GREENHOUSE GAS EMISSION MITIGATION OPTIONS IN IRON AND STEEL PRODUCTION IN THAILAND

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A THESIS SUBMITTED AS A PART OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN ENVIRONMENTAL TECHNOLOGY

THE JOINT GRADUATE SCHOOL OF ENERGY AND ENVIRONMENT AT KING MONGKUT'S UNIVERSITY OF TECHNOLOGY THONBURI

2ND SEMESTER 2014

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A Thesis Submitted as a Part of the Requirements
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The Joint Graduate School of Energy and Environment
at King Mongkut's University of Technology Thonburi

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ABSTRACT

The purposes of this study are to study energy and carbon dioxide intensities of Thailand's steel industry by using the 2006 IPCC guidelines in the boundary of the production process (gate to gate). The plant specific data in years 2004-2010 was collected. Greenhouse gas emission projection toward the year 2050 under three plausible scenarios from the Iron and Steel Institute of Thailand, S1: without integrated steel plant, S2: with a traditional integrated BF-BOF route and S3: with an alternative integrated DR-EAF route.

The iron making technology in Thailand was evaluated by using Multi-Criteria Decision Analysis (MCDA) based on environmental, economic and technology availability. The scope of assessment was focused on three iron-making technologies, which are blast furnace, corex and midrex. Additionally, the CO_2 abatement cost curve in 2030 for the Thailand's steel industry was proposed. The results showed that energy intensity of semi-finished steel product was 2.84 GJ/t semi-finished steel and CO_2 intensity was 0.37 tCO_{2e}/t semi-finished steel. Energy intensity of steel finishing process was 1.86 GJ/t finished steel and CO_2 intensity was 0.16 tCO_{2e}/t finished steel. In 2050, the CO_2 emissions from S1 (baseline scenario) was 4.84 million tonnes, S2 was 21.96 million tonnes increasing 4.54 times from baseline scenario. The CO_2 emissions from S3 was 7.12 million tonnes increasing 1.47 times from baseline scenario. Furthermore, this finding showed that blast furnace was the most preferred iron-making technology in Thailand followed by midrex and corex. The CO_2 abatement cost curve in 2030 showed potential CO_2 emission reduction following S2 was 2.46 million tCO_{2e} with total cost of 485.71 million USD.

Keyword: Greenhouse gas; Energy intensity; Carbon dioxide intensity; Thailand's steel industry; Multi-Criteria Decision Analysis; CO_2 abatement cost curve

ACKNOWLEDGEMENTS

I would like to express my gratitude to my advisor, Asst. Prof. Dr. Siriluk Chiarakorn, for her guidance, advice, assistance in writing the report and encouragement throughout the research work. I would like to sincerely thank Assoc. Prof. Dr. Sirintornthep Towprayoon, my co-advisor, and including my committee members, Asst. Prof. Wikrom Vajragupta, Assoc. Prof. Dr. Chompoonuh Kosalakorn Permpoonwiwat, Asst. Prof. Dr.-Ing. Vitoon Uthaisangsuk, for their valuable guidance, helpful, and assistance during the study. This extends to the external examiner Prof. Dr. Takateru Umeda for valuable comments and suggestions. In addition, I would like to thank the Iron and Steel Institute of Thailand (ISIT) for some data support and gratefully acknowledge the Joint Graduate School of Energy and Environment (JGSEE), King Mongkut's University of Technology Thonburi, and the Center of Excellence on Energy Technology and Environment, Ministry of Education Thailand for providing financial support for this study. Additionally, I would like to express my deep thanks to Sahaviriya Steel Industries PLC or SSI for encouraged me to study for the Ph.D and some financial support in this study.

Last but not least, I would also like to take this opportunity to expressly acknowledge to my family member who were happy and sad with me all throughout my life. I would like to thank them for encouraging me to study for the Ph.D. and for the financial support throughout my study.

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NOMENCLATURES

AHP	Analytic Hierarchy Process
BAHP	Bipolar analytical hierarchy process
BF-BOF	Blast furnace - Basic oxygen furnace
CO_{2e}	Carbon dioxide equivalent
DR-EAF	Direct reduced -Electric arc furnace
DRI	Direct reduction iron
EAF	Electric arc furnace
EEI	Energy Efficiency Index
GHG	Greenhouse gases
GJ	Giga Joule
IPCC	Intergovernmental Panel on climate Change
ISIT	Iron and Steel Institute of Thailand
MCDA	Multi-Criteria Decision Analysis
SEC	Specific energy consumption
TGO	Thailand Greenhouse Gas Management Organization
WSA	World Steel Association

CHAPTER 1
INTRODUCTION

1.1 Rationale/Problem Statement

Nowadays, global warming is a worldwide environmental and economic problem. Most of the warming over the past 50 years has been caused by emissions of carbon dioxide and other greenhouse gases especially from electricity production and fuel combustion. In Thailand, energy sector is contributed the most of greenhouse gas emissions (56.2%) followed by agriculture (24.1%), waste (7.7%), land use and forestry (6.6%) and industrial sector (5.4%) respectively [1]. The iron and steel industry is one of the fundamental industries in Thailand. In August 2012, amount of the iron and steel exported was 160,180 tonnes which was a increase of 53.33% compared with previous year [2]. However, the iron and steel industry is defined as one of the energy intensive manufacturing sectors. Many production processes takes place at high temperatures. Besides, when iron ore is converted in metallic iron by using carbon as reducing agent, other toxic pollutants and CO_2, the main cause of global warming, are emitted to environment. CO_2 can be emitted from many sources during the iron and steel production process due to chemical reactions, on-site burning of fossil fuels, and electricity used during the production process [3].

According to the Intergovernmental Panel on Climate Change (IPCC), the greenhouse gas emissions from iron and steel industry accounts for between 3-4% of total world greenhouse gas emissions. On average, 1.8 tonnes of carbon dioxide are emitted for every tonne of steel produced [4]. Especially, iron making process is contributed the most of CO_2 emission by 91% [5]. The main route of iron-making technologies in the world today have four routes: blast furnace (BF) is the most widely used (57.6%) followed by electric arc furnace (EAF) 37.9%, direct reduction 4.1% and smelting reduction 0.4% respectively [6]. Currently, in 2015 Thailand has no upstream iron and steel industry. Most of steel making in Thailand utilizes the electrical arc furnace (EAF) process using steel scrap as a raw material. As shown in Figure 1.1, the statistic report indicated that the amount of steel produced in Thailand is not adequate to its consumption due to no upstream steel industry. In 2014, the steel production was 9.58 million tonnes; however the apparent consumption was up to 20.13 million tonnes [7]. The increasing demand of steel was mainly from construction sector (54%), followed by the automotive industry (16%), machinery and industrial (13%), appliance (12%) and packaging (5%) [7].

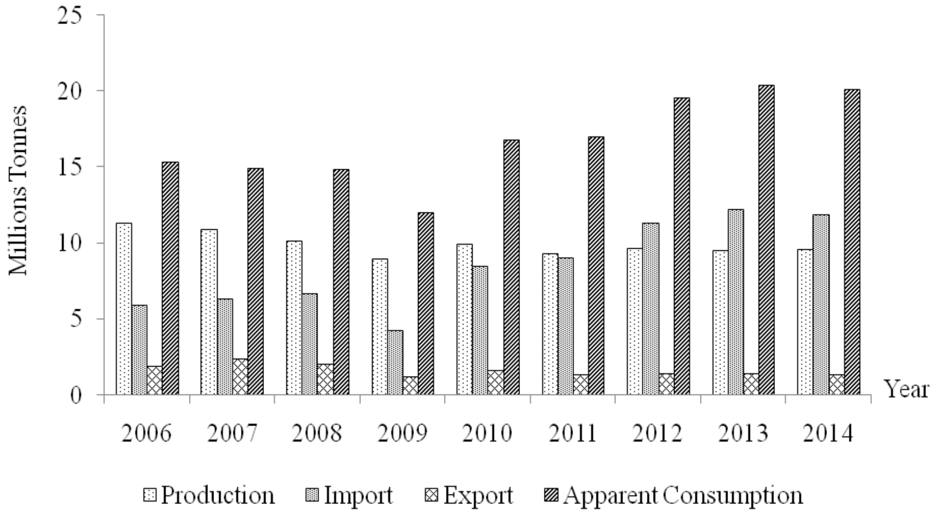


Figure 1.1 Overview of Thailand's steel industry [7]

In addition, it is obviously seen that high quality steels in Thailand are now almost supplied by imports, accounting for 42% of total steel consumption as shown in Figure 1.2. High quality steels import include bar, wire rod, wire, hot rolled coil, hot rolled plate, cold rolled coil, coated, pipe and tube from Japan, South Korea, Taiwan of China and the European Union. The high quality steel products were used for forging parts for automotive and machinery whilst the lower quality steel products were mainly used for civil and architecture engineering. Without upstream iron and steel production in Thailand, steel export is only 6% of apparent steel consumption. The establishment of upstream steel industry would lead to less imports higher qualities steels, higher exports and also increase country's long-term iron and steel manufacturing competitiveness.

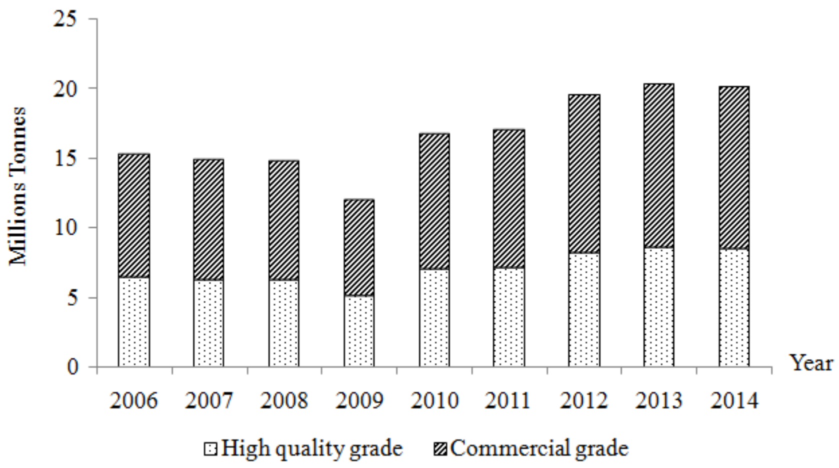


Figure 1.2 Thailand's high quality steel demand [7]

Due to the high domestic demand of iron and steel products, the Thailand Board of Investment (BOI) announced revisions to its promotion of the upstream sector with ASEAN's hub of high-quality steel in November 2007. Additionally, the Iron and Steel Institute of Thailand proposed three plausible scenarios which were without integrated steel plant (baseline scenario), with a traditional integrated BF-BOF route and with an alternative integrated DR-EAF route in the master plan of energy management for Thailand iron and steel industry [7]. The aims of the establishment of the upstream steel industry are to reinforce and sustain downstream industries, and improve the country's long-term manufacturing competitiveness. However, currently Thailand does not have an upstream steel industry due to high investment industry. Most of steel processing technology in Thailand is electrical arc furnace (EAF) using steel scrap as a raw material.

Even though the energy intensity and CO_2 intensity of some steel products were reported in Thailand, the numbers of plants were different and the activity data were somehow incomplete [8]. This reflects high uncertainty of the calculated intensity values. In addition, a number of previous researches in Thailand are focused only on the study of the energy consumption and greenhouse gas emissions of iron and steel industry excluding the study of available technologies for reducing energy and greenhouse gas emissions. Therefore upgrade CO_2 calculation methodology, plant specific activity data and energy saving potential and CO_2 emission reduction in a cost-efficient way are necessary for iron and steel industry in Thailand.

According to the Conference of Parties (COP) 18 in 2012, the United Nations Framework Convention on Climate Change (UNFCCC) encouraged the developing countries listed as non-Annex I parties to report their national greenhouse gas inventories compiled in the Biennial Update Reports (BUR) within the year 2014 and the proposed nationally appropriate mitigation actions (NAMA) with the greenhouse gas reduction target by the year 2020 [9]. Nevertheless, Thailand reported the first and the second national greenhouse gas inventories in the years 2000 and 2010, respectively. According to the previous national greenhouse gas inventories, the secondary data and default emission factors were mostly used to calculate the greenhouse gas emissions. This was due to the lack of activity data and country specific emission factors and only Tier 1 of the 1996 IPCC guidelines was applied.

Thailand has also been encouraged by the UNFCCC to submit the BUR and propose NAMA. In addition, according to a new international agreement, known as Intended Nationally Determined Contributions (INDCs) the commitments country will propose the steps to reduce emissions and adapt to climate change impacts on climate change conference of the parties (COP 21) in Paris in December 2015. The timeframe until 2030 is particularly interesting for the 2015 agreement [10]. To prepare the BUR and INDCs, the national greenhouse gas inventory should be carried out by using the 2006 IPCC guidelines and the greenhouse gas emissions should be forecasted to the year 2030. The establishment of upstream iron industry has the benefits in terms of economic. However, in environmental aspects the iron production causes adverse environmental impacts such as high energy consumption and greenhouse gas (GHGs) emission.

Thus, this research aims to study energy intensity and carbon dioxide intensity of Thailand's steel industry by using the 2006 IPCC guideline and greenhouse gas emission projection toward the year 2050.The potential to upgrade the methodology was evaluated from the availability of plant specific activity data, classified by the main types of steel products in Thailand. Evaluation and prioritization of iron making technology in Thailand were carried out by using multi criteria decision analysis (MCDA) based on environmental, economic and technology availability. Additionally, the evaluation of energy saving potential and the CO_2 abatement cost curve in 2030 for the Thailand’s steel industry was proposed. The output from this research will be the technical database for government and iron and steel industry to set up appropriated greenhouse gas reduction measures and data supporting NAMA and INDCs implementation contributed from iron and steel production in Thailand.

1.2 Literature Review

1.2.1 Energy consumption and CO_2 emissions from iron and steel industry

CO_2 is emitted from many sources during the iron and steel production process due to chemical reactions, on-site burning of fossil fuels, and electricity used during the production process [3]. According to the International Energy Agency (IEA) [11], energy consumption of the worldwide iron and steel sector in year 2005 accounted for approximately 10-15% of annual industrial energy consumption which contributed 4-5% to total world CO_2 emissions. Arens [12] stated that 4-7% of the anthropogenic CO_2 emissions originated from iron and steel industry. The energy consumption and CO_2 emissions from iron and steel industry have been reported in many studies. Lin *et al.* [13] estimated future energy intensity and energy saving potential of China’s steel industry from different policy scenarios during the period 1994 to 2008. The data on the Chinese iron and steel industry were obtained from the China Statistical Yearbook. In 1999, the primary steel produced using BF–BOF 82.8% but only 1.5% was produced by OHF technology. The secondary steel produced using EAF technology was 15.7%. The multivariate linear regression model combined with risk analysis was applied to predict the future energy intensity. The results indicated that the energy consumption of China’s iron and steel industry accounted for 17% of the total national energy consumption. The total energy consumption of the Chinese steel industry for the baseline scenario does not basically need steel industry policy support during the period from 2009 to 2015 would be 4,135 million tonnes of coal equivalent. In addition, Kirschen *et al.* [14] studied energy related carbon dioxide emissions of electric arc furnaces (EAF) in steel industry. The energy sources of the EAF process comprises of electrical energy and energy generated from oxidation reactions during refining balances. The results showed that the total energy requirement of modern EAFs ranged from 510 to 880 kWh/t, with energy efficiency values of between 40% and 75%. Total average CO_2 emissions of EAF steel plants were 250 kg CO_2/t in Germany and 350 kg CO_2/t in Europe, respectively. Additionally, Oda *et al.* [15] evaluated specific energy consumption (SEC) of blast furnace–basic oxygen furnace (BF–BOF) route and scrap-based electric arc furnace (Scrap-EAF) route using macro and micro approaches. The macro-statistics approach was based on IEA energy balances and basically covered all countries whilst the micro-statistics approach was based on company reports and the results of site surveys. The estimations were measured with primary energy base. As a result, the world specific energy consumption (SEC) for the BF–BOF route in 2005 based on a macro-statistics approach was 32.7 GJ/tonne of crude steel and 8.56 GJ/tonne of crude steel for the Scrap-EAF route.

In Thailand, the energy consumption and CO_2 emissions of iron and steel production in the base year 2000 was reported in the 2^{nd} National greenhouse gas inventory. The greenhouse gas emissions (GHG) was calculated using the 1996 IPCC guidelines. In 2000, there was no upstream iron making; thus, only the activity data of electric arc furnace (EAF) process collected from the Office of Industrial Economics (OIE) were reported. According to the 2^{nd} Thailand greenhouse gas inventory, the CO_2 emissions of steel production from EAF process accounted for 6.65 Gg [16] which contributed 0.04% of total CO_{2e} emissions from industrial processes. Additionally, energy and CO_2 intensities of the steel industry in Thailand were reported by Thailand Greenhouse Gas Management Organization (TGO). The 2006 IPCC guidelines was applied in this study and the plant specific activity data were collected from 5 plants (6 products) during the year 2004 to 2008. The results indicated that hot rolled coil from continuous process had the highest energy and CO_2 intensity which were 4.89 GJ/t hot rolled coil and 0.73 tCO_2/t hot rolled coil, respectively [8]. A recent study was performed by Sodsai and Rachdawong [17]. They evaluated the CO_2 emissions from the steel industry in Thailand for the year 2008. The basic equation (Tier 1) of 2006 IPCC guideline was applied and the activity data was collected from slab (continuous process), hot rolled coil, cold rolled coil and hot dip galvanized steel production plants. It was found that hot dip galvanized steel (HDG) had the highest specific energy consumption (2.05 GJ/t HDG), followed by hot rolled coil (HRC) (1.5 GJ/t HRC), slab (1.49 GJ/t slab), and cold rolled coil (CRC) (1.41 GJ/t CRC) respectively. Amongst all steel products, the slab product had the highest CO_2 intensity (309.11 $kgCO_2$/t slab).

1.2.2 Energy efficiency and CO_2 reduction technology in iron and steel industry

Currently, a number of previous research studies in Thailand focused only on the study of the energy consumption and greenhouse gas emissions of the iron and steel industry excluding its energy and CO_2 abatement cost curves. However, there are a number of studies in energy efficiency and CO_2 reduction technologies and measures including CO_2 abatement cost curve in iron and steel industry worldwide. The Asia Pacific Partnership on Clean Development and Climate presented the energy saving technology and environmental preservation technology in steelworks. The results showed that application of 10 energy saving technologies in the steel industry from the state of the art clean technology (SOACT Handbook) in 2005 can reduce 130 million tonnes CO_2 emissions per year [18]. In addition, Hasanbeigi *et. al.* [19] presented 56 emerging energy efficiency and carbon dioxide emissions reduction technologies for iron and steel industry. The detail of each technology comprises energy savings, environmental concern, costs and benefits and commercialization status. In another similar study by Hasanbeigi *et al* [20], the 23 energy efficiency technologies and measures for China's iron and steel industry were analyzed by using a bottom-up conservation supply curve models. The data collection based on the assessment of energy efficiency and CO_2 emission reduction potentials of the iron and steel industry in the U.S. Brunke *et al.* [21] assessed the CO_2 conservation cost curves from 32 energy conservation measures in the German iron and steel industry. Sensitivity analysis was conducted by varies electricity and carbon prices. Li and Zhu estimated that the cost curve of energy saving and CO_2 emissions reduction in China's iron and steel sector under two different discount rates of 20 % and 30 % [22]. The 41 technologies were selected based on different process of iron and steel production, and their investment, operation cost, energy saving. Additionally, working group III of IPCC presented mitigation of climate change for industry sector. This report showed significant potential for emissions reductions in the iron and steel sector including use of various energy efficiency technologies and increase energy recovery from process gases and waste streams. Reduction in emissions from selection of low CO_2 material and use material efficiency had also co-benefits to reduce yield loss [23].

It can be seen that the secondary data and default emission factors were mostly used to calculate the greenhouse gas emissions in previous studies in Thailand due to the lack of plant specific activity data and country specific emission factors and only Tier 1 of the 1996 IPCC guidelines was applied. Additionally, a number of research studies in Thailand are focused only on the study of the energy consumption and greenhouse gas emissions of iron and steel industry, excluding its energy saves and CO_2 abatement cost curves.

1.3 Research Objectives

1.3.1. To study the energy intensity and the carbon dioxide intensity of Thailand's steel industry and greenhouse gas emission projection toward the year 2050.

1.3.2. To evaluate and prioritize iron making technology in Thailand by using multi-criteria decision analysis (MCDA) based on environmental, economic and technological availability.

1.3.3. To evaluate energy saving potential and CO_2 abatement cost curves in 2030 for the Thailand's steel industry.

1.4 Scope of the Research

1.4.1. Greenhouse gas emissions from iron and steel production were calculated using the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines in the boundary of production process (gate to gate). Greenhouse gas emissions come from chemical reactions in process, fuel combustion and electricity used in the production process.

1.4.2. Evaluation and prioritization of iron-making technology in Thailand were carried out by using Multi-Criteria Decision Analysis (MCDA). The scope of assessment was focused on three iron-making technologies are blast furnace (BF), corex and midrex. Three iron-making technologies were evaluated by using bipolar analytical hierarchy process (BAHP) based on three main criteria and nine sub-criteria. The qualitative data was collected from government sector, private sector, education sector and institute sector. The qualitative data of relative preferences were changed to quantitative data by expert judgment following classical AHP method.

1.4.3. The most preferable of iron making technology was selected to assess the energy saving potential and CO_2 abatement cost curves in 2030 for Thailand's steel industry. The CO_2 emission mitigation options were obtained from the available and emerging technologies for reducing greenhouse gas emissions from the iron and steel industry (US.EPA, 2012). However, only measures that have payback period time less than three years are selected in this study.

CHAPTER 2
THEORIES

This chapter aims to present theories related to this study. They are divided into history of iron and steel industry, structure of iron and steel industry, iron and steel making process and technology, greenhouse gases emission of the iron and steel sector, alternatives for mitigating of CO_2 emission in iron and steel production and multi criteria decision analysis (MCDA).

2.1 History of Iron and Steel Industry

Iron is a hard, strong and heavy gray metal that is found in many mineral compounds in the earth's crust. The production of iron has begun in about 1300 BC by using charcoal as fuel and reducer in small furnaces. Steel is formed by removing impurities from the iron which carbon containing less than 2%. Steel becomes a much stronger, harder and tougher metal compound. Steel is used in various engineering and construction material. Up to the 1960s, there has been three main routes of iron-making processes: blast furnace, smelting reduction and direct reduction. The main process for reducing iron oxide was the blast furnace process while the smelting reduction process was still under development in that period. The several iron and steel making processes has been developed as shown in Table 2.1. In 1856, Henry Bessemer has invented the first Bessemer converter and then in 1866, William Siemens has developed the open hearth furnace to turn pig-iron into mild steel in large quantities. After that in 1879, Sidney Gilchrist-Thomas has presented steel produced from phosphoric ores by lining the converter with dolomite limestone. The iron and steel making processes has been continuously developed until in year 1952 the basic oxygen furnace (BOF) was developed by Robert Durrer. The basic oxygen furnace (BOF) is the state-of-the-art process also known as the Linz-Donawitz (LD) process [24].

Table 2.1 Key developments in iron and steel making [24], [25]

Year	Inventor	Invention
1784	Henry Cort	Developed the puddling process for making and then rolling out wrought iron
1828	James Neilson	Used heated air for the blast, which cut down the amount of fuel and improved the blast
1839	James Nasmyth	Invented a precise steam hammer to shape iron objects
1856	Henry Bessemer	Invented the Bessemer Converter, which turned molten pig-iron into mild steel in large quantities
1866	William Siemens	Developed the open hearth furnace to turn pig-iron into mild steel in large quantities
1879	Sidney Gilchrist-Thomas	Learned how to produce steel from phosphoric ores by lining the converter with dolomite limestone
1952	Robert Durrer	Developed the basic oxygen furnace (BOF)
1970	-	Processes were developed that used the concept of bottom-blowing

2.2 Structure of Iron and Steel Industry

The common structure of iron and steel industry is classified into three industry levels: upstream, midstream and downstream industry as shown in Figure 2.1. The upstream industry includes the production of hot metal and sponge iron. Midstream industry consists of basic oxygen furnace (BOF) and electric arc furnace (EAF) steel making use of scraps as raw materials. The products of this stage are semi-finished steel products which are utilized for further rolling/forging to produce finished steel products in downstream industry. The slab is used to produce flat products. Billet is used as input material for production of long products, while bloom, beam, and blank are used to produce heavy sections [26].

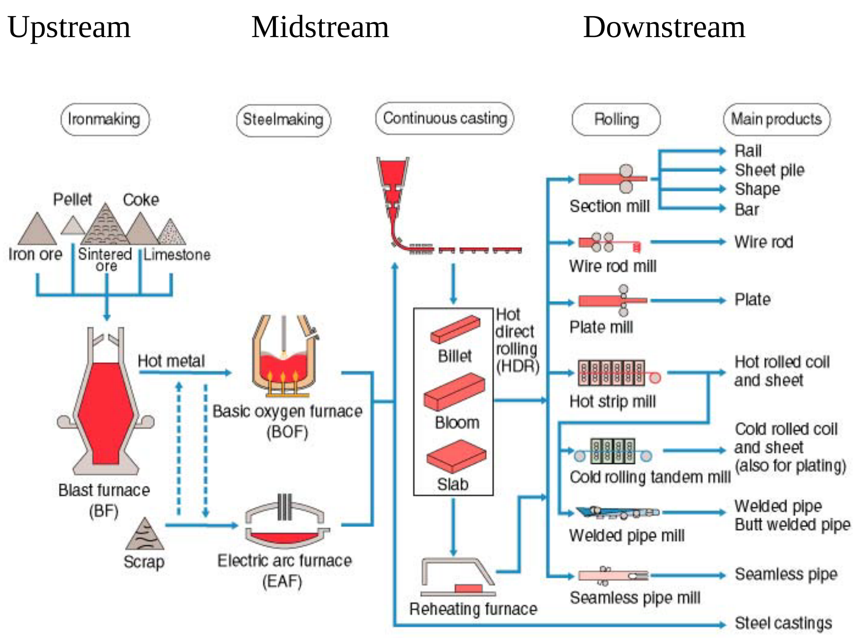


Figure 2.1 Structure of iron and steel industry [27]

2.3 Iron and Steel Making Process

The production of iron and steel is accomplished using several processes. The major operations are as follows [28], [29].

2.3.1 Treatment of Raw Materials Process

The raw materials preparation processes are consisted of coke making, sinter plants and pellet plants. Coke is produced from metallurgical grade coals and used as a main energy source of iron-making process. Carbon from coke is used to remove oxygen from iron ore and heat in order to produce molten iron in blast furnace. The remarkable properties of coke are strength and porous nature. Therefore, it is an important contributor to the formation of the permeable bed required for the optimization of blast furnace performance. In sintering process, iron-bearing wastes, iron ore fines and coke dust are mixed and combusted. The iron ore fine is mixed by heating and changing into coarse lumps that can be charged to a blast furnace. In pelletizing process, the beneficiated (iron-rich) ore is blended with a binding agent and then heated to create durable marble-sized pellets.

2.3.2 Iron Making Process

The iron-making process is referred to the most energy consumption, causing the largest CO_2 emissions process. In this process the iron ore (solid oxidized iron) is reduced into iron through the removal of the oxygen. Four routes are currently used worldwide for the production of steel: blast furnace/basic-oxygen furnace route, smelting reduction, direct reduction and direct melting of scrap (electric arc furnace), as illustrated in Figure 2.2.

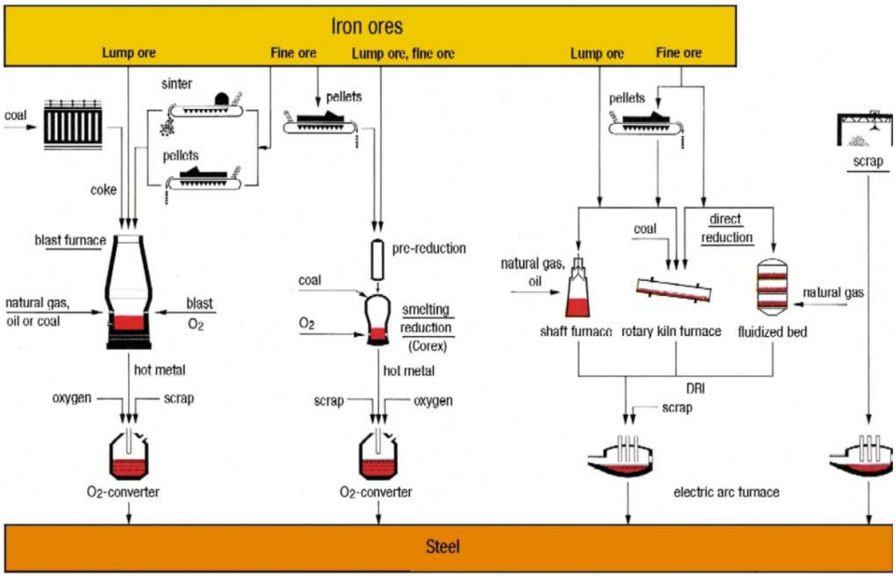


Figure 2.2 Iron-making process [30]

2.3.2.1 Blast Furnace Process

The blast furnace is a tall cylindrical counter current shaft furnace lined with refractory brick. The raw materials such as iron ore, coke and limestone are charged into the top of the furnace. The reduction gases, which has been generated by the combustion of the coke, are injected in the opposite direction from materials move downward. The air temperature is preheated to about 1,000-1,200^{o}C. The bottom of the vessel collects and taps the molten iron and slag. The hot metal contains about 94% of iron. With higher than 4% carbon, it becomes too brittle for most engineering application. Therefore, hot metal is further refined into steel in steelmaking process.

2.3.2.2 Smelting Reduction Process

The smelting reduction process has two separate process reactors: reduction in a shaft furnace and a melter-gasifier. The smelting reduction process is non-coking coal process. Coal is directly injected into a vessel also produce the gas for the direct reduction shaft furnace. This stage produces hot direct reduction iron (DRI) used for melting in a melter-gasifier. Oxygen is injected lower down into the vessel where it reacts with the char to produce heat and further CO. The DRI melts from heat from the combustion of the char.

The hot metal and slag are tapped periodically in the same feature as with a blast furnace operation.

2.3.2.3 Direct Reduction Process

Direct reduction process is an alternative steel production route to BF-BOF and Scrap-EAF, which reduces the iron ore in solid form by reducing gases. The reducing gas mostly comes from coal or natural gas which is mainly contains of hydrogen (H_2) and carbon monoxide (CO). The product in solid form is called direct-reduced iron (DRI) or sponge iron. There are various types of reactors for DRI processes such as rotary kilns, rotary hearth furnaces, shaft furnaces and fluidized bed reactors. However, the majority of direct reduction iron (DRI) is produced in shaft furnaces by using natural gas as the feedstock for the reducing agent. As a result, this process tends to be located near readily available natural gas supplies. The direct reduction iron (DRI) in solid stage can then be changed to steel in electric arc furnaces (EAF) steelmaking process.

2.3.2.4 Electric Arc Furnace (EAF) Steelmaking

Electric Arc Furnace (EAF) steelmaking is used to produce steels by recycling ferrous scrap. A wide range of scrap types can be used in EAF steelmaking. Scrap and solid iron feed materials are melted by heat supplied from electricity, where arc comes from graphite electrodes. EAF process does not require coke oven and associated plant processes like the blast furnace. Therefore, there is lower emission compared to the blast furnace process. EAF technology is widely used for mini-mills, which is operating economically at a smaller scale than larger integrated steelmaking.

2.3.3 Steelmaking Process

The impurities such as sulphur, phosphorus, and excess carbon are removed from the raw iron in steelmaking process. Alloying elements such as manganese, nickel, chromium and vanadium are added to produce the exact steel required. There are 3 processes of steelmaking: open hearth furnace, a basic oxygen furnace and electric arc furnace.

2.3.3.1 Open Hearth Furnace

Scrap and iron are melted in a pan lined with refractory bricks in an Open hearth furnace (OHF). The fuel and the combustion air are preheated below the melting pan in order to reach sufficient temperatures (1,650°C) when they burn directly over the steel. Excess carbon is removed by reducing rusty scrap (Fe_2O_3) to iron and carbon monoxide, which is oxidized to CO_2 using atmospheric oxygen. The open hearth furnace

(OHF) is a traditional and inefficient steel production technique which the world steel production share is constantly decreasing. The global steel production data has shown that only 3.2% of the global steel production came from open hearth furnaces. Russia and the Ukraine are the largest shares of OHF steel production.

2.3.3.2 Basic Oxygen Furnace

The basic oxygen furnace (BOF) is accounted for 63% of world steel production in 2004. The pure oxygen is used instead of air for the basic oxygen furnace (BOF). The advantage is reducing process duration and thus leads to a much higher level of energy efficiency and productivity. Currently, the open hearth furnace is being replaced by basic oxygen furnaces (BOF).

2.3.4 Casting Process

Casting is a manufacturing process by which molten metal is usually poured into the mold and which holds this material in shapes as solidify. Historically, a produced large steel ingot has been performed by pouring steel into moulds in a batch process. The ingot has been reheated prior to additional processing after cooling. Then, the continuous casting is developed to replace ingot casting because it produces large quantities of semi-finished steel closer to their final shapes. The resulting steel forms often proceed directly to rolling or forming while retaining significant heat, which reduces downstream reheat costs. Strip casting is an emerging technology for the casting area which uses two rotating casting rolls to directly produce strip of less 2 mm.

2.3.5 Rolling and Finishing Process

A semi-finished shape is changed into finished steel products by rolling and finishing process. These products are used by downstream customers directly or to make further goods. Finishing processes include: improve surface, strength, flexibility, and hardness and corrosion resistance.

2.3.6 Comparison of Iron-Making Processes

The comparison of the conventional blast furnace with the direct reduction and smelting reduction route in terms of scale of production, energy requirements, product quality, feed stocks, installation costs and environmental performance is shown in Table 2.2. It can be seen that the blast furnace is the principal route to iron-making [31].

Table 2.2 Comparison of the conventional blast furnace with the direct reduction and smelting reduction route [31]

Features	Blast Furnace (BF)	Direct Reduction (DR)	Smelting Reduction (SR)
Scale of Production	1. Long established and energy and resource efficient with unit plants through puts of 2Mt/a and greater 2. Still the principal route for iron making, accounting for 95% of world production	1. Gas based processes account for the vast majority of installed DR capacity worldwide, with 63% of that capacity being via the MIDREX route. Such processes have currently a maximum unit plant capacity of 1.3Mt/a. 2. DRI as produced is normally used as replacement for scrap in the electric arc furnace steelmaking route.	1. SR is still an emerging technology. Only the COREX process has been commercialised. 2. Currently, there is about 1Mt/a of installed operating capacity (two sites). 3. The latest and largest SR unit in operation has a capacity of 700,000 t/a.
Energy Requirements	1. Typically around 17-18 GJ/t of liquid iron (less gas, steam and heating credits from carbon in iron)	1. Typically 10.5 - 14.5 GJ/t solid DRI (gas based) assuming 100% lump ore operation. (Extra energy required for melting and pellets, if used)	1. Difficult to quantify as process efficiency is dependent on the credit given for exported power or production of more DRI by gas based DR process.
Product Quality	1. Stable and of dependable quality	1. Product prone to re-oxidation unless passivated or briquetted 2. Quality highly dependent on feed quality	1. Identical to BF iron
Feed Stocks	**Coal** 1. Coking coals required for coke making 2. Coke breeze & anthracite where used for sinter plants 3. Coal for BF injection (can be non-coking coal specification) **BF Injectants** 1. Besides coal, oil (inc. waste oil), natural gas and plastics have all been injected into BF **Metallics** 1. A wide range of feedstock of variable quality and specification can be used	**Coal** 1. Wide range of solid fuels from anthracite to lignite including charcoal (rotary kilns) **Gas** 1. Sulphur content of gas must be low to avoid poisoning of reformer catalyst and effecting product quality **Metallics** 1. As no physical change of state takes place in the process high quality pellets and lump ore are required	**Coal** 1. Non-coking coals, specification requirements more flexible than for BF route **Metallics** 1. Lump ore, sinter or pellets. Fine ores cannot be used directly as yet **Oxygen** 1. Large quantities of oxygen are required for the Corex process (with associated energy implications)
Installation Costs	1. 1,150 Millions EURO for 3.5Mt/a (including cost of sinter plant and coke ovens)	1. 210 Millions EURO for 1.36 Mt/a (assuming availability of suitable pellets or lump ore)	1. 240 Millions EURO for 600kt/a (including cost for oxygen plant and assuming lump ore)

Table 2.2 Comparison of the conventional blast furnace with the direct reduction and smelting reduction route (Cont') [31]

Features	Blast Furnace (BF)	Direct Reduction (DR)	Smelting Reduction (SR)
Environmental Performance	1. Releases to the environment include dusts, VOC, PAH and a variety of organic chemicals from the coke ovens 2. Sinter plants release SO_2, NOx, dust, VOC, PCB, PCDD/F and PAH 3. BF discharge dust and SO_2 from cast houses. The process route also uses large quantities of water. However, the route provides the recycling of various solid wastes/by-products which would not be available in many DRI processes 4. The desulphurising capability of the blast furnace also allows higher sulphur containing fuels and reductants to be used in an environmentally friendly manner 5. BF slag can be used for road construction or pelletised to make slag cement. Both by-products have the environmental advantage that they reduce the demand for primary aggregates	1. As most DR processes make use of iron pellets the environmental impact of releases from the pelletisation process should be taken into account. 2. The DRI product typically contains 2-4% gangue requiring further energy for processing and additional environmental releases to be considered. 3. Dust releases are similar to the BF route as raw material fines are screened before processing. There is a need to provide an environmentally satisfactory route for utilisation of fines if DR is to replace traditional ironmaking 4. NOx is released at the gas reforming stage 5. The most successful DR processes use natural gas although coal remains the largest energy source available to man 6. In terms of sustainable development it may be considered that gas should be reserved for the production of high value products.	1. In some SR processes large quantities of waste gas require to be utilised. 2. Besides Corex energy requirements and CO_2 emissions are higher than at the BF route 3. There is a need to provide and environmentally satisfactory route for utilisation of fines if SR is to replace traditional iron-making.

2.4 Iron-Making Technology

The iron-making technology can be divided into two groups according to the product type: liquid and solid condition as shown in the Figure 2.3. A blast furnace and direct smelting process are a type of metallurgical furnace used for smelting to produce liquid iron whilst direct reduction process is a process of producing solid iron product [32]. The direct smelting technologies are corex, finex, NST, romelt. The direct reduction technologies are divided in gas base and coal base as shown below. The most common technologies used for direct reduction is midrex. This technology use natural gas as the feedstock for the reducing agent.

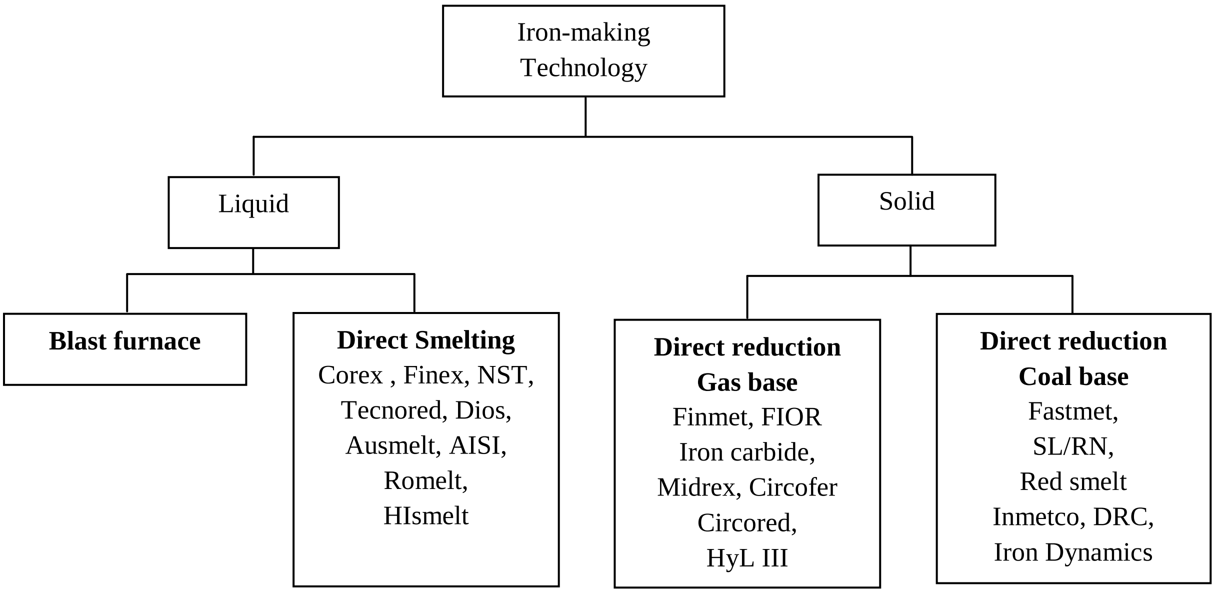


Figure 2.3 Iron-making technology [32]

2.4.1 The commercial development of iron-making technology

The commercial development of iron-making technology is illustrated in Table 2.3. The proven commercial technology is operating commercially in more than one economically-viable installation. Semi-commercial technology is undergoing start up in a first-of-a-kind commercial scale installation, or it is still in the process demonstration phase. This also includes those that are no longer being operated. The pilot scale technology has been operated at an integrated pilot scale [33]. It can be seen that the blast furnace, corex, midrex, HyL and SL/RN are the proven commercial technologies.

Table 2.3 Grouping of iron-making technology by stage of commercial development [33]

Proven Commercial	Semi-Commercial	Pilot Plant
Blast Furnace	Finmet	Tecnored
Corex	Circored	HIsmelt
Midrex	Iron Dynamic	Fastmet
HyL	Maumee	Dios
SL/RN	Inmetco	Romelt
	Redsmelt	ITmk3

2.4.2 Comparison of iron-making technology

Comparison of advantages and disadvantages of iron-making technology is presented in Table 2.4. The iron-making technology is classified by furnace types. Accordingly, midrex process is the most widespread gas based direct reduction technology while coal based direct reduction technology is being developed to the commercialization demonstration stage. The corex process is the smelting reduction technology used in commercial technology while other technologies are being developed alternative of iron making technology [34].

Table 2.4 Comparison of advantages and disadvantages of iron-making technology [32]

Iron-Making Technology	Advantages	Disadvantages
Shaft - MIDREX - HYL III - AREX	- High quality product - Accept able on industrial scale - Production, operations and economic data are sufficient - Less environmental impact - Without export gas	- Not suitable for countries with high gas prices - Use high quality of raw material so high costs - Process less flexibility - No waste recovery
Fluid Bed - FIOR - CIRCOFER - CIRCORED - FINMET - IRON CARBIDE	- High quality product - Low raw material costs because of use of iron ore fines - Environmental friendly - Without export gases	- High investment cost - High gas costs in some countries excluding CIRCOFER process use coal - Sensitive to size and quality of iron ore - Process control and manufacturing operations difficult

Table 2.4 Comparison of advantages and disadvantages of iron-making technology (Cont') [32]

Iron-Making Technology	Advantages	Disadvantages
Rotary Hearth - INMETCO - FASTMET	- Suitable for small capacity - Use iron ore fines and coal for smelting - Production process flexibility - Smelting process not long time because process is high temperature - Low investment cost - Recycle raw material waste	-Low-quality products - Sulfur from raw material preparation process - Limit capacity - Only a few plant use this technology - Requires off gas treatment - Contamination in metallic - Low product density - Use a lot of coal
Rotary Hearth+Electric Melter - REDSMELT - FASTSMELT	- The product in liquid form - Use iron ore fines and coal for smelting - Suitable for production in small scale - Without export gases	- High investment cost - Limit capacity - Only a few plants use this technology - Requires off gas treatment - High electricity consumption - Use a lot of coal
Smelt Reduction - AISI - DIOS - FINEX - HISMELT - ROMELT - TECNORED - COREX - AUSMELT - NST	- The product in liquid form - Use coal for smelting - Use fine raw ore except COREX process - Suitable for production in small and medium scale - Electricity power not necessary	- Lack of data on industrial production except COREX - High export gas - Need more oxygen - The process less flexible
Rotary Kiln - SL/RN - DRC	- Accept in industrial scale - Shape of mineral is not important - Process is not complicated - Suitable for small-scale production	-Low-quality products because slag and sulfur - Smelting process takes a long time - Limit capacity - Require waste gas treatment process - The process is less flexible - Use a lot of coal

Comparison of raw materials used for 1 tonne of steel production in blast furnace, direct smelting and direct reduction is shown in Table 2.5. The results show that conventional blast furnace uses lump ore more than that of compact blast furnace and mini-blast furnace. Coal and coke are energy sources used in various technologies except fimmet, midrex and Hyl. These technologies use natural gas and electricity as energy source. Water consumption for iron-making process is approximately 1-2 m^3 per ton of steel production.

Table 2.5 Raw materials used for 1 tonne of steel production of each technology [32]

Material	Unit	Blast Furnace			Direct Smelting		Direct Reduction						
		Conventional	Compact	Mini	Corex C-3000	HIsmelt	Finmet	Midrex	HyL	SL/RN	Fastmet	Inmetco	Iron Dynamic
Pellets	t	-	1.06	-	1.48	-	-	1.05	1.04	-	-	-	-
Lump	t	491	430	1.56	-	-	-	0.45	0.44	1.39	-	-	-
Sinter	t	1.3	-	-	-	-	-	-	-	-	-	-	-
Fine	t	-	-	-	-	1.48	1.5	-	-	-	1.35	1.22	1.33
Coal	kg	175	170	150	980	850	-	-	-	340	380	475	412
Coke	kg	335	380	400	-	-	-	-	-	-	-	-	-
Electricity	Kwh	127.5	100	120	75	-	165	125	125	-	150	60	90
NG	MBTU	-	4	2.84	-	2.76	13.3	33.2	33.2	8.36	2.97	2.78	2.41
Oil	kg	-	120	-	-	-	-	-	-	-	-	-	-
Water	m^3	-.	1.2	1.5	1.5	-	2	1.5	1.7	2	1	1	1
O_2	m^3	62	32	-	540	217	-	-	-	-	-	-	-
N_2	m^3	-	15	3	80	-	-	-	-	-	-	-	-
Additive	kg	183	250	242	0.11	-	-	-	-	40	20	24	-
Nominal Capacity	Mt/y	3.0	0.8-1.0	0.25-0.6	1.1	0.5-1.5	0.4	0.5-1.5	0.5-1.5	0.2-0.4	0.2-0.6	0.2-0.6	0.2-0.6

It can be seen that the blast furnace process is the oldest technology used for a long time which is 95% of world production. Midrex process is the most widespread gas based direct reduction technology and corex process is the most developed smelting reduction technology used in commercial. Therefore, these three iron making technologies are selected in this research.

2.5 Estimation of greenhouse gases emission from the iron and steel production

The greenhouse gas emissions (GHG) from the industry sector in 2000 was approximately 21% of world GHG emissions as shown in Figure 2.4. Within the industry sector, chemicals and petrochemicals, cement and iron and steel accounted for the largest shares of sector-wide emissions. Steel manufacturing found about 70 percent of emissions coming from direct fuel use and the remaining coming indirectly from electricity and heat [35].

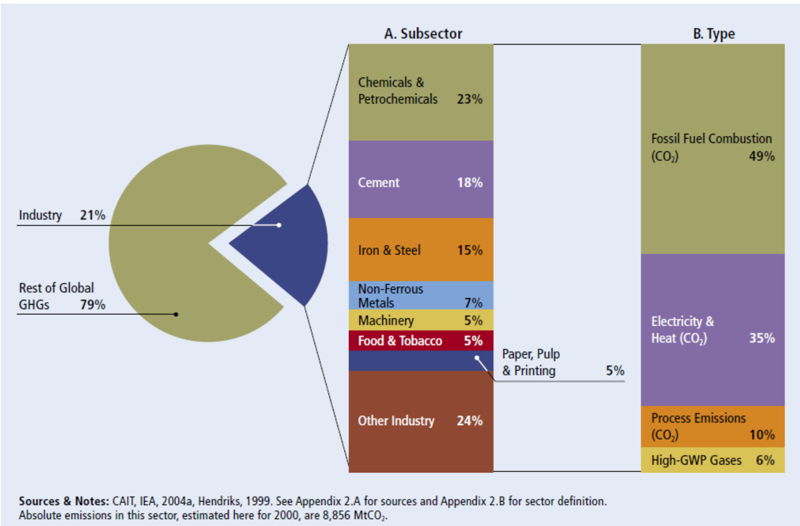


Figure 2.4 Greenhouse gas emissions (GHG) from industry sector [35]

There are different methods and technical guidelines for calculating greenhouse gas emissions for the iron and steel sector that have been developed by different international organizations. Their approaches are summarized as follows [36].

2.5.1 The 2006 IPCC Guidelines

The 2006 IPCC Guidelines present three tiers for estimating CO_2 emissions from chemical reactions in process. The Tier 1 method uses production-based emission factors in which default emission factors are multiplied by the quantity of material produced. Tier 2, method uses a mass balance approach and material-specific carbon contents whilst Tier

3 method requires plant-specific emissions or disaggregated activity data for estimating CO_2 emissions [37]. The calculation method of CO_2 emissions in each tier is shown below.

Tier 1 method

CO_2 emissions from chemical reactions in process can be calculated by multiplying activity data with default emission factors, as shown in Equation 2.1. In the case that some emission factors for steel production is not available, default CO_2 emission factors for iron and steel production is provided in Table 2.6.

$$CO_2 \text{ emission}_i = AD_i \times EF_i \tag{2.1}$$

Where,

AD_i is activity data of i product (t product)

EF_i is default emission factor of i product (t CO_2/t product)

Table 2.6 Tier 1 default CO_2 emission factors for iron and steel production [37]

Process	Emission Factor	Units
Sinter Production	0.20	t CO_2/t sinter produced
Coke Oven	0.56	t CO_2/t coke produced
Iron Production	1.35	t CO_2/t pig iron produced
Direct Reduced Iron Production	0.70	t CO_2/t DRI produced
Pellet Production	0.03	t CO_2/t pellet produced
Steelmaking process		
Basic Oxygen Furnace (BOF)	1.46	t CO_2 /t of steel produced
Electric Arc Furnace (EAF)*	0.08	t CO_2/t of steel produced
Open Hearth Furnace (OHF)	1.72	t CO_2/t of steel produced
Global Average Factor (65% BOF, 30% EAF, 5% OHF)	1.06	t CO_2 /t of steel produced

Remark: This table is not applicable to EAFs that use pig iron as a raw material

*The emission factor for EAF steelmaking does not include emissions from iron production.

Tier 2 method

Tier 2, a mass balance approach with material-specific carbon content, was applied in this study as illustrated in Equation 2.2. Tier 2 methods are appropriate if the inventory compiler has access to national data on the use of process materials for iron and steel production. The material-specific carbon contents for iron and steel and coke production are in Table 2.7.

$$CE_p = [\sum_{a=1}^{e}(Q_a \times C_a) - (S \times C_s)] \times 44/12 \qquad (2.2)$$

Where,

CE_p is CO_2 emissions from chemical reactions in process (tonne CO_2)

e is number of carbonaceous input types

a is type of carbonaceous material, namely 1 = scrap, 2 = coal, 3 = limestone, 4 = dolomite, and 5 = carbon electrodes

Q_a is quantity of carbonaceous material consumed in EAF process (tonne product)

C_a is carbon content of material input (tonne C/ tonne product)

S is quantity of steel product (tonne product)

C_S is carbon content of steel product (tonne C/ tonne product)

44/12 is stoichiometric ratio of CO_2 and C

Table 2.7 Tier 2 material-specific carbon contents for iron and steel and coke production [37]

Process Materials	**Carbon Content (kg C/kg)**
Blast Furnace Gas	0.17
Charcoal	0.91
Coal	0.67
Coal Tar	0.62
Coke	0.83
Coke Oven Gas	0.47
Dolomite	0.13
EAF Carbon Electrodes	0.82
EAF Charge Carbon	0.83

Table 2.7 Tier 2 material-specific carbon contents for iron and steel and coke production (Cont') [37]

Process Materials	Carbon Content (kg C/kg)
Fuel Oil	0.86
Gas Coke	0.83
Hot Briquetted Iron	0.02
Limestone	0.12
Natural Gas	0.73
Oxygen Steel Furnace Gas	0.35
Petroleum Coke	0.87
Purchased Pig Iron	0.04
Scrap Iron	0.04
Steel	0.01
Coking Coal	0.73
Direct Reduced Iron (DRI)	0.02

Tier 3 method

Unlike the Tier 2 method, the Tier 3 method uses plant specific data. The Tier 3 method provides an even more accurate estimate of emissions than the Tier 2 method because plants can differ substantially in their technology and process conditions.

2.5.2 U.S. GHG Inventory

The estimation of carbon contained in the steel produced is based on a mass balance approach. The raw materials consumption of sinter, pellet, and direct reduced iron production does not include in inventory but the GHG emissions from these other processes are included (but not separately identified) in the "Energy" section of the inventory. Methane emissions from metallurgical coke production and pig iron production are calculated by multiplying activity data with emission factors [36].

2.5.3 WRI/WBCSD Calculation Procedures

The calculation of CO_2 emissions from the production of coke, sinter, DRI, and iron and steel is based on a carbon balance approach. The Tier 3, requiring the facility-specific data, is preferred for calculation. However, in the absence of facility-specific data, the Tier 1 default factors for carbon contents of inputs and outputs are provided for GHG calculation. The WRI/WBCSD presented estimating CH_4 emissions from the production of coke, sinter, pig iron, and DRI by assuming 2 percent of the CH_4 in the gas is not burned [36].

2.5.4 European Union (EU) Emissions Trading System

The highest tier is used for estimate major emission source, which is similar to the IPCC Tier 2/3 methods. The calculation methodology is based on emission source and is defined as: (1) “de-minimus” sources that collectively contribute less than 1,000 MT CO_2/yr or that contribute less than 2% of total emissions up to 20,000 MT/yr; (2) “minor” sources that collectively contribute less than 5,000 MT CO_2/yr or that contribute less than 10% of total emissions up to 100,000 MT/yr; and (3) “major” sources that include all other streams [36].

2.5.5 The United States Department of Energy (DOE) Technical Guidelines

The DOE guideline focuses on raw-material that contains the most carbon such as limestone, dolomite, coke/coal, iron, steel, and graphite electrodes. There are 3 general approaches for calculation which are given a rating of A, B, or C. The approaches that use a carbon balance around the process with site-specific data for process inputs, outputs, and carbon content is defined as a rating of “A”. A rating of “B” is for approaches that use default values for carbon content. The “C” rating is used when the simply estimated is used such as 1.75 MT CO_2/ton of steel [36].

2.5.6 The American Iron and Steel Institute (AISI) Methodology

The AISI methodology is based on a carbon balance approach. The carbon balance focuses on major carbon emissions source that do not include minor contributors, for example scrap, iron ore and ferroalloys. The significant carbon emissions source such as iron carbide, carbon electrodes, charge carbon and limestone should be reported [36].

2.5.7 World Steel Association (WSA)

World steel association calculates greenhouse gas emission by Life Cycle Assessment (LCA) methodology. LCA is a technique to assess the environmental impacts throughout its life cycle. The four basic stages of LCA’s frameworks consist of goal and scope definition, inventory analysis, impact assessment and interpretation process [38].

2.6 Overview of iron and steel industry and CO_2 emissions in worldwide

2.6.1 Iron and steel production and consumption

In 2001, world crude steel production was 852 million tonnes. The global steel production has been increasing rapidly as shown in Figure 2.5. In 2009, crude steel production decreased 1,238 million tonnes due to world economic crisis [39]. In 2013, the world steel industry produced 1,606 million tonnes of crude steel.

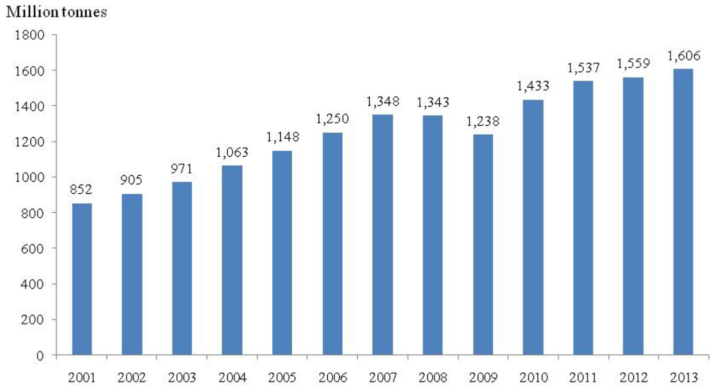


Figure 2.5 World crude steel productions from 2001 to 2013 [39]

Figure 2.6 indicated that China was the biggest steel producer (48.5%), followed by Asia (11.9%), EU-27 (10.3%), NAFTA (7.3%), Japan (6.9%) and CIS (6.7%), Others (5.9%) and Other Europe (2.4%) respectively [4].

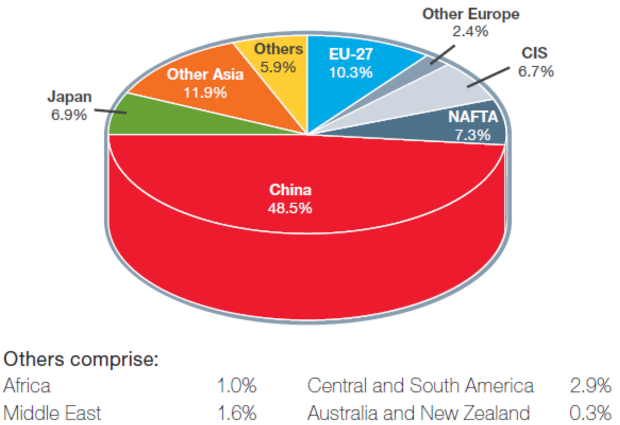


Figure 2.6 Crude steel productions in 2013 [4]

In 2013, world total apparent steel use (finished steel products) is 1,481 million tonnes. Similarly, China was the biggest apparent steel use (47.3%), followed by Asia (14.8%), EU-27 (9.3%), Others (9%), NAFTA (8.7%), Japan (4.4%) and CIS (4%), and Other Europe (2.5%) respectively as presented in Figure 2.7 [4].

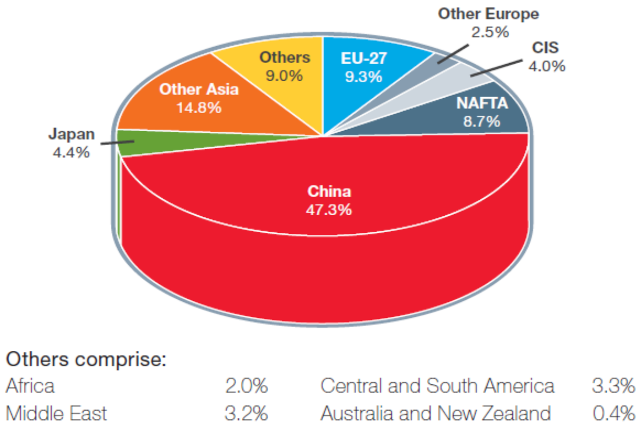


Figure 2.7 Apparent steel use (finished steel products) in 2013 [4]

Top steel producing companies in 2013 are presented in Table 2.8. ArcelorMittal is the largest producer in 2013.The capacity of crude steel production is 96.1 million tonnes, followed by Nippon Steel & Sumitomo, Hebei Steel Group, Baosteel Group, Wuhan Steel Group, POSCO, Shagang Group, Ansteel Group, Shougang Group and JFE, respectively [4].

Table 2.8 World crude steel production top producers in 2013 [4]

Rank	Company	Million tonnes
1	ArcelorMittal	96.1
2	Nippon Steel & Sumitomo	50.1
3	Hebei Steel Group	45.8
4	Baosteel Group	43.9
5	Wuhan Steel Group	39.3
6	POSCO	38.4
7	Shagang Group	35.1
8	Ansteel Group	33.7
9	Shougang Group	31.5
10	JFE	31.2

Due to economic growth, the demand in world iron and steel production is increasing gradually in each year, as shown in Figure 2.8. Quantity of world's ferrous scrap in year 2000-2008 was increased from 60 million tonnes to 90 million tonnes [40].

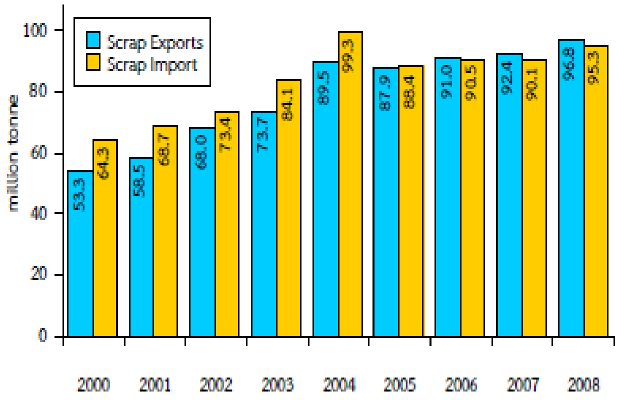


Figure 2.8: World's ferrous scrap import and export [40]

As illustrated in Figure 2.9, it can be seen that the traditional BF/BOF route is changed to the EAF-based mini-mills. The blast furnace operation trend is going to decrease in 2020 due to a major source of environmental emissions through their raw material preparation such as coke ovens, pellet and sinter plants. In 2020, the steel making trend showed OHF steel production technology is going to become obsolete due to their low efficiency and excessive environmental emissions. Despite, steel productions by EAF continuous growth the steel production should combine the use of the primary and secondary production methods due to not enough recycled steel [41].

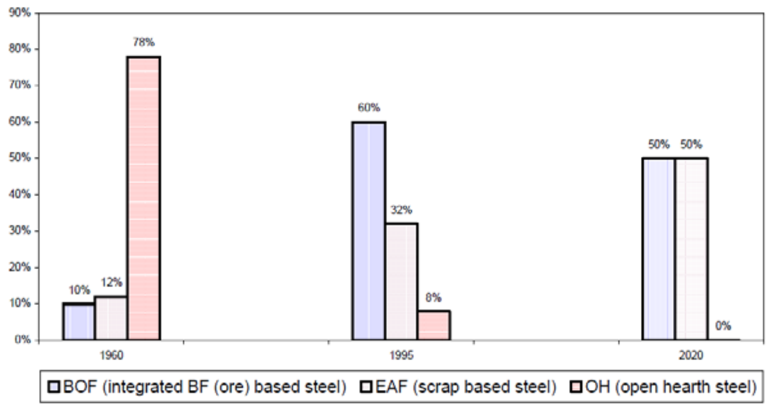


Figure 2.9 Steelmaking trends [42]

2.6.2 Energy and carbon dioxide intensities of iron and steel production in foreign countries

Today, the world steel industry accounts for 4 - 5 % of total man-made greenhouse gases. Over 90 % of emissions from the steel industry come from iron production in nine countries or regions: Brazil, China, EU-27, India, Japan, Korea, Russia, Ukraine, and the USA [43]. CO_2 emissions in iron and steel production are results from direct and indirect sources. CO_2 emissions indirect sources are come from fuel combustion and electricity consumption, while CO_2 emissions direct source come from iron and steel production process as shown in Equations 2.3-2.8.

- CO_2 emissions in coke combustion process and reaction in the smelting process

$$C + O_2 \longrightarrow CO_2 \qquad (2.3)$$

$$CO_2 + C \longrightarrow 2CO \qquad (2.4)$$

$$Fe_2O_3 + 3CO \longrightarrow 2Fe + 3CO_2 \qquad (2.5)$$

- CO_2 emissions in sinter production

$$CaCO_3 + Heat \longrightarrow CaO + CO_2 \qquad (2.6)$$

- CO_2 emissions in blast furnace combustion process

$$C + 0.5O_2 \longrightarrow CO + heat \qquad (2.7)$$

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O + heat \qquad (2.8)$$

The International Energy Agency (IEA) compares the CO_2 emissions for the three key processes of BF-BOF, DRI-EAF and scrap-EAF. The product in estimations is crude steel and the figures exclude rolling and finishing as shown in Figure 2.10. DRI process can reduce CO_2 emissions by using natural gas instead of coal and coke however DRI plant is mostly located near natural gas source countries such as the Middle East. The high and low-end ranges indicate CO_2-free and coal-based electricity and account for country average differences based on IEA statistics. The range is even wider for plant-based data.

According to IEA estimates, the indirect emissions of used electricity are also minor compared to blast furnace emissions. Crude steel production using scrap yields lower CO_2 emissions than other processes, but is limited by scrap availability [44].

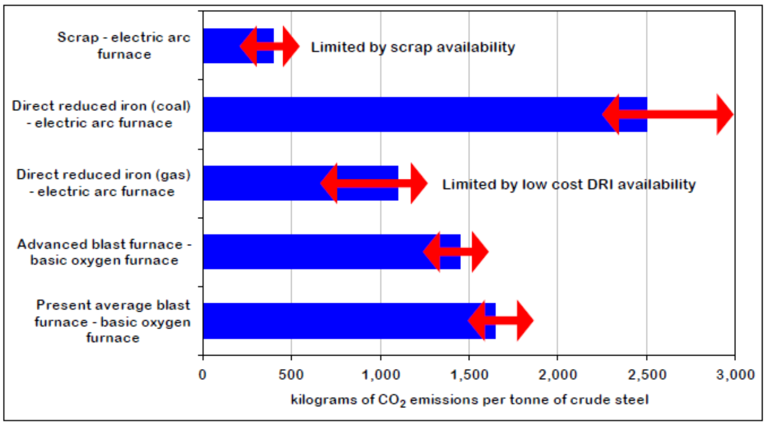


Figure 2.10 CO_2 emissions of iron and steel production process [44]

Energy intensity and CO_2 intensity within an integrated steel mill in the different processes found that blast furnaces (BF) contributed the most CO_2 emissions about 1.14-1.40 tCO_2/t liquid steel as shown in Table 2.9, because this process has a lot of fuel combustion at high temperature about 1500^o C. The energy intensity of fuel is more than energy intensity of electricity especially in blast furnace (BF) process. Comparison of CO_2 intensity between BF and DRI showed that CO_2 intensity of BF is more than that of DRI as 1.13 t CO_2/t liquid steel.

Table 2.9 Energy intensity and CO_2 intensity in integrated steel mill

Process	CO_2 intensity within an integrated steel mill		Energy intensity (GJ/t) [46]		Energy intensity (GJ/t) [47]	
	(tCO_2/t liquid steel) [45]	(tCO_2/t product) [37]	Electricity	Fuel	Electricity	Fuel
Coking	0.06-0.07	0.56	0.10	0.60	-	-
Pelletizing	0.03	0.03	-	-	-	-
Sintering	0.10-0.11	0.20	0.20	2.00	-	-
BF	1.14-1.40	-	0.10	11.40	-	-
BOF	-0.04-0.04	1.46	0.10	-0.70	-	-
BOF-slab	-	-	-	-	0.11	- 0.57
DRI	0.01	0.70	-	-	0.40	10.50
EAF (scrap)	-	0.08	-	-	-	-
EAF-slab	-	-	-	-	1.11	0.94
Pig iron	-	-	-	-	0.23	14.89

Table 2.9 Energy intensity and CO_2 intensity in integrated steel mill (Cont')

Process	CO_2 intensity within an integrated steel mill		Energy intensity (GJ/t) [46]		Energy intensity (GJ/t) [47]	
	(tCO_2/t liquid steel) [45]	(tCO_2/t product) [37]	Electricity	Fuel	Electricity	Fuel
Continuous casting	0.01	-	0.00	0.00	-	-
Hot rolling	-	-	-	-	0.35	1.53
Cold rolling	-	-	-	-	0.53	1.10
Rolling and finishing	0.20-0.29	-	0.30	1.30	-	-

World best practice final and primary energy intensity values for iron and steel are shown in Table 2.10. For primary energy consumption, losses in converting fuels to electricity and in transmission are taken into consideration. These are assumed to be 67%. The following table provides best practice energy consumption data for different commonly used process routes for iron and steel production. It should be noted that CO_2 intensity of different process routes highly depend on feedstock and material flows and can show significant variations between different plants. The smelt reduction - basic oxygen furnace is the highest total primary energy consumption, followed by direct reduced iron - electric arc furnace, blast furnace-basic oxygen furnace and scrap-electric arc furnace, respectively [46].

Table 2.10 World best practice final and primary energy intensity values for iron and steel (GJ/ tons of steel) [46]

Production step	**Process**	**Blast furnace-basic oxygen furnace**		**Smelt reduction - basic oxygen furnace**		**Direct reduced iron - electric arc furnace**		**Scrap-electric arc furnace**	
		Final	**Primary**	**Final**	**Primary**	**Final**	**Primary**	**Final**	**Primary**
Material preperation	Sintering	1.9	2.2	-	-	1.9	2.2	-	-
	Pelletizing	-	-	0.6	0.8	0.6	0.8	-	-
	Coking	0.8	1.1	-	-	-	-	-	-
Iron making	Blast furnace	12.2	12.4	-	-	-	-	-	-
	Smelt reduction	-	-	17.3	17.9	-	-	-	-
	Direct reduced iron	-	-	-	-	11.7	9.2	-	-
Steelmaking	Basic oxygen furnace	-0.4	-0.3	-0.4	-0.3	-	-	-	-
	Electric arc furnace	-	-	-	-	2.5	5.9	2.4	5.5
	Refining	0.1	0.4	0.1	0.4	-	-	-	-
Casting & rolling	Continuous casting	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Hot rolling	1.8	2.4	1.8	2.4	1.8	2.4	1.8	2.4
Sub-total		16.5	18.2	19.5	21.2	18.6	20.6	4.3	8

Comparison of CO_2 intensity for the iron and steel industry in six countries, Brazil, China, India (developing countries), Mexico and South Korea (newly industrialized countries) and the United States (industrialized country), are shown in Figure 2.11. The data used in this analysis are extracted from the database of the International Network for Energy Demand Analysis in the Industrial Sector (INEDIS). The database contains production data of intermediate and final products, electricity produced and energy use data in steel industry and electricity generation. Coke making has not been taken into account in this study. The result showed structural change in the product mix also contributed to changing emission characteristics. In Brazil, China, India and the US have a shift to a more CO_2 intensive product mix either a change to more integrated steel production, such as in Brazil and China or more CO_2 intensive final products in US. On the other hand, in South Korea and Mexico, there is a shift to a less CO_2 intensive product mix, upward trend in the share of EAF. Changes in power generation contributed only to a reduction of specific emissions in the case of South Korea. In the case of Brazil, a trend away from capital intensive hydropower generation to fossil-power electricity generation has resulted in a significant contribution to the increase in CO_2 emissions from steelmaking [47].

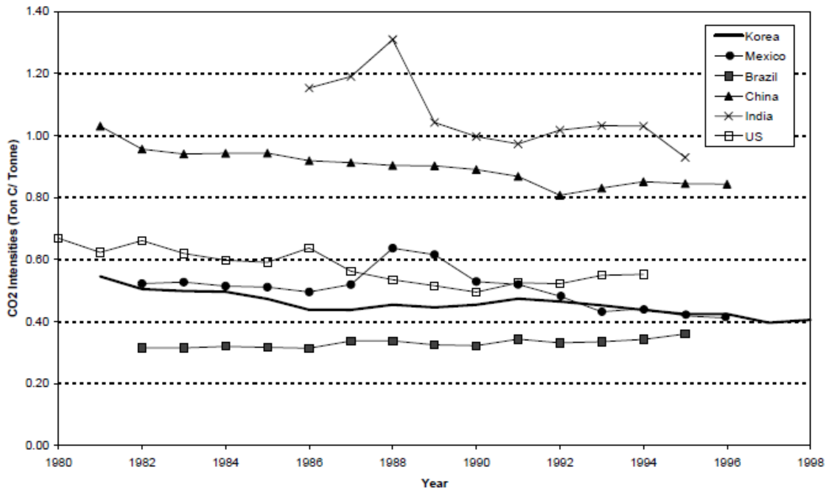


Figure 2.11 CO_2 intensities for the iron and steel industry in six countries [47]

Figure 2.12 showed the comparison of CO_2 intensity for the iron and steel production in ten countries. The scopes of CO_2 emission calculation include direct emissions and indirect emissions. Direct CO_2 emissions are emissions from sources that are owned or controlled by the company. CO_2 is emitted from during the iron and steel production process due to chemical reactions, on-site burning of fossil fuels, and electricity used. Indirect CO_2 emissions are emissions that are a consequence of the activities of company, but occur at sources owned or controlled by another entity. Indirect CO_2 emissions come from consumption of purchased electricity, heat or steam. The results showed that Russia contributed the most of total CO_2 intensity and followed by China, India, Maxico, Canada, Brazil, United States, Korea, Japan and EU 25, respectively. There is plenty of obsolete technology in Russia. On the other hand, in Japan and EU 25, there is less CO_2 intensive due to energy efficiency improvements and applying best available technology to outdated steel plants. For direct CO_2 emissions, US steel production is the least direct CO_2 emissions due to nearly half of all steel in the United States is made in mini-mills that use electricity to recycle scrap steel rather than starting from burning coal and coke to melt iron ore into iron. The electric arc furnaces (EAF) employed by the mini-mills emit only one fourth of the amount of CO_2 per ton of steel [48].

(tons of CO_2 emissions per ton of steel)

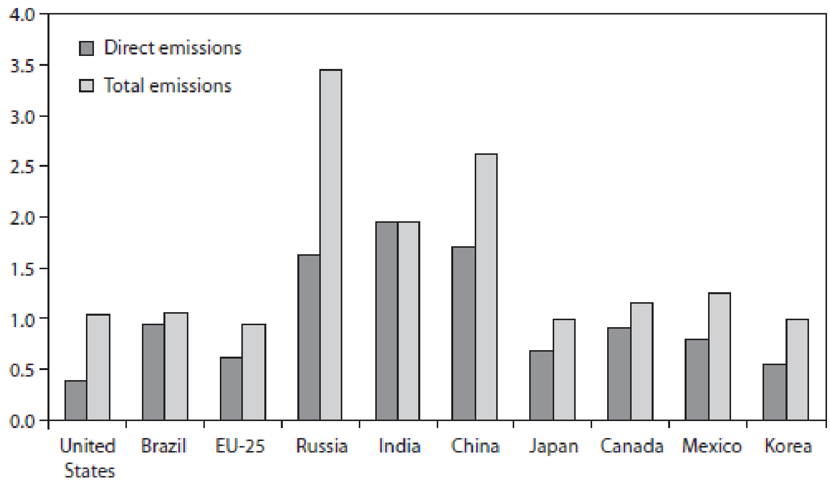


Figure 2.12 CO_2 intensity of steel production in 2005 [48]

In addition, the study of IEA in 2007 found that CO_2 intensity of eleven iron and steel producers varies substantially between countries as seen in Table 2.11. This is due to differences in production processes and energy efficiency. The data comes from fuel combustion only without process emissions. The world carbon intensity average was 1.61 tCO_2/t products. China contributed the most of CO_2 intensity from fuel combustion, followed by Russia, India, Brazil, Mexico and South Korea, respectively [49].

Table 2.11 CO_2 intensities from fuel combustion in 2007 [49]

Country	**CO_2 intensity (t CO_2/t product)**
China	2.51
India	2.16
Brazil	1.03
Mexico	1.01
South Korea	1.00

Table 2.11 CO_2 intensities from fuel combustion in 2007 (Cont') [49]

USA	0.96
Japan	0.96
Russia	2.32
EU 27	0.64
Other developing countries	1.51
Other developed countries	0.64
World Total	**1.61**

2.7 Overview of iron and steel industry and CO_2 emissions in Thailand

2.7.1 Iron and steel production and consumption in Thailand

The structure of the iron and steel industry in Thailand proposed by the Iron and Steel Institute of Thailand (ISIT) is illustrated in Figure 2.13. Currently, Thailand does not have an upstream iron and steel industry. Only midstream and downstream iron and steel industries are available. The processing technology in the midstream industry is the electrical arc furnace (EAF) using scrap steel as the raw material. The products of this stage are semi-finished steel products, which are material inputs to produce finished steel products in the downstream industry [26].

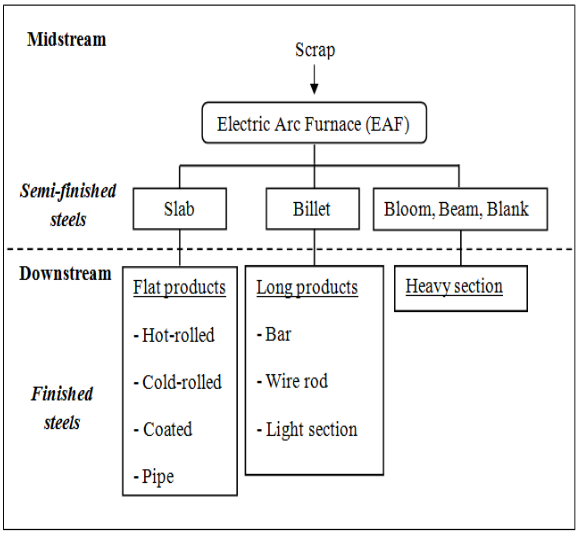


Figure 2.13 The structure of iron and steel industry in Thailand [26]

In 2010, the structure of semi-finished steel production in Thailand found that there were 16 companies that produced billet. The capacity was 4.11 million tonnes per year. The big producers were Chow Steel Industry, Siam Construction Steel, N.T.S. Steel and Siam Iron and Steel which is a subsidiary of Tata Steel Thailand. Slab manufacturers were from two companies, GJS and G-steel. The total capacity was 3.0 million tonnes per year, as shown in Table 2.12 [40].

Table 2.12 Structure of semi-finished steel production in Thailand [40]

Products	Company	Capacity (tonnes/year)
Billet	Siam Construction Steel	520,000
	N.T.S. Steel	445,000
	Siam Iron and Steel (2001)	375,000
	UMC Metals	420,000
	Bangkok Steel Industry	300,000
	NamhengSteel	300,000
	Bangkok Iron and Steel Works	240,000
	B.N.S. Steel	250,000
	Triumph Steel	120,000
	Thai Steel Bars	120,000
	TICO Steel (Thailand)	78,000
	Kasemsak Trading	60,000
	Siam Steel Syndicate	110,000
	Chow Steel Industry	730,000
	T.S.B Steel	36,000
	STD Steel	8,000
Slab	GJS	1,500,000
	G-steel	1,500,000

The overviews of semi-finished steel products in Thailand are shown in Figure 2.14 [7]. It is obviously seen that domestic steel production is inadequate for the domestic steel consumption for semi-finished products. This is due to the lack of domestic upstream iron production in Thailand. Consequently, imported intermediate steel products, such as slab, bloom, billet, are necessary.

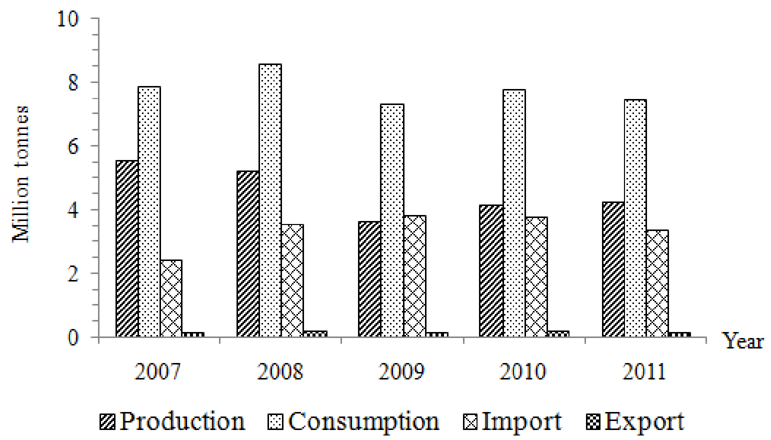


Figure 2.14 Overview of semi-finished steel products in Thailand [7]

There is insufficient demand for billet production in the country. Therefore Thailand has to import a huge amount of billet as shown in Figure 2.15. In 2010, billet was imported from Russia (53%) and follow by Ukraine (24%) and Brazil (8%), Turkey (5%), Italy (3%), Taiwan (3%), South Korea (2%) and other countries (2%) respectively.

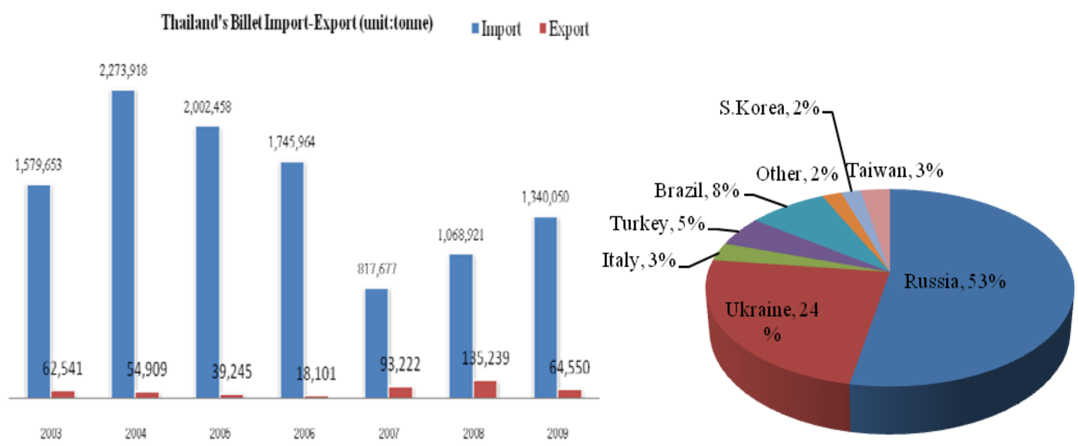


Figure 2.15 Billet import and export in Thailand [40]

Additionally, Thailand imported a huge amount of slab in 2010. Slab was imported from Russia and the Ukraine with approximately 60% of the slab imported markets of Thailand, as presented in Figure 2.16.

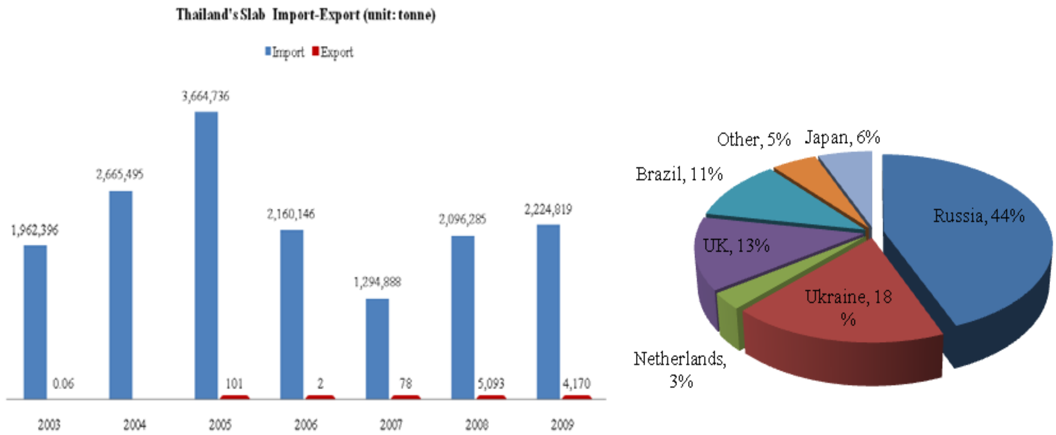


Figure 2.16 Slab import and export in Thailand [40]

The overviews of finished steel products in Thailand are shown in Figure 2.17 [7]. It is obviously seen that domestic finished steel production is inadequate for the domestic finished steel consumption. Consequently, the imported finished steel products in Thailand are required.

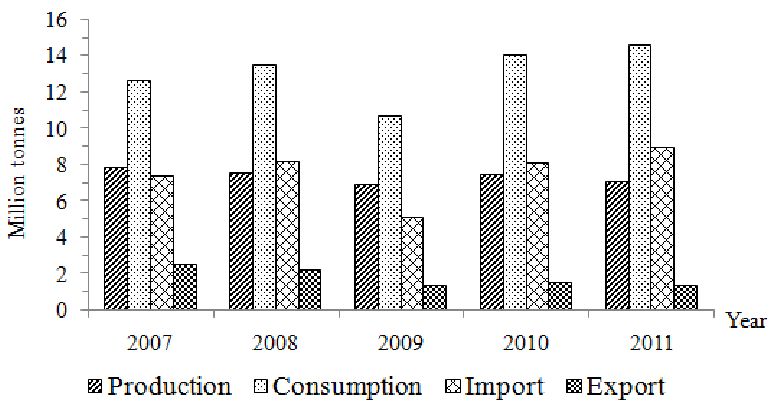


Figure 2.17 Overview of finished steel products in Thailand [7]

Japan is the major country for Thailand’s imported finished steel, accounting for 61% followed by China (15%), South Korea (11%), other countries (5%), Australia (4%) and Taiwan (4%) respectively as shown in Figure 2.18 [40].

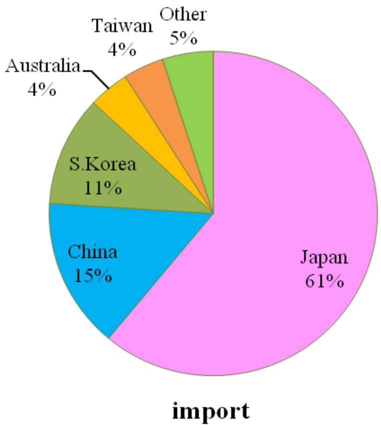


Figure 2.18 Thailand’s finished steel imports [40]

Among all types of finished steel consumption in Thailand, approximately 29% is hot rolled coil sheet & plate, followed by bar & section (26%), coated steel (21%), wire rod (13%) and cold rolled carbon & stainless (11%), as shown in Figure 2.19 [40].

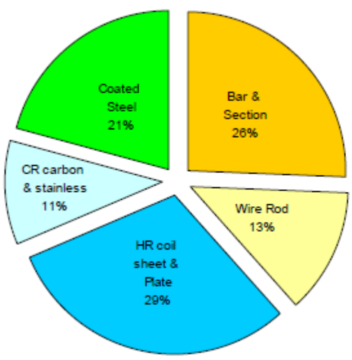


Figure 2.19 Type of finished steel consumption in Thailand [40]

Currently, steel is produced in Thailand by electric arc furnaces (EAF) using scrap as a feedstock. However, the domestic consumption of scrap is still much higher than its domestic supply, as shown in Figure 2.20. The scrap supply in 2000 was 1.99 million tonnes, increasing to 3.12 million tonnes in 2008. However, the scrap consumption was up to 2.64 million tonnes in 2000, increasing to 5.33 million tonnes in year 2008 [40]. The increasing demand of scrap for the iron and steel industry was mainly generated by the demand of steels for some development projects, especially the infrastructural works and real estate such as transportation, housing and construction. Therefore, the import of scrap steel will still be required. In 2008, scrap imports amounted to 2.58 million tonnes whilst only 0.36 million tonnes are exported. According to the study of ISIT, domestic scrap supply in 2050 would be 16.1 million tonnes, whilst the domestic scrap consumption would increase to 24.79 million tonnes [40]. Due to the high demand of scrap in each year, ISIT believed that use of scrap for only the production of steel might not be feasible, because there was inadequate domestic and imported scrap in Thailand. Therefore, an alternative integrated DR-EAF (Direct reduction-Electric arc furnace) route based on natural gas was proposed.

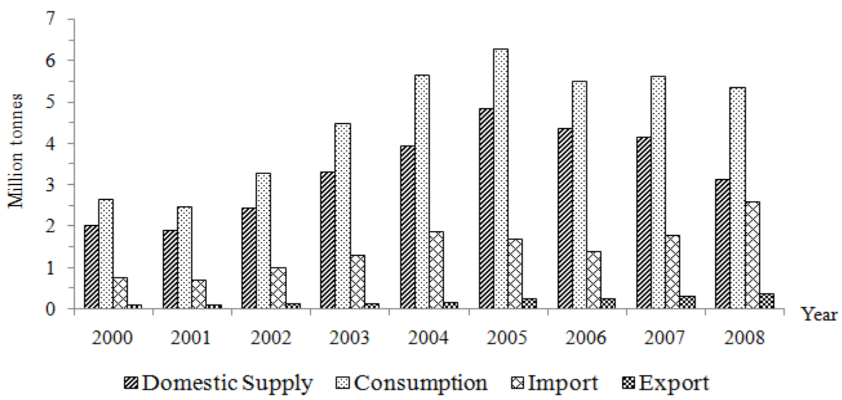


Figure 2.20 Thailand scraps demand and supply [40]

In 2012, it was reported that the increasing demand of steel was mainly from the construction sector (54%), followed by the automotive industry (16%), machinery and industrial (13%), appliance (12%) and packaging (5%), respectively as illustrated in Figure 2.21 [7].

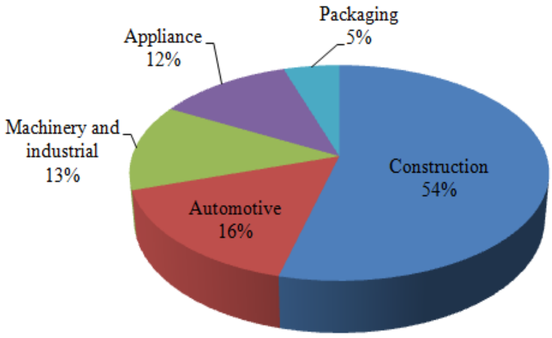


Figure 2.21 Steel applications in Thailand [40]

From the data above, it can be seen that iron and steel supply in Thailand is not sufficient to its demand. This is due to the lack of upstream industry in Thailand. As a result, raw materials, as well as both semi-finished and finished steel products, have to be imported from foreign countries.

2.7.2 Energy and carbon dioxide intensities of iron and steel production in Thailand

Pui-Ock and Tangtakul studied the specific energy consumption of Thailand's steel industry. The products were classified by process into 15 types. The specific energy consumption of process was calculated from energy consumption of all factories in the same process divided productivity in the same process. The total specific energy consumption was calculated from total energy consumption (electricity consumption and fuel consumption) divided by total productivity. Steel wire rod product with electric arc furnace was highest specific energy consumption in Thailand's steel industries, followed by hot rolled plate with electric arc furnace and round bar with electric arc furnace as illustrated in Table 2.13. The energy consumption of Thailand's steel industry in 2004 was 613 ktoe [50].

Table 2.13 The specific energy consumption in Thailand's steel industries in 2004 [50]

Group	Consumption					
	Specific energy average (MJ/ton)	**Electricity (kWh/t)**	**Oxygen (MJ/t)**	**Fuel (MJ/t)**	**Total energy (toe/t)**	**Total energy (ktoe)**
1. Round bar (with EAF)	5,095	728	531	1,942	0.12	71
2. Round bar (without EAF)	2,075	111	0	1,674	0.05	27
3. Wire rod (with EAF)	6,442	817	1,180	2,320	0.15	29
4. Wire rod (without EAF)	3,212	291	0	2,163	0.08	32
5. Hot rolled plate (with EAF)	6,051	680	796	2,807	0.14	87
6. Hot rolled plate (without EAF)	2,886	85	0	2,850	0.07	8
7. Hot-rolled flat product (with EAF)	4,710	758	657	1,324	0.11	181
8. Hot-rolled flat product (without EAF)	2,246	158	0	1,677	0.05	115
9. Cold- rolled coil	1,787	210	0	1,030	0.04	40
10. Hot dip galvanizing	1,439	72	0	1,179	0.03	4
11. Electro galvanizing	1,300	234	0	459	0.03	6
12. Tin plating	876	146	0	350	0.02	10
13. Section (C shape)	21	6	0	0	0.0005	0.01
14. ERW pipe	235	65	0	0	0.01	2
15. Zinc coated pipe	1,670	129	0	1,207	0.04	3
Total						**613**

In addition, the study of Good Governance for Social Development and the Environment Institute has [51]. The data came from energy consumption only. The results found that average CO_2 intensity of iron and steel production in Thailand was 0.43 tonne CO_2/tonne product as shown in Table 2.14.

Table 2.14 CO_2 emissions of iron and steel production in Thailand [51]

Year	Total CO_2 equivalent (Mg)	Iron production (tonne)	Tonne CO_2/tonne product
2001	2,672,362.24	5,560,120.79	0.47
2002	2,417,269.20	5,633,734.32	0.43
2003	3,345,803.68	8,238,374.93	0.41
2004	3,897,117.48	9,287,628.76	0.42
2005	3,186,916.34	9,254,782.89	0.34
2006	4,195,384.85	8,817,909.46	0.48
Average	**3,285,808.97**	**7,798,758.53**	**0.43**

The process routes of iron and steel production in Thailand are midstream and downstream industries. Processing technology in Thailand is mostly electrical arc furnace (EAF) using steel scrap as raw materials. Thus, CO_2 emissions result from fuel and electricity use. The process uses recycled scraps, result in lower CO_2 emissions than that from integrated steel work. In 1996, IISI carried out a “cradle to gate” LCI study. The results from LCI study showed that the CO_2 emissions of BF-BOF route were approximately 3.5 times as high as those of the EAF route in the upstream industry. Comparison of CO_2 intensity between Thailand and global average indicated that EAF: rebar-wire rod process in Thailand had lower CO_2 intensity than global average as 0.16 tonne CO_2 /tonne product as shown in Table 2.15.

Table 2.15 Comparisons of CO_2 intensity between Thailand and Global Average

Process	**Global Average** [52] **(tonne CO_2 /t product)**			**Thailand (tonne CO_2 /t product)** [51]
	Maximum	**Minimum**	**Average**	
BF- one ton of hot rolled coil and plate	2. 60	1. 61	1. 97	-
EAF: section	0. 77	0. 31	0. 54	-
EAF: rebar-wire rod-eng. steel	1. 08	0. 15	0. 59	0.43

2.8 Iron and steel production scenarios in Thailand

The Iron and Steel Institute of Thailand (ISIT) proposed three plausible scenarios in the master plan of energy management for Thailand iron and steel industry, which were S1: without integrated steel plant (baseline scenario), S2: with a traditional integrated BF-BOF route and S3: with an alternative integrated DR-EAF route [53]. Accordingly to the study of ISIT, the projection of steel demand from 2011 to 2030 was based on the demand structure of the steel market. The growth rate of steel demand was estimated based on the potential for the growth in five major steel consuming sectors in Thailand comprising automotive, construction, machinery, appliances and packaging [7]. All steel demand was averaged as 2.7 % per year, in line with the growth in these five sectors. Thus, the projection of steel demands in this study was evaluated by using the same growth rate of each steel product reported from ISIT study. The demand growth rates of the specific steel products used in this study were 2.1% (semi-finished steel product), 2.6 % (hot rolled long product), 1.9 % (hot rolled flat product), 4.6 % (coated sheet product), 1.2% (cold rolled steel product) and 5% (pipes) respectively. The details for each scenario are shown in Table 2.16. Scenario 1 has no integrated steel plant in Thailand. Currently, most of steel making processes in Thailand are electrical arc furnace (EAF) process using scrap steel as the raw material. The production capacity of each steel product in this study increases not in excess of 80% of the maximum production capacity of these products. For Scenario 2, the integrated steel plants using blast furnace-basic oxygen furnace (BF-BOF) route will be established in 2019. The maximum production capacity up to 9 million tonnes per year for BF-BOF plant is proposed. The iron and steel production capacity is divided into two phases. The production capacity for BF-BOF route for the first four years will be 25-47.5 % of maximum production capacity. The ISIT forecasts that the production capacity will be 89.7% of maximum production capacity for the second phase during 2023 to 2030 due to high end steel demand in Thailand. An alternative integrated DR-EAF (Direct reduced-Electric arc furnace) route based on natural gas was proposed in Scenario 3. The direct reduced iron process will be established in 2019 with a production capacity of 1 million tonnes per year for long products and 1 million tonnes per year for flat products. The production of direct reduced iron in this study uses natural gas as a reducing agent. The production capacities will be 55.5% and 77.8% of the maximum production capacity in 2019 and 2020, respectively. According to the interviews with experts from the Iron and

Steel Institute of Thailand (ISIT), the production capacity scenario for direct reduced iron will reach its maximum production capacity to serve high- end steel production in Thailand during the year 2021 to 2030.

Table 2.16 Iron and steel production scenarios in Thailand [53]

Scenarios	Implementation year	Production capacity of iron making
S1: Without integrated steel plant (baseline scenario)	2011-2030	No iron making Holds current capacity and further demand is supported by imports
S2: With a traditional integrated BF-BOF route	2019-2022	25-47.5 % of maximum production capacity
	2023 – 2030	89.7 % of maximum production capacity
S3: With an alternative integrated DR-EAF route	2019-2020	55.5 % and 77.8% of maximum production capacity (1 million tonnes per year for long products and 1 million tonnes per year for flat products)
	2021 -2030	Maximum production capacity (1 million tonnes per year for long products and 1 million tonnes per year for flat products)

However, the projections of steel demands in this research were carried out by using the relevant economic driver as the growth rates of steel demand studied by Iron and Steel Institute of Thailand [53]. The data and the assumption of the proposed scenarios was verified and updated with ISIT in December 2013.

2.9 Alternatives for mitigating of CO_2 emissions in iron and steel production

Enhancing energy efficiency and employing energy saving/recovering technologies can be short-term approaches to reduce greenhouse gas emissions. The long-term approaches to achieving a significant reduction in CO_2 emissions from the steel industry would be through developing and applying CO_2 breakthrough technologies for iron and steel making [54]. There are many options to reduce CO_2 emissions in iron and steel production as presented below.

2.9.1 Available and emerging technologies for reducing greenhouse gas emissions from the iron and steel industry

There are many researches reporting about energy efficiency in the iron and steel process such as the study of IEA. It was found that improvement in the blast furnace was the main saving potential as illustrated in Figure 2.22 [49]. Ukraine ranks the first in terms of having the biggest potential CO_2 emission reduction that is 0.7 t CO_2/t steel, the biggest of any country followed by India, Brazil, China, Russia and respectively. While China emits most of the CO_2 emissions, followed by OECD Europe, the Ukraine, Russia and India.

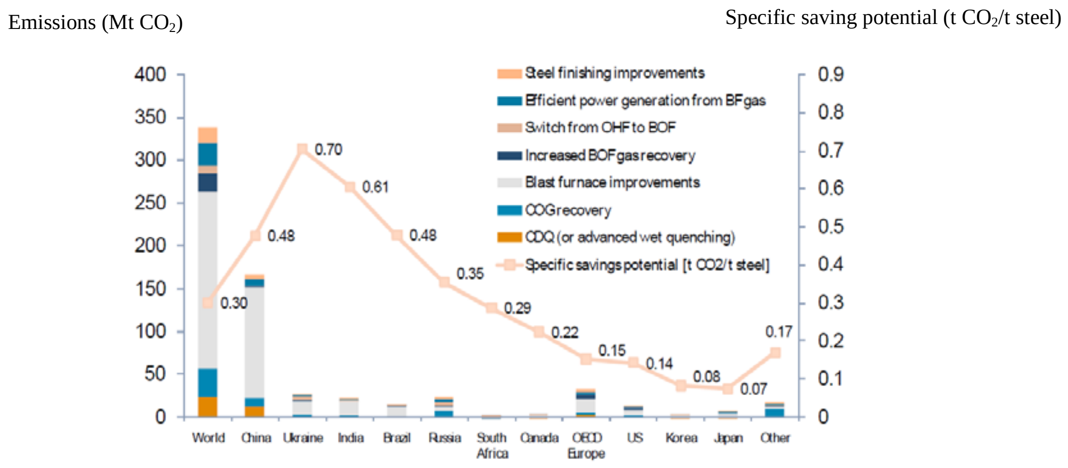


Figure 2.22 CO_2 reduction potentials based on best available technology in 2005 [49]

Additionally, the US Environmental Protection Agency (US.EPA) studied the available and emerging technologies for reducing greenhouse gas emissions from the iron and steel industry, as illustrated in Table 2.17. The details of CO_2 mitigation options includes energy savings, CO_2 emission reduction, operating costs and retrofit capital costs and payback time. It also should be noted that costs in year 2008 is used for calculation. [55]. In addition, this study showed that the options with payback times of more than three years are not likely to be considered economically feasible by a facility.

Table 2.17 Available and emerging technologies for reducing greenhouse gas emissions from the iron and steel industry [55]

Options	Emission Reduction ($kgCO_2/t_p$)	Fuel Savings (GJ/t_p)	Electricity Savings (GJ/t_p)	Annual Operating Costs ($\$/t_p$)	Retrofit Capital Costs ($\$/t_p$)	Payback Time (years)
Iron Ore Preparation						
Sinter plant heat recovery	57.2	0.55	0.0	0.0	4.7	2.8
Sintering						
Reduction of air leakage	2.0	0.0	0.0	0.0	0.14	1.3
Increasing bed depth	9.9	0.09	0.0	0.0	0.0	0.0
Process control	5.0	0.05	0.0	0.0	0.21	1.4
Use of waste fuels (e.g., lubricants) in sintering plant	19.5	0.18	0.0	0.0	0.29	0.5
Coke making						
Coal moisture control	6.7	0.30	0.0	0.0	76.6	> 50
Programmed heating	3.8	0.17	0.0	0.0	0.37	0.7
VSD COG compressor	0.12	0.0	0.0	0.0	0.47	21.2
Coke dry quenching	27.5	1.2	0.0	0.78	109.5	35.7
Iron making - Blast Furnace						
Pulverized coal injection to 130 kg/ton iron	47.0	0.77	0.0	-3.1	11.0	2.0
Pulverized coal injection to 225 kg/ton iron	34.7	0.57	0.0	-1.6	8.1	2.4
Injection of natural gas to 140 kg/ton iron	54.9	0.90	0.0	-3.1	7.8	1.3
Top pressure recovery turbines (wet type)	17.6	0.0	0.11	0.0	31.3	29.8
Recovery of BFG	4.0	0.07	0.0	0.0	0.47	2.3
Hot-blast stove automation	22.6	0.37	0.0	0.0	0.47	0.4
Recuperator hot-blast stove	4.9	0.08	0.0	0.0	2.2	8.7
Improved blast furnace control systems	24.4	0.40	0.0	0.0	0.56	0.4
BOF gas plus sensible heat	46.0	0.92	0.0	0.0	34.4	11.9
VSD on ventilation fans	0.51	0.0	0.003	0.0	0.31	9.9

Table 2.17 Available and emerging technologies for reducing greenhouse gas emissions from the iron and steel industry (Cont') [55]

Options	Emission Reduction ($kgCO_2/t_p$)	Fuel Savings (GJ/t_p)	Electricity Savings (GJ/t_p)	Annual Operating Costs ($\$/t_p$)	Retrofit Capital Costs ($\$/t_p$)	Payback Time (years)
Casting						
Efficient caster ladle/tundish heating	1.1	0.02	0.0	0.0	0.09	1.3
Near net shape casting - thin slab	728.8	3.5	0.64	-54.8	234.9	3.3
General Measures for Rolling Mills						
Energy efficient drives	1.6	0.0	0.01	0.0	0.30	3.2
Hot Rolling						
Hot charging	30.2	0.60	0.0	-2.1	23.5	5.9
Process control in hot strip mill	15.1	0.30	0.0	0.0	1.1	1.2
Recuperative burners	35.2	0.70	0.0	0.0	3.9	1.8
Insulation of furnaces	8.0	0.16	0.0	0.0	15.6	31.0
Controlling oxygen levels and VSDs on combustion air fans	16.6	0.33	0.0	0.0	0.79	0.8
Waste heat recovery (cooling water)	1.9	0.03	0.0	0.11	1.3	> 50
Cold Rolling and Finishing						
Heat recovery on the annealing line	17.5	0.30	0.02	0.0	4.2	4.0
Reduced steam use (pickling line)	9.9	0.19	0.0	0.0	4.4	7.3
Automated monitoring and targeting system	35.3	0.0	0.21	0.0	1.7	0.8
General						
Preventive maintenance	35.7	0.43	0.02	0.03	0.02	-
Monitoring and management system	9.5	0.11	0.01	0.0	0.23	0.5
Heat and power/cogeneration	82.1	0.03	0.35	0.0	22.7	6.1

Table 2.17 Available and emerging technologies for reducing greenhouse gas emissions from the iron and steel industry (Cont') [55]

Options	Emission Reduction ($kgCO_2/t_p$)	Fuel Savings (GJ/t_p)	Electricity Savings (GJ/t_p)	Annual Operating Costs ($\$/t_p$)	Retrofit Capital Costs ($\$/t_p$)	Payback Time (years)
Variable speed drive (VSD) flue gas control, pumps, and fans	1.5	0.0	0.02	0.0	2.0	10.7
Steelmaking - Electric Arc Furnace (EAF)						
Improved process control (neural network)	17.6	0.0	0.11	-1.6	1.5	0.5
Transformer efficiency ultra-high power transformers	10.0	0.0	0.06	0.0	4.3	5.2
Bottom stirring/stirring gas injection	11.7	0.0	0.07	-3.1	0.94	0.2
Foamy slag practice	10.6	0.0	0.07	-2.8	15.6	4.2
Oxy-fuel burners	23.5	0.0	0.14	-6.2	7.5	0.9
DC arc furnace	52.9	0.0	0.32	-3.9	6.1	0.7
Scrap preheating-tunnel furnace (Consteel)	35.2	0.0	0.22	-3.0	7.8	1.3
Scrap preheating, post-combustion-shaft furnace (Fuchs)	35.3	-0.70	0.43	-6.2	9.4	1.0
Flue gas monitoring and control	8.8	0.0	0.05	0.0	3.1	4.3
Eccentric bottom tapping on existing furnace	8.8	0.0	0.05	0.0	5.0	6.8
Twin-shell DC with scrap preheating (DC = direct current)	11.1	0.0	0.07	-1.7	9.4	3.5

2.9.2 CO_2 breakthrough technologies

Currently, no single breakthrough technology that could reduce emissions drastically but the combination of practical options for CO_2 mitigation in iron and steel industry is interesting available in the iron and steel sector [49]. The World Steel

Association has launched the CO_2 breakthrough programme in 2003. The main purpose of this programme is information exchange on CO_2 emission reduction activities all over the world. Research has taken place in various countries such as in the EU (ultra-low CO_2 steelmaking, or ULCOS 1), the USA (the American Iron and Steel Institute), Canada (the Canadian Steel Producers Association), South America (Arcelor Mittal Brazil), Japan (Japanese Iron and Steel Federation), Korea (POSCO), China (Baosteel) and Taiwan (China Steel), and Australia (Bluescope/One Steel and HIsmelt) [56]. The CO_2 reduction target of the ultra low CO_2 steelmaking project (ULCOS project, supported by the EU) is over 50% of CO_2 emissions reduction in the long term. Four main processes have been studied in the first phase of ULCOS which had a budget of EUR 75 million [57].

2.9.2.1. Top gas recycling blast furnace with CCS

Top gas recycling blast furnaces depend on the separation of the off-gases. The useful components in off-gases separation can be used as a reducing agent into the furnace. The injection of oxygen substitute of preheated air to facilitate the CO_2 capture and storage (CCS). The implementation cost of the top gas recycling blast furnace with CCS is approximately 590 M€ for an industrial demonstrator with the production capacity 1.2 Mt hot metal per year. The timeline for industrial demonstrator is about 10 years, allowing further market roll-out post 2020 [57].

2.9.2.2. The ULCORED (advanced Direct Reduction with CCS)

Direct-reduced iron is produced from the direct reduction of iron ore by a reducing gas produced from natural gas. The reduced iron is first in solid state and needs an electric arc furnace for melting. An experimental pilot plant is being planned in Sweden, with market roll-out foreseen for 2030. The potential reduction of CO_2 emissions of this process is 70-80% [57].

2.9.2.3. The HIsarna technology

The HIsarna technology combines the preheating of coal and partial pyrolysis in a reactor, a melting cyclone for ore melting and a smelter vessel for final ore reduction and iron production. The market roll-out is foreseen for 2030. Combined with CCS the potential the CO_2 emissions reduction of this process is 70-80%. A pilot plant (8t/h, without CCS) is under construction in Ijmuiden, Netherlands and is to be commissioned in the first half of 2011 [57].

2.9.2.4. ULCOWIN and ULCOSYS

ULCOWIN and ULCOSYS are electrolysis processes that are tested on a laboratory scale. There is a clear need to support this ULCOS research effort with a high share of public funds and to lead the global framework market towards conditions that ease the prospective deployment of these breakthrough technologies [57].

2.10 Multi-Criteria Decision Analysis (MCDA)

Multi-criteria decision analysis studies decisive problems in which the alternatives are evaluated on several dimensions or viewpoints. Since the 1950s, many MCDA methods have been developed to assist decision-making with analyzing and solving multiple criteria decision problems [58]. The general objective of MCDA is to assist a decision maker or a group to choose the best alternative from a range of alternatives in an environment of conflicting and competing criteria. Typically, a classification of MCDA is often divided in two types are MADM (multi-attribute decision making) and MODM (multi-objective decision making) based on the size of the set of strategies. The difference between MADM and MODM is that MADM is a small number of alternatives that are to be evaluated against a set of attributes that are often hard to quantify. In another word, it is concerned with choosing from a small, finite, or countable number of strategies. On the other hand, MODM alternatives are not predetermined but instead a set of objective functions is optimized subject to a set of constraints [59]. The basic step of MCDA is shown in Figure 2.23.

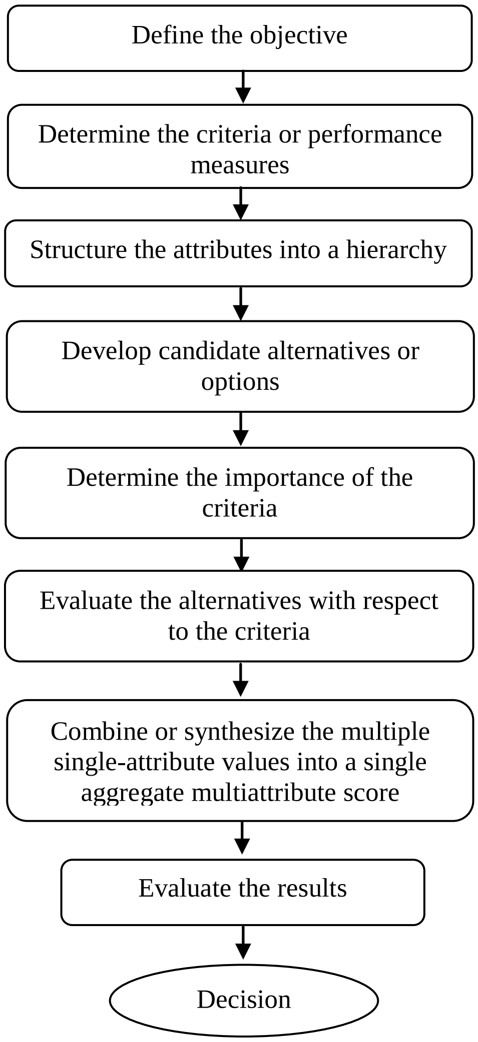


Figure 2.23 Basic steps of MCDA [60]

In recent years, there are several methods that have been proposed to deal with MCDA problems such that the appropriate method depends on the problem characteristic. The different methods are described as follows [60].

2.10.1 Weighted sum method (WSM)

The weighted sum method is the most well known and simplest multi-criteria decision analysis for evaluating a number of alternatives in terms of a number of decision criteria. It is very important to state here that it is applicable only when all the data are expressed in exactly the same unit especially in single dimensional problems. If there are M alternatives and N, criteria then the best alternative is the one that satisfies the following expression [61]:

$$A^*_{WSM} = Max\sum_{i}^{j} a_{ij}w_j \quad \text{for} \quad i = 1, 2, 3, \ldots M \tag{2.9}$$

Where:

A^*_{WSM} is the WSM score of the best alternative

aij is the actual value of alternative in terms of that criterion

wj is the weight of importance of the criterion.

The total value of each alternative is equal to the sum of products. The difficulty with this method emerges when it is applied to multi-dimensional decision-making problems. In combining different dimensions, and consequently different units, the additive utility assumption is violated.

2.10.2 Weighted product method (WPM)

The WPM is very similar to WSM. The main difference is that instead of addition in the model, there is multiplication. Each alternative is compared with the others by multiplying a number of ratios, one for each criterion as the ratio are raised to the power equivalent to the relative weight of the corresponding criterion. In order to compare the alternatives, AK and AL, the following product is usually acquired [61]:

$$R(A_K/A_L) = \sum_{i=1}^{N} (a_{kj}/a_{Lj})^{W_j} \tag{2.10}$$

Where:

N is the number of criteria

aij is the actual value of the alternative in terms of that criterion

wj is the weight of the importance of the criterion.

If R (AK/AL) is greater than one, then alternative AK is more desireable than alternative AL (in the maximization case).

2.10.3 Multi-attribute utility theory (MAUT)

Multi-attribute utility theory takes into consideration the decision maker’s preferences in the form of the utility function which is defined over a set of attributes. The utility value can be determined by deviations of multi-attribute utility functions and evaluating of single attribute utility functions followed by the verification of preferential and utility independent conditions. The utility functions can be either additively separable or multiplicatively separable subjected to single attribute utility. The multiplicative form of equation for the utility value is defined as follows [61]:

$$1 + ku(x_1, x_2, \ldots\ldots, x_n) = \prod_{j=1}^{n} (1 + kk_j u_j(x_j)) \tag{2.11}$$

Where:

j is the index of attribute

k is overall scaling constant (greater than or equal to -1)

kj is the scaling constant for attribute j

u(.) is the overall utility function operator

uj(.) is the utility function operator for each attribute j

2.10.4 Analytical Hierarchy Process (AHP)

An AHP consists of an overall goal, a group of options or alternatives for reaching the goal, and a group of factors or criteria that relate the alternatives to the goal. The hierarchy can be visualized, as shown in a Figure 2.24 below, with the goal at the top, the alternatives at the bottom, and the criteria in the middle [61].

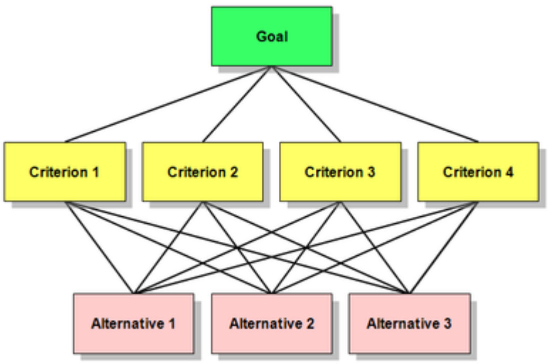


Figure 2.24 Analytical Hierarchy Process (AHP) [61]

The steps for considering decision problems by the Analytical Hierarchy Process (AHP) has been shown in Figure 2.25. Firstly, establish a structural hierarchy, then do comparative judgments by pair wise comparisons. The elements at given hierarchy level are compared in pairs to assess their relative preference with respect to each of the elements at the next higher level. The verbal terms of the Saaty's fundamental scale of 1–9 is used to assess the intensity of preference between two elements. The value of 1 indicates equal importance, 3 moderately more, 5 strongly more, 7 very strongly and 9 indicates extremely more importance. The values of 2, 4, 6, and 8 are allotted to indicate compromise values of importance. Ratio scale and the use of verbal comparisons are used for the weighting of quantifiable and non-quantifiable elements [62].

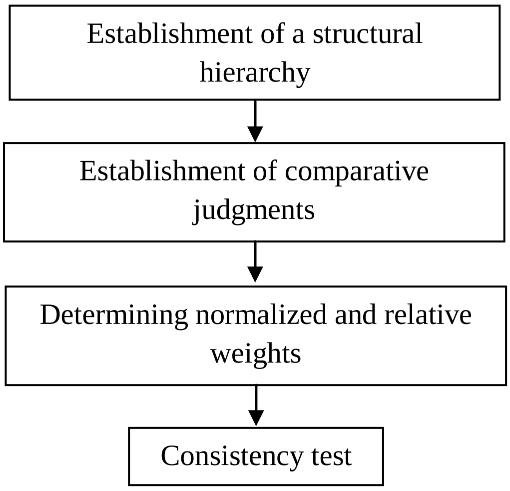


Figure 2.25 The steps for considering decision problems by Analytical Hierarchy Process (AHP) [62]

After pair-wise comparison, determine the normalized and relative weights by using Equations 2.12 and 2.13.

Normalization Matrix

$$\alpha_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{i1}} \tag{2.12}$$

Relative weights

$$r_i = \frac{\beta_i}{n} \tag{2.13}$$

Where:

aij is data in pair-wise

ail is total in each column in pair-wise matrix

βi is total in each normalized row

n is size of squared matrix

Finally, test the consistency ratio (CR) by using Equations 2.14 and 2.16. This index is important for the decision-maker to assure that the judgments were consistent and that the final decision is made well. The acceptable CR range varies according to the size of matrix i.e. 0.05 for a 3x 3 matrix, 0.08 for a 4x 4 matrix and 0.1 for all larger matrices $\geq$ 5. The higher value of consistency ratio requires re-evaluation of pair wise comparisons [62].

$$C.R. = C.I. / R.I. \qquad (2.14)$$

$$C.I. = (\lambda - n)/(n - 1) \qquad (2.15)$$

$$\lambda = \frac{\sum_{i=1}^{n} \left(\frac{K_i}{r_i}\right)}{N} \quad , \quad K_i = r_i \times a_{ij} \qquad (2.16)$$

Table 2.18 Random Consistency Index (R.I.) [62]

N	1	2	3	4	5	6	7	8	9	10
R.I.	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Where:

C.R. = Consistency ratio

C.I. = Consistency Index

N is size of the squared matrix

λ is the eigenvalue

After obtaining the weight vector and testing the consistency ratio, it is then multiplied with the weight coefficient of the element at a higher level (that was used as the criterion for pair-wise comparisons). The procedure repeats upward for each level, until the top of the hierarchy is reached. The overall weight coefficient, with respect to the goal for each decision alternative is then obtained. The alternative with the highest weight coefficient value should be taken as the best alternative [59].

However, there is a limitation for classical AHP in the case that of negative preferences are combined with positive preference. Measurements in classical AHP are based on restricting all values of alternatives on a criteria to be positive, even where the alternative is known to have an undesirable attribute. In addition, the classical AHP derives criteria weights by asking the decision-maker to compare the importance of the criteria independent of the actual alternatives. From the limitation of classical AHP, Bipolar AHP (BAHP) is developed. Bipolar AHP modifies from the classical AHP methodology to reflect the accommodation of both positive and negative desirability as opposed to the strictly positive view of the AHP.

2.10.5 Bipolar Analytical Hierarchy Process (BAHP)

The bipolar analytical hierarchy process (BAHP) is an improvement of the classical AHP. Bipolar AHP (BAHP) reflects the accommodation of both positive and negative desirability as opposed to the strictly positive view of the classical AHP. A bipolar scale is appropriate when the decision maker is able to tell whether he perceives each alternative positively or negatively with respect to each viewpoint comparison with a neutral reference point. The scale of BAHP is divided in two zones by a neutral point; a positive feeling or a good performance is associated to the zone above the neutral point or above “zero” lies. The zone of evaluations corresponding to a negative feeling or bad performance is the zone below this point. The central 0 value encodes the neutral effect, which is neither good nor bad. It can be seen that the bipolar nature of the scale often amounts to treating the good and the bad performances differently. The BAHP requires several relatively simple modifications to the AHP user interface and computational process. The step for calculate Bipolar AHP is shown below [63].

2.10.5.1. Identification of quantitative data of relative preferences in each alternative

The qualitative data of relative preferences is going to change into quantitative data by expert judgment through pair wise comparisons that follow the classical AHP method [63].

2.10.5.2. Rescale units for summed across criteria

Although within criteria the relative preferences are in commensurate units. Between the criteria, they are not because each criterion is using a different scale. Therefore, commensurate units for all preferences can be summed across criteria and reflect the relative priority values across alternatives and criteria. Since the scale used under each criterion is stretched to the point where the extreme alternative receives a value of 1 (or −1 if negative), anchoring the elicitation of relative weights to these extreme values provides a simple and accurate method for unifying these scales. The rescaling units equation is shown in Equation 2.17, of which 99% of x' is in the [0, 1] range [64].

$$x' = \frac{\frac{x-\mu}{3\sigma}+1}{2} \qquad (2.17)$$

Where,

x' is value from rescaling units

x is value of preferences

μ is average value

σ is standard deviation

2.10.5.3. Indicating negative or positive criteria and alternatives. (The BAHP matrix)

The Bipolar AHP approach recognizes negative desirability as negative numbers, and normalizes all partial values to the most extreme alternative under each criterion. Each designated node is in the criteria and alternative hierarchy as associated with negative or positive preferences. Once a criterion node is designated as negative, all lower nodes branching from it should inherit that designation. Users should designate criterion nodes as negative when the criterion reflects performance aspects that, in the majority of the alternatives, cause a reduction in preference. Typical examples include criteria such as cost, time, distance, risk, pain, and effort [63].

2.10.5.4. Criteria weights

Relative criteria weight can be defined as the absolute value of the relative preference of the extreme values of priorities under each criterion. Extreme values assigned partial priority values of one or negative one. Criteria weight may also be interpreted as the relative marginal priority, trade-off gradients, or scaling factors. All of these views produce the same result, but give rise to different elicitation protocols. With the "absolute value" elicitation procedure, decision makers would be asked to compare the absolute value of the extreme alternative under each criterion [63].

2.10.5.5. Evaluate and prioritize of iron and steel production technology

Evaluate iron and steel production technology by multiplying quantitative data in the BAHP matrix to the criteria weight. The results show the important priority of each alternative by using MCDA (bipolar method) based on environmental, economic and technology availability [63].

There are many methods of MCDA not mentioned in this study, for example PROMETHÉE (Outranking), Multi-Attribute Global Inference of Quality (MAGIQ), Data envelopment analysis, and etc. The choice of which model is the most appropriate depends on the characteristic in each problem. In this study the Bipolar Analytical Hierarchy Process (BAHP) is selected as a decision-maker. The reason is that in the presence of alternatives with negative values, Bipolar AHP produces correct results while AHP does not. Furthermore, unlike AHP, Bipolar AHP not only recognizes partial negative priorities, but also identifies alternatives with negative overall priority. It can be seen that AHP and BAHP come up with significantly different results.

CHAPTER 3
METHODOLOGY

The research in this study consists of four phases as illustrated in Figure 3.1. Firstly, data of iron and steel production were collected, and energy and CO_2 intensities and CO_2 emissions from iron and steel imports in Thailand were then calculated. Secondly, the projection of greenhouse gas emissions from iron and steel production from 2011 to 2050 were studied. Thirdly, the evaluation and prioritization of iron and steel production technology by using Multi-Criteria Decision Analysis (MCDA) based on environmental, economic and technology availability were examined. Finally, the energy savings potential and the CO_2 abatement cost curve in 2030 for Thailand's steel industry was then analysed.

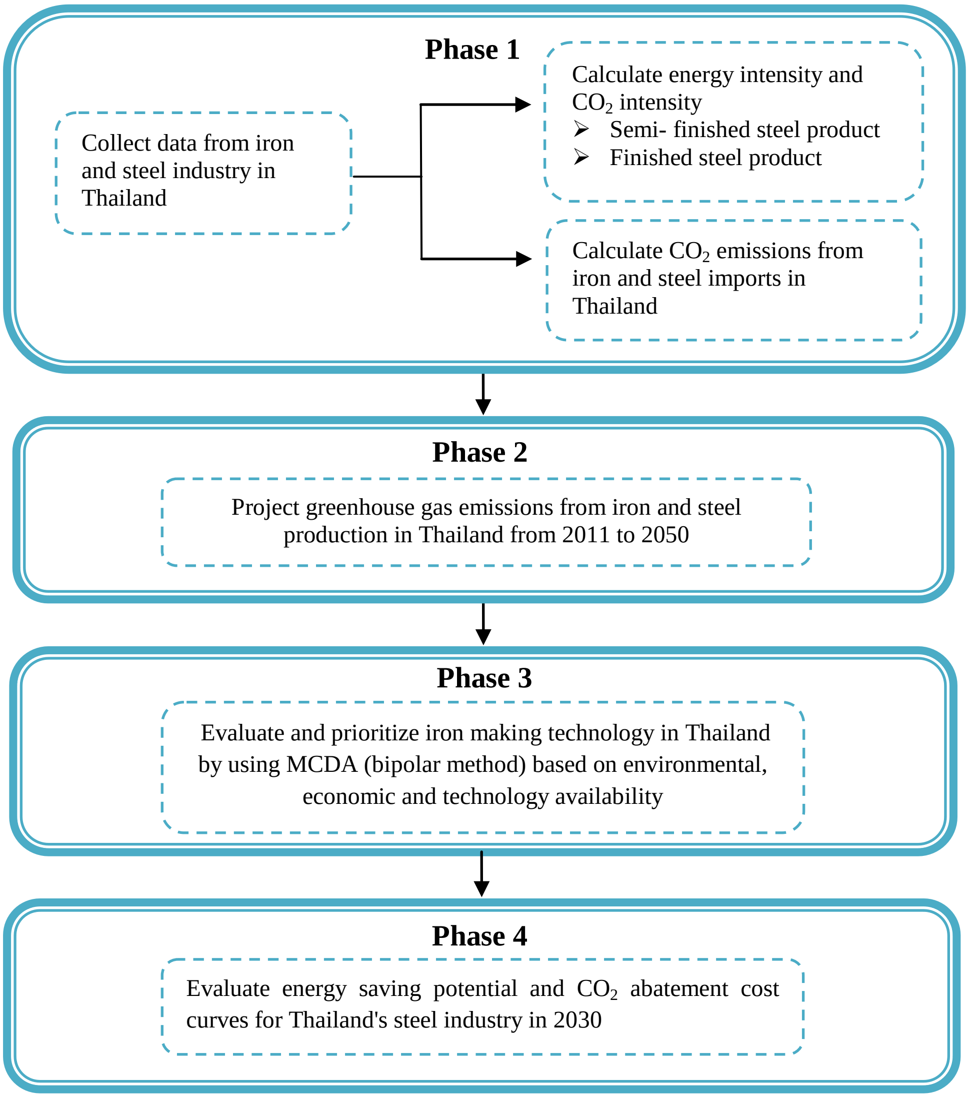


Figure 3.1 Flow chart of this research

3.1. Data collection and calculation of energy and carbon dioxide intensities from iron and steel imports in Thailand

3.1.1. Data collection from iron and steel industry in Thailand

The structure of the iron and steel industry in Thailand proposed by the Iron and Steel Institute of Thailand (ISIT) is illustrated in Figure 3.2. Currently, Thailand does not have an upstream iron and steel industry. Only midstream and downstream iron and steel industries are available. The processing technology in the midstream industry is electrical arc furnace (EAF) using scrap steel as a raw material. The products of this stage are semi-finished steel products, which are material inputs used to produce finished steel products in the downstream industry [26]. The iron and steel production capacity of each product collected in this study compared with the total production capacity of each product in 2010 is summarized in Table 3.1. The plant specific data in years 2004-2010 were obtained from 6 semi-finished steel production plants and 21 finished steel production plants, which represent 60.44% of total semi-finished steel production capacity and 64.70% of total finished steel production capacity. The plant specific data of pipe production collected from 5 plants, accounted for 14.30% of all pipe production capacity in Thailand. The data was collected from hot rolled steel sheet and plate, cold rolled steel, coated steel and bar, accounting for more than 50% of the total production capacity. For slab products, the data were collected from all slab production plants.

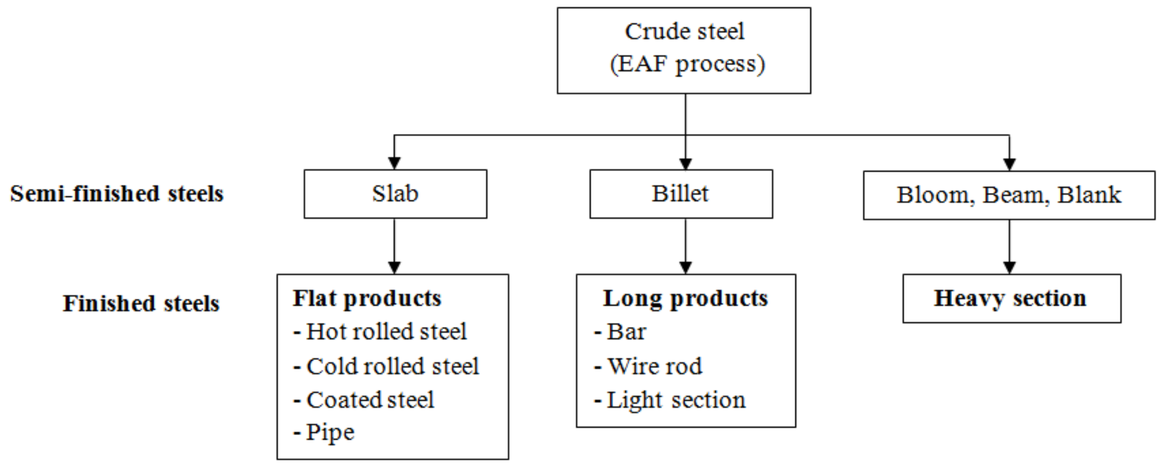


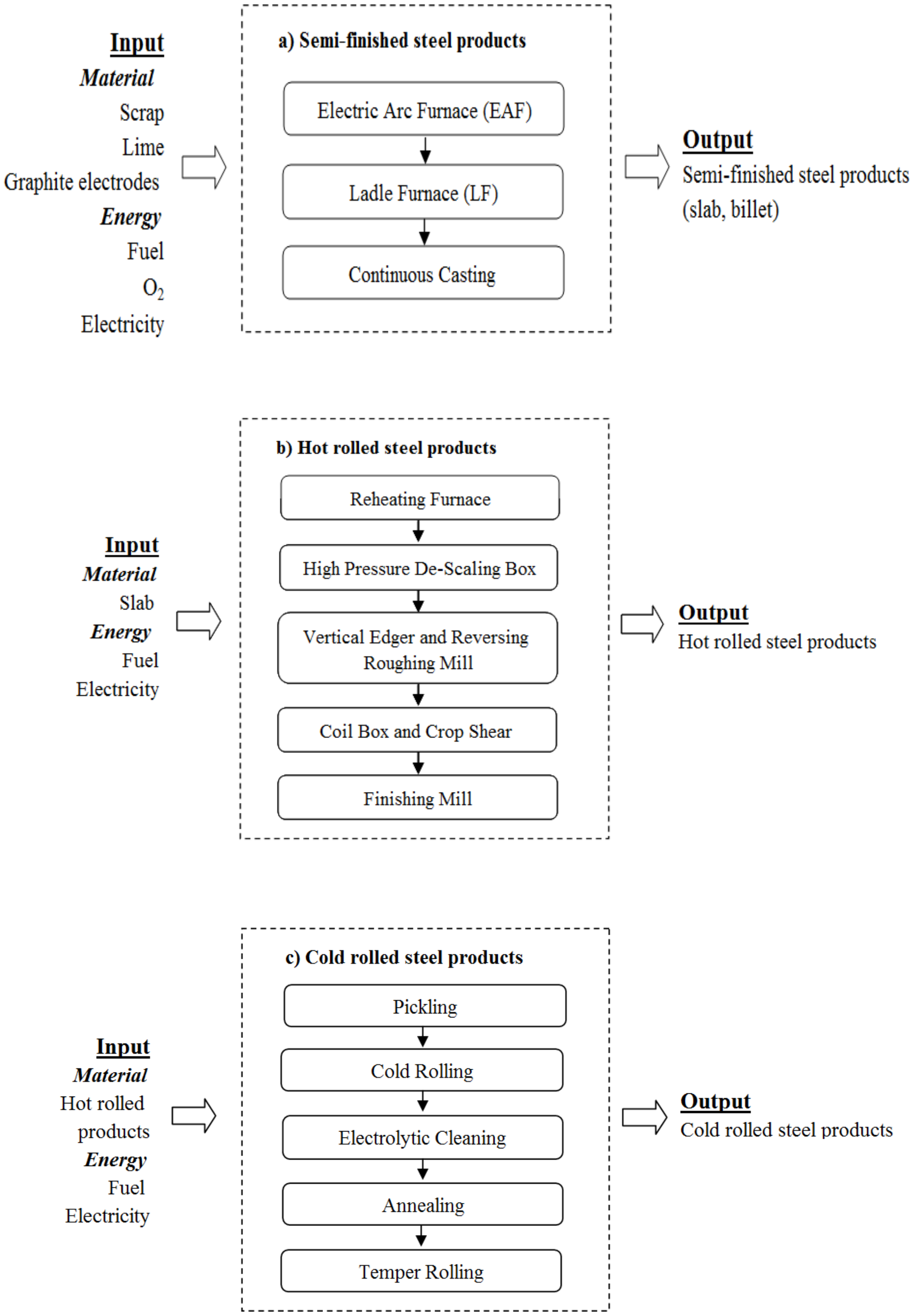
Figure 3.2 Structure of iron and steel industry in Thailand [26]

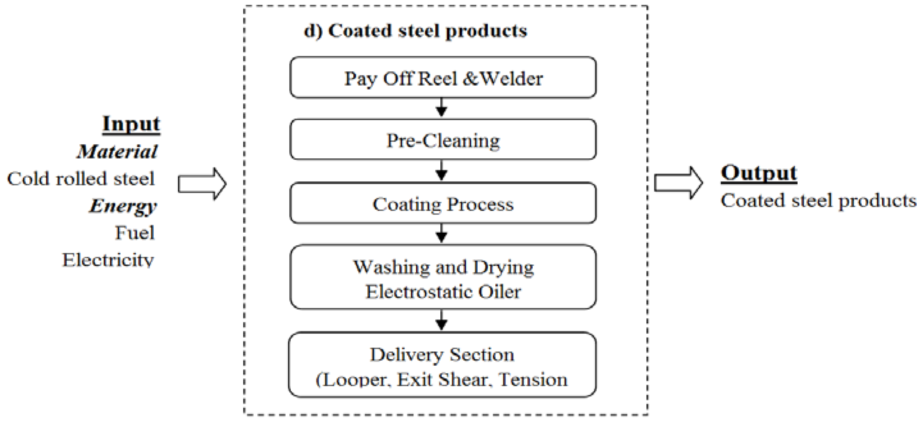
Table 3.1 Production capacity of Thailand's iron and steel industry collected in this study compared with total production capacity in 2010 [40]

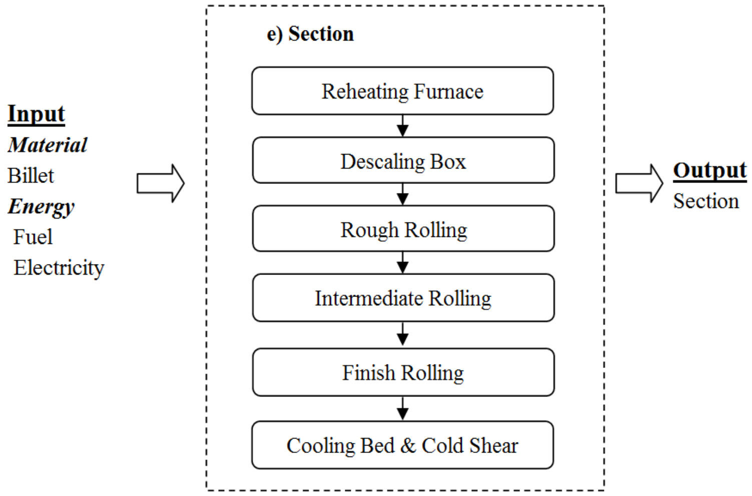
Iron and steel products	Total production capacity in 2010 (million tonnes)	Production capacity in this study (%)
1. Semi-finished steel (EAF process)		
1.1. Slab	3.00	100.00
1.2. Billet	4.43	42.53
2. Finished steel		
2.1. Flat products		
2.1.1. Hot rolled steel sheet and plate	5.40	81.48
2.1.2. Cold rolled steel	2.50	88.00
2.1.3. Coated steel (Hot-dipped galvanizing, Hot-dipped tin plate, tin free, Electro-galvanized)	1.21	79.83
2.2. Long products		
2.2.1. Bar	5.12	50.51
2.2.2. Wire rod	1.93	36.21
2.2.3. Light section	0.43	30.52
3. Pipe		
3.1. Electric resistance welded (ERW) pipe	0.97	14.30

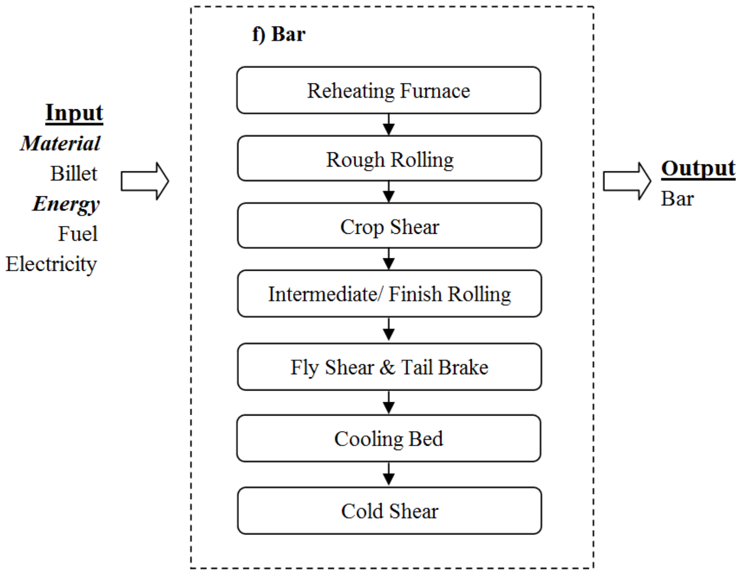
3.1.2. System boundary of iron and steel production process in this study

The gate-to-gate boundaries for iron and steel production process applied in this study are illustrated in Figure 3.3 (a–h). Material inputs for semi-finished steel production from the EAF process are scrap, lime and graphite electrode. Lime is used as a flux for removing impurities, whilst graphite electrodes are electrical conductors used to make a circuit. The energy consumption of semi-finished steel products come from three sources: (1) from the fuel combustion, (2) from the oxygen used in the EAF process and (3) from the electricity supplied to the process. Finished products in this study consist of hot rolled steel products, cold rolled steel products, coated steel products, section, bar, wire rod and electric resistance welded (ERW) pipe which require physical reformation and surface finishing in the downstream industry. Therefore, there are no CO_2 emissions from chemical reactions in the steel finishing process. Energy consumption of the steel finishing process comes from fuel combustion and electricity supplied to the process.




d) Coated steel products
Input
Material
Cold rolled steel
Energy
Fuel
Electricity
Pay Off Reel &Welder
Pre-Cleaning
Coating Process
Washing and Drying
Electrostatic Oiler
Delivery Section
(Looper, Exit Shear, Tension
Output
Coated steel products


e) Section
Input
Material
Billet
Energy
Fuel
Electricity
Reheating Furnace
Descaling Box
Rough Rolling
Intermediate Rolling
Finish Rolling
Cooling Bed & Cold Shear
Output
Section


f) Bar
Input
Material
Billet
Energy
Fuel
Electricity
Reheating Furnace
Rough Rolling
Crop Shear
Intermediate/ Finish Rolling
Fly Shear & Tail Brake
Cooling Bed
Cold Shear
Output
Bar

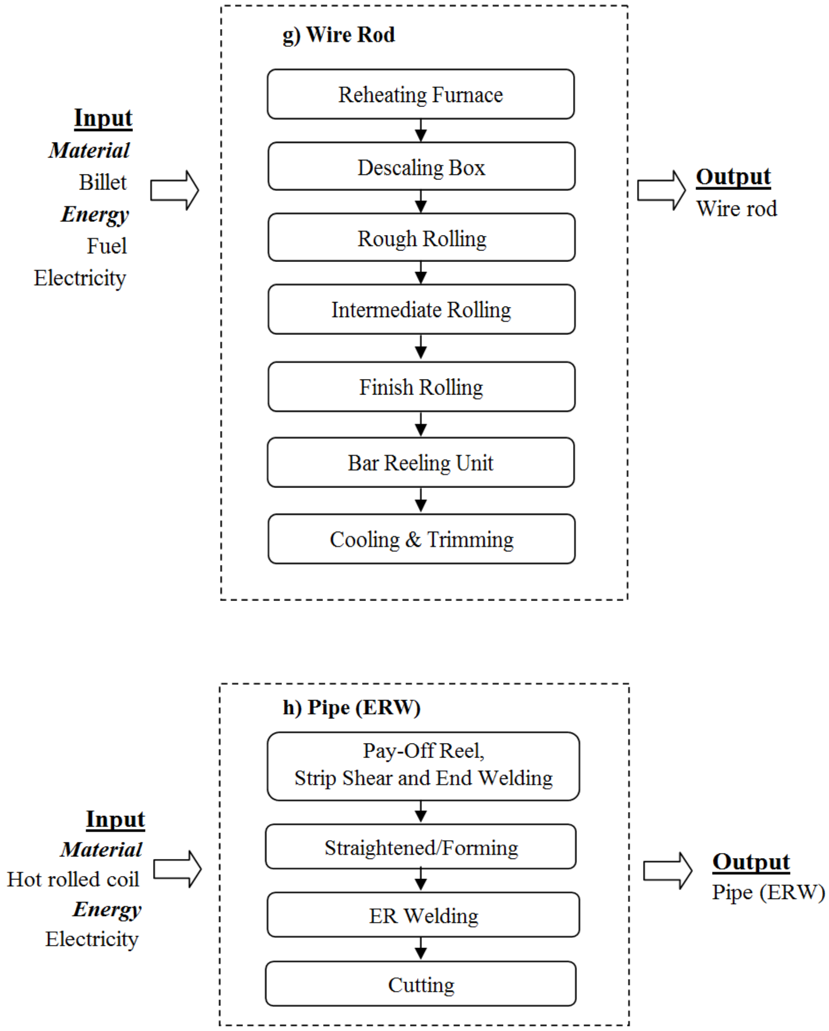


Figure 3.3 System boundaries of iron and steel production processes (gate-to-gate)

3.1.3. Calculation of energy intensity

The primary energy was estimated by converting the electricity from end use to primary use by using power generation efficiency, transmission and distribution (T&D) losses. The average of the power generation efficiency from various generating technologies in Thailand is 35% [8]. Electric power transmission and distribution losses include losses in transmission between sources of supply and points of distribution and in the distribution to consumers. According to the World Bank report, the electric power transmission and distribution loss in Thailand from 2004 to 2010 was approximately 7% [65]. The energy intensity was reported as a unit of energy consumed per unit output (GJ/t product). The calculations of energy consumption and energy intensity a demonstrated by Equations 3.1 and 3.2, respectively. Moreover, the energy efficiency index (EEI) was further calculated in order to determine the energy-efficiency potential gap between the energy intensity of Thailand’s steel industry with that of the world best practice [46]. The EEI was calculated by using Equation 3.3 [66].

$$EC = \sum_{j=1}^{m}(X_j \times NCV_j) \quad (3.1)$$

$$EI_{TH} = EC/W \quad (3.2)$$

$$EEI = EI_{TH}/EI_{BPT} \quad (3.3)$$

Where,

EC is energy consumption (GJ)

m is number of fuel types

j is fuel type, namely 1 = fuel oil, 2 = natural gas, 3 = LPG, and 4= kerosene

X_j is amount of fuel (j) (unit of $fuel_j$ consumed)

NCV_j is net calorific value of fuel (j) (Joules/ unit of $fuel_j$ consumed)

EI_{TH} is energy intensity of iron and steel production in Thailand (GJ/tonne product)

W is production capacity of product (tonne)

EEI is energy efficiency index for iron and steel production (dimensionless)

EI_{BPT} is the world best practice energy intensity (GJ/tonne product)

3.1.4. Calculation of CO_2 intensity

The amount of GHG emissions in the unit of tonne CO_e per tonne of product was calculated by the method derived from the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse gas inventory [37]. The GHG emissions were scoped only on the production process or gate-to-gate boundary. The details of the calculations are described below.

a) Calculation of CO_2 emissions from chemical reactions in process.

According to the 2006 IPCC Guidelines, the methodology to calculate CO_2 emissions from chemical reactions in process is divided into 3 Tiers. Tier 1 method is based on default emission factors and national production data. Tier 2 method uses a mass balance approach and material-specific carbon contents whilst Tier 3 method requires plant-specific emissions or disaggregated activity data for estimating CO_2 emissions (IPCC, 2006). The calculation method of CO_2 emissions in each tier is shown below.

However, in this study Tier 2, a mass balance approach with material-specific carbon content was applied for process emission as illustrated in Equation 3.4 [37].

Tier 2 method

Tier 2, a mass balance approach with material-specific carbon content, was applied in this study as illustrated in Equation 3.4. Tier 2 methods are appropriate if the inventory compiler has access to national data on the use of process materials for iron and steel production. The material-specific carbon contents for iron and steel, and coke production are in Table 3.2 [37].

$$CE_p = [\sum_{a=1}^{e}(Q_a \times C_a) - (S \times C_s)] \times 44/12 \quad (3.4)$$

Where,

CE_p is CO_2 emissions from chemical reactions in process (tonne CO_2)

e is number of carbonaceous input types

a is type of carbonaceous material, namely 1 = scrap, 2 = coal, 3 = limestone, 4 = dolomite, and 5 = carbon electrodes

Q_a is quantity of carbonaceous material consumed in EAF process (tonne product)

C_a is carbon content of material input (tonne C/ tonne product)

S is quantity of steel product (tonne product)

C_S is carbon content of steel product (tonne C/ tonne product)

44/12 is stoichiometric ratio of CO_2 and C

Table 3.2 Tier 2 material-specific carbon contents for iron and steel and coke production [37]

Process Materials	Carbon Content (kg C/kg)
Blast Furnace Gas	0.17
Charcoal	0.91
Coal	0.67
Coal Tar	0.62
Coke	0.83
Coke Oven Gas	0.47
Dolomite	0.13

Table 3.2 Tier 2 material-specific carbon contents for iron and steel and coke production (Cont') [37]

Process Materials	Carbon Content (kg C/kg)
EAF Carbon Electrodes	0.82
EAF Charge Carbon	0.83
Fuel Oil	0.86
Gas Coke	0.83
Hot Briquetted Iron	0.02
Limestone	0.12
Natural Gas	0.73
Oxygen Steel Furnace Gas	0.35
Petroleum Coke	0.87
Purchased Pig Iron	0.04
Scrap Iron	0.04
Steel	0.01
Coking Coal	0.73
Direct Reduced Iron (DRI)	0.02

b) Calculation of CO_2 emissions from fuel combustion.

The amount of fuel used was calculated in terms of heating values of each fuel. Default emission factors for stationary combustion in manufacturing industries came from the 2006 IPCC and the heating values of each fuel were obtained from the Department of Alternative Energy Development and Efficiency (DEDE), Thailand [67]. The CO_2 emissions from fuel combustion; calculated by using Equation 3.5 [37].

$$CE_f = \sum_{k=1}^{n}(H_k \times EF_k) \tag{3.5}$$

Where,

CE_f is CO_2 emissions from fuel combustion (tonne CO_2)

n is number of fuel type consumed

k is fuel type, namely 1 = fuel oil, 2 = natural gas, 3 = LPG, and 4= kerosene

H_k is heating value of fuel (TJ)

EF_k is the emission factor of $fuel_k$ (tonne CO_2 /TJ)

c) Calculation of CO_2 emissions from electricity consumption.

The average CO_2 emission factor of electricity production in Thailand was obtained from a report by the Thailand Greenhouse Gas Management Organization (TGO), which was 0.511 tonne CO_2/MWh [68]. The CO_2 emissions from electricity consumption; calculated by Equation 3.6 [37].

$$CE_e = E_c \times EF_e \tag{3.6}$$

Where;

CE_e is CO_2 emission from electricity consumption (tonne CO_2)

E_c is electricity consumption (MWh)

EF_e is emission factor of electricity production in Thailand (0.511 tonne CO_2/MWh)

CO_2 intensity calculated as a unit of tCO_e /t product, as shown in Equation 3.7. In this study, activity data came from several steel plants; thus the weighted average CO_2 intensity of steel production in Thailand; determined from Equation 3.8.

$$CI_i = CE_i / W_i \tag{3.7}$$

$$\overline{CI}i = \sum_{i=1}^{n}(w_i \times CI_i) / \sum_{i=1}^{n} w_i \tag{3.8}$$

Where;

CI_i is CO_2 intensity of product from each selected $plant_i$, (tonne CO_2/tonne $product_i$)

CE_i is CO_2 emissions of $product_i$, (tonne CO_2)

W_i is actual production from each selected plant (tonne $product_i$)

$\overline{CI}i$ is weighted average of CO_2 intensity of $product_i$, (tonne CO_2/tonne $product_i$)

n is number of plant used in this study

d) Uncertainty assessment

The uncertainty of the calculated CO_2 intensity was evaluated by following the Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories [69]. The uncertainties can be estimated from two convenient rules under addition and multiplication as shown in Equations 3.9 and 3.10 below.

Rule A: Where uncertain quantities are to be combined by addition

$$U_{total} = \frac{\sqrt{(U_1 * X_1)^2 + (U_2 * X_2)^2 + \cdots (U_n * X_n)^2}}{X_1 + X_2 + \cdots + X_n} \quad (3.9)$$

Where;

U_{total} is percentage uncertainty in the sum of the quantities.

X_i and U_i are uncertain quantities and the percentage uncertainties associated with them, respectively.

Rule B: Where uncertain quantities are to be combined by multiplication

$$U_{total} = \sqrt{U_1^{\,2} + U_2^{\,2} + \cdots + U_n^{\,2}} \quad (3.10)$$

Where;

U_{total} is percentage uncertainty in the product of the quantities.

U_i is percentage uncertainties associated with each of the quantities.

The greenhouse gas inventory is principally the sum of multiplying between emission factors and activity data. Therefore, Rules A and B can be used repeatedly to estimate the uncertainty of the total inventory. The uncertainty range of emission factor and activity data are shown in Table 3.3. In this study, the uncertainty of plant specific data is approximately ± 5% and the uncertainty of emission factors (from Tier 2) is ± 10%.

Table 3.3 Uncertainty range of data source [69]

Method	Data Source	Uncertainty Range
Tier 1	Default Emission Factors National Production Data	± 25% ± 10%
Tier 2	Material-Specific Default Carbon Contents National Reducing Agent & Process Materials Data	± 10% ± 10%
Tier 3	Company-Derived = Process Materials Data Company-Specific Measured CO_2 and CH_4 Data Company-Specific Emission Factors	± 5% ± 5% ± 5%

3.1.5. Assessment of CO_2 emissions from iron and steel imports in Thailand

The CO_2 emissions embodied in imported product is significant. The CO_2 emissions embodied in imported products are over 30% of domestic production in Denmark, Finland, France, Netherlands, Korea, New Zealand, Norway and Sweden [70]. Therefore, in this study CO_2 emissions from iron and steel import in Thailand; calculated as shown in Equation 3.11. The data of quantity of steel import in Thailand is derived from the Iron and Steel Institute of Thailand.

$$CO_2 \text{ emission} = Q_i \text{ x } C_i \qquad (3.11)$$

Where,

Q_i is quantity of steel import (t product)

C_i is CO_2 intensity of steel from imported country (tCO_{2e}/t product)

However, there is no specific data of CO_2 intensity from imported steel. This study applies CO_2 intensity of imported steel from the World Steel Association database, as shown in Table 3.4. The World Steel Association evaluates life cycle assessment (LCA) of various steel products by considering the potential impacts from all production stages. The data are collected from world steel member companies in 2005 to 2007. The study is a cradle-to-gate LCI study, including 85% recycling rate [71]. Additionally, the CO_2 intensity of semi-finished products is based on carbon footprint average for steel production via the BF/BOF route (cradle-to-gate).

Table 3.4 CO_2 intensity of steel products of World Steel Association database [71]

Products	CO_2 intensity (tCO_2/t product)
1. Semi-finished steel	1.670
2. Hot rolled plate	1.122
3. Hot rolled coil	1.003
4. Tinplate	1.365
5. Cold rolled coil	1.170
6. Hot dip galvanized	1.344
7. Electro-galvanized steel	1.385
8. Bar	1.015
9. Sections	1.197
10. Welded pipe (ERW)	1.300
11. Wire rod	1.293
12. Tin-free (ECCS)	1.242
13. Organic coated	1.671

3.2. Projection of greenhouse gas emissions from iron and steel production in Thailand from 2011 to 2050

In this study, the data of the proposed scenarios was verified and updated from the study of Iron and Steel Institute of Thailand [53] in February 2014. However, the specific information used in this study was obtained from the reports and the interviews with the experts from ISIT. The projection of steel demands in this study was evaluated by using the growth rate of steel average from 2000 to 2013. The projected demands are assumed that the production should not exceed 80% of maximum production capacity for each steel product. The demand growth rates of the specific steel products used in this study were 5.71% (semi-finished steel product), 5.59% (hot rolled long product), 3.51% (hot rolled flat product), 1.34% (coated sheet product), 2.8% (cold rolled steel product) and 4.72% (pipes) respectively. The CO_2 emissions from iron and steel production were then forecasted by the growth rate of each steel product multiplied with weighted average of CO_2 intensity of each steel product from this study. Three plausible scenarios proposed in the master plan of energy management for Thailand iron and steel industry, which were S1: without integrated steel plant (baseline scenario), S2: with a traditional integrated BF-

BOF route and S3: with an alternative integrated DR-EAF route [53] were adopted in this study. The details for each scenario are shown in Table 3.5.

Table 3.5 Iron and steel production scenarios in Thailand [53]

Scenarios	Implementation year	Production capacity of iron making	Emission factors
S1: Without integrated steel plant (baseline scenario)	2011-2050	- No iron making - Holds current capacity and further demand is supported by imports	n/a
S2: With a traditional integrated BF-BOF route	2023-2026	- 25-47.5 % of maximum production capacity	2.12 tCO_2/t crude steel [72]
	2027-2050	- 89.7 % of maximum production capacity	
S3: With an alternative integrated DR-EAF route	2023-2024	- 55.5 % and 77.8% of maximum production capacity (1 million tonnes per year for long products and 1 million tonnes per year for flat products)	1.14 tCO_2/t DRI [72]
	2025-2050	- Maximum production capacity (1 million tonnes per year for long products and 1 million tonnes per year for flat products)	

Remark: n/a is not applicable

S1): Without integrated steel plant in Thailand (baseline scenario)

This scenario has no integrated steel plant in Thailand. Currently, most of the steel making processes in Thailand are electrical arc furnace (EAF) processes using scrap steel as the raw material. The production capacity of each steel product in this study increases not in excess of 80% of the maximum production capacity of these products. The maximum production capacity of semi-finished steel product is 8.8 million tonnes and the maximum production capacity of finished steel product is 21.4 million tonnes [40]. Therefore, only CO_2 emissions from midstream and downstream iron making using electrical arc furnaces (EAF) are reported.

S2): With a traditional integrated BF-BOF route in Thailand

The specific information of integrated steel plants used in this study was obtained from the reports and the interviews with the experts from the Iron and Steel Institute of Thailand [53]. The integrated steel plants using blast furnace-basic oxygen furnace (BF-BOF) route was expected to be established in 2023. Iron ore is converted into metallic iron by using carbon as a reducing agent that causes emissions of other toxic pollutants and CO_2 emissions. The maximum production capacity for BF-BOF plant is proposed up to 9 million tonnes per year. The iron and steel production capacity is divided into two phases. The production capacity for BF-BOF route for the first four years will be 25-47.5 % of maximum production capacity. The ISIT forecasts that the production capacity will be 89.7% of maximum production capacity for the second phase during 2027 to 2050 due to high end steel demand in Thailand. The amount of CO_2 intensity of BF-BOF route was 2.12 tCO_2/t crude steel, which came from chemical reactions in the process, electricity used and miscellaneous sources at the steel plant [72].

S3): With an alternative integrated DR-EAF route in Thailand

Currently, the iron and steel making process in Thailand is an electric arc furnace (EAF) process using scrap as a feedstock. However, the domestic consumption of scrap is still much higher than its domestic supply, as shown in Figure 3.4. The scrap supply in 2000 was 1.99 million tonnes, increasing to 3.12 million tonnes in 2008. However, the scrap consumption was up to 2.64 million tonnes in 2000, increasing to 5.33 million tonnes in year 2008 [40]. The increasing demand of scrap for the iron and steel industry was mainly generated by the demand of steel for some development projects, especially the infrastructural works and real estate, such as transportation, housing and construction. Therefore, the import of scrap steel will still be required. In 2008, imported scrap amounted to 2.58 million tonnes whilst only 0.36 million tonnes was exported. According to the study of ISIT, domestic scrap supply in 2050 would be 16.1 million tonnes whilst the domestic scrap consumption would increase to 24.79 million tonnes [40]. Due to the high demand of scrap in each year, ISIT believed that the use of scrap for only the production of steel might not be feasible, because there was inadequate domestic and imported scrap in Thailand. Therefore, an alternative integrated DR-EAF (Direct reduced-Electric arc furnace) route based on natural gas was proposed in this scenario. The direct reduced iron process will expected to be established in 2023 with a production capacity of 1 million tonnes per year for long products and 1 million tonnes per year for flat products. The production of direct reduced iron in this study uses natural gas as a reducing agent. The production capacities will be 55.5% and 77.8% of the maximum production capacity in 2023 and 2024, respectively. According to the interviews with experts from the Iron and Steel Institute of Thailand (ISIT), the production capacity scenario for direct reduced iron will reach its maximum production capacity to serve high end steel production in Thailand during the years 2025 to 2050. This process directly reduces the iron ore in solid form by reducing gases. The CO_2 intensity of the direct reduced iron process was 1.14 tCO_2/t DRI which came from fuel 0.8 tCO_2/t DRI and electricity 0.34 tCO_2/t DRI [72].

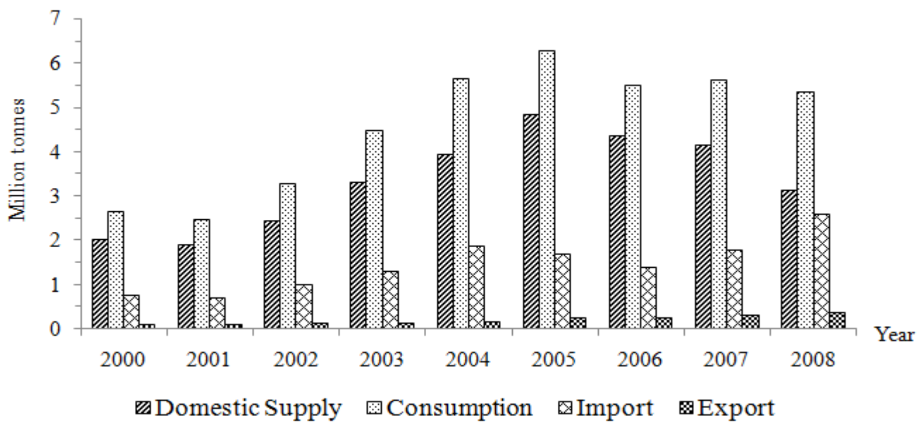


Figure 3.4 Thailand scraps demand and supply [40]

3.3. Evaluation and prioritization of iron making technology in Thailand by using MCDA (bipolar method) based on environmental, economic and technology availability

3.3.1. The structure of iron making technologies in Thailand

The scope of assessment was focused on the three iron-making technologies, which are blast furnace (BF), corex and midrex, due to proven commercial technology, as shown in Figure 3.5. Three iron-making technologies were evaluated by using bipolar analytical hierarchy process (BAHP) based on three main criteria and nine sub-criteria. The main criteria consisted of economic, environmental and technology. Sub-criteria of economic consisted of direct costs, indirect costs, direct benefits and indirect benefits. Sub-criteria of environmental consisted of energy consumption, greenhouse gas (GHG) emissions and resource depletion. Sub-criteria of technology consisted of barrier of materials acquisition and complexity of technical operation.

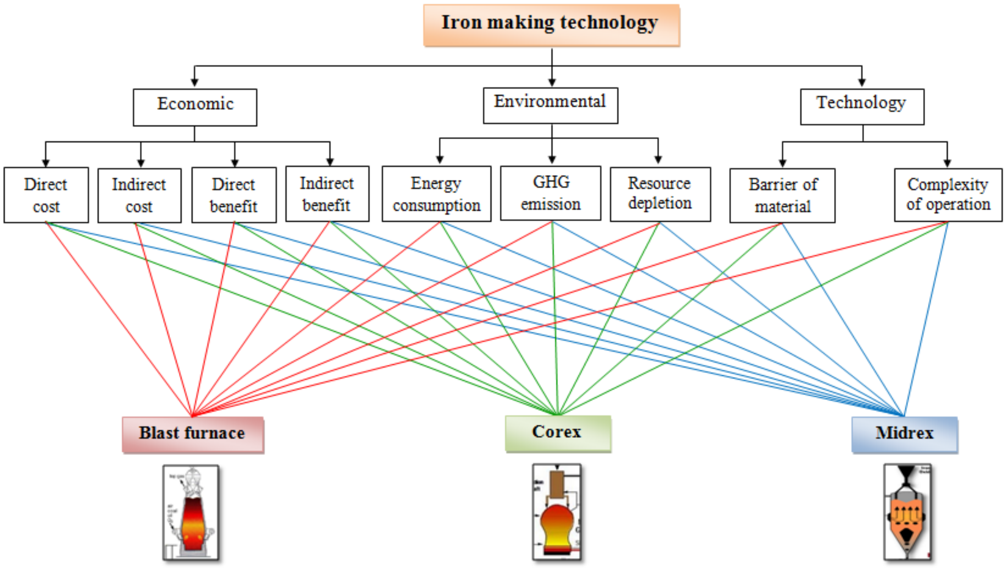


Figure 3.5 The structure of iron making-technology in Thailand

3.3.2. Collection of iron-making technology data

Qualitative data and quantitative data were collected in this study. The quantitative data of economic and environmental aspects came from a literature review. The environmental costs per unit of pollutants were derived from LCA-based inventory represented via willingness to pay (WTP) of the society, as shown in Table 3.6 [73]. This study assesses environmental and cost performance of molasses-based ethanol (MoE) in Thailand, using a life cycle approach. The cost estimates includes not only the direct production/distribution costs, but also the external environmental costs. The energy consumption, pollution emissions and total social costs have been considered in the analysis. The task is accomplished using the Swedish EPS (Environmental Priority Strategies in product design) model. Background information is extracted from LCA-based inventory of the process studied and the results are represented via willingness to pay (WTP) of the society. To adapt this model to Thailand, it is hypothesized that the WTP is proportional to capita income (GDP expressed in terms of purchasing power) Information about GDP (PPP) per capita for Thailand and Sweden is obtained from the World Fact Book [73].

$$WTP_{Thailand} = (WTP_{Sweden} \times \text{PERCAP-GDP (PPP)}_{Thailand})/\text{PERCAP} - \text{GDP(PPP)}_{Sweden}$$

Table 3.6 Environmental costs per unit of pollutants [73]

Environmental costs	Emissions							
	CO_2	CH_4	N_2O	CO	NO_2	SO_2	VOC	PM_{10}
PV_{2008} (baht/kg)	1.40	34.50	485.00	4.20	27.00	41.90	27.10	457.20
FV_{2013} (baht/kg)	1.76	43.47	611.10	5.29	34.02	52.79	34.15	576.07

The time value of money was applied for calculation in economic criteria. The present value of money was converted to the future value of money as illustrated in Equation 3.12. The money in unit of USD was changed to the unit of Thai baht. The base year for future value of money calculation was 2013 for which the interest rate average 4.76 % [74]. The qualitative data were collected from fifteen experts in government sector, private sector, education sector, and institute sector as presented in Table 3.7. The qualitative data of relative preferences were changed to quantitative data by expert judgment following classical AHP method. The Saaty's fundamental scale of 1–9 in Table 3.8 was used to assess the intensity of preference between two elements [62].

$$FV = PV \times (1+r)^t \qquad (3.12)$$

Where;

PV is the present value of money

FV is the future value of money

r is the interest rate

t is the number of years

1 USD = 30.22 baht, 1 Euro = 40.23 baht (Average January 2013) [70]

Table 3.7 Experts and organization in this study

Experts name	Organization
Government sector	
1. Venus Suetrong	Office of Industrial Economics (OIE)
2. Songwuth Srisawang	Office of Natural Resources and Environmental Policy and Planning (ONEP)
3. Dr. Satid Therdkiattikul	Department of Primary Industries and Mines (DPIM)
4. Tawatchai Yongnate	Department of Primary Industries and Mines (DPIM)
Education/Research sector	
5. Dr.-Ing. Sakhob Khumkoa	School of Metallurgical Engineering, Institute of Engineering, Suranaree University of Technology (SUT)
6. Asst. Prof. Dr. Pichaya Rachdawong	Faculty of Engineering, Chulalongkorn University (CU)
7. Athiwat Jirajariyavech	National Metal and Materials Technology Center (MTEC)
Private sector	
8. N.T.S. Steel Group Public Company Limited	N.T.S. Steel Group Public Company Limited
9. Sahaviriya Steel Industries Public Company Limited	Sahaviriya Steel Industries Public Company Limited
10. G J Steel Public Company Limited	G J Steel Public Company Limited
11. G Steel Public Company Limited	G Steel Public Company Limited
Institute sector	
12. Thongchai Indarangkura Na Ayudhaya	Advisor of Iron and Steel Institute of Thailand (ISIT)
13. Dr.Buntoon Sethasiroj	Good Governance for social development and the environment institute (GSEI)
14. Naruetep Lecksiwilai	Thailand Environmental Institute (TEI)
15. Krisada Wechwitayakhlung	Thailand Board of Investment (BOI)

Table 3.8 The Saaty's rating scale [62]

Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favour one over the other
5	Much more important	Experience and judgement strongly favour one over the other
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity
2,4,6,8	Intermediate values	When compromise is needed

3.3.3. Normalization and consistency test

After the qualitative data of relative preferences was changed to quantitative data by expert judgment following the classical AHP method, the next step was determining normalized and relative weights by using Equations 3.13 and 3.14.

Normalization

$$\alpha_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{i1}} \qquad (3.13)$$

Relative weights

$$r_i = \frac{\beta_i}{n} \qquad (3.14)$$

Where:

aij is data in pair-wise

ail is total in each column in pair-wise matrix

βi is total in each normalized row

n is size of squared matrix

The consistency ratio (CR) index is important for the decision-maker to assure that judgments are consistent and the final decision is made well. If the CR exceeds 0.1, the expert judgments are untrustworthy, because they are too close for comfort to randomness and the exercise is valueless or must be repeated. The equation for calculation CR is shown in Equations 3.15-3.17.

$$C.I. = (\lambda_{max} - n)/(n - 1) \quad (3.15)$$

$$C.R. = C.I. / R.I. \quad (3.16)$$

$$\lambda = \frac{\sum_{i=1}^{n}(\frac{K_i}{r_i})}{N}, \qquad K_i = r_i \times a_{ij} \quad (3.17)$$

Table 3.9 Random Consistency Index (R.I.) [62]

n	1	2	3	4	5	6	7	8	9	10
R.I.	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Where:

C.I. is consistency index

C.R. is consistency ratio

n is size of squared matrix

λ_{max} is eigenvalue (calculated from MATLAB program)

3.3.4. Calculation of the bipolar analytical hierarchy process (BAHP)

The bipolar analytical hierarchy process (BAHP) is a multi-criteria decision tool improved from classical AHP by BAHP. The benefit of BAHP is that it can reflect both positive and negative desirability as opposed to the strictly positive of the classical AHP. The steps of BAHP calculation is shown in Figure 3.6.

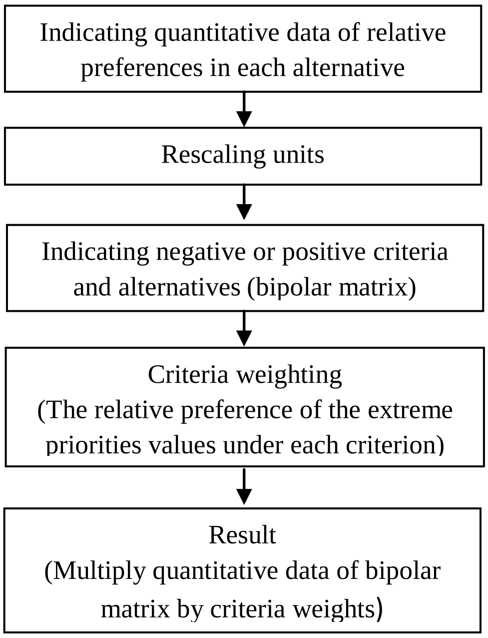


Figure 3.6 The steps of bipolar analytical hierarchy process (BAHP)

The next step after indicating quantitative data is rescaling units to sum across criteria. The rescaling units equation is shown in Equation 3.18, which is 99% of x' is in the [0, 1] range. The final results came from multiply bipolar matrix by criteria weight matrix [64].

$$x' = \frac{\frac{x-\mu}{3\sigma}+1}{2} \tag{3.18}$$

Where;

x' is value from rescaling units

x is preferences value

μ is average value

σ is standard deviation

3.4. Evaluation of energy saving potential and the CO_2 abatement cost curve for the Thailand's steel industry in 2030

The most preferential of iron making technology is selected to assess energy saving potential and CO_2 abatement cost curves in 2030 for Thailand's steel industry.

3.4.1. Evaluation of energy reduction target of Thailand's iron and steel industry

The Iron and Steel Institute of Thailand (ISIT) proposed energy reduction target for three plausible scenarios of Thailand's iron and steel industry in the master plan of energy management for Thailand iron and steel industry as presented in Table 3.10 [53]. According to the study of ISIT, the plant specific data of specific energy consumption, existing technology, the potential for energy savings and investment costs from steel producers in Thailand were collected and analyzed. The energy reduction target for Thailand's iron and steel industry are classified in short plan, medium plan and long plan. In this study, the time period of energy reduction target for iron and steel production in Thailand will be verified and updated in accordance with the ISIT's plan. It can be seen that the energy reduction target from baseline consumption of S1: without integrated steel plant (baseline scenario), S2: with a traditional integrated BF-BOF route and S3: with an alternative integrated DR-EAF route in 2030 are 20.97 %, 15.37 % and 19.31%, respectively. However, this research will evaluate the potential of energy reduction and CO_2 emission reduction under two reduction target scenarios, which are scenario A: achieve ISIT's plan and scenario B: maximum energy reduction when all measures in this study are implemented.

Table 3.10 The energy reduction target of iron and steel industry in Thailand [53]

Scenarios	**Energy reduction target (%)**		
	Short Plan 2015-2019	**Medium Plan 2020-2024**	**Long Plan 2025-2030**
S1: Without integrated steel plant (baseline scenario)	4.35	12.05	20.97
S2: With a traditional integrated BF-BOF route	4.40	9.17	15.37
S3: With an alternative integrated DR-EAF route	4.44	10.83	19.31

3.4.2. Study of CO_2 abatement measures for the iron and steel industry

Due to no specific energy saving technologies and measures and CO_2 emission mitigation options for the iron and steel industry in Thailand in this research, the CO_2 emission mitigation options were obtained from the available and emerging technologies for reducing greenhouse gas emissions from the iron and steel industry reported by the US.EPA [55]. However, only measures that have the payback period time less than three years are selected in this study as shown in Table 2.17 in Chapter 2. There are 12 CO_2 emission mitigation options for electric arc furnace processes and 13 CO_2 emission mitigation options for integrated steel processes.

3.4.3. Construction of CO_2 abatement cost curves

The CO_2 abatement cost curve is a graph that shows the cost per tonne of CO_2 reduction and the cumulative amount of CO_2 avoided, which was applied as a tool for evaluating CO_2 emission mitigation options in this study. The CO_2 abatement cost curve was calculated as presented in Equation 3.17. The CO_2 abatement costs were calculated by dividing the total abatement cost by the amount of abated emissions. In addition, the time value of money was applied to calculate the CO_2 abatement cost of each measure in this study. The present value of money was converted to the future value of money by multiplying with interest rate over a given period of time as can be calculated from Equation 3.12. This research used the interest rate from NIDA's study and used average interest rate from 2010 to 2024 (4.27%) in year 2030 [74]. Additionally, ISIT proposed the energy reduction target for Thailand's steel industry for a long plan in 2030 [53]. Therefore in this study the CO_2 abatement cost curve in year 2030 was presented. To avoid double counting, the options that have low cost and high reduction potential are preferable. After calculating the costs of CO_2 abatement, the measures were ranked in ascending order from low cost to high cost, and construct the CO_2 abatement cost curve.

$$CO_2 \text{ abatement cost (USD/tCO}_2\text{)} = \frac{\text{Product (t) x } CO_2 \text{ abatement cost (USD/t product)}}{\text{Product (t) x } CO_2 \text{ reduction (tCO}_2\text{/t product)}} \qquad (3.19)$$

3.4.4. Sensitivity analysis

This research uses an interest rate of 4.27% from NIDA's study to calculate CO_2 abatement cost curves for Thailand's steel industry in 2030. Different interest rates were used for sensitivity analysis in order to identify the influence of interest rates on the investment costs. The interest rate plus-minus one from average interest rate (4.27%) was used for calculation. Therefore, the low interest rate of 3.27% and, the high interest rate of 5.27% were used for sensitivity analysis in this study.

CHAPTER 4
RESULTS AND DISCUSSION

The results in this study are divided into four parts following the research procedure as follows.

4.1. Energy intensity, carbon dioxide intensity and CO_2 emissions from iron and steel imports in Thailand

4.1.1. Energy intensity of iron and steel production in Thailand

Semi-finished steel products in this study consist of slab and billet products. The primary energy intensity of slab production from electric arc furnace (EAF) process is 3.98 GJ/t slab and the final energy intensity of slab production from electric arc furnace (EAF) process is 2.75 GJ/t slab. Electricity consumption is a major source of energy (61.80 %), followed by oxygen (27.95 %) and fuel combustion (10.25%), respectively. The primary energy intensity of billet production is 4.23 GJ/t billet and the final energy intensity of billet production is 2.97 GJ/t billet of which 58.75% is contributed by electricity consumption, followed by oxygen (27.70%) and fuel combustion (13.55%) as, shown in Table. 4.1.

Table 4.1 Energy intensities of iron and steel production in Thailand

Iron and steel products	Primary energy (GJ/t product)	Final energy (GJ/t product)
Semi-finished steel (EAF process)		
- Slab	3.98	2.75
- Billet	4.23	2.97
Steel finishing process		
- Hot rolled steel	2.43	2.13
- Cold rolled steel	2.11	1.63
- Coated steel	1.24	0.92
- Bar	2.13	1.81
- Annealed wire	3.24	2.60
- Light section	3.11	2.88
- Pipe	0.46	0.27

The energy intensity of billet production is slightly more than that of slab production due to the difference of EAF technology. The ConSteel technology, a modern EAF, has been recently adopted for slab production in Thailand. With regards to ConSteel technology, the heat from gas is directly recycled for scrap preheating, resulting in electrical energy savings. The weighted average of primary energy intensity of semi-finished steel products in Thailand is 4.08 GJ/t semi-finished steel and the weighted average of final energy intensity of the semi-finished steel products in Thailand is 2.84 GJ/t semi-finished steel. The energy intensity of the steel finishing process in Thailand shows that the final energy intensity of the light section is the highest, followed by annealed wire, hot rolled steel, bar, cold rolled steel, coated steel and pipe, respectively. The majority of energy consumption is from fuel combustion which accounts for 71.87%, while electricity consumption shares merely 28.13%. Fuel is used as an energy source in the reheating furnace and the annealing process for the steel finishing process. The energy consumption for pipe production by electric resistance welded (ERW) process is totally from electricity. The coated steel products in this study consisted of hot-dipped galvanized steel, hot-dipped tin plate, tin free and electro-galvanized steels. The energy consumption of these products depends on their production technology. The electro-galvanized steels consume energy mainly from electricity while the hot-dipped steels use fuel combustion as its energy source. The weighted average of primary energy intensity of all steel finishing processes in Thailand is 2.22 GJ/t finished steel and the weighted average of final energy intensity of all steel finishing process in Thailand is 1.86 GJ/t finished steel.

4.1.2. The comparison of final energy intensity from this study with other studies in Thailand and the world best practice

Figure 4.1 presents the comparison of final energy intensity from this study with the specific energy consumption (SEC) reported in Thailand's best practice technologies for iron and steel industry [53] using the same methodology [37], calculation boundary (gate to gate) and unit (GJ/t product). The graphs exhibit the energy intensities calculated from this research (except semi-finished steel production), which are more than those from the published Thai best practice technologies [53]. This result indicates the potential gaps to improve energy efficiency in steel production in Thailand. Among all steel products, hot-rolled flat products have the most energy conservation potential.

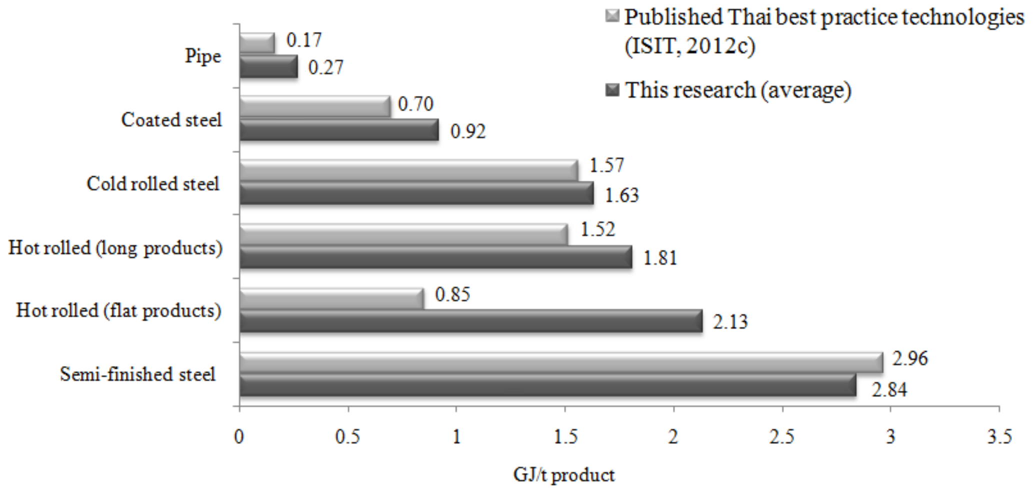


Figure 4.1 Comparison of energy intensity of steel production from this research with that of the published Thai best practice technologies

Table 4.2 illustrates the technical energy conservation potential of steel production reported from this study compared with the world best practice [46] in terms of the Energy Efficiency Index (EEI). The EEIs of all steel production processes are greater than 1.00, suggesting that there is technical potential for Thailand's steel production to improve energy consumption efficiency. The most potential belongs to hot rolling for wire (23.85%), followed by electric arc furnace process (11.97%), cold rolling and finishing (3.68%) and hot rolling for bar (3.31%) respectively.

Table 4.2 Comparison of energy intensities of steel products from this research with the world best practice in terms of Energy Efficiency Index (EEI)

Process	Energy intensity (GJ/t steel)		
	World best practice [46]	This research	EEI
Electric arc furnace (EAF)	2.50	2.84	1.14
Hot Rolling (bar)	1.75	1.81	1.03
Hot Rolling (wire)	1.98	2.60	1.31
Cold rolling and Finishing	1.57	1.63	1.04

4.1.3. CO_2 intensity of iron and steel production in Thailand

The CO_2 emissions from the production of steel comes from fuel combustion, electricity and chemical reaction caused by combustion of some carbonaceous inputs, such as scrap steel, graphite electrode, limestone and dolomite. As presented in Figure 4.2, the CO_2 intensity of slab production from electric arc furnace (EAF) process is 0.367±0.03 tCO_{2e}/t slab mainly from electricity consumption (64.26%), followed by chemical reaction in the process (31.92 %) and fuel combustion (3.82%). The CO_2 intensity of billet production from electric arc furnace (EAF) process is 0.370±0.03 tCO_{2e}/t billet, contributed from electricity consumption (70.11%), followed by chemical reaction in process (23.46%) and fuel combustion (6.43%). The weighted average of CO_2 intensity of semi-finished steel production from the electric arc furnace (EAF) process in Thailand is 0.368 tCO_{2e}/t semi-finished steel.

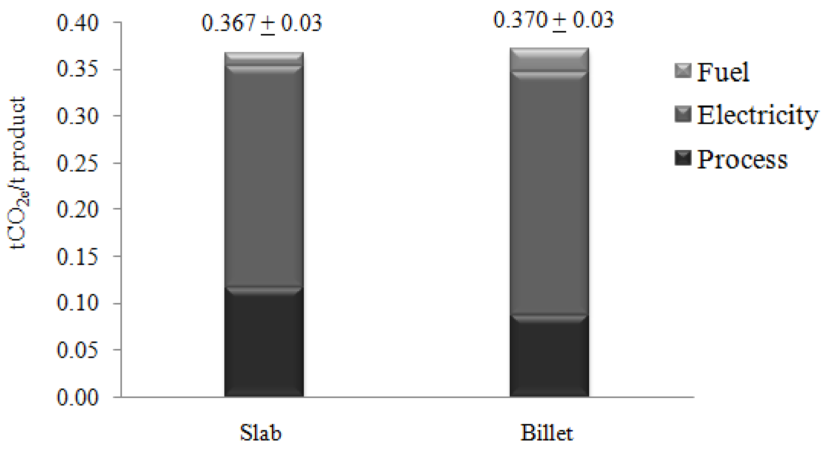


Figure 4.2 CO_2 intensity of semi-finished steel products (slab and billet) in Thailand

The CO_2 intensities of steel finishing process are in the order of annealed wire, light section, hot rolled steel, cold rolled steel, bar, coated steel and pipe, as shown in Figure 4.3. In summary, the CO_2 emissions of the steel finishing process in Thailand is contributed by fuel combustion (57.29%) and electricity consumption (42.71%). The weighted average of the CO_2 intensity of the steel finishing process in Thailand is 0.16 tCO_{2e}/t finished steel with an uncertainty factor less than 10%.

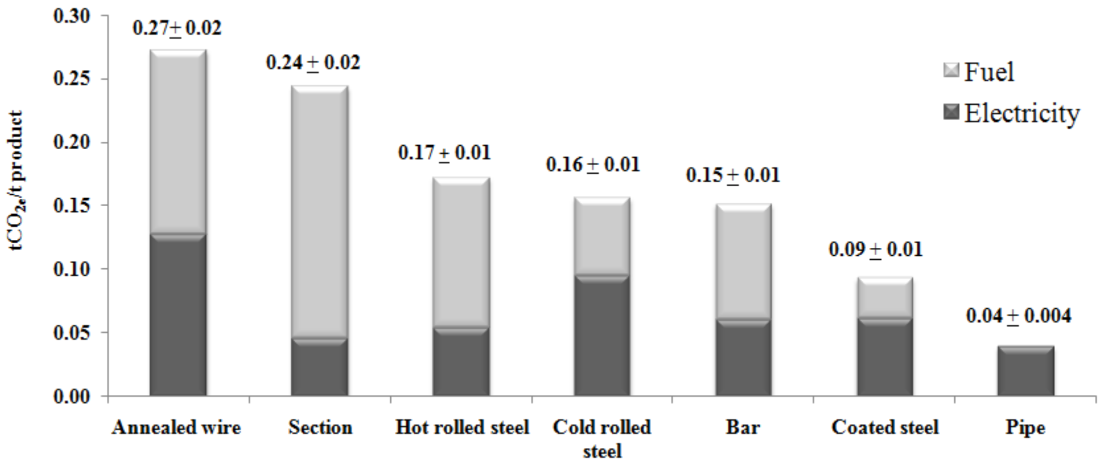


Figure 4.3 CO_2 intensity of steel finishing process in Thailand

4.1.4. The comparison of CO_2 intensity from this research with other studies in Thailand and EU-27

Table 4.3 shows the comparison of CO_2 intensity from this research with other studies in Thailand [16] and EU-27 [75]. According to the study from Sodsai and Rachdawong, the CO_2 intensity was evaluated in the year 2008. The basic equation (Tier 1) of 2006 IPCC guideline was applied and the activity data covers slab and finished steel production. The CO_2 emissions were separately reported from energy emissions and non-energy or process emissions. Energy emissions include stationary fuel combustion and purchased electricity, whilst non-energy or process emissions were primarily from chemical reactions. Thailand's national grid emission factor was obtained from the Electricity Generation Authority of Thailand (EGAT) which was 0.58 kg CO_2 per kWh in the year 2008. The results indicate that the CO_2 intensities from this research are slightly higher than that from the study of Sodsai and Rachdawong. The CO_2 intensity of semi-finished steel products from this research are higher than those of Sodsai and Rachdawong 0.06 tCO_{2e}/t semi-finished steel product. This might be due to different scopes, number of plants, total production capacity and the emission factors used. The information on iron and steel plants in the EU 27 was obtained based on the VDEh Plantfacts database on the update of 17 December 2009. This database contains information and data for each facility in EU. Direct CO_2 emissions into the air due to use of a material together with the upstream emissions is given in Table 4.3. However, the CO_2 intensities of steel products from this research are higher than those of EU 27 benchmarks. In 2009, the average CO_2 emission factor of electricity production in EU 27 was 0.461 tonne CO_2/MWh [77] which was lower than that of CO_2 emission factor of electricity production in Thailand (0.511 t CO_2/MWh). As a result, there is the potential gap to reduce CO_2 emissions from iron and steel production in Thailand to EU 27 benchmark level. Generally, the more energy conservation, the fewer CO_2 emissions. In Thailand, energy efficiency conservation program, research and development of low carbon technology with reasonable investment and economical feasibility are the attractive measures to minimize CO_2 emission from iron and steel production. The recommended measures with the payback period less than three years are improving process control, scrap preheating (Consteel) and oxy-fuel burners for semi-finished steel production from electricity arc furnace (EAF) process [55]. Moreover, energy efficiency measures for hot strip mill are controlling oxygen levels and VSDs on combustion air fans whilst energy efficiency measure for cold mill is automated monitoring and targeting system [55].

Table 4.3 Comparison of CO_2 intensities from this research with other studies

Iron and steel Products	**CO_2 intensity (tCO_{2e}/t product)**		
	This research	**Other study in Thailand** [17]	**EU 27** [76]
Semi-finished steel (EAF process)	0.37± 0.03	0.31	0.24
Finished steel			
- Hot rolled steel	0.17 ± 0.01	0.15	0.12
- Cold rolled steel	0.16 ± 0.01	0.13	0.15

4.1.5. CO_2 emissions from iron and steel imports in Thailand

Figure 4.4 illustrated quantity of steel imported by Thailand from 2000-2014. It can be seen that semi-finished steel product is imported increasingly into Thailand from year 2003 to 2005 due to the growth demand of steel in construction sector. The average of steel import in Thailand from 2000 to 2014 indicated that semi-finished steel product is imported the highest, followed by hot rolled coil and hot dip galvanized respectively.

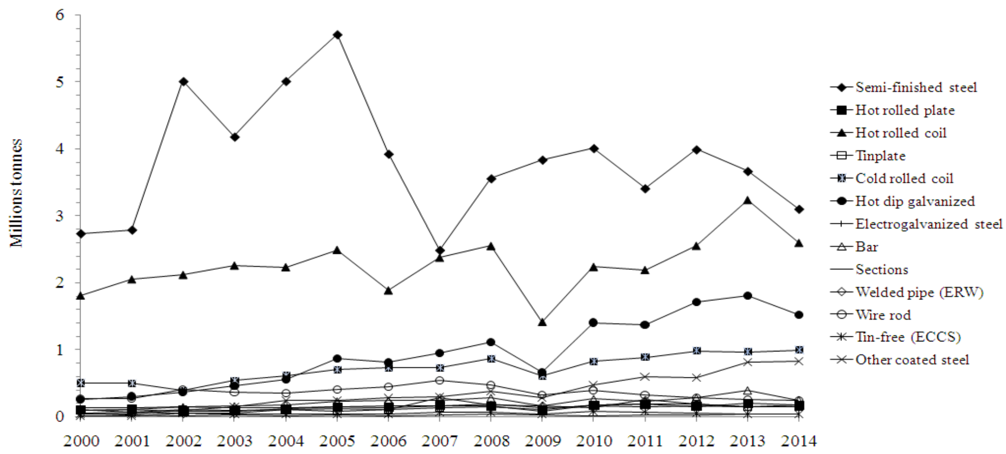


Figure 4.4 Quantity of steel imported into Thailand from 2000-2014

Figure 4.5 illustrated CO_2 emissions from steel imported into Thailand from 2000-2014. The average CO_2 emission of semi-finished steel imported into Thailand is the highest (6.39 million tCO_{2e}) and followed by hot rolled coil (2.27 million tCO_{2e}), hot dip galvanized (1.27 million tCO_{2e}), cold rolled coil (0.85 million tCO_{2e}), other coated steel (0.59 million tCO_{2e}), wire rod (0.47 million tCO_{2e}), bar (0.22 million tCO_{2e}), electro-galvanized steel (0.20 million tCO_{2e}), welded pipe (ERW) (0.18 million tCO_{2e}), tinplate (0.17 million tCO_{2e}), hot rolled plate (0.16 million tCO_{2e}), tin-free (0.06 million tCO_{2e}) and sections (0.03 million tCO_{2e}) respectively. The annually average CO_2 emission from steel imported into Thailand from 2000-2014 is 12.86 million tCO_{2e}/years.

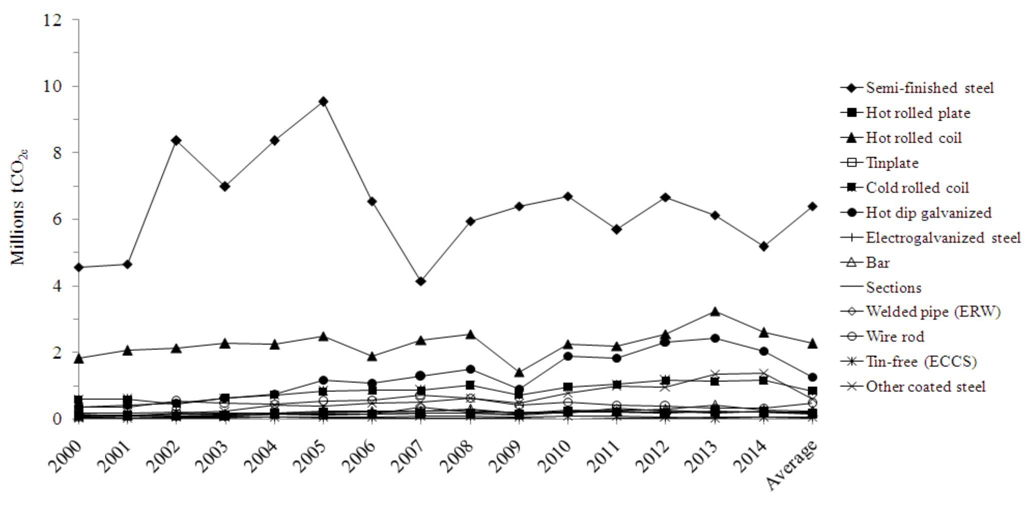


Figure 4.5 CO_2 emissions from steel imported into Thailand from 2000-2014

4.2. The projections of greenhouse gas emissions from iron and steel production in Thailand from 2011 to 2050

The projections of greenhouse gas emission of three plausible scenarios, which were S1: without integrated steel plant (baseline scenario), S2: with a traditional integrated BF-BOF route and S3: with an alternative integrated DR-EAF route are shown below.

S1: Without integrated steel plant in Thailand (Baseline scenario)

The CO_2 emissions of iron and steel production in Thailand from 2011 to 2050 are shown in Figure 4.6. The largest share of CO_2 emissions is from the production of semi-finished steel. Its CO_2 emission trend increases sharply from the year 2010 until the production reaches 80% of the maximum production capacity of 6.29 million tonnes in the year 2024, resulting in 2.33 million tonnes of CO_2 emissions. In contrast, the CO_2 emissions of the other steel products increase gradually. The flat lines of the forecasted CO_2 emissions in S1 occur when the projected demands are assumed that the production should not exceed 80% of maximum production capacity for each steel product. In 2050 total CO_2 emissions of all steel production in Thailand will be 4.84 million tonnes, increasing by 1.55 times as compared to the 2010 level.

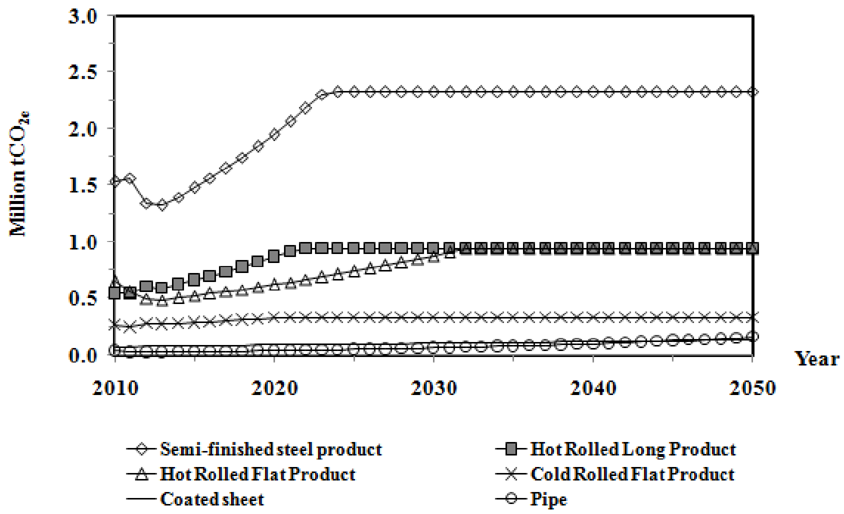


Figure 4.6 Forecast of CO_2 emissions under S1: without integrated steel plant in Thailand (Baseline scenario)

S2): With a traditional integrated BF-BOF route in Thailand

According to the ISIT plan, the upstream steel industry based on blast furnace-basic oxygen furnace (BF–BOF) route is expected to be established in 2023, leading to the CO_2 emissions of 17.12 million tonnes in 2050, increasing by 3.59 times from 2023 level, as shown in Figure 4.7. The CO_2 emissions from the process of BF–BOF is significantly rising from the year 2023. The flat line of the forecasted CO_2 emissions during 2027–2050 is based on the assumption that the BF–BOF production under S2 does not exceed 89.7% of maximum production capacity or 8.08 million tonnes of BF–BOF steel. Aside from the iron-making process, in 2050 the production of semi-finished steel products account for 2.33 million tonnes of CO_2 emissions. The rests are hot rolled long products (0.94 million tonnes), hot rolled flat products (0.94 million tonnes), cold rolled flat products (0.33 million tonnes), coated sheet (0.13 million tonnes) and pipe (0.16 million tonnes). By 2050, total CO_2 emissions from all iron and steel products will be 21.96 million tonnes increasing 2010 levels by 7.05 times.

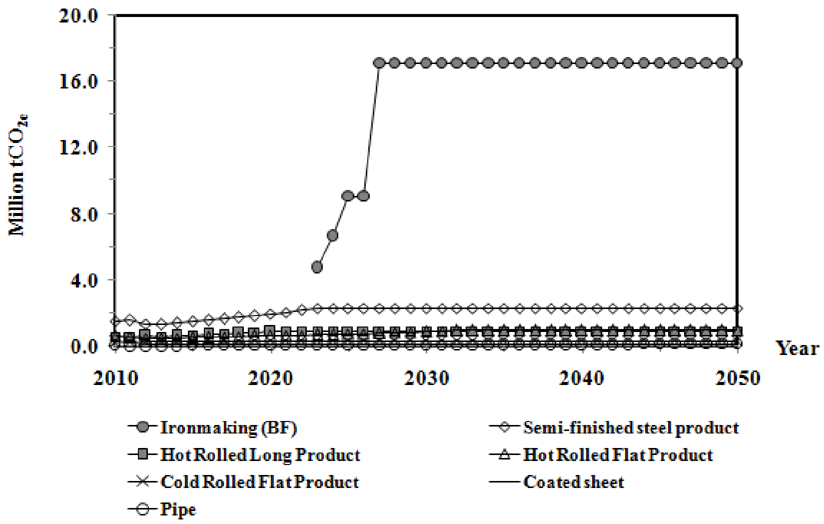


Figure 4.7 Forecast of CO_2 emissions under S2: with a traditional integrated BF-BOF route in Thailand

S3): With an alternative integrated DR-EAF route in Thailand

Currently, most steel processing technology in Thailand is electrical arc furnace (EAF) using scrap steel as a raw material, which is mostly imported. Direct reduced iron based on natural gas is proposed to be established in 2023. The CO_2 emissions from iron making by direct reduced iron plant in 2050 will be 2.28 million tonnes increasing of 1.8 times from the 2023 level as shown in Figure 4.8. As a result, total CO_2 emissions of all iron and steel products in Thailand in 2050 will be 7.12 million tonnes increasing 2.29 times that from the 2010 level. It is obviously seen that the CO_2 emissions from semi-finished steel production from the EAF process is higher than that of iron making from direct reduction iron (DRI) product as 0.98 times in 2050. This is because the production capacity of semi-finished steel is approximately 3.14 times higher than that of the direct reduction iron (DRI).

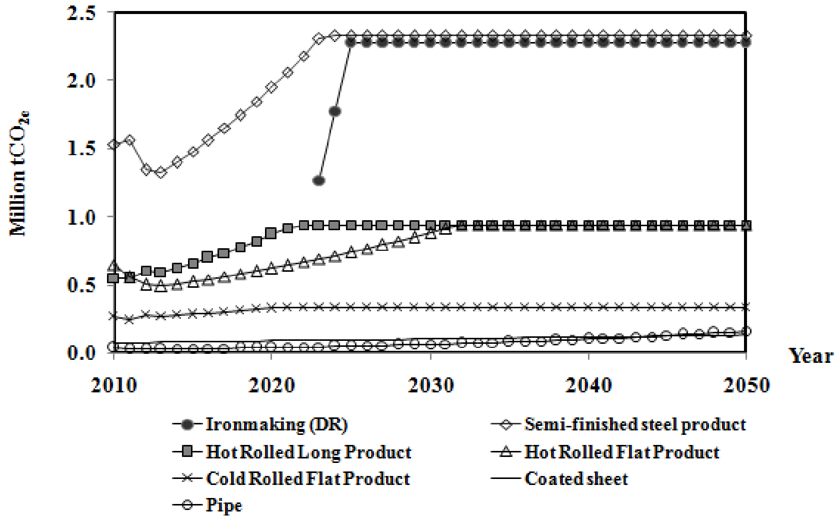


Figure 4.8 Forecast of CO_2 emissions under S3: with an alternative integrated DR-EAF route in Thailand

Among these three scenarios, the establishment of integrated iron making by BF-BOF process is determined as the worst case for CO_2 emissions. This conclusion is only based on the energy consumption and greenhouse gas emission aspects excluding its economic benefits. However, the forecasted results bring about the serious concern how to balance the benefits from iron and steel investment and its climate change impacts. The potential options for energy conservation and greenhouse gas emission reduction with regard to the iron and steel production should be investigated in details, covering all impacts such as environmental impacts, economic costs and benefits, and technical and social concerns.

4.3. Evaluation and prioritization of iron-making technology in Thailand by using MCDA (bipolar method) based on environmental, economic and technological availability

The establishment of upstream iron industry has economic benefits. However, in environmental aspects the iron production causes adverse environmental impacts such as high energy consumption, resource depletion and greenhouse gas (GHGs) emission. Thus, in this research; the impacts of three iron making technologies blast furnace (BF), corex and midrex were evaluated by using Multi-Criteria Decision Analysis MCDA (Bipolar Approach). The results from this study are shown below.

4.3.1. Comparisons of iron making technology data in economic, environmental and technology criteria

a) Economic criteria

The economic sub-criteria consist of direct costs, indirect costs, direct benefits and indirect benefits. Direct costs includes investment cost and operating and maintenance cost. Indirect costs are environmental costs calculated from environmental cost per unit of pollutants. The costs were derived from LCA-based inventory represented via willingness to pay (WTP) of the society as shown in Table 4.4 [73]. The time value of money was applied in this study. The present value of money is converted to the future value of money and changed to unit of Thai baht. The data in 2013 used as based year for calculation. It can be seen that the environmental costs of CO_2 emissions are the lowest costs comparing to other pollutants. Even though, CO_2 emissions have global warming impact there is neither law nor regulation regarding to CO_2 emissions in Thailand. Direct benefits are price per tonne of product while indirect benefits are the benefits from waste utilization and heat recovery.

Table 4.4 Environmental costs per unit of pollutants [73]

Environmental costs	**Emissions**							
	CO_2	**CH_4**	**N_2O**	**CO**	**NO_2**	**SO_2**	**VOC**	**PM_{10}**
PV_{2008} (baht/kg)	1.40	34.50	485.00	4.20	27.00	41.90	27.10	457.20
FV_{2013} (baht/kg)	1.76	43.47	611.10	5.29	34.02	52.79	34.15	576.07

Noted: PV is present value of money; FV is future value of money

Comparisons of ironmaking technology with four sub-criteria are shown in Table 4.5. It can be seen that corex technology has the highest direct costs, followed by midrex and blast furnace technology, respectively. Direct benefits of blast furnace and corex technology are equal due to the same product price. The direct-reduced iron (DRI), also called sponge iron is cheaper than pig iron produced from blast processes. Additionally, corex has the highest indirect benefit per tonne of steel due to high export gas generated by this process. There are no indirect benefits from midrex in this study due to no exported gases and slag generated from this process. Indirect costs, are found that corex technology has the highest costs, followed by blast furnace and midrex technology. Midrex exhibits fewer environmental impacts because it uses natural gas while BF and corex use coke and coal as reducing agents.

Table 4.5 Comparison of iron-making technology in economic criteria

Economic criteria	Blast furnace	Corex	Midrex	Data Sources
1. Direct cost 1.1. Investment costs	216 USD/t = 6,527.52 baht/t	351 USD/t = 10,607.22 baht/t	270 USD/t = 8,159.40 baht/t	[78]
1.2. Operation and maintenance cost	15.48 Euro/t = 1,027.47 baht/t	21.96 Euro/t = 1,457.53 baht/t	22 Euro/t 1,460.35 baht/t	[79]
Total direct costs	7,554.99 baht/t	12,064.75 baht/t	9,619.75 baht/t	
2. Direct benefits	Pig iron 23,500 Rupee	Pig iron 23,500 Rupee	Sponge iron 20,100 Rupee	[80]
Total direct benefits	12,455 baht/t	12,455 baht/t	10,653 baht/t	
3. Indirect benefits - Export gases for power generation 3.3 baht/kWh - Granulated slag utilization 74.25 baht/t	1. Export gases 515.4 kWh/t = 1,700.82 baht 2. Slag 0.265 t/t steel = 19.68 baht	1. Export gases 1,540.4 kWh/t = 5,083.32 baht 2. Slag 0.35 t/t steel = 25.99 baht	1. Export gases 0 kWh/t 2. Slag 0 t/t steel	[81]
Total indirect benefits	1,720.5 baht/t	5,109.31 baht/t	0 baht/t	

Table 4.5 Comparison of iron-making technology in economic criteria (Cont')

Economic criteria	Blast furnace	Corex	Midrex	Data Sources
4. Indirect costs Emissions to air after abatement	(kg/t) SO_2 = 2.12 NO_2 = 1.38 Dust = 0.386 CO = 30.48 CO_2 = 823.7 CH_4 = 0.027 VOC = 0.19	(kg/t) SO_2 = 0.053 NO_2 = 0.114 Dust = 0.13 CO_2 = 1,450	(kg/t) SO_2 = 0.025 NO_2 = 0.51 Dust = 0.056 CO_2 = 500	[31]
Total indirect costs	1,999.84 baht/t	2,633.57 baht/t	930.93 baht/t	

Note: direct costs compared to the same capacity 1 mt

1USD = 30.22 baht (Average January 2013) [75]

1Euro = 40.23 baht (Average January 2013) [75]

1 Rs = 0.53 baht (15 April 2013) [80]

b) Environmental criteria

The environmental criteria consist of three sub-criteria, which are energy consumption, greenhouse gas emissions and resource depletion, as shown in Table 4.6. The comparison of energy consumption of three iron making technologies exhibit the primary energy requirements of corex technology as the highest, followed by midrex technology and blast furnace technology. It can be seen that electricity is the main energy source for midrex technology. Greenhouse gas emissions from midrex technology has the lowest impacts because it uses only natural gas, while BF and corex use coke and coal as reducing agents. The raw material used in ironmaking process such as iron ore, coal, coke, fuel and additive is listed in Table 4.7. It can be seen that the amount of iron ore consumption of these three technologies after rescaling unit is between 1.48-1.50. Additives such as dolomite and limestone are used as fluxs only in smelting reduction furnace for corex and blast furnace technology. Due to different scales of iron making technology, the rescaling unit is applied in this study.

Table 4.6 Comparison of iron-making technology in environmental criteria

Environmental criteria	Blast furnace	Corex	Midrex	Data Sources
1. Energy consumption	Sintering = 2.20 GJ Coking = 1.10 GJ BF = 12.40 GJ BOF = -0.30 Refining = 0.40 GJ	Pelletizing = 0.80 GJ Smelting reduction = 17.90 GJ BOF = -0.30 GJ Refining = 0.40 GJ	Sintering = 2.20 GJ Pelletizing = 0.80 GJ Direct reduction = 9.20 GJ EAF = 5.90 GJ	[82]
Total energy consumption	**15.8 GJ**	**18.8 GJ**	**18.1 GJ**	
2. GHG emissions (Exclude excavation of ore and transportation)	1. coal 2,030 kg CO_2 2. gas recycle from coke oven and BF -40 kg CO_2 3. electricity 160 kg CO_2 4. slag utilization -30 kg CO_2	1. coal 2,810 kg CO_2 2. recycle gas -390 kg CO_2 3. electricity 220 kg CO_2 4. slag utilization -200 kg CO_2	1. NG gas 800 kg CO_2 2. electricity 340 kg CO_2	[83]
Total GHG mission	**2,120 kg CO_2/t steel**	**2,440 kg CO_2/t steel**	**1,140 kg CO_2/t steel**	

Table 4.7 Resources used for 1 tonne of steel production [81]

Material		Unit	Blast Furnace	Corex	Midrex
1. Iron ore		**t**	**1.49**	**1.48**	**1.50**
	Pellets	t	1.06	1.48	1.05
	Lump	t	0.43	0	0.45
2. Coal/Coke		**t**	**0.55**	**0.98**	**0**
	Coal	t	0.17	0.98	0
	Coke	t	0.38	0	0
3. Fuel		**GJ**	**11.52**	**0**	**35.05**
	NG	MBTU	4	0	33.2
	Oil	t	0.12	0	0
4. Additives such as dolomite, limestone		**t**	**0.18**	**0.24**	**0**

c) Technology criteria

Sub-criteria of technology consist of barriers to material acquisition and complexity of technical operation. The qualitative data of relative preferences in technology criteria were changed to quantitative data by expert judgment, following classical AHP method. By following this method, a consistency ratio (CR) is evaluated in order to assure that judgments were consistent and the final decision is reasonable. The results show that the consistency ratio (CR) does not exceed 0.1. This means the expert judgments are reliable. The weight prioritize of barriers to material acquisition by expert is shown in Figure 4.9. The results of weight prioritize of barriers to material acquisition by government sector and private sector show that midrex has the highest to barrier of material acquisition, followed by blast furnace (BF) and corex technology respectively. Midrex uses natural gas as a reducing agent leading to lower pollutant emissions. However, it is not appropriates for countries that have high gas prices. While the results of weights prioritize of barriers to material acquisition from experts in education sector and institute sector show that BF has the highest to barrier of material acquisition, followed by midrex and corex technology respectively. The expert opinion shown that BF use resource intensive compare with other process and iron ore fine can't use directly in BF process. However, the weight average of barrier of material acquisition from all experts found midrex has the highest to barrier of material acquisition, followed by BF and corex respectively.

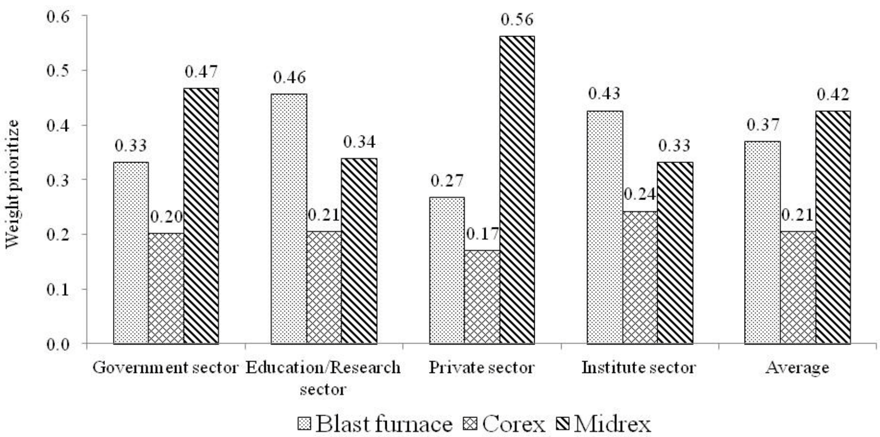


Figure 4.9 Weight prioritization of barriers to material acquisition

The weights prioritization of complexity of the technical operation by the expert is shown in Figure 4.10. The results of weight prioritizing of complexity of technical operation by education/research sector and institute sector show that BF has the most operational complexity, followed by corex and midrex technologies respectively. The weights prioritized by complexity of technical operation by private sector show that midrex has the most operation complexity, followed by corex and BF respectively. The expert’s opinion show that BF is a proven engineering for all equipment for a long time, fast and reliable start up while midrex and corex technology are low flexible. Especially, midrex use natural gas as a reducing agent that reformer gas process is essential. Additionally, the corex process consists of two separate process reactors, which are reduction shaft process and melter-gasifier process. The weights prioritization of complexity of technical operation by government sector shows that corex has the most operation complexity, followed by midrex and BF respectively. The weight average of operation complexity from all experts found that corex has the most complexity of technical operation, followed by BF and midrex respectively.

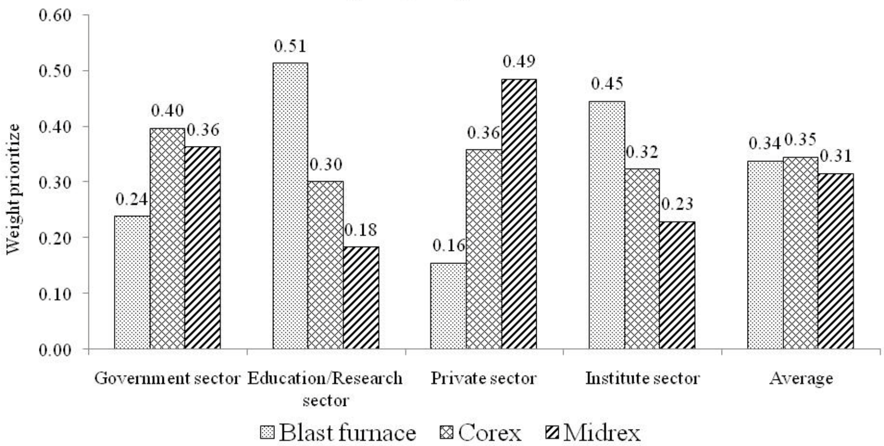


Figure 4.10 Weight prioritization of complexity of technical operation

4.3.2. The Bipolar Analytical Hierarchy Process (BAHP)

BAHP can reflect both positive and negative desirability, as opposed to the strictly positive of the classical AHP. The next step after indicating quantitative data was rescaling units to sum across criteria. The final results came from multiplying bipolar matrix by criteria weight matrix. The final results in negative values were converted to positive values by normalization (one minus the absolute value of negative result and then divided by summation of all values). The evaluation and prioritization of iron-making technology in Thailand by using bipolar approach based on environmental, economic and technology criteria are presented as follows.

a) Economic criteria

Tables 4.8 and 4.9 illustrate quantitative data of relative preferences of ironmaking alternative in rescale unit. In this study direct costs and indirect costs represented negative criteria while direct benefits and indirect benefits represented positive criteria as shown in Table 4.10. The direct and indirect costs of corex are the highest due to its highest investment costs and emission abatement costs. The relative economic criteria weights in Table 4.11 defined the ratio of the absolute value of the relative preference of the most extreme values under each criterion in Table 4.9. A criteria weight of BAHP is concerned with the performance of the dominance of each alternative. The results of economic criteria weights show that direct cost (0.26) and indirect benefit (0.26) were the highest important criteria for evaluating ironmaking technology in Thailand, followed by indirect cost (0.25) and direct benefit (0.23).

Table 4.8 Quantitative data of relative preferences in economic criteria

Iron-making technology	**Sub-criteria of economic**				
	Direct cost (baht/t)	**Direct benefit (baht/t)**	**Indirect benefit (baht/t)**	**Indirect cost (baht/t)**	**Total net benefit (baht/t)**
BF	7,554.99	12,455.00	1,720.50	1,999.84	4,620.67
Corex	12,064.75	12,455.00	5,109.31	2,633.57	2,865.99
Midrex	9,619.75	10,653.00	0	930.93	102.32

Table 4.9 Rescale units in economic criteria

Iron-making technology	**Sub-criteria of economic**			
	Direct cost	**Direct benefit**	**Indirect benefit**	**Indirect cost**
BF	0.30	0.62	0.46	0.53
Corex	0.71	0.62	0.72	0.68
Midrex	0.49	0.26	0.32	0.28
The most extreme values	0.71	0.62	0.72	0.68

Table 4.10 Indicating negative or positive criteria (bipolar matrix) in economic criteria

Iron-making technology	Sub-criteria of economic			
	Direct cost	**Direct benefit**	**Indirect benefit**	**Indirect cost**
BF	-0.43	1.00	0.63	-0.78
Corex	-1.00	1.00	1.00	-1.00
Midrex	-0.69	0.42	0.44	-0.41

Table 4.11 Economic criteria weights

Sub-criteria of economic	Direct cost	Direct benefit	Indirect benefit	Indirect cost	Mean	Normalization
Direct cost	1.00	1.15	0.98	1.04	1.04	0.26
Direct benefit	0.87	1.00	0.86	0.90	0.91	0.23
Indirect benefit	1.02	1.17	1.00	1.06	1.06	0.26
Indirect cost	0.96	1.11	0.95	1.00	1.00	0.25

In economic criteria, the results showed that BF technology had the positive preference in terms of economic criteria due to its high net profit. Whilst corex and midrex technologies had the negative preference due to their high investment costs. Especially, a high quality of raw material is required for midrex resulting in high costs of raw materials. Figure 4.11 indicated that the most preferred iron-making technology in terms of economic belongs to BF, followed by corex and midrex respectively.

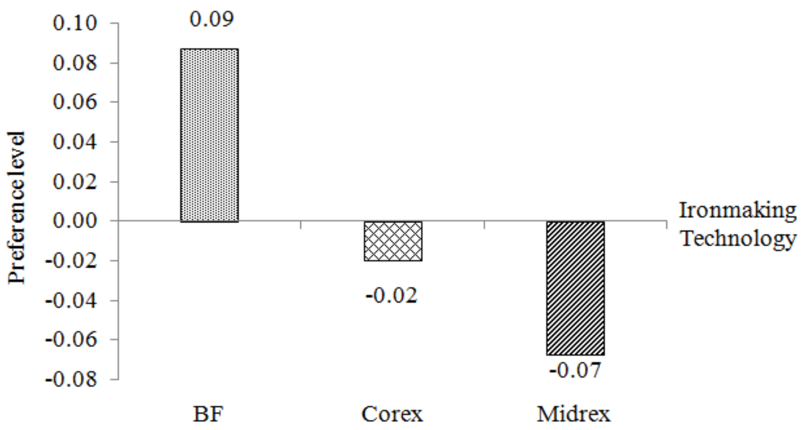


Figure 4.11 The preference levels of iron-making technology based on economic criteria

b) Environmental criteria

The data of relative preferences of iron making technology and rescale unit are shown in Tables 4.12 and 4.13. Sub-criteria of environmental consisted of resource depletion, energy consumption and greenhouse gas emission (GHG). The most extreme value of resource depletion belonged to BF while the most extreme value of energy consumption and GHG emission belonged to corex. All sub-criteria in this study were negative criteria due to the adverse effects of pollution from iron making process. The most extreme value of alternative under negative criterion is -1 as shown in Table 4.14. The relative environmental criteria weights in Table 4.15 can be defined as the ratio of the absolute value of the relative preference of the most extreme values under each criterion in Table 4.13. The result of environmental criteria weights shows resource depletion was the most important criteria among all environmental criteria.

Table 4.12 Quantitative data of relative preferences in environmental criteria

Iron-making technology	Sub-criteria of environmental		
	Resource depletion (normalized unit)	Energy consumption (GJ/t)	GHG emission (kg/t)
BF	2.04	15.80	2,120
Corex	1.98	18.80	2,440
Midrex	1.99	18.10	1,140

Table 4.13 Rescale units in environmental criteria

Iron-making technology	Sub-criteria of environmental		
	Resource depletion	Energy consumption	GHG emission
BF	0.73	0.27	0.57
Corex	0.35	0.66	0.66
Midrex	0.42	0.57	0.27
The most extreme values	0.73	0.66	0.66

Table 4.14 Indicating negative or positive criteria (bipolar matrix) in environmental criteria

Iron-making technology	**Sub-criteria of environmental**		
	Resource depletion	**Energy consumption**	**GHG emission**
BF	-1.00	-0.41	-0.85
Corex	-0.48	-1.00	-1.00
Midrex	-0.57	-0.86	-0.41

Table 4.15 Environmental criteria weights

Sub-criteria of environment	**Resource depletion**	**Energy consumption**	**GHG emission**	**Mean**	**Normalization**
Resource depletion	1.00	1.11	1.11	1.07	0.36
Energy consumption	0.90	1.00	1.00	0.96	0.32
GHG emission	0.90	1.00	1.00	0.97	0.32

In environmental criteria, the results indicate that all iron making technologies had the negative preference, as shown in Figure 4.12, due to the adverse effects of iron making on resource depletion, energy consumption and greenhouse gas emissions. Even though all environmental criteria are negative preference, the most preferences of iron making technology in terms of environmental concerns belonged to midrex, followed by BF and corex, respectively. Midrex exhibits less environmental impacts because it uses natural gas. Moreover, the corex process differs from BF process in that it uses non-coking coal. As a result, coking plant is not necessary. However, the primary energy consumption in smelting reduction process and greenhouse gas emission of corex are still higher than that of BF.

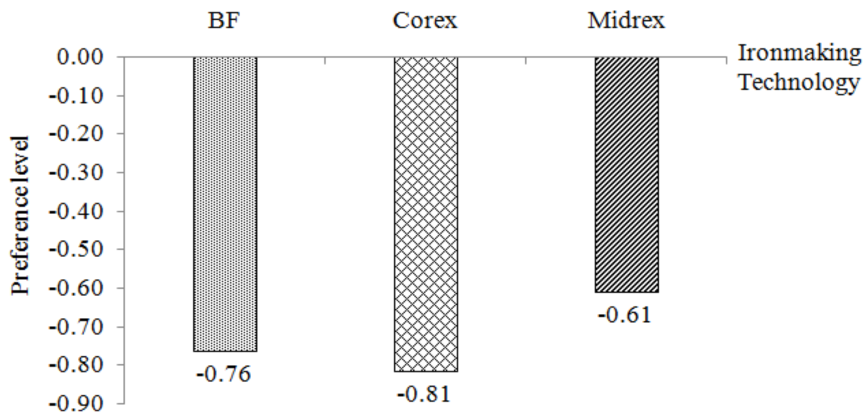


Figure 4.12 The preference levels of iron-making technology based on environmental criteria

c) Technology criteria

The data of relative preferences of iron-making technology and rescale unit are shown in Tables 4.16 and 4.17. Sub-criteria of technology consisted of barrier of material acquisition and complexity of technical operation. Table 4.18 showed all sub-criteria in this study which are negative criteria. The most extreme value of alternative under negative criterion is -1. The technology criteria weights in Table 4.19 can be defined as the ratio of the absolute value of the relative preference of the most extreme values under each criterion in Table 4.17. The result of technology criteria weights shows complexity of technical operation is more important criteria than that of barrier of material acquisition for evaluating iron making technology in Thailand.

Table 4.16 Quantitative data of relative preferences in technology criteria

Iron-making technology	Sub-criteria of technology	
	Barrier to material acquisition	Complexity of operation
BF	0.37	0.34
Corex	0.21	0.35
Midrex	0.42	0.31

Table 4.17 Rescale units in technology criteria

Iron-making technology	Sub-criteria of technology	
	Barrier of material acquisition	**Complexity of operation**
BF	0.57	0.54
Corex	0.27	0.68
Midrex	0.66	0.28
The most extreme values	0.66	0.68

Table 4.18 Indicating negative or positive criteria (bipolar matrix) in technology criteria

Iron-making technology	Sub-criteria of technology	
	Barrier of material acquisition	**Complexity of operation**
BF	-0.86	-0.80
Corex	-0.41	-1.00
Midrex	-1.00	-0.41

Table 4.19 Technology criteria weights

Sub-criteria of technology	Barrier of material acquisition	Complexity of operation	Mean	Normalization
Barrier of material acquisition	1.00	0.98	0.99	0.49
Complexity of operation	1.03	1.00	1.01	0.51

The results of technology assessment are presented in Figure 4.13. The most preferred of iron-making technology belonged to midrex, followed by corex and BF, respectively. Analysis of technology assessment was considered on two subcriteria: barrier of raw material acquisition and complexity of technical operation. According to expert judgement, midrex has the highest barrier of raw material because the process uses natural gas as a reducing agent which is not suitable for countries that have high gas price, like Thailand. However, midrex has the lowest complexity of operation. Although corex has the lowest barrier of raw material, it has highest complexity of operation because corex has two separated process reactors which are the reduction shaft and the melter gasifier.

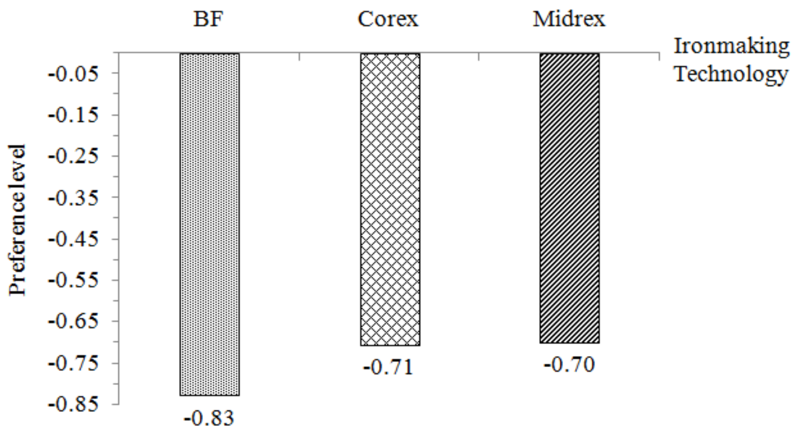


Figure 4.13 The preference levels of iron-making technology based on technology criteria

d) Evaluation and prioritization of iron making technology in Thailand by using MCDA (bipolar method) based on environmental, economic and technological availability

The data of relative preferences of ironmaking technology in three main criteria and rescale unit are shown in Tables 4.20 and 4.21. It can be seen that BF technology had the positive preference in economic criteria and the most preferences of iron making technology in terms of environmental and technology concerns belonged to midrex. All sub-criteria in environmental and technology are negative criteria as shown in Table 4.22. The most extreme value of alternative under positive criterion is 1 and the most extreme value of under negative criteria is -1. The relative of three main criteria weights was shown in Table 4.23

Table 4.20 Quantitative data of relative preferences in each alternative

Iron making Technology	**Main criteria**		
	Economic	**Environmental**	**Technology**
BF	0.09	-0.76	-0.83
Corex	-0.02	-0.81	-0.71
Midrex	-0.07	-0.61	-0.70

Table 4.21 Rescale units of economic, environmental and technological criteria

Iron-making Technology	Main criteria		
	Economic	**Environmental**	**Technology**
BF	0.66	0.56	0.74
Corex	0.27	0.66	0.39
Midrex	0.56	0.27	0.37
The most extreme values	0.66	0.66	0.74

Table 4.22 Indicating negative or positive criteria (bipolar matrix)

Iron-making Technology	Main criteria		
	Economic	**Environmental**	**Technology**
BF	1.00	-0.85	-1.00
Corex	-0.41	-1.00	-0.53
Midrex	-0.85	-0.41	-0.51

Table 4.23 Main criteria weights of economic, environmental and technological criteria

Main criteria	Economic	Environmental	Technology	Mean	Normalization
Economic	1.00	1.00	0.90	0.97	0.32
Environmental	1.00	1.00	0.90	0.97	0.32
Technology	1.11	1.11	1.00	1.07	0.36

The final results in negative values were converted to positive values by normalization. The total result of the most preferred of iron making technology after normalization is equal to 1. The higher number of preference level of iron making technology showed the technology is suitable alternative for iron making technology in Thailand based on this stufy. The final evaluations based on technology, economic and environment aspects using bipolar analytical hierarchy process (BAHP) exhibited that BF technology was the most preference of iron making technology in Thailand with the preference level 0.48, followed by midrex (0.28) and corex (0.24) as shown in Figure 4.14.

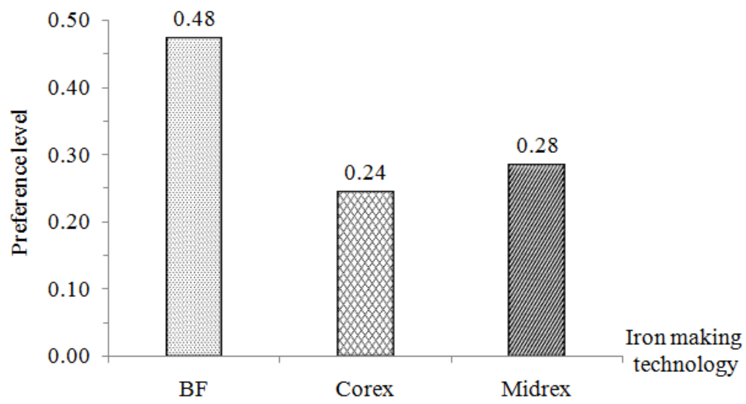


Figure 4.14 Overall preference levels of iron-making technology in Thailand

Further study will focus on the marginal CO_2 abatement cost curves for the Thailand iron and steel industry. Additionally, the potential of energy consumption reduction and greenhouse gas emission reduction under reduction target scenarios for iron and steel production in Thailand will be proposed.

4.4. Energy saving potentials and CO_2 abatement cost curves for Thailand's steel industry in 2030

Based on technological, economic and environment criteria blast furnace technology was the most preference of iron making technology in Thailand. Therefore, scenario S2: with a traditional integrated BF-BOF route in Thailand is selected to study energy saving potentials and CO_2 abatement cost curve in 2030 for the Thailand's steel industry. Several available technologies such as improving energy efficiency in the processes, improving blast furnace control system could be potentially introduced for greenhouse gas reduction from iron and steel industry in Thailand. The average interest rate 4.27% was used for calculation of CO_2 abatement cost curve in 2030 [74].

4.4.1. The CO_2 abatement cost curve in 2030

This study presents the greenhouse gas emission mitigation options and CO_2 abatement costs under S2: a traditional integrated BF-BOF route in Thailand. The CO_2 abatement measures which had payback period less than three years were selected in this study. The CO_2 abatement cost curve in year 2030 is shown in Figure 4.15. It can be seen that the highest CO_2 emission reduction measure for BF-BOF process in Thailand’s steel industry belongs to injection of natural gas to 140 kg/ton iron, contributing 0.443 million tCO_{2e} with the mitigation cost of 219.87 USD/tCO_{2e}, followed by recuperative and regenerative burners (0.403 million tCO_{2e}), pulverized coal injection to 130 kg/ton iron (0.38 million tCO_{2e}) preventive maintenance (0.288 million tCO_{2e}) respectively. The CO_2 emission mitigation cost of energy efficient drives is the highest due to high additional cost of high efficiency alternative current motors. Whilst preventive maintenance measure can reduce high CO_2 emission with low mitigation cost. Overall the CO_2 emission reduction according to all greenhouse gas emission mitigation options listed in Table 4.24 is 2.46 million tCO_{2e} with total cost of 485.71 million USD in 2030.

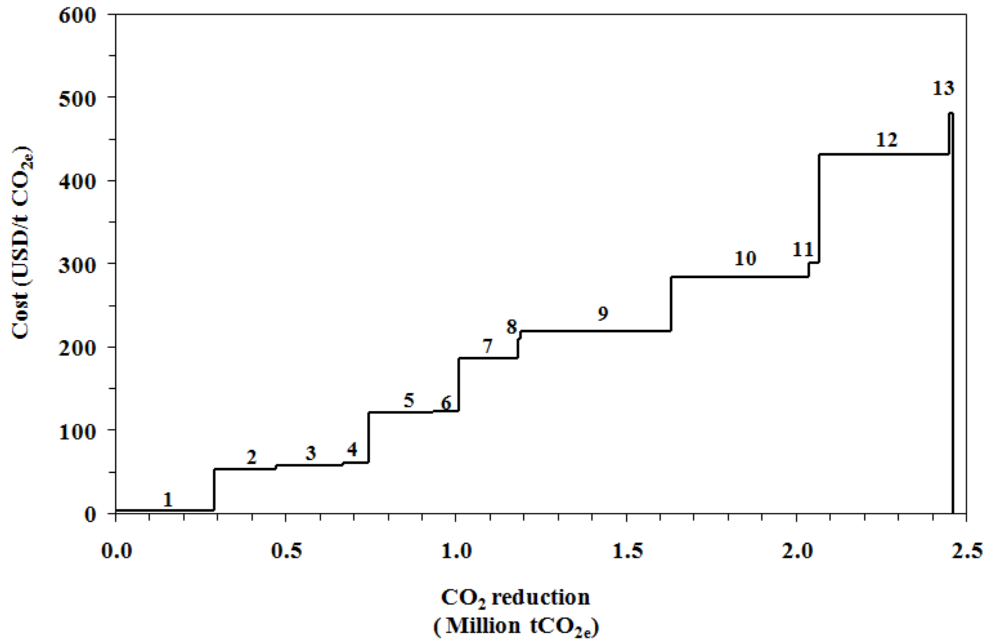


Figure 4.15 The CO_2 abatement cost curves of blast furnace – basic oxygen furnace (BF-BOF) process in 2030

(The mitigation option numbers are relevant to Table 4.24)

Table 4.24 CO_2 emission reduction and mitigation costs of BF-BOF process in 2030

Measures	CO_2 emission reduction (Million t CO_{2e})	Energy reduction (10^6 GJ)	Mitigation cost (USD/t CO_{2e} reduction)
1. Preventive maintenance	0.288	3.633	3.60
2. Hot-blast stove automation	0.182	2.988	53.41
3. Improved blast furnace control systems	0.197	3.230	58.95
4. Energy monitoring and management systems	0.077	0.969	62.18
5. Controlling oxygen levels and/or speed on combustion air fans	0.190	3.779	122.23
6. Automated monitoring and targeting system	0.073	0.436	123.69
7. Process control in hot strip mill	0.173	3.435	187.10
8. Efficient caster ladle/tundish heating	0.009	0.162	210.14
9. Injection of natural gas to 140 kg/ton iron	0.443	7.267	219.87
10. Recuperative and regenerative burners	0.403	8.015	284.56
11. Recovery of BFG	0.032	0.565	301.78
12. Pulverized coal injection to 130 kg/ton iron	0.380	6.218	431.70
13. Energy efficient drives	0.013	0.081	481.56

4.4.2. The potentials of energy consumption reduction and greenhouse gas emission reduction under reduction target scenarios

This study evaluated the potential of energy and CO_2 reduction of S2: with a traditional integrated BF-BOF route in Thailand under two reduction target scenarios which are Scenario A: achieve ISIT' plan and Scenario B: maximum energy reduction. The results are as follows.

Scenario A: Achieve ISIT's plan

To achieve the energy reduction target of S2 according to ISIT's plan, which is 15.37 % (25.06 million GJ), 9 energy saving measures are adopted, as presented in Figure

4.16. The energy saving measures are preventive maintenance, hot-blast stove automation, improved blast furnace control systems, energy monitoring and management systems, controlling oxygen levels and/or speed on combustion air fans, automated monitoring and targeting system, process control in hot strip mill, efficient caster ladle/ tundish heating and injection of natural gas to 140 kg/ton iron. The energy reduction of S2 is 25.90 million GJ and CO_2 emission reduction is 1.63 million tCO_{2e} in year 2030. The investment costs required for CO_2 emission reduction measure of S2 is 191.07 million USD in 2030. In 2030, total CO_2 emission from all iron and steel products will be 20.13 million tonnes decreasing from baseline emission levels by 1.63 million tCO_{2e}.

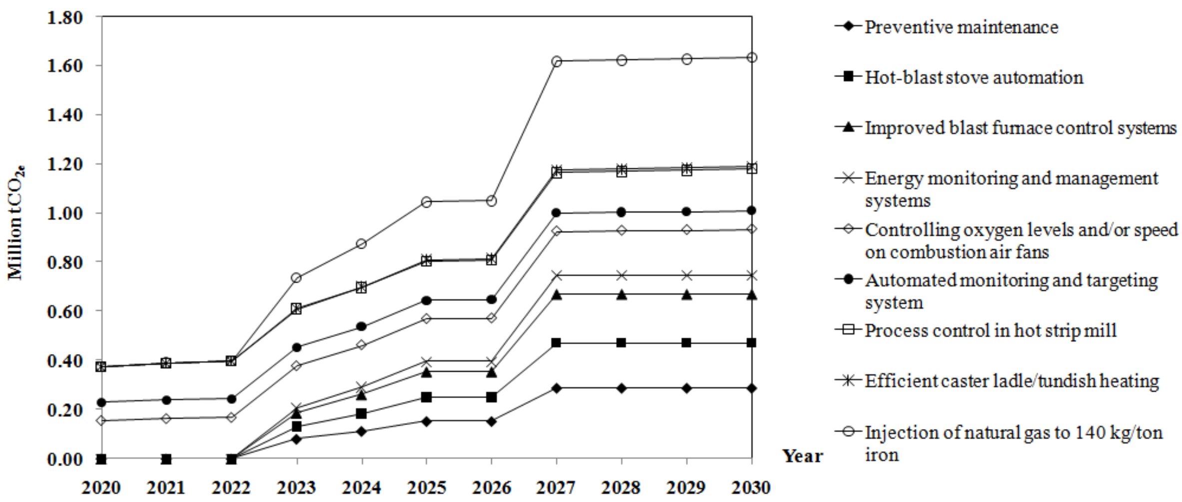


Figure 4.16 The CO_2 emission reduction of S2: with integrated steel plant (BF-BOF) according to ISIT's plan in 2030

Scenario B: Maximum energy reduction

The energy consumption reduction of S2 when all measures are implemented is 40.7 million GJ, 2.46 million t CO_{2e} reduction. The investment cost required is 485.71 million USD in 2030. It can be seen that the energy and CO_2 emissions reduction under scenario B: maximum energy reduction increase from scenario A: Achieve ISIT' plan as 14.8 million GJ and 0.83 million t CO_{2e}. This is because there are four energy saving measures, added up from energy reduction measures from ISIT's plan which are recuperative and regenerative burners, recovery of BFG, pulverized coal injection to 130 kg/ton iron and energy efficient drives respectively as show in Figure 4.17. In 2030, total CO_2 emission from all iron and steel products will be 19.31 million tonnes decreasing from baseline emission levels by 2.46 million t CO_{2e}.

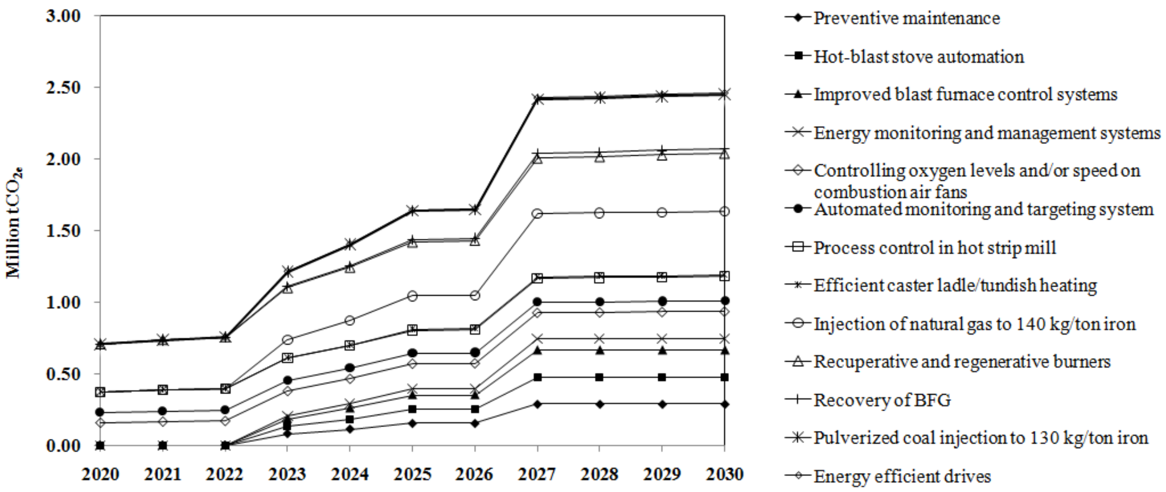


Figure 4.17 The CO_2 emission reduction of S2: with integrated steel plant (BF-BOF) plant according to maximum energy reduction potentials in 2030

4.4.3. Sensitivity Analysis

The different interest rates were used for sensitivity analysis in order to analyse the impact of changing interest rates on the investment cost. The interest rate plus-minus one from average interest rate (4.27%) was used for the calculation. The low interest rate as 3.27% and high interest rate as 5.27% were used for sensitivity analysis in this study.

Scenario A: ISIT's plan

As presented in Figure 4.18, it can be seen that increasing interest rates will increase the investment cost. The amounts of CO_2 emission reduction remain constant. The investment costs of CO_2 abatement for S2 were 162.2 million USD, 191.07 million USD and 224.71 million USD for the interest rates of 3.27%, 4.27% and 5.27%, respectively.

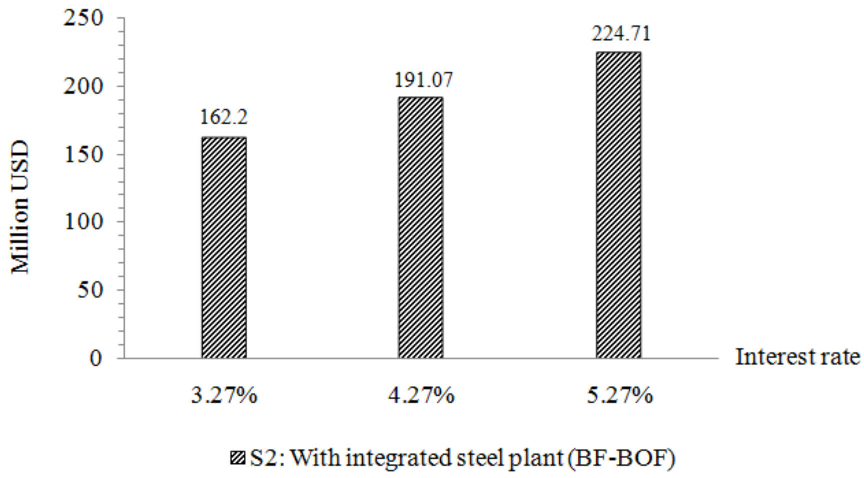


Figure 4.18 Investment costs of CO_2 abatement potentials with different interest rates according to ISIT's plan

Scenario B: Maximum energy reduction

Investment costs of CO_2 abatement when all measures were implemented under S2 were 412.31 million USD, 485.71 million USD and 571.23 million USD for the interest rates of 3.27%, 4.27% and 5.27%, respectively. Similar to scenario A: ISIT's plan that changing interest rate will influence the investment costs as illustrated in Figure 4.19.

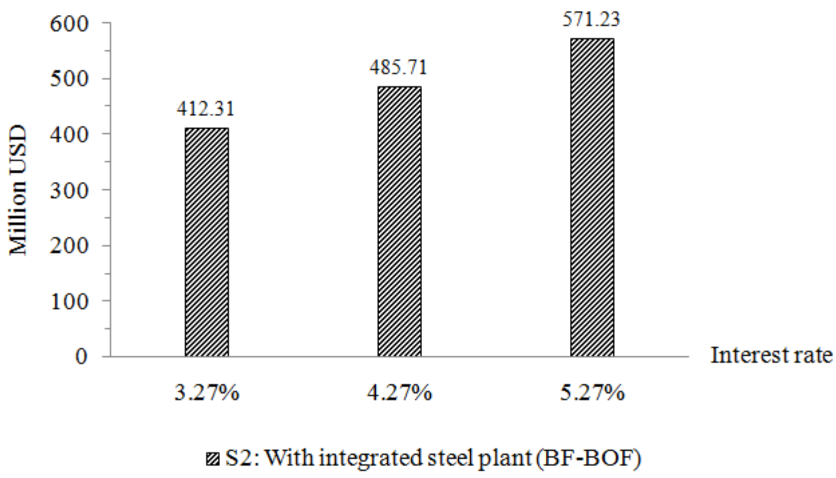


Figure 4.19 Investment costs of CO_2 abatement potentials with different interest rates according to maximum energy reduction scenario

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes the results by highlighting the key findings in this research work. The key findings of this study are summarized as follows.

5.1. Conclusions

This research aims to study the energy intensity and carbon dioxide intensity of Thailand's steel industry and greenhouse gas emission projection toward the year 2050. The amount of GHG emissions was calculated by using the 2006 IPCC guidelines in the boundary of production process (gate to gate). The country-specific energy intensity and carbon dioxide intensity of various iron and steel products were reported. Greenhouse gas emission projection toward the year 2050 under three plausible scenarios from the Iron and Steel Institute of Thailand, S1: without integrated steel plant, S2: with a traditional integrated BF-BOF route and S3: with an alternative integrated DR-EAF route. The result showed that the primary energy intensity of semi-finished steel process and steel finishing process in Thailand were 4.08 GJ/t semi-finished steel and 2.22 GJ/t finished steel whilst the final energy intensity of semi-finished steel process and steel finishing process in Thailand were 2.84 GJ/t semi-finished steel and 1.86 GJ/t finished steel, respectively. While the CO_2 intensity of semi-finished steel and steel finishing process in Thailand were 0.37±0.03 tCO_{2e}/t semi-finished steel and 0.16 ± 0.03 tCO_{2e}/t finished steel, respectively. Greenhouse gas emission projection toward the year 2050 under three plausible scenarios from the Iron and Steel Institute of Thailand, S1: without integrated steel plant (baseline scenario), S2: with a traditional integrated BF-BOF route and S3: with an alternative integrated DR-EAF route indicated that the establishment of upstream iron production (BF–BOF route) in Thailand causes dramatically increasing emission of greenhouse gas compared to the baseline. Total CO_2 emissions from all iron and steel products of S2: with a traditional integrated BF-BOF route in Thailand was 21.96 million tonnes in 2050 increasing 4.54 times from baseline scenario. However, establishment of upstream iron and steel industry has the benefits in terms of economic. Currently, the amount of steel produced in Thailand is not adequate for its consumption. Without upstream iron production in Thailand, high quality steels are almost supplied by imported, accounting for

42% of total steel consumption in Thailand. Much attention has been focused only on the CO_2 directly emitted by each country, but relatively little attention has been paid to the amount of emissions associated with CO_2 emissions embodied in the products of import and export trade. The global warming is nationwide problem rather than at the firm or process level, it threatens the welfare of people around the globe. The results in this study found that the annually average CO_2 emissions from imported steel in Thailand average from 2000-2014 is 12.86 million tCO_{2e}/years. In 2050, if the steel imported in Thailand increase only 35% from average value in 2000-2014, the CO_2 emissions embodied in the products of imports will be 17.36 million tCO_{2e}. If the CO_2 emissions embodied in the imported products is considered, total CO_2 emissions under S1 (baseline scenario) will be 22.20 million tonnes, which is higher than that of S2: with a traditional integrated BF-BOF route in Thailand. Accordingly, the establishment of upstream iron and steel industry through BF-BOF is one of the attractive options to reinforce downstream industries and improve the country's long-term manufacturing competitiveness.

In addition, three iron-making technologies, such as blast furnace (BF), corex and midrex were evaluated and prioritized by using the Multi-Criteria Decision Analysis MCDA (Bipolar Approach) in this study. The results showed that BF technology was the most preferred of iron making technology in Thailand, followed by midrex and corex, respectively. Even though midrex technology uses natural gas as a reducing agent that results in lower pollutant emissions, it is not suitable for countries that have high gas prices. While corex is environmentally friendly production of hot metal compared to BF, the process is still less flexible and limited for large-scale production. Accordingly, BF is recommended for suitable iron and steel production in Thailand. To overcome the limitations of BF technology in Thailand, the best practices for BF technology should be further explored and detailed feasibility study should be investigated.

Then thirteen mitigation measures from the US Environmental Protection Agency reports (US.EPA, 2012) regarding the establishment of the integrated BF-BOF route in Thailand were analysed by the following technology, economic and environmental criteria. The CO_2 emission reduction according to all greenhouse gas emission mitigation options is 2.46 million tCO_{2e} with total cost of 485.71 million USD in 2030. The highest CO_2 emission reduction measure for BF-BOF process in Thailand's steel industry belonged to injection of natural gas to 140 kg/ton iron, contributing 0.443 million tCO_{2e} with the mitigation cost of 219.87 USD/tCO_{2e}. Whilst preventive maintenance measure can reduce high CO_2 emissions with low mitigation costs. By following the ISIT's plan (energy reduction target of 15.37 % or 25.06 million GJ), total CO_2 emissions from all iron and steel products was 20.13 million tonnes decreasing from baseline emission levels by 1.63 million tCO_{2e} in 2030. There are several available and emerging technologies that could be potentially introduced for greenhouse gas reduction from iron and steel industry in Thailand. However, high investment cost is one of important factors for the private sector to make a decision on GHG mitigation. Co-benefits in terms of energy savings and abatement of other pollutants as well as internal and external market drivers might increase the cost effectiveness of GHG mitigation investment. The results of this study will be important information to policy maker to encourage the establishment of upstream iron and steel industry in Thailand.

5.2. Recommendations

According to this study, there are some aspects needed to improve for future work, as follows:

5.2.1. In this study, the integrated steel plants using blast furnace-basic oxygen furnace (BF-BOF) route and the direct reduced iron route were expected to be established in 2023. However, the establishment of upstream iron and steel industry in Thailand is dependent upon government policy at that time. Therefore, the data of the proposed scenarios should be verified and updated for the future study.

5.2.2. The assessment of iron-making technology in Thailand in this study was focused on three iron-making technologies, which are blast furnace (BF), corex and midrex which are the proven commercial technology at this time. In future, innovative technologies such as hydrogen production from the steam reforming of coke oven gas, indirect reduction of iron oxides in blast furnace and the CO_2 reduction technologies from ULCOS (Ultra-Low CO_2 Steel making) such as CCS, biomass and hydrogen reduction will be attractive alternatives for future study.

5.2.3. In this study, three iron-making technologies were evaluated by using bipolar analytical hierarchy process (BAHP) based on economic, environmental and technology availability. However, the impacts of the establishment of upstream iron and steel industry on various aspects, such as social and environmental determinants of health also should be evaluated for further study.

5.2.4. Due to the limitations of specific energy saving measures and CO_2 emission mitigation options for the iron and steel industry in Thailand, the data used in this research were referred from the US.EPA reports (US.EPA, 2012). This data should be updated by using national data in the future.

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APPENDIXES

APPENDIX A
QUESTIONNAIRE

Table A-1 Data collection of iron and steel production in Thailand (Gate-to-Gate)

Items	(%CC)	Unit	Quantity							% Error (data)
			2004	2005	2006	2007	2008	2009	2010	
1. Materials inputs										
Scrap										
Pig iron										
Graphite electrodes consumed										
Coke										
Burnt lime										
Coal										
Antracite										
Dolomite										
Other										
2.Materials outputs										
Product										
3. By product and Waste										
EAF slag										
EAF dust										
Other										
4. Fuel inputs										
Natural gas										
Fuel oil										
LPG										
Kerosene										
5. Electricity										
Process										
Utility										
Other										

แบบสอบถามการเปรียบเทียบทางเลือกเทคโนโลยีการผลิตเหล็กต้นน้ำในประเทศไทย โดยใช้วิธี

Multi-Criteria Decision Analysis (MCDA)

คำชี้แจง: แบบสอบถามนี้จัดทำขึ้นเพื่อใช้ในการประเมินทางเลือกของเทคโนโลยีการผลิตเหล็กต้นน้ำในประเทศไทยโดยการพิจารณาเปรียบเทียบเทคโนโลยีการผลิตเหล็ก ต้นน้ำ 3 เทคโนโลยี ทางเลือก ได้แก่ Blast furnace, Corex และ Midrex เปรียบเทียบเทคโนโลยี การผลิตเหล็กต้นน้ำ ด้านข้อจำกัดของทรัพยากรที่ใช้ (Barrier of material acquisition) และ ข้อจำกัดด้านความซับซ้อน ทางเทคนิค ของเทคโนโลยี (Complexity of technical operation)

ตาราง ที่ A-2 การเปรียบเทียบเทคโนโลยีการผลิตเหล็ก ต้นน้ำของประเทศไทย โปรดทำเครื่องหมาย ✓ เพื่อเปรียบ เทียบระดับความสำคัญของเทคโนโลยีแต่ละคู่ โดยความหมายของคะแนนความสำคัญแสดงดังตาราง

คะแนนความสำคัญ	**ความหมาย**
1	เท่ากัน (Equally Preferred)
3	ปานกลาง (Moderately Preferred)
5	ค่อนข้างมาก (Strongly Preferred)
7	มาก (Very Strongly Preferred)
9	มากที่สุด (Extremely Preferred)
2, 4, 6,8	กรณีปัจจัยด้านซ้ายและขวามีความ ก้ำกึ่งกัน ผู้ประเมินใช้เพื่อลดช่องว่างระหว่างระดับความรู้สึก

ตารางที่ A-3 โปรดทำเครื่องหมาย✓ เพื่อเปรียบเทียบระดับความสำคัญของเทคโนโลยีแต่ละคู่

1.ข้อจำกัดของทรัพยากรที่ใช้ในการผลิต (Barrier of material acquisition)													
เทคโนโลยี	ข้อจำกัด (Barrier)			เทคโนโลยี	**คะแนนความสำคัญ**								
	(>)	**(=)**	**(<)**		1	2	3	4	5	6	7	8	9
Blast furnace				Midrex									
Blast furnace				Corex									
Midrex				Corex									
2. ข้อจำกัดด้านความซับซ้อนทางเทคนิคของเทคโนโลยี (Complexity of technical operation)													
Blast furnace				Midrex									
Blast furnace				Corex									
Midrex				Corex									