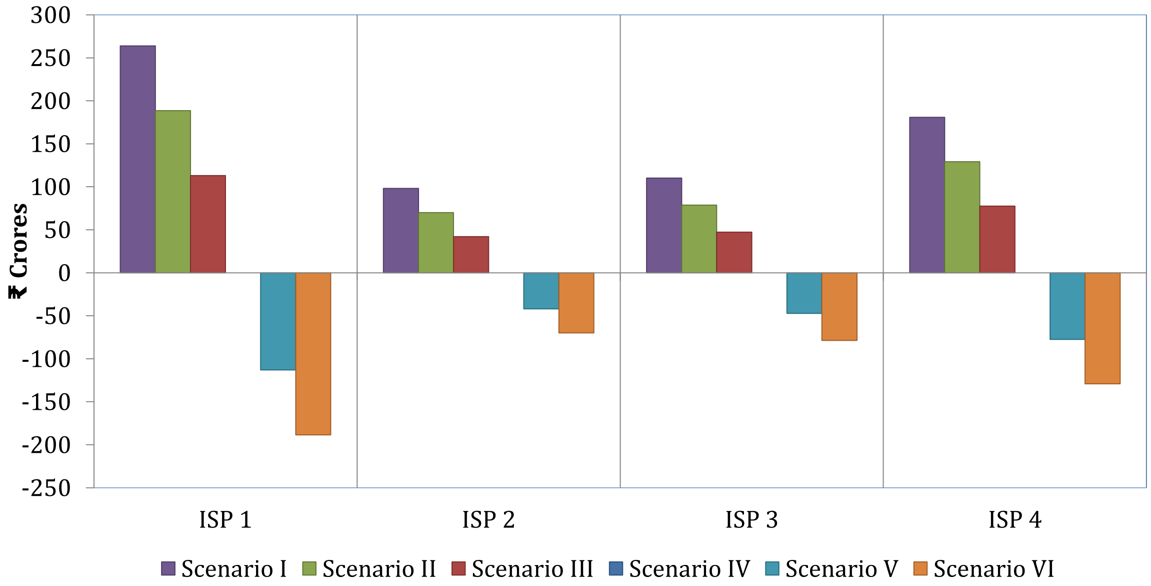


Figure 81: Savings at BL production under Low Cost Scenario for Sample ISP Plants

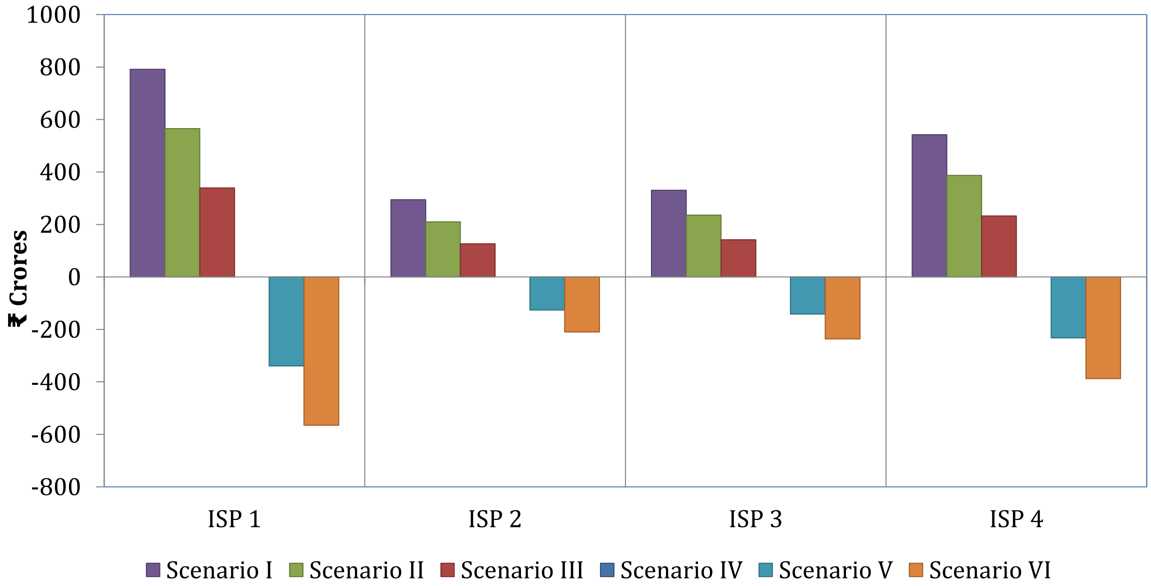


Figure 82: Savings at BL Production under High Cost Scenario for sample ISP plants

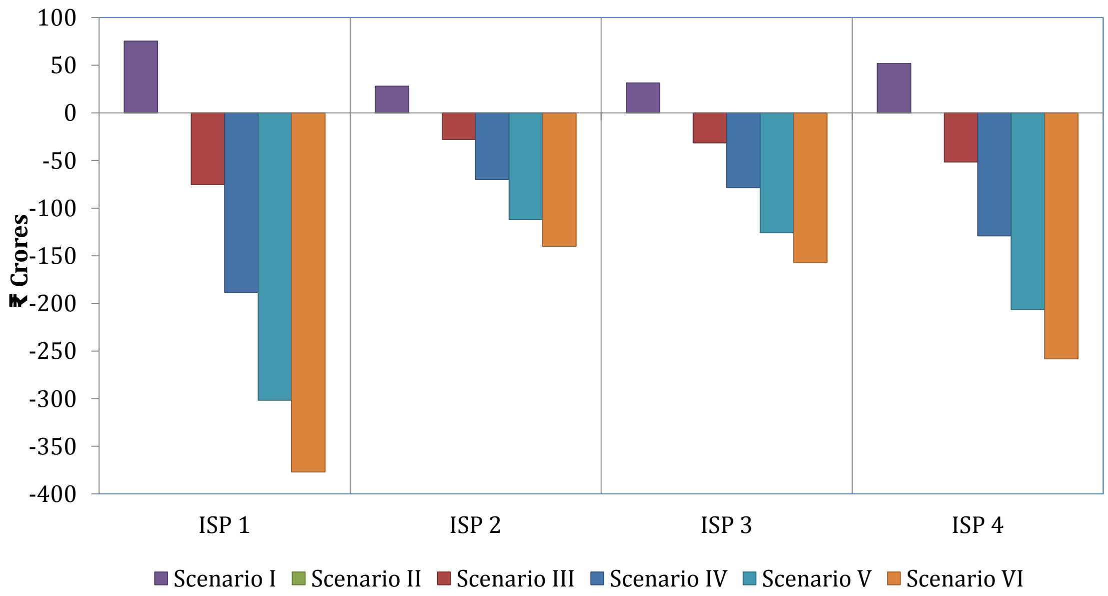


Figure 83: Savings beyond target under Low Cost Scenario for Sample ISP plants

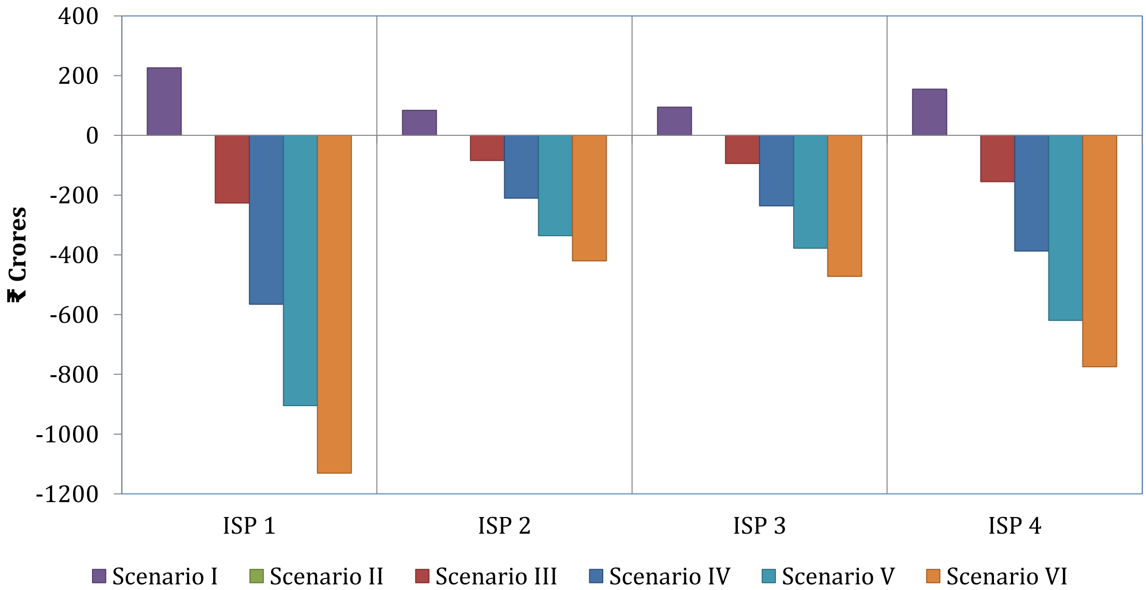


Figure 84: Savings beyond target under High Cost Scenario for Sample ISP plants

From the analysis it is observed that each plant has a unique scenario based on the SEC reduction that it is able to achieve in the three years of the first PAT cycle from 2012-15. Plants which exceed their target are likely to have considerable savings of energy which will improve their annual financial performance going forward. The analysis gives an indication of the amount of energy that would be saved by each plant under different scenarios of actual SEC reduction in calorific as well as monetary terms. The scenario results are shown in Figure 81 to Figure 86.

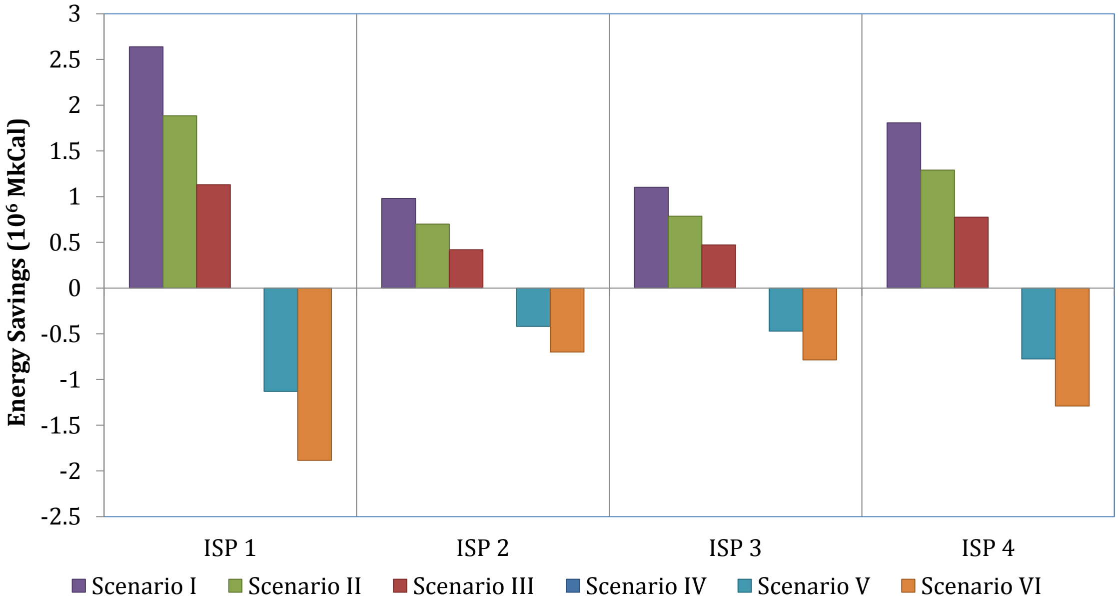


Figure 85: Energy saved at BL Production for different Scenarios for Sample ISP plants

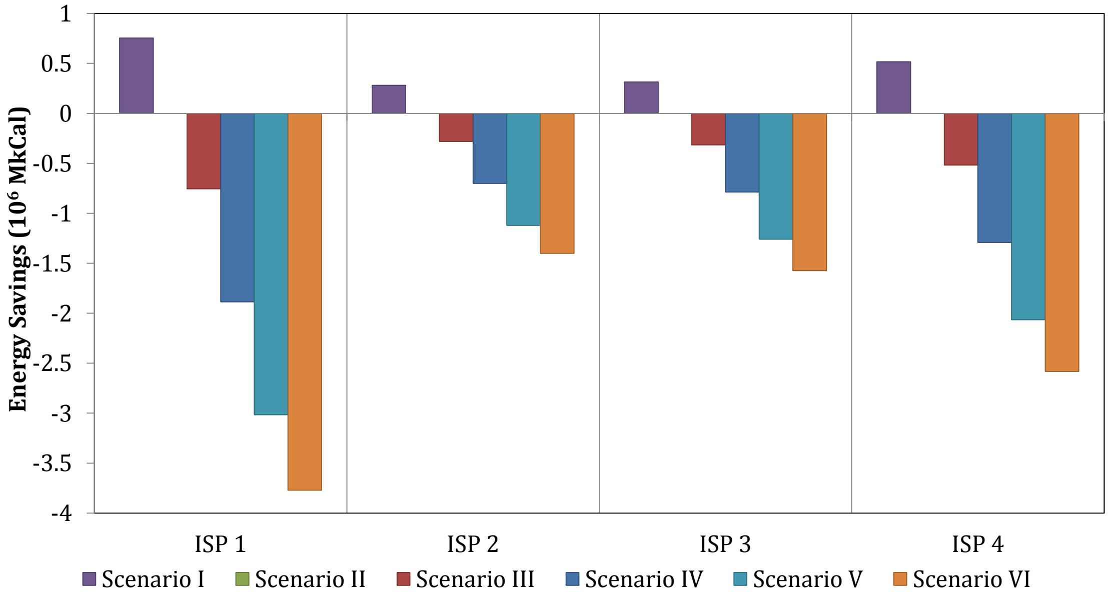


Figure 86. Energy saved beyond target for different Scenarios for Sample ISP plants

5.3 PAT Focused Scenarios for sample Sponge Iron Plants

Scenario analyses for selected plants (SI 1 – SI 4) based on the reduction target percentage are shown in Table 32. Savings are calculated based on the Baseline (BL) SEC and target SEC. Their corresponding energy savings or shortfalls are computed for two cost scenarios.

Table 32: Baseline data, SEC reduction target and estimated cost for sample SI plants

PERFORMANCE ASSESSMENT		SI 1	SI 2	SI 3	SI 4
Baseline Production - BL Prod	Mt	0.10	0.15	0.22	0.20
Baseline Energy - BL Energy	10^6MillionkCal	0.77	1.13	1.75	1.59
Baseline SEC - BL SEC	GCal/t	7.578	7.593	7.829	7.872
SEC Reduction Target	%	-5			
Target SEC	GCal/t	7.199	7.213	7.437	7.478

Figure 87 to Figure 90 illustrate the monetary value of energy savings under various scenarios from the sample sponge iron plants at baseline production and beyond the targeted SEC.

5.4 Results of Scenario Analysis for Sponge Iron Plants

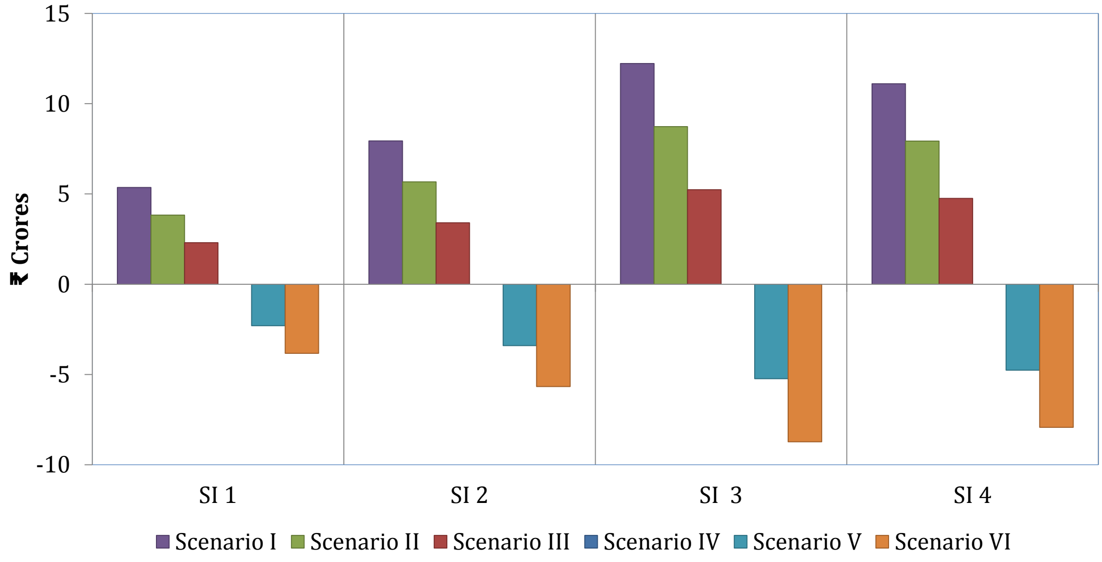


Figure 87: Savings at BL Production under Low Cost Scenario for sample Sponge Iron Plants

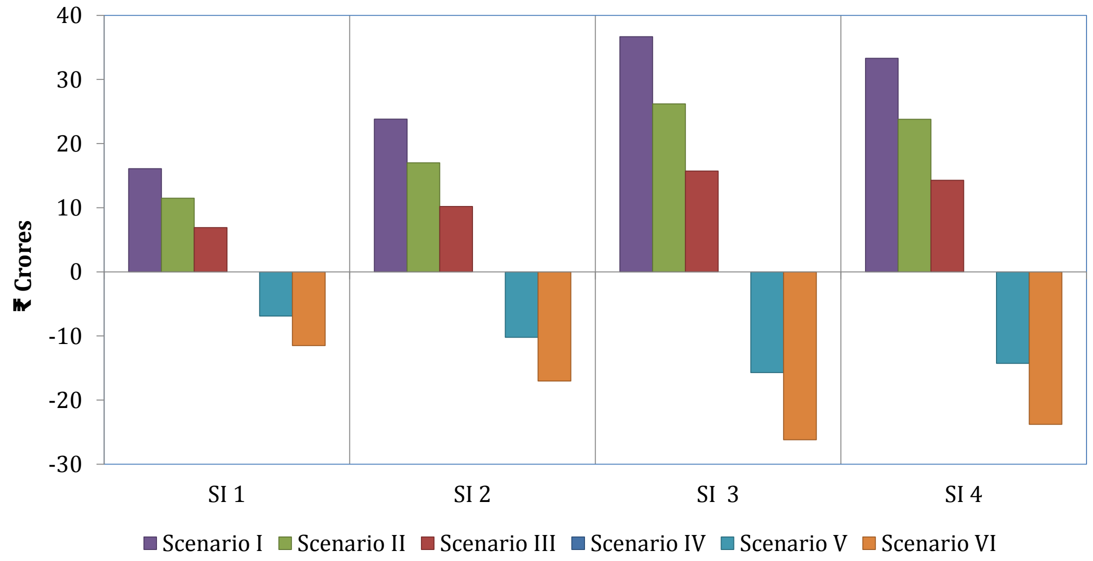


Figure 88: Savings at BL Production under High Cost Scenario for sample Sponge Iron plants

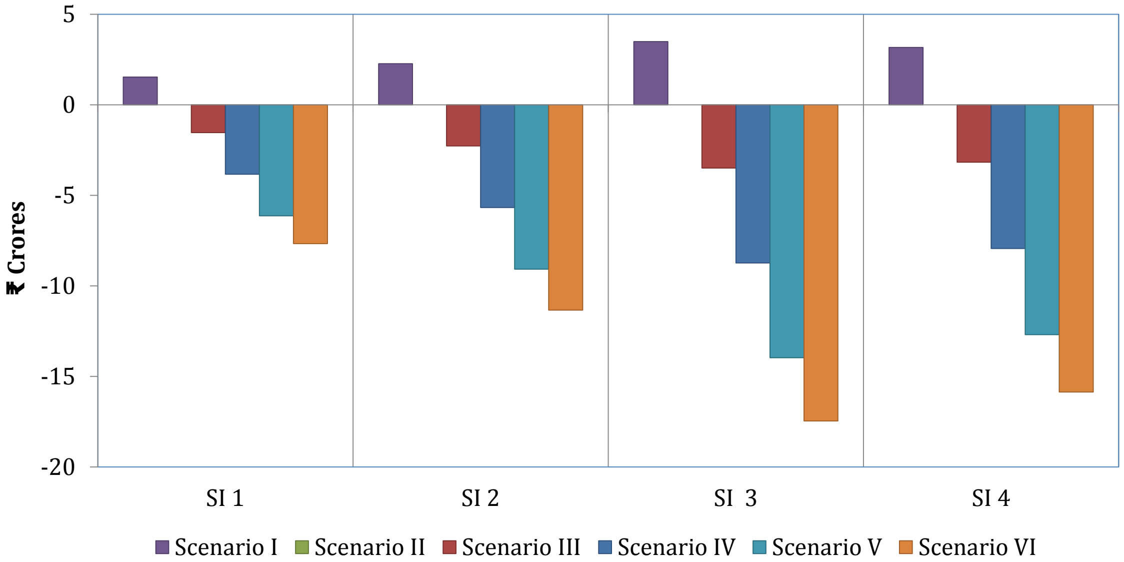


Figure 89**:** Savings beyond target under Low Cost Scenario for sample Sponge Iron Plants

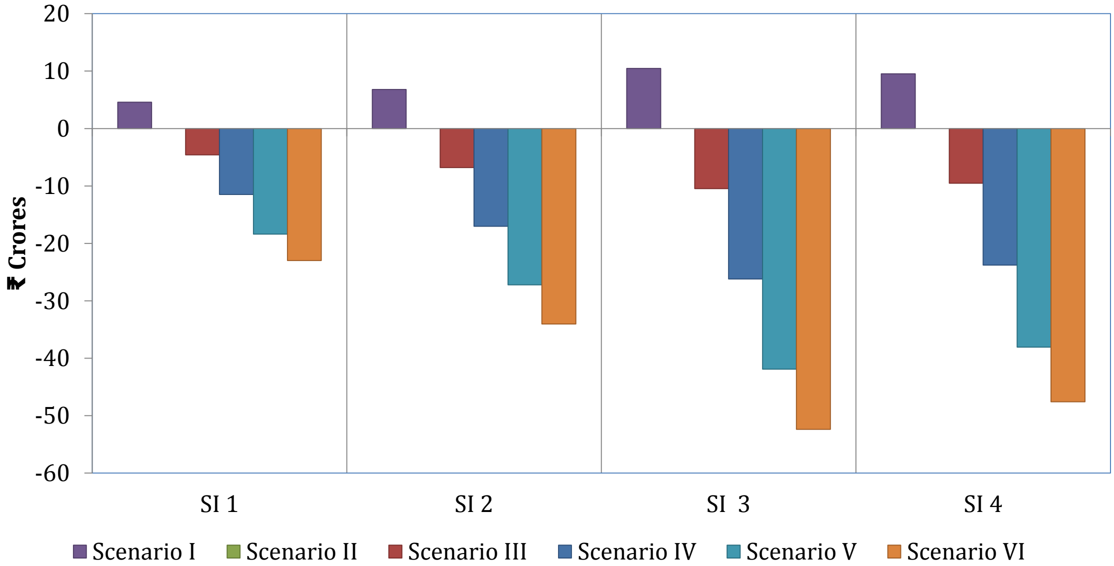


Figure 90: Savings beyond target under High Cost Scenario for sample Sponge Iron Plants

Figure 91 to Figure 92 illustrate the energy savings scenarios from the sample sponge iron plants at baseline production and beyond the targeted SEC.

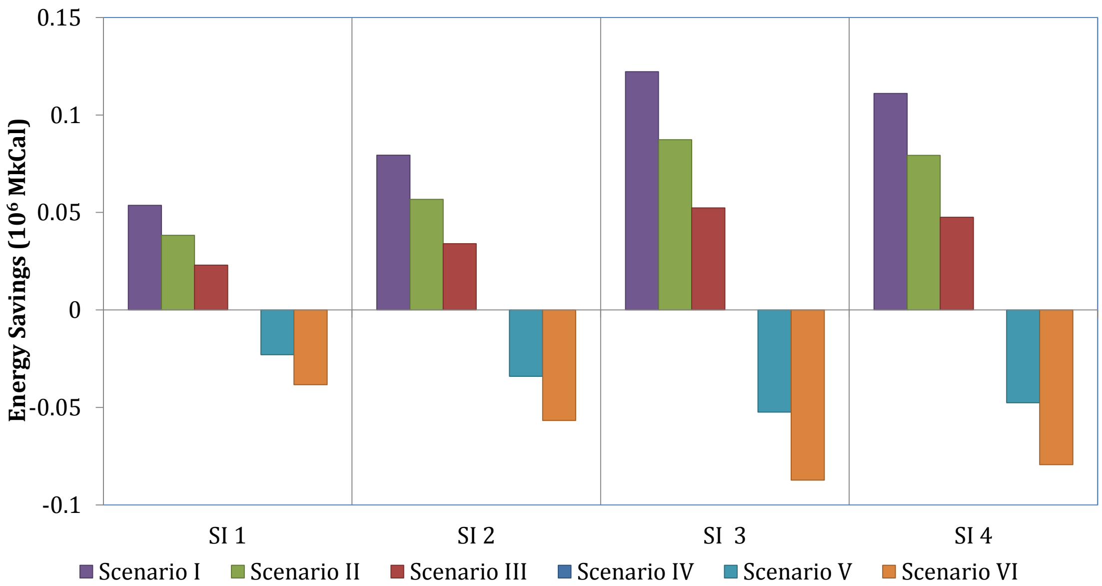


Figure 91: Energy saved at BL Production for different Scenarios for sample sponge iron plants

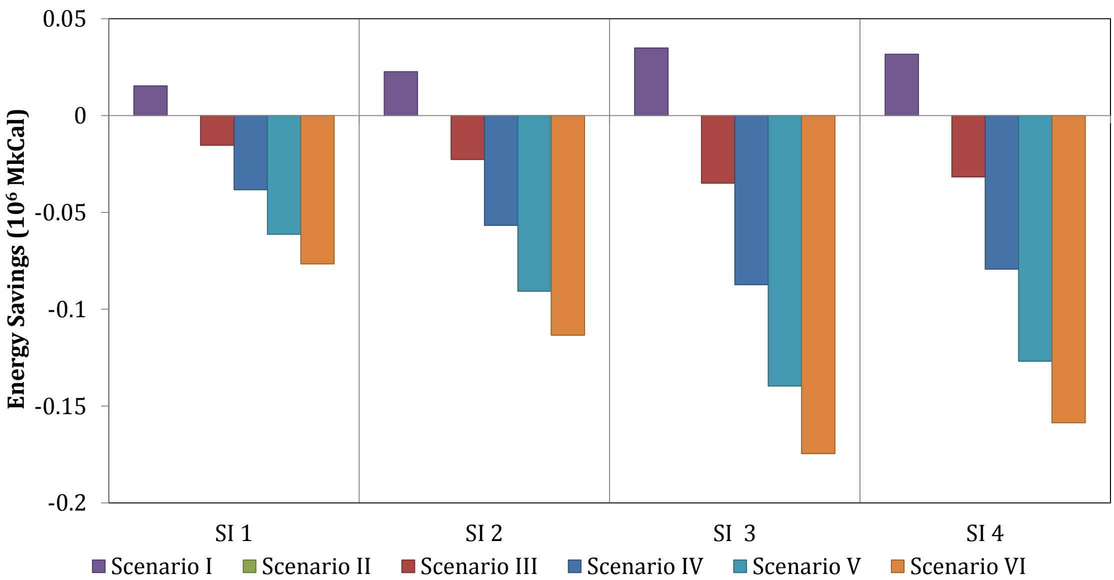


Figure 92: Energy saved beyond target for different Scenarios for sample sponge iron plants

There are several breakthroughs in ULCOS technologies which are deployed around the world and in India as well such the Coke Dry Quenching and Top Recovery Turbine among others. Technologies which could have a significant impact on improving energy efficiency a few years into the future are the use of hydrogen or electrolysis for reducing or extracting iron from the ore. The ITmk3 process is a new technology that indicates lower specific emissions and use of non-coking coal. SAIL has drafted plans to improve the performance of its five ISPs with an emphasis on technology upgradation and research and development at centres such as the Research and Development Centre for Iron and Steel, at Ranchi.

6. Challenges and Policy Inputs

Indian industrial sectors have faced and sustained several challenges in the form of meeting the demand for products, adapting technologies, optimized operations of equipment, raw material availability and quality, energy security, human resource and more. This section highlights some of the challenges which the Iron and Steel industry is faced with.

- **Scrap Utilization**

Scrap is an important raw material for secondary steel makers which reduce the energy demand per ton of crude steel production. According to the Bureau of International –what? recycling scrap purchases by steel works worldwide has increased by 17.2% to 340million tonnes in2010 (30). European Union which includes 27 countries has utilised 110.77 million tonnes of scrap followed by United States which utilised 56 million tonnes scrap in 2011.

The total world scrap import was 117.7 Mt in 2010. United States leads the scrap importing countries with10.52 Mt; whereas Indian scraps import is 3.6 Mt for the year 2010. The total world scrap export was 102 Mt in 2010. United States of America leads the scrap importing countries with 20.56 Mt in 2010; whereas Indian scraps export was 0.521 Mt for the same year.

- **Fly Ash Consumption**

As steel is an energy intensive industry, many plants have their own captive power generation units. Many CPP's use coal as fuel for power generation and it is important to address the waste (Fly ash) management issues associated with the CPP. According to the Ministry of Commerce, the Indian cement industry consumed 35 Mt of fly- ash during 2008-09 (31).

The projections of coal demand for electricity and corresponding ash generation are shown in Figure 93. The coal demand for power generation is expected to reach 1650 Mt in 2031-32 and corresponding ash generation is 510 Mt.

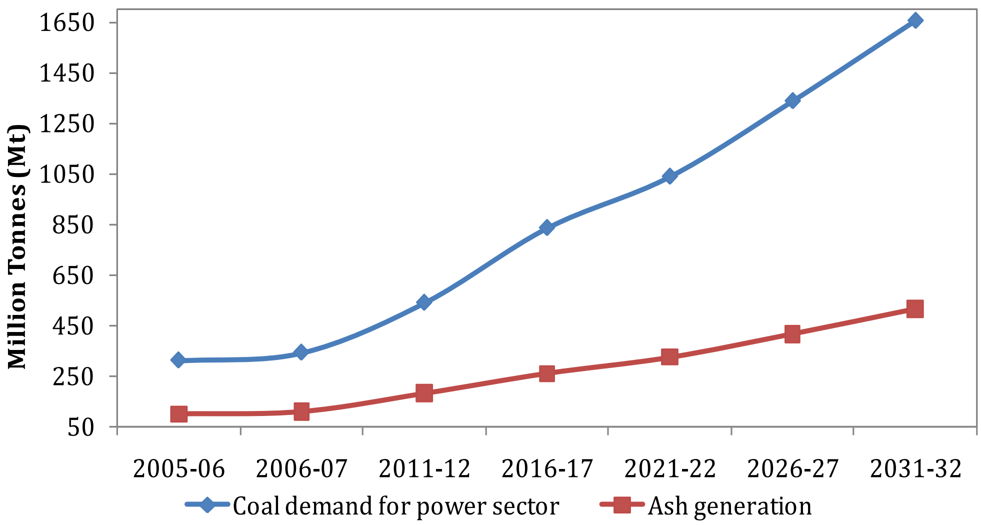


Figure 93: Projections for coal and ash generation (32)

- **Slag Consumption**

Slag is a by-product generated during the manufacturing of pig iron and steel. The slag is crushed, pulverised and screened for use in various applications, particularly in cement production because of its pozzolanic characteristics. According to the Ministry of Commerce, the Indian cement industry consumed 7.5 Mt of slag in 2008-09 (31).

- **Use of Alternative Fuels in Blast Furnace**

Blast furnace is the most energy intensive sub process in an ISP. The main energy source for the process is coke which is expensive. India has low reserves of coking coals and mostly depends on import of coking coals. It is necessary to search for alternative fuels injection in blast furnace to reduce energy consumption and minimize the import dependency.

The possible alternative energy sources that can be used in the blast furnace operation are biomass, biochar, waste plastics, natural gas, fuel oil, etc.

- **Availability and Quality of Iron Ore**

Importance of raw materials in steel making is realized by the fact that it accounts for 25-30% of the cost of steel. The Indian iron ore resources as per 2010 findings was 28.526 billion tonnes, out of which Hematite resources were 17.882 billion tonnes and Magnetite resources were 10.644 billion tonnes. Only about 8.1 billion tonnes of Hematite ore reserves are verified in India. The total iron ore requirement is 206.2 million tonnes to meet the 2016-17 targets. In fact, as per projections, present known reserves may not last beyond the next twenty years unless special efforts are made to augment our reserves (33).

- **Availability and Quality of Coal**

Coal is another major source and according to present situation the availability of coking coal is a matter of serious consideration for steel industry for different reasons. Direct usage of Indian coking coals is a constraint due to high ash content. It should either be washed or blended with imported coal before usage. The production of quality coking coal is low in India. As per 2011 findings, the total coking coal reserves in India was 33.474 billion tonnes with 17.67 billion tonnes of "substantiated" category and total non-coking coal resources of 252.39 billion tonnes with 96.33 billion tonnes of "substantiated" category. The total coal requirement including coking coal is 613.62 million tonnes to meet the 2016-17 targets (33).

- **Environmental Pollution Norms**

Iron and Steel sector has high emissions due to the energy intensive processes utilised. Indian steel industry emissions are higher than the global steel producers and emission levels and this could be due to technology or raw material variations. The emission standards for Iron and Steel industry are described below (34)

Coke Ovens:

- The effluent standards for coke ovens are suspended solids 100 mg/l, oil and grease 10 mg/l, Ammonical nitrogen as N 50 mg/l and phenol 1 mg/l
- Stack emission standards are SO_2 800 mg/Nm^3, NO_x 500 mg/Nm^3, PM 50 mg/Nm^3 and sulphur in coke oven used for heating is 800 mg/Nm^3

Sinter Plant:

- The effluent standards for suspended solids, oil and grease are 100 mg/l and 10 mg/l respectively from sinter plant
- Stack emission standards are PM is 150 mg/Nm^3

Blast Furnace:

- The suspended solids 50 mg/l, oil and grease 10 mg/l, ammonical nitrogen as N 50 mg/l are the effluent standards for blast furnace
- Stack emission standards are SO_2 250 mg/Nm^3, NO_x 150 mg/Nm^3, PM 50 mg/Nm^3 and CO 1% (v/v)

Steel Making Process:

- The effluent standards for steel making process are suspended solids 100 mg/l, oil and grease 10 mg/l
- Stack emission standards are SO_2 200 μg/Nm^3, NO_x 150 μg/Nm^3, PM 100 mg/Nm^3 and CO is 5000 μg/Nm^3 for 8 hour operation, 10000 μg/Nm^3 (34)

Integrated Steel Plant:

- Waste water generation standard for an ISP is 16 m^3 per ton of finished steel
- Stack emission standards are SO_2 800 mg/Nm^3, NO_x 500 mg/Nm^3, PM 50 mg/Nm^3 and sulphur in coke oven used for heating is 800 mg/Nm^3.

- **Corporate Responsibility for Environmental Protection (CREP)**

The Ministry of Environment & Forests/ Central Pollution Control Board (CPCB) has taken up the initiative along with the Ministry of Steel and the major steel plants to protect the environment by reducing environment pollution, water consumption, energy consumption, solid waste & hazardous waste disposal. The initiative was based on mutually agreed targets to regulate the regulatory norms for prevention & control of pollution through various measures including waste minimisation, in-plant control & adoption of clean technologies. National task force of CPCB is the monitoring committee for the implementation of the process. Ministry of Steel is coordinating with MoEF & CPCB on Corporate Responsibility on Environment Protection (CREP) and National Task Force for energy, environment and waste management in steel plant and Formulation/implementation of Environment Standards/Guidelines in iron & steel sector. MOS along with MoEF is finding ways to complete utilise/recycle the steel making slag (35).

- **Inputs from the Working Group on Steel: XII Five Year Plan**

In order to achieve the strategic objective of the XII five year plan, the potential existing and emerging technologies are listed below:

Coke making: Non-recovery coke ovens, Stamp charging & Partial briquetting of coal charge, tall ovens, Coke dry quenching, SCOPE1, DAPS, on-line heating control technology for coke ovens, optimisation of coal blend, refractory welding.

Sintering/Agglomeration: Increased use of multi-slit burners, proper MgO addition, use of super fines, vibrating granulation equipment, high agitating mixture, high pressure sintering, pellet sintering technology.

Blast Furnace: Higher use of alternative fuels, increase in oxygen enrichment and hot blast temperature, introduction of Cu-staves, increased blast volume and flow rate, increasing the useful volume by superior refractories, increased use of prepared burden, waste plastic granules, TRT, use of waste heat stove gas, extensive use of probes, models and expert system for process analysis, up-gradation of cast house equipment.

Direct Reducing/Smelting reduction: Coal gasification, COREX process, FINEX process, HISMELT process, FASTMET/FASTMELT process and ITMK3 process.

New developments in some areas are taking place such as Hot metal pre-treatment, electric steel making, secondary refining, continuous finishing, cold rolling and finishing, rail mill, high strength steel process, continuous annealing. The industry should speed up the cost-benefit analysis of these technologies for the early adoption of efficient technologies.

Another policy recommendation for the energy efficiency of steel industry is energy auditing at regular intervals by certified energy auditors and energy efficiency labelling for the equipment. As per National Electricity Policy and policy framework provided by the Electricity Act 2003, the industry is expected to meet their renewable energy purchase obligation which is mandated by respective State Electricity Regulatory Commission (SERC) (36)

The specific focus areas for the 12th plan (2012-2017) for reducing carbon and energy intensity are as follows:

- Implementation of energy conservation measures in the existing steel units
- Adoption of clean and greener energy efficient technologies in all new plants
- Implementation of energy efficient technologies in all segments of iron and steel making process
- Improvement of quality of raw material (iron ore and coal) by research and development
- Improving process operations and energy efficiency in secondary steel sector
- Incentives utilisation for Energy Conservation
- Energy auditing and energy levelling (36)

The focus for the low carbon economy is summarised below:

- Climate Change Committee (CCC) setting up under MOS
- Measures to research and implementation of carbon capture and sequestration (CCS)
- Facilitation of new steel making routes directly or through involvement in research projects like ULCOS

- Promotion of Climate change initiatives listed under low carbon economy
- Life Cycle Assessment of various steel products development
- Awareness of environment friendliness of steel products and promoting recycling oriented society
- Introduction of EMS (ISO-14001) in all sectors of steel making (36)

- **Financing to Meet the EE Goals**

PAT has set realistic goals and strives to drive the nation's industrial economy towards a more energy efficient one. Some of the measures that can be considered to ensure sound financing of EE measures in the steel industry are listed below:

- Soft loans to the industry for specific energy efficiency improvement measures.
- Interest subsidies can be provided in case of standard loans availed by DCs from financial institutions.
- Partial Risk Guarantee funds such as those designed under the NMEEE.

- **Monitoring and Validation**

Monitoring and Validation (M&V) is one of the most important aspects of a program and is a key indicator to measure the success or failure of a program. Any M&V schema requires a clear elucidation of goals which should then be periodically measured. Ideally, the program(s) should be flexible enough to allow mid-course corrections.

The M&V protocols comprise determining baseline, verifying energy conservation savings and M&V implementation procedures and protocols (37).

- **ISO 50001 Initiative**

ISO 50001 enables the organisation to develop energy management policy, identify the energy intensive areas and target energy reductions. ISO stands for International Organisation for Standardisation which helps organisations to establish the system and processes to improve the energy performance. The incorporation of these standards leads to reduction in energy consumption, energy costs and greenhouse emissions. It is mainly designed to collate with other management standards, especially ISO 14001 on environmental management and ISO 9001 on quality management (38).

ISO 50001 specifies requirements for factors affecting (39):

- Energy supply, use and consumption
- Measurement, documentation and reporting
- Design and procurement practices for energy using equipment, processes, system and personnel

ISO 50001 is based on the ISO management system which follows the Plan-Do-Check-Act (PDCA) process to improve the energy management system over time based on the best available data to the organisation. PDCA process involves three steps: 1. Planning 2. Doing 3. Checking Process

Planning process pertains to establishing the baseline, energy performance indicators (EPIs), conducting the energy use assessment, objectives, targets and action plans necessary to deliver results that will improve energy performance. Doing process involves the implementation of energy management action plans and the other Checking process is monitoring and measurement of results to be taken to determine the energy performance against energy policy and objectives.

- **Barriers and Challenges in Indian Steel & Ferro Alloy Industry**

The Indian iron and steel industry has been working consistently and contributing to the infrastructure development and economic growth of the country in the face of several barriers and challenges. Some of these can be summarised as follows:

- Availability of raw materials such as ores and coal resources
- Supply chain and associated infrastructure (roadways and railways)
- Variation in the international prices
- Land acquisition and grant of environment clearance
- Techno-economics, and production efficiency benchmark in compliance with international standards
- Sustaining in a competitive environment due to global trade agreements
- Reckonable restrictions and high tariff barriers
- Non-availability of high grade ore in India and availability of raw material linkages
- Non-availability of low ash, low phosphorous coking coal in the country for the production of desired coke necessitating the import of such coke at a high cost

To overcome these challenges, suitable economic policy framework needs to be formulated to facilitate continuous up gradation to best available technology, adoption of energy saving measures with the focus from specific national policy mechanisms such as PAT (40)

7. Summary and Conclusions

The Indian Iron & Steel sector has plants which are energy efficient and are comparable to the best in the world after adjusting for the availability and quality of the key inputs such as iron ore and coal. Some of the major plants in India recover most of the useful by-product gases and reuse their inherent calorific value in other processes. However, there are plants which operate under conditions of smaller scale, older technology, lower grade iron ore and coal and without adequate access to knowledge of best practices and finance options for deployment of EE measures. The PAT mechanism under the NMEEE seeks to address the national goals of energy access, energy security and environmental concerns while providing capacity building, best practice knowledge, financing initiatives and energy saving opportunities to industrial units.

This report provides a comprehensive study of the Iron and Steel manufacturing process, review and analyse material and energy flows, process modeling and techno-economic assessments. The study has examined manufacturing units of diverse operating factors in order to estimate the normalised baseline SEC of steel industry. ASPEN Plus, process simulation software was used to model the energy intensive blast furnace process and its supporting sub-processes to analyse the behaviour and response towards input variations. The analysis exhibited key insights on the impact of utilising low grade ore resulting in the formation of high gangue, increased slag rate, and increased pulverised coal injection rate and eventually consuming more energy. In addition, simulation of the DRI process reactions showed performance with the application of alternate coals in conjunction with different operating scenarios.

Consumption of electrical energy within the iron and steel Industry is enormous and the demand by the steel industry is estimated to increase to 16,000 MW in 2025-26 from around 8200 MW in 2016-17. Major processes such as electric arc furnace, submerged arc furnace and induction furnace and various other processes in the secondary steel making process require electrical energy. Review and analysis of such furnaces have been presented in order to understand the operating characteristics and response. Transformers capacity and efficiencies are significant parameters in electrical furnace performance. The sensitivity analysis on a sample SAF unit showed there could be potential reduction in energy consumption as the efficiency of the transformers improves.

The standards and guidelines for emissions in steel plants have been reviewed, followed by a detailed analysis of the emissions intensity assessment across each sub-process with a discussion of potential low carbon roadmaps.

The key levers for improving EE in a typical Iron and Steel plant include sub-process Energy Efficient technologies such as Pulverised Coal Injection, Coke Dry Quenching and Top Recovery Turbine can be deployed in order to contribute to energy savings. Recycling Blast furnace slag, Waste Heat Recovery options, effective Alternate Fuel Resources are other such options that can be implemented in iron and steel plants.

This study has attempted to provide useful engineering, economic and policy inputs in the context of the iron and steel sector participation within the PAT mechanism. The report discusses some of the challenges being faced by the iron and steel industry and how policy mechanisms need to be tuned to addressing them. It also highlights the importance of policy initiatives to facilitate the financing of different EE measures in order to facilitate the achievement of the PAT targets by the DCs. Such initiatives have been provided under the framework of the NMEEE.

It is observed that focused effective mechanisms such as PAT can contribute to an accelerated mitigation of the energy intensity of the Indian iron and steel sector when accompanied by a robust framework to support the financing of EE projects. Such mechanisms can contribute to reducing the projected energy intensity of the iron and steel industry, and of the country, simultaneously lowering GHG emissions intensity, thereby mitigating environmental pollution, global warming and climate change.

Energy efficiency in India is a national priority given that large sections of rural households do not have access to energy. The Indian iron and steel industry and energy policy implementing agencies such as the BEE have embarked on a cooperative journey which is vital to the country's roadmap for low-carbon inclusive growth.

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Appendix I

List of Acronyms	
ISP	Integrated Steel Plant
BF	Blast Furnace
BOF	Basic Oxygen Furnace
DRI	Direct Reducing Iron
EAF	Electric Arc Furnace
SAF	Submerged Arc Furnace
IF	Induction Furnace
WSA	World Steel Association
HS	Hot Stove
PCI	Pulverised Coal Injection
NG	Natural Gas
Fe	Iron
Fe_2O_3	Hematite
Fe_3O_4	Magnetite
FeO	Wustite
Si_2O	silica
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
GHG	Green House Gas
GDP	Gross Domestic Product
CAGR	Compound Annual Growth Rate
MoS	Ministry of Steel
I&S	Iron & Steel
NMEEE	National Mission on Enhanced Energy Efficiency
NSP	National Steel Policy
PAT	Perform, Achieve and trade
HC	High Carbon
MC	Medium Carbon
LC	Low Carbon
IFAPA	Indian Ferro Alloy Producers Association
BAU	Business as Usual
HG	High Growth
SEC	Specific Energy Consumption
PBCC	Partial Briquetting of Coal Charge
DCQ	Dry Coal Quenching
CO	Carbon monoxide
CO_2	Carbon dioxide
SO_2	Sulphur dioxide
SO_x	Sulphur Oxides
NO_x	Nitrogen Oxides

List of Acronyms	
MBF	Mini Blast Furnace
OAF	Open Arc Furnace
RAFT	Raceway Adiabatic Flame Temperature
HMS	Heavy Melt Scrap
CV	Calorific Value
IMF	Induction Melting Furnace
EOS	Emission Optimised Sintering
PM	Particulate Matter
NEDO	New Energy and Industrial Technology Development Organisation
ESP	Electrostatic Precipitator
SCOPE	Super Coke Oven for Productivity and Environmental Enhancement
HAP	Hasardous Air Pollutants
DI	Drum Index
BFG	Blast Furnace Gas
HRSG	Heat Recovery Steam Generation
TRT	Top Pressure Recovery Turbine
HM	Hot Metal
CS	Crude Steel
OG	Oxygen Converter Gas Recovery
IC	Internal Combustion
IDF	Induced Draft Fan
EE	Energy Efficiency
NPV	Net Present Value
IRR	Internal Rate of Return
TRS	Ton of Rolled Steel
WHR	Waste Heat Recovery
WHRB	Waste Heat Recovery Boiler
CPP	Capital Power Plant
AFR	Alternative Fuel Resource
VFD	Variable Speed Drive
ID	Induced Draft
PA	Primary Air
ACC	Air Cooled Condenser
HP	High pressure
LP	Low Pressure
BFP	Boiler Feed Water Pump
ACW	Auxiliary cooling water
HH	High Temperature
LL	Low Temperature
CEP	Condensate Extraction Pump
EAGER	Energy Efficiency Analysis and Greenhouse Gas Emission Reduction

List of Acronyms	
MAT	Minimum Alternate Tax
EoL	End of Life
IISI	International Iron & Steel Institute
UHP	Converting the Furnace Operation to Ultra-high Power
ADS	Adjustable Speed Drives
DC	Direct Current
SEI	Specific Emission Intensity
EF	Emission Factor
DR	Discount Rate
ESV	Emission Saving Over Life Time
ULCOS	Ultra Low Carbon dioxide Steel
VPSA	Vacuum Pressure Swing Absorption
CCS	Carbon Capture and Sequestration
HB	Humidified Blast
NGI	Natural Gas Injection
PLI	Plastic Material Injection
HRG	Hot Reducing Gas
NSP	National Steel Policy
DCs	Designated Consumers
M&V	Monitoring & Validation
CPCB	Central Pollution Control Board

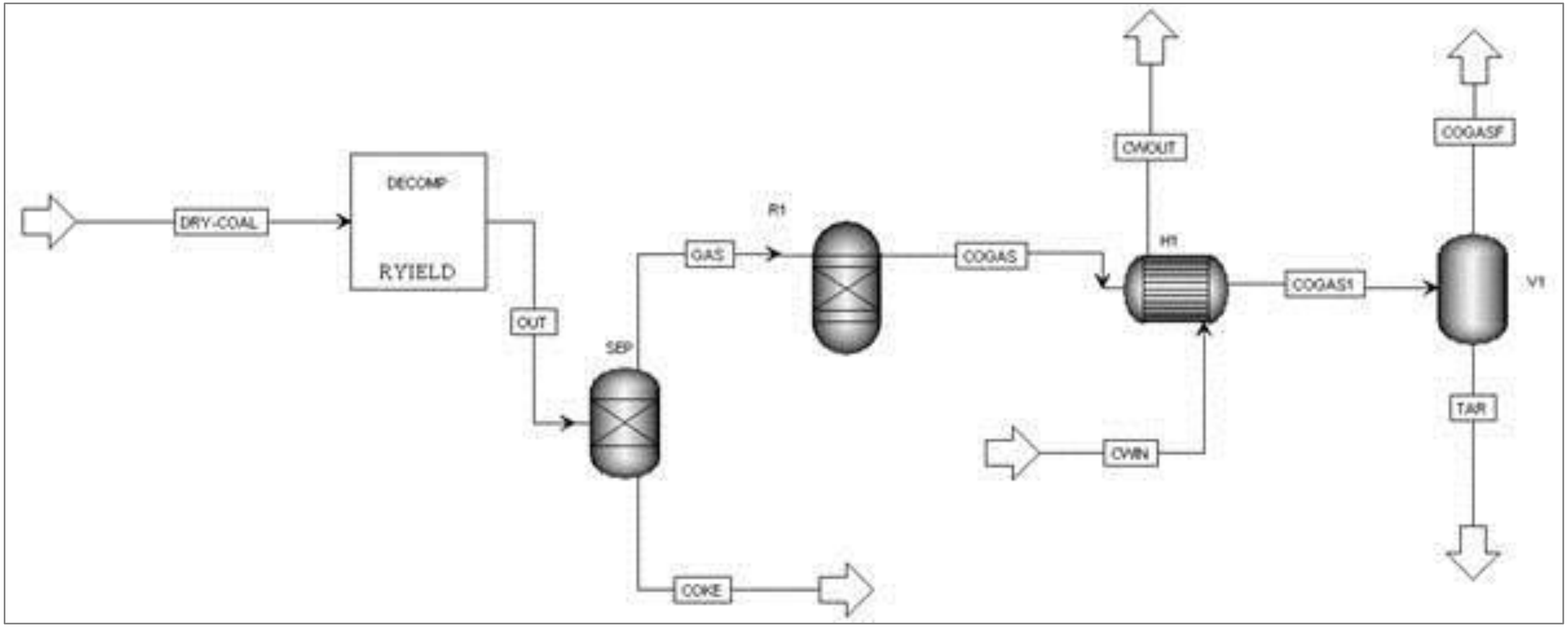
Appendix II

List of Units	
A	Amperes
V	Voltage
kWh	kilo watt hour
m^3/kg	cubic meters per kilogram
kW	kilo watt
^{0}C	Degree Celsius
K	Kelvin (Temperature scale)
kCal	kilocalorie
kCal/kg	kilocalorie per kilogram
kg	kilogram
kJ	kilo joule
kPa	kilo Pascal
kWh/t	kilo watt hour per tonne
m	Meter
kg/h	kilogram per hour
MW	Mega watt
m^3/h	cubic meters per hour
m^2	square meters
kCal/kWh	kilocalories per kilo watt hour
mm	millimeter
cm^2	Square centimeter
kKg/cm^2	Kilogram per square centimeter
kW/m	kilo watt per meter
mm.Wg	millimeter water gauge
Mt	Million tonnes
GCal	Giga Calorie
GJ	Giga Joule
toe	metric ton of oil equivalent
Mtoe	Million tonnes of oil equivalent
µg	micro gram
tpa/tpa	Tonnes Per Annum
tpd/tpd	Tonnes Per Day
tph/tph	Tonnes Per Hour
Pa	Pascal
MPa	Mega Pascal
kmol	kilo mole
kWh/t	kilo watt hour per metric ton
kCal/kg ^{0}C	kilocalories per kilogram degree Celsius
T/T	Ton/ton
$	US Dollar
T/m^3/day	Tonnes per cubic meter per day

List of Units	
kWh/MT	kilo watt hour per million ton
MVA	Million volt ampere
psi	Pounds per square inch
$t/m^3/day$	Tonnes per cubic meter per day
kVA	Kilo volt ampere
kW	Kilo watt
GJ/t	Giga joule per ton
$kJ/Nm^3/^0C$	Kilo joule per normal cubic meter per degree centigrade
$kCal/Nm^3$	Kilocalorie per normal cubic meter
Mton	Million tonnes
kL	Kilo liters
mg	Milligram
g	Gram
GWh	Giga watt hour
hrs/day	Hours per day
MWh	Megawatt hour
Gt	Giga tonnes
mg/l	Milligram per liter

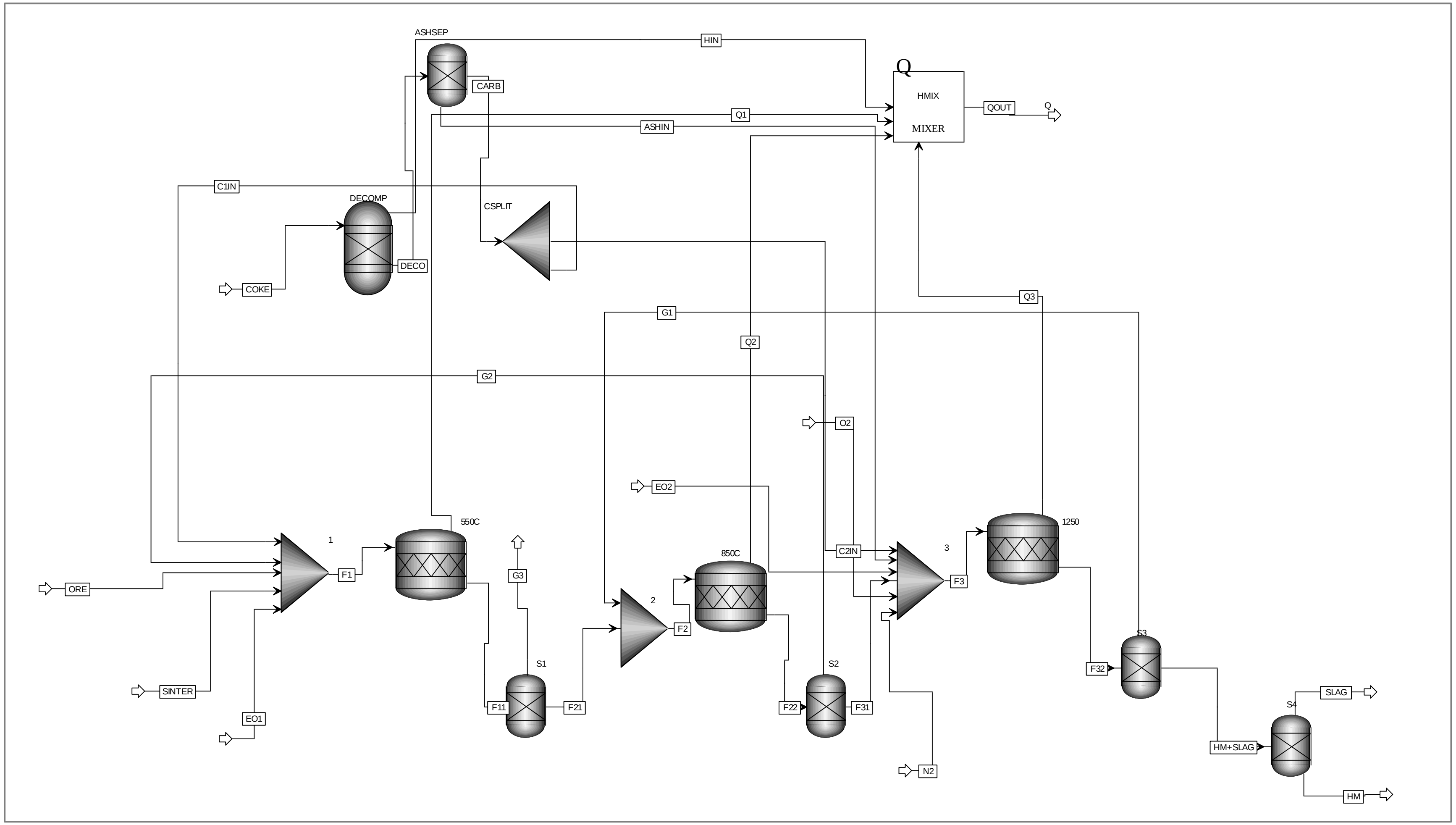
Units Conversion	
1 toe	10^7kCal
1 kWh	860 kCal
1 kWh	36×10^5 J
1 Mtoe	41.87 PJ
1 kWh	3.6 MJ

Coke Oven Model

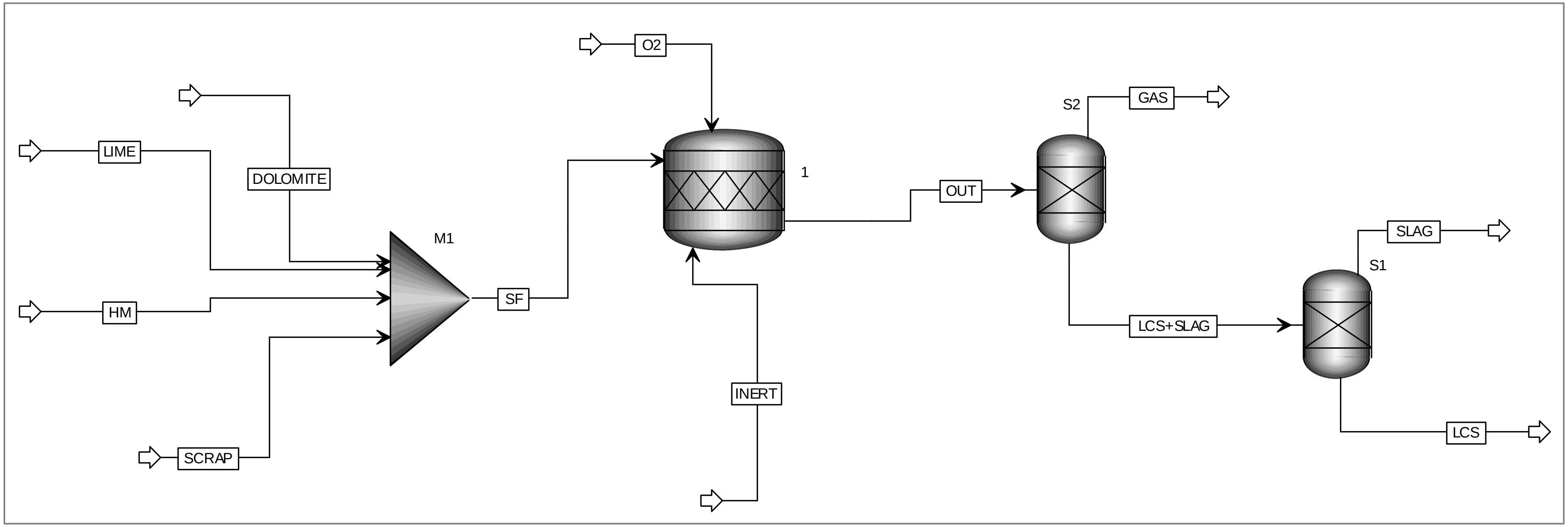


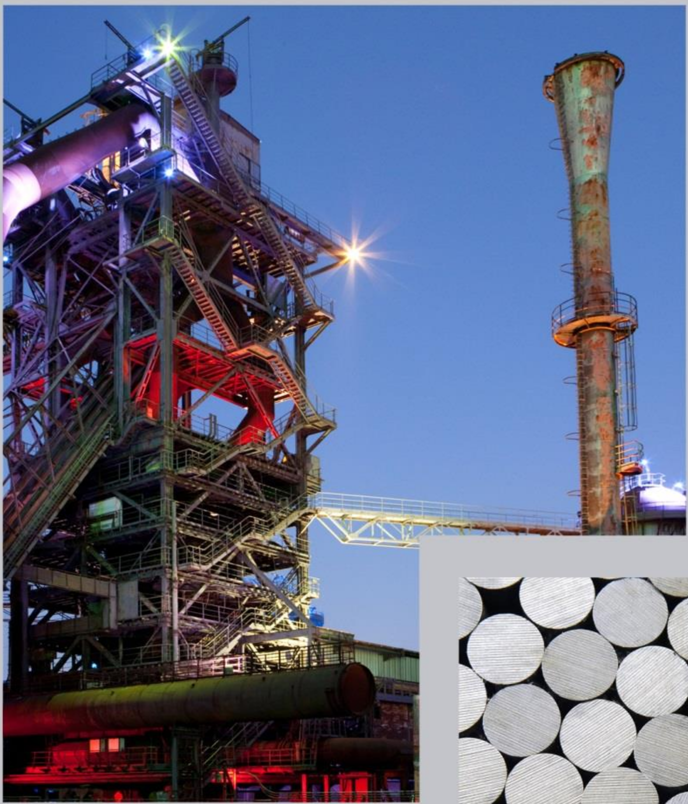
Coke Oven Model

Blast Furnace Model



Basic Oxygen Furnace Model







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