Carbon Capture, Utilisation and Storage in China’s Iron/Steel Sector

Lower Carbon Technology Approaches for Steel Manufacturing in China

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### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>BATs</td>
<td>Best Available Technologies</td>
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<tr>
<td>BF</td>
<td>Blast Furnace</td>
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<td>BOF</td>
<td>Basic Oxygen Furnace</td>
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<tr>
<td>CCPP</td>
<td>Combined-cycle Power Plant</td>
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<td>CCS</td>
<td>Carbon Capture and Storage</td>
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<td>CCU</td>
<td>Carbon Capture and Utilisation</td>
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<td>CDQ</td>
<td>Coke Dry Quenching</td>
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<tr>
<td>CNEEX</td>
<td>Shanghai Environment and Energy Exchange</td>
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<td>CMC</td>
<td>Coal Moisture Control</td>
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<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
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<td>CO₂e</td>
<td>Carbon dioxide equivalent</td>
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<td>CSP</td>
<td>Compact Strip Production</td>
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<td>DOE</td>
<td>US Department of Energy</td>
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<td>DRI</td>
<td>Direct Reduced Iron</td>
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<tr>
<td>EAF</td>
<td>Electric Arc Furnace</td>
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<td>ECOARC</td>
<td>Environmentally-friendly and Economical Arc Furnace</td>
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<td>EPC</td>
<td>Environmental Pre-heating and Continuous Charging System</td>
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<td>ESP</td>
<td>Endless Strip Production</td>
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<td>GHG</td>
<td>Greenhouse Gas</td>
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<td>Gigajoule</td>
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<td>IEA</td>
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<td>LT</td>
<td>Lurgi Thyssen Process</td>
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<td>Monoethanol Amine</td>
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<td>Pressure Swing Adsorption</td>
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<td>PV</td>
<td>Present value</td>
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<td>RITE</td>
<td>Research Institute of Innovative Technology for the Earth</td>
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<td>Thermoelectric Generation</td>
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<tr>
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<td>TRT</td>
<td>Top Gas Recovery Turbine Unit</td>
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<td>Thin Slab Casting and Rolling</td>
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<td>Ultra-Low CO₂ Steelmaking project</td>
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<td>UPV</td>
<td>Uniform present value</td>
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<td>Vacuum Pressure Swing Adsorption</td>
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<td>Wuhan Iron and Steel Corporation</td>
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1. **Executive Summary**

- The steel sector is one of the largest industrial sources of CO\(_2\) emissions, contributing around 28% of global industry sector’s direct greenhouse gas emissions. Since 2012, China has accounted for approximately half of global steel production, rendering it critical to explore ways to decarbonise the Chinese steel sector. However, there was a lack of knowledge exchange on low-carbon options in the iron and steel sector.

- This study investigates lower carbon technology options to reduce carbon emissions in steel plants in China based on literature review and industry consultation. The research objective of the report is to identify key low-carbon technical trajectories in the steel sector in China (excluding carbon capture and storage and fuel switching options) and illustrate a generic abatement cost curve for the crude steel manufacturing process.

- The average carbon dioxide emissions from steel production in China are approximately 2.1 tonnes CO\(_2\) per tonne crude steel (tcs) in 2010 (Hasanbeigi et al., 2015). Through an analysis of marginal abatement costs, it is found that the cumulative CO\(_2\) emission reduction potential is 898 kgCO\(_2\)/tcs, if all the 25 abatement options in the recommended energy-saving and carbon reduction technology package were adopted, accounting for about 43% of the average CO\(_2\) emissions per tonne of crude steel produced in China.

- The cumulative carbon abatement capacity of the nine most cost-effective technologies is 426 kgCO\(_2\)/tcs, accounting for about 20% of the average CO\(_2\) emissions per tonne of crude steel produced in China.

- Over half of the selected technologies promoted by the 12\(^{th}\) Five Year Plan were found to be cost-ineffective but are likely to become cost-effective technologies in the future when considering the bias of this model and the projected increase in energy and carbon prices, as well as future policy interventions in the Chinese iron/steel industry.

- Further studies and industry knowledge exchange are required to update the data and to monitor application of new technologies. A deep cut of emissions in the iron and steel sector would require carbon capture and storage or a significant modification of the manufacturing process, such as a hydrogen-based steel production process.
2. Introduction

Climate change caused by anthropogenic greenhouse gas emissions from industrialisation is a global challenge. The 2015 Paris Agreement sets out a global action plan to set the world on track to avoid dangerous climate change by limiting global warming to well below 2°C above pre-industrial levels in the long-term, and to pursue best efforts to limit the increase in warming to 1.5°C. To achieve this target, the Agreement emphasised the need for global greenhouse gas (GHG) emissions to peak as soon as possible and to undertake rapid reductions with best available technologies (BATs).

Although there are different scenarios of mitigation pathways (Edenhofer, 2014), the 2°C warming target can be translated into a budget, for the 2000-2050 period, of 1.47-1.83 trillion tonnes of anthropogenic carbon dioxide emissions (Allen et al., 2009). Fossil fuels are still the primary source of energy and raw material supply for the power, steel, cement and petrochemical industries. Direct and indirect emissions from the non-power industrial sector accounted for 14.5 billion tonnes of carbon dioxide (tCO₂) in 2015, or 30% of total anthropogenic carbon dioxide emissions (Leeson, 2017).

Among the various industrial activities, the iron/steel industry remains one of the most energy- and carbon-intensive, as iron- and steel-making processes rely heavily on fossil fuel consumption – especially coal combustion – emitting a significant amount of CO₂ into the atmosphere (Quader, 2015). The iron/steel industry accounted for approximately 22% of total industrial energy use and 31% of industrial direct emissions in 2012 (IEA, 2015).

Due to its large population base and rapidly growing economy, China is the largest CO₂ emitter in the world, contributing more than a quarter of global emissions. In 2016, the estimated emissions from fossil fuels in China reached 10.4 billion tonnes (Janssens-Maenhout et al., 2017), approximately equivalent to 1% of the remaining carbon budget. Due to rapid growth in developing countries, the demand for iron and steel has also been increasing rapidly over the last decade (Quader et al., 2015).

China’s steel sector contributed 44% of global crude steel production in 2015 (Worldsteel, 2016). The aim of this study is to identify a comprehensive portfolio of technologies to lower carbon dioxide emissions in China’s steel sector, and to illustrate the abatement cost curve for the sector.
There are two main routes for steel production: (1) primary steel production, in which raw materials of iron ore and coal are used for steel production and (2) secondary steel production from recycled steel scrap (Napp et al., 2014). The Blast Furnace-Basic Oxygen Furnace (BF-BOF) route is the dominant steelmaking route for primary steel production in China and in the world as well.

The Direct Reduced Iron-Electric Arc Furnace (DRI-EAF) process is an alternative primary steel production route that many developed countries, such as the USA, use as a dominant steelmaking route. Secondary steel production mainly utilises the scrap-EAF route, where steel scrap, cast iron and direct reduced iron are used to make steel (Zeng et al., 2009).

Figure 1 shows the simplified steelmaking routes including the main production steps. The last route shown has been phased out in recent years due to its high energy penalty and over-intensive greenhouse gas emissions.

Source: (Hasanbeigi, 2013)

Figure 1. Steelmaking routes

Ironmaking – Steelmaking - Rolling are three key phases in steel production. Iron ore is smelted into pig iron in a blast furnace, and then pig iron and scrap steel are smelted into rough steel through a converter and electric furnace, and finally the steel products are produced through a rolling mill. During the past two decades, almost 60% of steel has been derived from pig iron (also called hot metal), although the share of steel produced from direct
reduced iron has steadily increased. Pig iron is produced in blast furnaces. Today, about 5% of global steel is produced from direct reduced iron, while 35% of all crude steel is derived from scrap (Quader et al., 2015).

In China, coal consumption is the dominant energy source, accounting for 70% of total energy consumption. Electricity, while still produced through energy intensive means on average, is the second largest energy source in the Chinese iron and steel industry, accounting for 26.4% of its total energy consumption (Wang & Zhang, 2017). The fleet of steel plants in China has higher energy efficiency than the global average. The average energy consumption per tonne of steel was 555 kgce/tcs (kg coal equivalent per tonne steel production) in China in 2018 (CISA, 2019), which is lower than the global average of 693 kgce/tcs (Worldsteel, 2018). The technology used is important as it significantly affects energy use and CO₂ emissions in steel plants (IEA, 2007).

Figure 2 compares CO₂ emissions of different routes. It shows that the DRI-EAF route based on coal consumption emits the largest amount of CO₂ per tonne of crude steel, while the scrap-EAF route is the least emissions-intensive. However, using the same DRI-EAF route with natural gas nearly halves CO₂ emissions compared to the same route using coal. CO₂ emissions from the widely-used BF-BOF route do not vary much between the advanced and conventional process, but there is still scope to improve technical performance to reduce emissions.

The comparison in Figure 2 does not imply that emissions could be dramatically reduced by switching steel making processes, as the processes are not interchangeable. Project developers need to take into account actual available options and their economic viability, such as the supply and cost of scrap and the availability of alternative low-carbon fuels. There are other alternative energy sources, such as renewable electricity and biomass, for iron and steel production, as well as the possibility of using hydrogen (instead of carbon) as a reducing agent. However, the high costs of using cleaner energy sources in CO₂ abatement from iron and steel production remain an obstacle and there is a lack of cost information to apply renewable sources for steel production, and therefore the study does not consider these technologies within its abatement curve.
Source: (Quader et al., 2015)

Figure 2. CO₂ emissions by process per tonne of crude steel
3. **Low-carbon technology options**

In the iron/steel industry, there are three key approaches to achieve significant energy savings and abatement of CO$_2$ emissions (Napp et al., 2014):

1. Switch to more energy-efficient production routes and increase the usage of scrap in the EAF route;
2. Increase the recovery of waste gases and heat integration from BF-BOF route; and
3. Adopt more efficient methods of casting and rolling in the final crude steel production.

Different processes in the iron and steel production have different energy-efficient technologies to save energy and reduce carbon emissions. Technologies for specific processes are discussed in the following sections.

3.1. **Sintering and pelletising process**

Sintering and pelletising are complementary processes for preparing raw materials for primary steelmaking which contribute up to 6% of the CO$_2$ emissions from a typical integrated iron and steel plant (Guo & Fu, 2010). Sintering is an agglomeration process that converts powdered iron ore into larger pieces of sinter with better qualities for feeding into a blast furnace, through a process of combustion with coke fines and various fluxes (such as limestone). Pelletising also produces suitable raw material for a blast furnace, by mixing powdered iron ore with various additives, and forming this into pellets which are dried, roasted at high temperature and cooled in a grate-rotary kiln-ring cooler. Ooi et al. (2011) found that charcoal derived from biomass can be used as a suitable alternative solid fuel that can be both effective and carbon-neutral. However, if the production of charcoal involves land use change, or the diversion of biomass away from other uses, this can result in increased indirect emissions: the net impacts should therefore be carefully evaluated using consequential carbon accounting (Searchinger et al., 2009; Sanchez et al., 2012; Brander & Ascui, 2018).

Other energy-efficient technologies and measures, such as waste heat utilisation technologies including sinter plant heat recovery (EPA, 2012), waste heat power generation (NECC, 2012) and the use of waste sintering fuels (EPA, 2012) are also important approaches to save energy in the sintering and pelletising process.
3.1.1. Thick Layer Sintering

Thick Layer Sintering is a sintering process which involves a high paving thickness of iron ore on the grate of the sintering furnace, which can effectively improve the quality of sinter, and also has significant effect on improving sinter production and saving fuel consumption.

Thick Layer Sintering was implemented at two 360 m² sintering machines in No. 3 Iron-making Plant of Masteel, with an increase in the feeding thickness to 900 mm reducing fuel consumption by 4.63 kgce/t sinter (Zhang, 2014). Similarly, increasing the feeding thickness from 750 mm to 850 mm (without changing the side boards) at the 240 m² sintering machine in Qingdao Special Iron and Steel Co Ltd. decreased fuel consumption by 4.79 kgce/t sinter (Zheng et al., 2017).

3.1.2. Waste Heat Recovery in Sintering Process

Waste heat is an important secondary energy resource for the iron and steel industry. Recovering waste heat can provide valuable energy sources and reduce overall energy consumption. In China, 8.44 GJ of residual heat is generated per tonne of steel produced, of which only 28% is currently recovered (He & Wang, 2017). As such, waste heat recovery and utilisation in the iron/steel industry has significant potential.

Steam production by waste heat

Waste heat recovery has been applied in some steel plants in China. The first waste heat recovery system at a large-scale modern sintering plant in China (Baoshan Steel) has been operating since 1991, recovering waste heat from sintering flue gas and the cooler’s waste gas. The total waste heat recovery of unit 3 sintering machine in Bao Steel was 33.4 ktce/year in 2007-2008 (SECSC, 2009), which is about 88 ktCO₂/year by approximate conversion. The heat pipe waste heat boiler system in Xuanhua Steel 360m² sintering machine has reduced process energy consumption by 2.9 kgce/tcs in 2017, compared with the same period in 2016 (NDRC, 2014). The heat pipe steam production system in No.1 Sintering Plant of WISCO (Wuhan Iron and Steel Corporation) produces 50-60kg steam/t sinter (Chen et al., 2001).

Power Generation using waste heat

Waste heat can also be used to generate electricity. In the sintering process, sinter is cooled by blast in a belt or ring cooler, and the cold air from the bottom is heated when it passes through the hot sinter bed, becoming high temperature waste gas. These high-temperature
exhaust gases can be introduced into a boiler through an induced draft fan, heating water in the boiler to produce steam, which drives a turbine to generate electricity.

On September 1, 2004, the first domestic waste heat power generation system was built on two 300 m$^2$ sintering machines in the No.2 Ironmaking Plant of Maanshan Iron and Steel Co., Ltd. Subsequently, large iron and steel companies such as Jigang, Baosteel and Taiyuan Iron and Steel Co. began to apply the same technology, and now it is basically universal.

**Vertical Tank Waste Heat Recovery System**

Vertical tank waste heat recovery and utilisation is a new technology for high efficiency of recovery and utilisation of sinter waste heat resources. The technology and equipment are designed and developed by Beijing Metallurgical Equipment Research Design Institute Co Ltd. Sinter flows downward as a solid, and cooling gas flows upward, absorbing the sensible heat of the sinter. Simulation results show that average temperature of 642.3°C hot air can be obtained by the vertical counter-current waste heat recovery system under 750°C input. If all the hot air is used for power generation, the potential output is 27-35kWh/t sinter (Dong et al., 2012).

**3.1.3. Waste Heat Recycling in Pelletising Process**

Employing waste heat recycling technology in the pelletising process can reduce fuel consumption by an average of 3 kgce/t pellet. In addition, by avoiding the high-temperature exhaust gas from the rotary kiln section and ring cooler section being directly discharged into the atmosphere, it also reduces the emission of high-temperature dust. In addition, the high temperature exhaust gas cycle reduces the amount of dust removal points, which is conducive to reducing investment in environmental protection treatment devices. Total investment is about 45 million CNY and the operating cost is about 5.5 million CNY/year.

**3.1.4. Pellet Production by Chain Grate - Rotary Kiln**

The energy consumption of pellet produced by the grate-rotary kiln pelletising process is 20-25 kgce/t pellet, which is 10 kgce/t less than with the traditional shaft furnace pelletising process in China. If we assume that the annual pellet production is about 100 million tonnes in China, about 1 million tonnes of standard coal could be saved. The estimated investment cost of chain grate -rotary kiln pellet production is about 120 CNY/t pellet, and the operating cost is 1100 CNY/t pellet/year.
3.2. Coke making process

The coke making process involves the carbonisation of coal at high temperatures (1100°C) in an oxygen-deficient environment. The main energy consumption in the coke making process is coal combustion for heating, contributing 12% of total process energy consumption in China in 2014 (Guo & Fu, 2010). Current energy saving pathways can reduce heat consumption by increasing waste heat and gas recycling and improving production system control (He & Wang, 2017).

3.2.1. Coke Dry Quenching (CDQ)

Coke can be cooled by wet (CWQ) or dry (CDQ) quenching processes. CDQ coke has lower moisture content (0.1 to 0.3%) than CWQ coke (2 to 5%), meaning that a lower ratio of coke is required in the blast furnace. Combustible component and coke dust are burned by blowing air into the circulating gas, raising its temperature and thus enabling increased steam generation by the waste heat boiler. A high annual operating ratio of 95% can be achieved by combining Double Flue technology, appropriate refractories and highly reliable equipment. Steam generation of 500-700 kgce/t coke and power generation of 140-185 kWh/t coke can be obtained, according to CDQ operation and steam conditions (Steel Plantech, 2015).

Shougang Jingtang Steel implemented CDQ waste heat recovery, recovering heat from converter gas (100m³/t steel), coke oven gas (440m³/t coke) and blast furnace gas (1,442m³/t steel); in total 5,000,000 t steam/year was recovered from these three processes and supplied to the production process, power generation and desalination and cooling (Zhou, 2009).

3.2.2. Coal Moisture Control (CMC)

Coal moisture control reduces the moisture of the feed for coke making from a normal 8 - 10% to around 6% using low-pressure steam or sensible heat recovered from coke oven gas. This technology reduces the carbonisation heat demand, improves productivity and enhances coke quality, and increases the production capacity by 4% (MIIT et al., 2012).

3.2.3. Coke Oven Rising Tube Heat-recovering Technology

The rising tube heat-recovering process can recover sensible raw gas heat, produce low pressure saturated steam and save energy. The technology has been implemented in Hansteel of Hebei Iron and Steel Group, reducing energy consumption by 8 to 10kgce/t coke and CO₂ emissions by 25,000 tCO₂/year (Zhang et al., 2017).
3.3. Blast-Furnace ironmaking process

The blast furnace (BF) is the vessel where iron ore is turned into liquid hot iron and is purified by eliminating the iron-bearing materials. This process is the most energy intensive process in steelmaking. In China, energy consumption in the ironmaking process accounts for approximately 70% of the total metallurgical energy consumption, to which the blast furnace alone contributes 39% (Guo & Fu, 2010).

Enhancing energy efficiency in the BF ironmaking process entails reducing fuel combustion, increasing energy recovery and improving the efficiency of hot stoves. Hot Oxygen Injection with coal offers better coal dispersion at high local oxygen concentrations, optimising the use of oxygen in the BF and increasing coal injection. Hot Oxygen Injection has the potential to increase productivity by 15% and reduce GHG emissions (Riley, 2002).

3.3.1. Top Combustion Stove

The regenerative hot blast stove can be divided into top combustion, internal combustion and external combustion. It first burns gas, heating the lattice bricks of the regenerator with the generated flue gas, then heating the cold air through the hot lattice bricks, and then alternately burning and supplying the hot blast stove, so that the blast furnace can continuously obtain high temperature hot air. The top-fired hot stove eliminates the combustion chamber, thus eliminating the main defects of the internal combustion and external combustion hot stoves. By increasing the vault temperature, the high air temperature is obtained.

3.3.2. Pulverized Coal Injection and Oxygen Enrichment

Pulverized coal injection in the blast furnace involves direct injection of anthracite or bituminous pulverized coal, or mixed pulverized coal from a blast furnace tuner to replace coke as both heating and reducing agent, thus reducing coke ratio and pig iron cost. Energy consumption can be reduced by 80 to 100kgce/t steel per tonne of pulverized coal injected (MIIT et al., 2012).

3.3.3. Dry Dusting Transport System of Blast Furnace Gas

China is one of the earliest countries to use a dry process of bag dust removal technology in blast furnace gas, with more than 40 years’ experience. Using a dry process of dust removal
can realise energy savings and emission reductions, as well as comprehensive utilization (Wang et al., 2011). The system reduces water consumption by 1.86 million t/year and power consumption by 20.96 GWh/year, and the TRT power generation reaches 50kWh/t steel (MIIT et al., 2012).

3.3.4. Blast Furnace Top Gas Recovery Turbine Unit (TRT)

A blast furnace top recovery turbine unit (TRT) converts the pressure energy and heat energy of BF top gas, the by-products from blast furnace smelting, into electrical energy, and can reduce fuel consumption by 34kgce/t steel (MIIT et al., 2012)

3.3.5. Molten Slag Waste Heat Recovery

Molten slag has a very high temperature when exhausted and is a potential resource for energy and materials recycling. POSCO (Pohang Iron and Steel Company) has developed a method to recover heat from molten slag with a 50% recovery rate at a temperature of 460°C (POSCO, 2013). Kuroki et al. (2014) introduced a thermoelectric generation (TEG) system to produce electrical power directly from converting waste heat of hot molten slag to achieve energy savings and emission reductions.

3.3.6. Plasma Technology

Plasma technology has been adopted successfully in various industries around the world. Plasmas are gaseous collections of electrically-charged particles that carry energy. In the Plasma BF, particles release the energy on the surface of the metal to melt the metal. Plasma technology can both raise the temperature more rapidly and efficiently than conventional melting technologies, and minimise metal loss from oxidation and contamination (BCS, 2005). Plasma BF is very likely to reduce carbon consumption by 50% and has a high potential to cut BF energy consumption (Hacala & Michon, 2011).

Plasma furnaces have been successfully applied to the production of a variety of materials, particularly ferro-alloys. Ferrochromium is produced on an industrial scale in a 40 MVA plasma furnace at Palmiet Ferrochrome in Krugersdorp, with an increase in chromium recovery relative to conventional submerged-arc furnace production (Jones et al., 1993).
3.4. Basic Oxygen Furnace steelmaking process

The Basic Oxygen Furnace (BOF) process involves using molten iron and scrap as well as oxygen to remove the carbon from the iron, thus producing steel. The BOF process is the least energy consuming amongst these main production processes, with a high potential to reuse the primary off-gas, carbon monoxide. CO can be combusted to CO$_2$ and the energy can be transferred to the metal, which increases the energy efficiency and allows for scrap melting in the BOF. This reaction is referred to as post combustion and significantly reduces the energy required in steelmaking (Fruehan, 2004).

3.4.1. Gas Recovery in Converter

The Lurgi Thyssen LT process is applied for flue gas purification in the 250t converter of Baosteel, as a first of its kind in China. The converter gas can be directly supplied to the energy sector due to its low dust content (less than 10mg/Nm$^3$). Gas recovery reaches 100 Nm$^3$/t steel, with heat value of 8,360kJ/Nm$^3$ (Wang & Cai, 2004).

3.4.2. Negative Energy Consumption on Converter

The outlet flue gas from Maanshan Steel (Masteel) 95t converter is recovered in the form of gas and steam. The main product of the reaction between carbon and oxygen in the converter is CO, making up about 90% of the converter flue gas (with very limited CO$_2$). The application of advanced technologies can help to further shorten the smelting cycle, improve the quality of steel and increase the energy recovery. Supported by these technologies, Baosteel has set a world record of negative energy consumption in the converter phase of the steelmaking process (Shi et al., 2004).

3.5. Electric Arc Furnace steelmaking process

Compared to the BOF process, EAF is much simpler, as the sintering and pelletising and coke-making processes are eliminated, saving energy and GHG emissions. As a result, the energy intensity of crude steel production through the EAF route is 60% lower than that of the BF-BOF route (Worrell et al., 2008). In 2014, the Electric Arc Furnace (EAF) process accounted for 17.5% of energy consumption in the iron and steel sector in China (Guo & Fu, 2010). Energy-efficient technologies for the EAF process mainly focus on reduced energy consumption, waste heat and gas recovery, and material preheating.
However, the adaptation of EAF is restricted by limited raw material – scrap – in China. Thus, recycling of scrap at the end of use plays an important role in the future implementation of these technological options.

### 3.5.1. EPC System

An Environmental Pre-heating and Continuous Charging System (EPC System), adopts scrap preheating technology in the process of smelting scrap steel in the electric furnace, preheating scrap steel to 700-800°C with exhaust gas from the furnace, which can reduce power consumption and correspondingly improve furnace productivity (Zhang, 2017).

### 3.5.2. Waste Heat Recovery in EAF

More than 70% of energy losses in EAF are related to off gas, through which around 20% of EAF energy inputs are lost as sensible heat. Thus, heat recovery is very likely to save substantial energy in EAF. Tenova GmbH in Germany has developed an evaporative cooling system technology for EAF heat recovery. This system replaces the conventional low-pressure water-cooled ducting with high-pressure boiler tubes designed to withstand the harsh EAF fume system conditions, and uses the heat of evaporation to produce high temperature steam which can be used to supplement or replace an in-plant steam generation boiler (Zuliani et al., 2010). This sensible heat recovery is reported to be able to save energy use for steam and power generation and achieve 75-80% recovery of total energy content in the waste gas heat, equivalent to around 20% of the EAF primary energy input (Zuliani et al., 2010).

Waste heat recovery technology has been applied to the dust collecting system from the fourth opening of the EAF in some steel plants in China, such as Tianjin Steel and Laiwu Steel. After replacing the original diesel steam boiler with a waste heat steam boiler, the fuel consumption of the diesel steam boiler is reduced by 11 kg diesel/tcs; the waste heat recovered from the waste heat boiler is about 18.7kWh/tcs, and the recovery efficiency of the waste heat of flue gas reaches 38% (Zhu et al., 2010).

### 3.5.3. ECOARC

JFE Engineering (2004) has developed an electric arc melting furnace called ECOARC (Ecologically-Friendly and Economical Arc Furnace). This arc furnace connects the preheating shaft and the melting chamber to maintain a continuous scrap charge in the chamber and shaft while melting. ECOARC has extremely efficient electricity consumption and reduces the
amount of exhaust gas to half of that in a conventional arc furnace (JFE Engineering, 2004).

3.6. Casting process

In the casting process, energy consumption is mainly in drying up, preheating and moving the equipment (He & Wang, 2017). To save energy and reduce CO₂ emissions in the process, different technologies exist including thin-slab casting and strip casting processes in near-net-shape casting, and continuous temperature monitoring and control in continuous casting.

3.6.1. Compact Strip Production

Compact in design, Compact Strip Production (CSP) produces high-quality hot strip in a single manufacturing line that combines casting, heating, and rolling. Compared with the traditional approach, CSP compacted the production processes, improves the unit’s productivity and reduces energy consumption. CSP has been applied to WISCO in March 2009, and CSP<sub>plus</sub> (the third generation) to Masteel in September 2003 in China (Chang, 2012; Yan & Feng, 2004).

3.6.2. Endless Strip Production

The Arvedi Endless Strip Production (ESP) line started operation in Acciaieria Arvedi, Cremona, Italy in May of 2009. Compared to the traditional production line, the energy consumption of ESP has been reduced by 45% (Arvedi et al., 2011).

3.6.3. Strip casting process in near-net-shape casting

Compared with the traditional rolling process, the strip casting process in near-net-shape casting technology simplifies the production process of hot strip steel. Baosteel has reduced the strip production line to 50m from 1000m (BPC, 2015). Compared with traditional continuous casting and rolling, BAOSTRIP<sup>®</sup> saves energy by 800kJ/t steel, while CO₂ emissions can be reduced by 85% (Fang et al., 2009).

3.7. Rolling and finishing process

The rolling and finishing process transforms semi-finished steel into finished products with different shapes. The process can involve hot rolling, cold rolling, forming or forging, where hot rolling consumes approximately twice as much energy as cold rolling (He & Wang, 2017). The energy consumption in rolling and finishing process accounts for around 7.8% of total energy consumption, which is mainly from the heating furnace (Guo & Fu, 2010).
Thermochemical Recuperation for High Temperature Furnaces is an approach to fully utilise the waste heat from the exhaust gas. The heat is used to transform the hydrocarbon fuel into a reformed fuel for process heating. This approach has a potential benefit of reducing fuel consumption by more than 25% when the initial source fuel is natural gas (U.S. DOE, 2011).

3.7.1. Hot Delivery and Hot Charging of Continuous Casting Billet

The direct roller supply was applied to Tangsteel unit 6 caster hot rolling and hot charging of bar in 2000, reducing energy (fuel) consumption from 12kgce/t steel in 2000 to 6kgce/t steel in 2001. The energy consumption of unit 3 is reduced from 10kgce/t steel in 2000 to 7kgce/t steel in 2001 (Meng et al., 2003).

3.7.2. Low Temperature Rolling Techniques

Low-temperature rolling techniques can improve the surface quality of hot-rolled strips, and reduce the burning loss and energy consumption, thus reducing the cost of hot-rolled strip production. Low-temperature rolling techniques include (1) lowering the slab temperature and (2) reducing the finishing rolling temperature. The formation of iron oxide scale in the finishing zone can be reduced by lowering the starting rolling temperature and the finishing rolling temperature, and hot-rolled strips with good surface quality can thus be obtained. The technology can reduce fuel consumption by 8kgce/t steel, which is equivalent to about 20.74 kWh/t steel, and in total reduce the process energy consumption by 15.29 kWh/t steel (MIIT et al., 2012). The technique has been applied in 2050mm Hot Strip Rolling in Baosteel (Huang et al., 1999).

3.7.3. Regenerative Reheating Furnace

The isolated regenerator or regenerative burner can preheat air or gas, and greatly reduce fuel consumption. With the technology, the heat recovery rate is increased to more than 80%, the energy consumption decreases from 73.2 kgce/t to 49.2 kgce/t, and the energy saving rate reaches 32.8%; and in addition, CO₂ emissions are reduced by 10-70% (MIIT et al., 2012; Chen, 2017).

3.8. Waste Heat Energy Recovery Technology

During steel production, various processes generate a great amount of heat and high-calorific gases. It is estimated that around 20-50% of energy input is lost as waste heat in the forms of high-temperature exhaust gases and cooling water, and heat loss from hot equipment...
surfaces, molten slag and heated products (BCS, 2008). The currently used waste heat and residual energy recovery technologies include coke oven waste heat recovery, sintering waste heat recovery, blast furnace waste heat recovery, converter gas recovery, which have been explained in relation to each process in preceding sections; plus Combined Cycle Power Plant (CCPP), waste heat recovery from high-temperature molten BF slag, etc.

3.9. Energy Management System

The energy management system is an integrated management and control system. By adopting techniques such as automation and dynamic monitoring and management of energy production, transmission, distribution and consumption, energy utilisation efficiency can be improved by about 2% to 5% (MIIT et al. 2012). After the implementation of an energy management system in Angang Steel in 2006, the energy consumption reduced by 78kgce/t steel, and in total saved about 1.25Mtce/year. (Ren, 2001).

3.10. Carbon capture and storage

Carbon capture and storage (CCS) is generally recognised as one of the key global warming and climate change mitigation approaches – one that can also be applied within the iron and steel industry. CO₂ capture may be economically feasible in steel production as a result of future rising costs of carbon emissions. CCS is projected to account for 33% of emission mitigation in industry by 2050, of which more than 80% of the carbon dioxide captured is projected to come from iron and steel and cement industries (IEA, 2010).

There are three main CO₂ capture processes: post-combustion, pre-combustion and oxyfuel combustion, with the choice of capture process depending on the type of combustion process (Quader et al., 2015). The technologies used in carbon capture include chemical, physical or hybrid absorption, adsorption by solid adsorbents, membrane physical separation, phase separation by cryogenics and gas hydrates, and chemical bonding via mineral carbonation (Carpenter, 2012).

One of the most advanced potential CCS technologies for the iron and steel industry is the top-gas recycling blast furnace (TGR-BF), which separates the useful component in the off-gases and recycles it back into the furnace. Considering the CO₂ concentration in TGR-BF, physical adsorption technologies are regarded as currently the most effective in terms of technical performance as well as operational and capital costs (UNIDO, 2010). The technology has the potential to reduce coke consumption compared by up to 30% to a conventional BF
and to reduce onsite CO\textsubscript{2} emissions by up to 76% compared to a conventional BF with CO\textsubscript{2} capture (Kuramochi et al., 2011).

In DRI production, a new production process, ULCORED, has been developed to reduce natural gas consumption by replacing conventional reforming technology by partial oxidation of the natural gas. This technology is particularly important for countries with limited natural gas supply but with more coal supply, such as in China (Hasanbeigi, 2013). CO\textsubscript{2} from the gasification process can be captured through pre-combustion technology (UNIDO, 2010). This technology is reported to be able to make full use of oxygen, using the shifter to convert CO in the top gas into hydrogen and CO\textsubscript{2}, cleaning CO\textsubscript{2} in the off-gas after the shift for further storage and recycling the hydrogen (Hasanbeigi, 2013).

### 3.10.1. CO\textsubscript{2} capture by physical adsorption in JFE

Japan JFE Steel Corp uses physical adsorption technology to separate CO\textsubscript{2} from blast furnace gas. JEF has set up a small test facility, with CO\textsubscript{2} processing capacity of 3 tCO\textsubscript{2}/d and 300m\textsuperscript{3} gas/hour in West Japan Works (Fukuyama District). The project is included in the COURSE50 programme in Japan (Ujisawa et al., 2016).

After being pressurised by the compressor, the blast furnace gas is first cooled, then flows through the dehumidification tower and the desulphurisation tower to remove water and sulphides, and enters the core processing unit of the pressure swing adsorption (PSA) process. The PSA core processing unit is divided into two segments: Section 1 is the CO\textsubscript{2}-PSA in which CO\textsubscript{2} is separated from the blast furnace gas. The CO\textsubscript{2}-free BF gas is then sent to Section 2, the CO-PSA, where the CO adsorbent is used to recover CO from the BF gas for the separation of CO and N\textsubscript{2}. The recovered CO gas can be used as fuel.

### 3.10.2. CO\textsubscript{2} Separation technology in RITE

The Research Institute of innovative Technology for the Earth (RITE) in Japan developed a low-cost CO\textsubscript{2} capture system with chemical absorption for the removal of CO\textsubscript{2} from blast furnace gas (COC\textsubscript{S} Project FY2004-2008). A 1 tCO\textsubscript{2}/d (100m\textsuperscript{3}/hour blast furnace gas) test plant was built using 30% MEA as absorbent and the steam from the plant, with an estimated cost of 6000 Yen (USD54)/tCO\textsubscript{2}. If using the novel chemical solvents RITE-5 and RITE-6, which were developed by RITE with a moderately-low heat of reaction and a moderately-high absorption rate, and with further optimisation of operation and plant specification, it is estimated that the potential cost could be reduced to 50% of the baseline cost (Goto et al., 2013).
3.10.3. CO₂ Separation Technology in POSCO

POSCO has also developed a carbon dioxide separation technology for blast furnace gas, where ammonia is used as a chemical absorbent (Song et al., 2017). The basic process is similar to the amine-based technology in RITE, but the desorption temperature (80°C for the ammonia method) is much lower than that of RITE (120°C for the amine method), and hence the energy consumption of desorption is largely reduced. In addition to the chemical absorption method, POSCO is also researching a PSA process for CO₂ separation of blast furnace gas. A small test platform has been set up with a scale of 1m³/hour. The basic principle and process are similar to the PSA technology in JFE.

3.10.4. CO₂ Separation in Eisenhüttenstadt-EHS

CO₂ is separated from oxygen blast furnace gas using vacuum PSA (VPSA) technology in the 700,000t/year blast furnace in Eisenhüttenstadt-EHS in Germany (Song et al., 2017). The project mainly studies the feasibility of top gas recovery and the closed loop operation in the blast furnace, using the VPSA method to purify CO₂ with CO₂ as the off-gas. Compared with PSA, VPSA offers a more thorough treatment of the impurities in the off-gas, but with the disadvantage of adding extra power equipment and a vacuum tank. Thus, the fixed investment and operation cost will accordingly increase.

3.10.5. Bao-CCU Technology in Baosteel

The Baosteel Carbon Capture and Utilization (BAO-CCU) plan has been proposed to improve the utilisation efficiency of BF gas and capturing CO₂ by using the recovered heat, which not only reduces carbon emissions, but also creates economic benefits (Song et al., 2017).

The waste heat in the steel plant would be used as the energy source for CO₂ capture by the chemical absorption method to obtain a high-purity CO₂ product, while also increasing the calorific value of the blast furnace gas per unit volume. Under ideal conditions, 0.18m³ of CO₂ can be extracted from 1m³ of blast furnace gas, obtaining 0.82 m³ of high-quality blast furnace gas with a calorific value of 4.1 MJ/m³ (Song et al., 2017).

3.11. Cost estimation

The study selects 33 recommended energy-efficient and carbon abatement technologies available for the iron and steel industry – both domestically (in China) and internationally. These technologies cover the whole iron and steel production process including sintering,
coking, iron-making blast furnace, steelmaking BOF, steelmaking EAF, casting, rolling and finishing as well as a general technical option.
Table 1 lists the technologies with data on fuel and electricity savings per tonne of steel produced, their calculated primary energy and CO₂ emission reduction, and the share of Chinese annual production in 2018 from the applied technology.
Table 1. Energy saving, CO₂ emission reduction of 33 recommended energy-efficient and carbon abatement technologies for China iron and steel sector

<table>
<thead>
<tr>
<th>No</th>
<th>Technology</th>
<th>Fuel Saving (GJ/tcs)</th>
<th>Electricity Saving (GJ/tcs)</th>
<th>Primary Energy Savings (GJ/tcs)</th>
<th>CO₂ Emission Reduction (kgCO₂/tcs)</th>
<th>Share of Measures Applied (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1. Sintering &amp; Pelletising</td>
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<td></td>
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<td>48.50</td>
<td>30</td>
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<td>2. Coking</td>
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<td></td>
<td></td>
<td></td>
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<td>3. Iron-making BF</td>
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<td>32.43</td>
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<td>12</td>
<td>3.5 TRT</td>
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<td>0.09</td>
<td>0.26</td>
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<td>3.6 Waste Heat Recovery from BF Slag-washing Water</td>
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<td>0</td>
<td>0.23</td>
<td>20.72</td>
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<td>3.7 Dry Dusting Dust Transport System of Blast Furnace Gas</td>
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<td>0</td>
<td>0.18</td>
<td>16.21</td>
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<td>15</td>
<td>3.8 Waste Plastic Injection</td>
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<td>0.11</td>
<td>9.91</td>
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<td>4. Steelmaking BOF</td>
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<td>4.1 Negative Energy Consumption on Converter</td>
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<td>4.2 Heat Recovery of BOF Gas</td>
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<td>0.50</td>
<td>45.04</td>
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<td>18</td>
<td>4.3 LT-PR of Converter Gas</td>
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<td>0.14</td>
<td>12.61</td>
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<td>No</td>
<td>Technology</td>
<td>Fuel Saving (GJ/tcs)</td>
<td>Electricity Saving (GJ/tcs)</td>
<td>Primary Energy Savings (GJ/tcs)</td>
<td>CO₂ Emission Reduction (kgCO₂/tcs)</td>
<td>Share of Measures Applied (%)</td>
</tr>
<tr>
<td>----</td>
<td>------------------------------------------------</td>
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<td>----------------------------</td>
<td>-------------------------------</td>
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<td>19</td>
<td>Waste Heat Recovery</td>
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<td>0.72</td>
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<td>Twin Shell Direct Current Arc Furnaces</td>
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<td>0.13</td>
<td>0.38</td>
<td>34.23</td>
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<td>22</td>
<td>EAF Process Optimization</td>
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<td>0.33</td>
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<td>Eccentric Bottom Tapping</td>
<td>0.19</td>
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<td>25.22</td>
<td>30</td>
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<tr>
<td>24</td>
<td>Thin Slab Casting</td>
<td>1.18</td>
<td>0.09</td>
<td>1.44</td>
<td>129.72</td>
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<td>25</td>
<td>Continuous Casting</td>
<td>0.25</td>
<td>0.06</td>
<td>0.42</td>
<td>37.83</td>
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<td>26</td>
<td>Process control in hot strip mill</td>
<td>0.26</td>
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<td>0.26</td>
<td>23.42</td>
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<td>27</td>
<td>Waste heat recovery in casting</td>
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<td>28</td>
<td>Efficient ladle preheating</td>
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<td>0.02</td>
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<td>29</td>
<td>Regenerative Reheating Furnace</td>
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<td>30</td>
<td>Hot Delivery and Hot Charging of Continuous</td>
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<td>0.65</td>
<td>58.10</td>
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<td>31</td>
<td>Automated Monitoring and Targeting System</td>
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<td>0.38</td>
<td>34.23</td>
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<td>32</td>
<td>Low Temperature Rolling Techniques</td>
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<td>0.23</td>
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<td>33</td>
<td>Energy Management System</td>
<td>0.32</td>
<td>0.03</td>
<td>0.35</td>
<td>31.53</td>
<td>90</td>
</tr>
</tbody>
</table>

Note 1: Data on energy saving and CO₂ emission reduction is estimated by the team based on (Li & Zhu, 2014; NDRC, 2018; MIIT et al., 2012), verified by Shandong Energy Conservation Association.

Note 2: Production Ratio: Sinter/pellet: Iron = 1.5:1; Coke: Iron = 1:4; Iron: Steel = 1:1:

Note 3: Heat Value of Electricity = 3600 kJ/kWh; Heat Value of Coal = 29.307 GJ/tce

Note 4: CO₂ emission factor = 2.64 tCO₂/tce
Considering that some technologies cannot be applied in the process at the same time - e.g. Power Generation using waste heat and Steam production using waste heat, Pulverized Coal Injection and Oxygen Enrichment and Waste Plastic Injection - a package of 25 technologies is selected from the 33 recommended energy-efficient and carbon abatement technologies available for the iron and steel industry in China. These 25 abatement options are selected based on recommendations by experts from the representative steel enterprises.

Based on the parameters needed for the Marginal Abatement Cost Curve (MACC) in this study, the team has selected and collected data pertaining to the technology package of 25 abatement options. These technologies cover the whole iron and steel production process. Table 2 lists the technologies with data on fuel and electricity savings per tonne of crude steel produced, their calculated primary energy and CO₂ emission reduction, annualised capital investment cost (over an assumed 15-year lifetime for all technologies), annual cost changes in operation and maintenance, and the share of Chinese annual production in 2018 from the applied technology.
Table 2. Energy saving, cost, \( CO_2 \) emission reduction of the technology package of 25 recommended energy-efficient and carbon abatement options for China iron and steel sector

<table>
<thead>
<tr>
<th>No</th>
<th>Technology</th>
<th>Fuel Saving (GJ/tcs)</th>
<th>Electricity Saving (GJ/tcs)</th>
<th>Primary energy savings (GJ/tcs)</th>
<th>( CO_2 ) emission reduction (kgCO(_2)/tcs)</th>
<th>Annualised Retrofit Capital Cost (CNY/tcs)</th>
<th>Annual O&amp;M Cost (CNY/tcs)</th>
<th>Applied (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Power Generation using waste heat</td>
<td>0.35</td>
<td>0.00</td>
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<td>31.53</td>
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<tr>
<td>2</td>
<td>Thick Layer Sintering</td>
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<td>0.00</td>
<td>0.21</td>
<td>18.92</td>
<td>0.24</td>
<td>0.00</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>Coke Dry Quenching (CDQ)</td>
<td>0.38</td>
<td>0.00</td>
<td>0.38</td>
<td>34.23</td>
<td>10.58</td>
<td>1.23</td>
<td>80</td>
</tr>
<tr>
<td>4</td>
<td>Coke Oven Rising Tube Heat-recovering Technology</td>
<td>0.08</td>
<td>0.00</td>
<td>0.08</td>
<td>7.21</td>
<td>1.00</td>
<td>5.00</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Coal Moisture Control (CMC)</td>
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<td>0.00</td>
<td>0.14</td>
<td>12.61</td>
<td>6.08</td>
<td>1.91</td>
<td>15</td>
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<td>6</td>
<td>Pulverized Coal Injection and Oxygen Enrichment</td>
<td>0.62</td>
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<td>0.62</td>
<td>55.85</td>
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<td>-29.74</td>
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<td>CCPP</td>
<td>0.90</td>
<td>0.00</td>
<td>0.90</td>
<td>81.07</td>
<td>20.00</td>
<td>12.50</td>
<td>90</td>
</tr>
<tr>
<td>8</td>
<td>Blast Furnace Control</td>
<td>0.36</td>
<td>0.00</td>
<td>0.36</td>
<td>32.43</td>
<td>10.69</td>
<td>2.00</td>
<td>30</td>
</tr>
<tr>
<td>9</td>
<td>Top Combustion Stove</td>
<td>0.30</td>
<td>0.00</td>
<td>0.30</td>
<td>27.02</td>
<td>15.58</td>
<td>0.00</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>TRT</td>
<td>0.17</td>
<td>0.09</td>
<td>0.26</td>
<td>23.42</td>
<td>2.00</td>
<td>0.00</td>
<td>100</td>
</tr>
<tr>
<td>11</td>
<td>Waste Heat Recovery from BF Slag-washing Water</td>
<td>0.23</td>
<td>0.00</td>
<td>0.23</td>
<td>20.72</td>
<td>1.00</td>
<td>5.00</td>
<td>80</td>
</tr>
<tr>
<td>12</td>
<td>Heat Recovery of BOF Gas</td>
<td>0.50</td>
<td>0.00</td>
<td>0.50</td>
<td>45.04</td>
<td>11.13</td>
<td>0.00</td>
<td>10</td>
</tr>
<tr>
<td>13</td>
<td>LT-PR of Converter Gas</td>
<td>0.00</td>
<td>0.14</td>
<td>0.14</td>
<td>12.61</td>
<td>5.00</td>
<td>3.47</td>
<td>20</td>
</tr>
<tr>
<td>14</td>
<td>Waste Heat Recovery</td>
<td>0.72</td>
<td>0.00</td>
<td>0.72</td>
<td>64.86</td>
<td>37.50</td>
<td>0.00</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>EAF Process Optimization</td>
<td>0.22</td>
<td>0.11</td>
<td>0.33</td>
<td>29.73</td>
<td>31.75</td>
<td>-33.42</td>
<td>50</td>
</tr>
<tr>
<td>16</td>
<td>Eccentric Bottom Tapping</td>
<td>0.19</td>
<td>0.09</td>
<td>0.28</td>
<td>25.22</td>
<td>12.18</td>
<td>0.00</td>
<td>30</td>
</tr>
<tr>
<td>17</td>
<td>Thin Slab Casting</td>
<td>1.18</td>
<td>0.09</td>
<td>1.27</td>
<td>114.40</td>
<td>32.00</td>
<td>-125.32</td>
<td>100</td>
</tr>
<tr>
<td>18</td>
<td>Continuous Casting</td>
<td>0.25</td>
<td>0.06</td>
<td>0.31</td>
<td>27.93</td>
<td>25.00</td>
<td>-178.79</td>
<td>100</td>
</tr>
<tr>
<td>19</td>
<td>Process control in hot strip mill</td>
<td>0.26</td>
<td>0.00</td>
<td>0.26</td>
<td>23.42</td>
<td>4.00</td>
<td>0.00</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>Efficient ladle preheating</td>
<td>0.02</td>
<td>0.00</td>
<td>0.02</td>
<td>1.80</td>
<td>1.67</td>
<td>0.00</td>
<td>100</td>
</tr>
<tr>
<td>21</td>
<td>Regenerative Reheating Furnace</td>
<td>0.70</td>
<td>0.00</td>
<td>0.70</td>
<td>63.06</td>
<td>5.00</td>
<td>0.00</td>
<td>50</td>
</tr>
<tr>
<td>22</td>
<td>Hot Delivery and Hot Charging of Continuous Casting Billet</td>
<td>0.65</td>
<td>0.00</td>
<td>0.65</td>
<td>58.55</td>
<td>0.50</td>
<td>0.00</td>
<td>5</td>
</tr>
<tr>
<td>23</td>
<td>Automated Monitoring and Targeting System</td>
<td>0.00</td>
<td>0.38</td>
<td>0.38</td>
<td>34.23</td>
<td>4.00</td>
<td>0.00</td>
<td>5</td>
</tr>
<tr>
<td>24</td>
<td>Low Temperature Rolling Techniques</td>
<td>0.23</td>
<td>0.00</td>
<td>0.23</td>
<td>20.72</td>
<td>2.00</td>
<td>3.00</td>
<td>80</td>
</tr>
<tr>
<td>25</td>
<td>Energy Management System</td>
<td>0.32</td>
<td>0.03</td>
<td>0.35</td>
<td>31.53</td>
<td>1.11</td>
<td>2.00</td>
<td>90</td>
</tr>
</tbody>
</table>

Source: Data on Annualised Retrofit Capital Cost and Annual O&M Cost are estimated by the team based on (Li & Zhu, 2014; NDRC, 2018; MIIT et al., 2012), verified by Shandong Energy Conservation Association.
4. Cost Analysis Methodology

The session outlines the methodology used to assess the cost of CO$_2$ avoided by different abatement technologies. To analyse and compare the costs of the CO$_2$ abatement potential and the abatement cost of the selected technology package of 25 abatement options, the study applies a marginal abatement cost curve (MACC) model. Through the modelling exercise, the abatement cost of each technology is analysed. The methodology has been widely applied to make an economics comparison of abatement technology options with different capital costs, different operating costs, different lifetimes, and different abatement potential. For example, McKinsey & Company (2009) investigated the costs of different options in various sectors for achieving energy and eco-friendly sustainability in China. Hasanbeigi et al. (2010) has further clarified the methodology of the MACC model. The MACC model calculates the incremental resource costs compared with the baseline scenario, as per equation (1).

\[
C_A = \frac{C_a - C_b}{E_b - E_a}
\]  

[1]

where $C_A$ represents the cost per kilogram of CO$_2$ emissions reduced in the production of iron and steel (CNY/kgCO$_2$); $C_a$ stands for the full cost of the abatement options while $C_b$ is the full cost of the baseline options; $E_b$ is the total CO$_2$ emissions from the baseline options and $E_a$ is the total CO$_2$ emissions from the abatement options.

In this model, the baseline is assumed to be the status of the iron and steel industry in China in 2015. This research will investigate the implementation of selected carbon abatement technologies and assess the marginal carbon abatement costs of these technologies in the period 2015 to 2030. It is assumed that apart from the installed carbon abatement technologies, no other technology will be newly installed within the scenario period. Therefore, in Equation (1), the full cost of the baseline option is taken as zero.

In the following sections, each parameter in equation (1) will be specified. The full cost of an abatement option is taken as equal to the present value of costs minus the present value of revenue, given by equation (2) below:

\[
C_a = PV_C - PV_R
\]  

[2]

where $PV_C$ stands for the present value of costs (calculated as per equation 3 below); and $PV_R$ is the present value of revenues from fuel and electricity savings.
\[ PV_C = C_C + PV_{OM} \]  \[ \text{[3]} \]

where \( C_C \) is the total capital cost (CNY/t) for investing in the project in the baseline year (2015); and \( PV_{OM} \) is the present value of the changes in operation and maintenance (O&M) costs from 2015 to 2030.

To determine the present value of the equal amounts \( (A_0) \) over the scenario period of \( n \) years, the Uniform Present Value (UPV) formula, following Fuller & Peterson (1996), will be adopted given by equation (4) below:

\[
PV = A_0 \times \sum_{t=1}^{n} \frac{1}{(1+d)^t} = A_0 \times \frac{(1+d)^n-1}{d(1+d)^n} \]

\[ \text{[4]} \]

This study assumes a fixed discount rate of 15% (Hasanbeigi et al., 2013). Once the discount rate \( d \) is determined as 15% and the length of scenario period \( n \) is 15 years, the value of the latter part of Equation 4 can be calculated as 5.85. It is also assumed that the cost change of operations and maintenance will remain constant during the scenario period, as given by equation (5) below:

\[
PV_{OM} = A_{OM} \times 5.85 \]

\[ \text{[5]} \]

where \( A_{OM} \) is the cost change of operations and maintenance per ton of production annually (CNY/t). \( PV_R \) is calculated as equation (6) below:

\[
PV_R = PV_f + PV_e \]

\[ \text{[6]} \]

where \( PV_f \) is the present value of revenue from fuel savings, while \( PV_e \) is the present value of revenue from electricity savings. Energy price changes should also be taken into account to avoid over- or under-estimations. To determine the present value of the amount that results with the changes annually at a fixed escalation rate \( (e) \) and a fixed discount rate \( d \) during the scenario period \( n \) years, the Uniform Present Value for price escalation (UPV*) equation (7) below will be used for calculating the PV Revenue from fuel and electricity savings (Fuller & Peterson, 1996).

\[
PV = A_0 \times \frac{(1+e)}{(1+d)} \times \left[ 1 - \frac{(1+e)^n}{(1+d)^n} \right] \]

\[ \text{[7]} \]

where \( PV \) is the present value of cumulative cost savings during the scenario period; \( n \) is the scenario period (assumed to be 15 years in this study); \( d \) is the real discount rate (15%), excluding the inflation rate; and \( e \) is the real energy price escalation rate which can be either positive or negative. The equation for \( PV \) of the revenue from fuel and electricity savings (equation 8) can be written as:
\[ PV_E = S_E \times UPE \times \left(\frac{1+e}{1+d}\right) \times \left[ 1 - \left(\frac{1+e}{1+d}\right)^n \right] \]  

where \( PV_E \) stands for the present value of the revenue from the energy (fuel or electricity) saving; \( S_E \) is the total amount of the fuel or electricity saving; \( UPE \) is the unit price for fuel or electricity (CNY/GJ). All price units in this study are prices in the baseline year (2015 money).

To simplify the calculation, \( e \) is assumed to be a fixed rate based on historical data, whereas in reality the escalation rate varies from one year to another. According to previous data of industrial electricity prices (SERC, 2011) and fuel prices (Wu et al., 2016) in China, the average annual growth rate of the energy price for the iron and steel industry from 2000 to 2015 has been calculated and is regarded as a nominal energy price escalation rate. The real energy price escalation rate can be calculated with equation (9) below (Fuller & Peterson, 1996):

\[ e = \frac{1+E}{1+l} - 1 \]

where \( E \) is the nominal energy price escalation rate and \( l \) the inflation rate.

Data on the inflation rates between 2001 to 2015 in China is collected and the real energy price escalation rate in each year between 2001 and 2015 is calculated according to Equation (9). The average real energy price escalation rate will be applied to Equation (8).

Carbon emissions from the baseline and abatement options in Equation (1) can be calculated as equation (10) below:

\[ R_C = E_b - E_a \]

where \( R_C \) is CO₂ emissions reduced by applying carbon abatement technical options in the scenario period per tonne of steel produced (kgCO₂/t); \( E_b \) is the CO₂ emission level in the baseline year and \( E_a \) represents the CO₂ emission level under an abatement scenario.

Finally, Equation (1) can be simplified as equation (11) below:

\[ C_A = \frac{PV_C - PV_R}{R_C} \]
5. Results and Discussion

Based on the methodology outlined above and the data in Table 2 collected from peer-reviewed literature and official documents, the Marginal Abatement Cost Curve was constructed to assess the cost-effectiveness of the package of 25 recommended technologies as well as their carbon abatement potentials in the iron and steel industry in China. Of all the energy-efficient and carbon emission reduction technical options assessed here, 10 technologies were already either technically- or economically-applicable to the iron and steel industry in China (the share of technology applied was over 90%), and 8 technologies, including Power Generation using Waste Heat, Thick Layer Sintering, Pulverized Coal Injection and Oxygen Enrichment, TRT, Thin Slab Casting, Continuous Casting, Process Control in Hot Strip Mill, Efficient Ladle Preheating, have already been fully-adopted by the iron and steel industry in China by 2018. Among the technology package, 23 technologies were fuel-saving options while 8 technologies were electricity-saving options, while 6 technologies can save both fuel and electricity.

The MACC, using a lifetime of 15 years and a discount rate of 15%, is shown in Figure 3, where the x-axis represents the carbon abatement potential of each technology option while the y-axis represents the assumed carbon abatement cost. Negative abatement costs indicate that the carbon abatement technology is cost-effective, with profitable benefits from energy savings during the scenario period. Positive abatement cost values indicate that the technology applied requires further economic incentives to achieve reductions in carbon emissions. Of the technology package, 9 abatement technologies exhibit negative or zero abatement costs, in comparison to 16 technologies with positive abatement costs. All of the technologies featuring negative abatement costs contribute to energy savings in the production process. The global average carbon dioxide consumption remains approximately 2.1 tonnes CO₂ per tonne crude steel (Hasanbeigi et al., 2015). The cumulative carbon dioxide emission reduction potential from the recommended technology package of 25 abatement options is 898 kgCO₂/tcs. Put differently, if all the 25 aforementioned abatement options were adopted, they would result in a 43% reduction in emissions per tonne of crude steel produced in China.
Shanghai is one of the first five carbon market pilots in China, is leading the carbon market and its carbon price can be used as a standard in cost-effective analysis of carbon abatement technologies. The carbon price of Shanghai Emission Allowances (SHEAs) in Shanghai has been quasi-constant at around 40 CNY/tCO₂ in 2018 (CNEEEX, 2019). It follows that if the carbon price is taken as equivalent to 0.04 CNY/kgCO₂, 9 technologies can be regarded as cost-effective technologies. The cumulative carbon abatement potential of these cost-effective technologies is 426 kgCO₂/t, accounting for 20% of average CO₂ emissions per tonne of crude steel produced in China. The carbon price in China’s carbon market has been continuously increasing year by year. It is predicted that the average carbon price in China will rise to 51 CNY/tCO₂ in 2020 and to 86 CNY/tCO₂ in 2025 (CCF, 2018). Nevertheless, considering that China has only recently launched the national carbon market scheme (Power Industry) (in
December 2017, to be operational in 2020) and that it still has a long way to establish a comprehensive data collection system on baseline industrial emission levels, this study will not take possible increases in the carbon price into account.

Table 3 shows the selected 25 energy-efficient and carbon abatement technologies for the iron and steel industry in China, ranked by their corresponding abatement cost. It shows that Continuous Casting, Thin Slab Casting and Improved Process Control for EAF Process are the top three most cost-effective options with the lowest carbon abatement costs. In contrast, Coke Oven Rising Tube Heat-recovering Technology, Power Generation using waste heat and Waste Heat Recovery from BF Slag-washing Water exhibit the highest carbon abatement costs. For those technologies with positive carbon abatement costs, all their carbon abatement costs exceed Shanghai’s carbon price of 0.04 CNY/kgCO2.

Table 3. Carbon abatement options for iron and steel industry in China ranked by carbon abatement costs

<table>
<thead>
<tr>
<th>No</th>
<th>Technology</th>
<th>CO₂ Emission Reduction (kgCO₂/ts)</th>
<th>Abatement Cost (CNY/kgCO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.2</td>
<td>Continuous Casting</td>
<td>27.93</td>
<td>-36.80</td>
</tr>
<tr>
<td>6.1</td>
<td>Thin Slab Casting</td>
<td>114.40</td>
<td>-6.27</td>
</tr>
<tr>
<td>5.4</td>
<td>EAF Process Optimization</td>
<td>29.73</td>
<td>-5.87</td>
</tr>
<tr>
<td>3.1</td>
<td>Pulverized Coal Injection and Oxygen Enrichment</td>
<td>55.85</td>
<td>-2.73</td>
</tr>
<tr>
<td>7.3</td>
<td>Automated Monitoring and Targeting System</td>
<td>34.23</td>
<td>-0.79</td>
</tr>
<tr>
<td>3.5</td>
<td>TRT</td>
<td>23.42</td>
<td>-0.28</td>
</tr>
<tr>
<td>7.2</td>
<td>Hot Delivery and Hot Charging of Continuous Casting Billet</td>
<td>58.55</td>
<td>-0.07</td>
</tr>
<tr>
<td>1.3</td>
<td>Thick Layer Sintering</td>
<td>18.92</td>
<td>-0.07</td>
</tr>
<tr>
<td>7.1</td>
<td>Regenerative Reheating Furnace</td>
<td>63.06</td>
<td>0.00</td>
</tr>
<tr>
<td>6.3</td>
<td>Process control in hot strip mill</td>
<td>23.42</td>
<td>0.09</td>
</tr>
<tr>
<td>5.5</td>
<td>Eccentric Bottom Tapping</td>
<td>25.22</td>
<td>0.13</td>
</tr>
<tr>
<td>4.2</td>
<td>Heat Recovery of BOF Gas</td>
<td>45.04</td>
<td>0.16</td>
</tr>
<tr>
<td>8.1</td>
<td>Energy Management System</td>
<td>31.53</td>
<td>0.25</td>
</tr>
<tr>
<td>2.1</td>
<td>Coke Dry Quenching (CDQ)</td>
<td>34.23</td>
<td>0.44</td>
</tr>
<tr>
<td>3.4</td>
<td>Top Combustion Stove</td>
<td>27.02</td>
<td>0.49</td>
</tr>
<tr>
<td>5.1</td>
<td>Waste Heat Recovery</td>
<td>64.86</td>
<td>0.50</td>
</tr>
<tr>
<td>3.3</td>
<td>Blast Furnace Control</td>
<td>32.43</td>
<td>0.61</td>
</tr>
<tr>
<td>6.5</td>
<td>Efficient ladle preheating</td>
<td>1.80</td>
<td>0.84</td>
</tr>
<tr>
<td>7.4</td>
<td>Low Temperature Rolling Techniques</td>
<td>20.72</td>
<td>0.86</td>
</tr>
<tr>
<td>3.2</td>
<td>CCPP</td>
<td>81.07</td>
<td>1.07</td>
</tr>
<tr>
<td>4.3</td>
<td>LT-PR of Converter Gas</td>
<td>12.61</td>
<td>1.10</td>
</tr>
<tr>
<td>2.3</td>
<td>Coal Moisture Control (CMC)</td>
<td>12.61</td>
<td>1.29</td>
</tr>
<tr>
<td>3.6</td>
<td>Waste Heat Recovery from BF Slag-washing Water</td>
<td>20.72</td>
<td>1.38</td>
</tr>
<tr>
<td>1.1</td>
<td>Power Generation using waste heat</td>
<td>31.53</td>
<td>1.55</td>
</tr>
</tbody>
</table>
Among all the carbon abatement technologies, Thin Slab Casting, CCPP and Waste Heat Recovery in EAF Process have the first, second and third highest potential in carbon abatement respectively. Efficient ladle preheating has the lowest annual capital cost and a potential for annual operation and maintenance savings. Pulverized Coal Injection and Oxygen Enrichment, CCPP, Waste Heat Recovery in EAF process, EAF Process Optimization, Thin Slab Casting and Continuous Casting all have capital costs over 20 CNY/t crude steel. However, Pulverized Coal Injection and Oxygen Enrichment, EAF Process Optimization, Thin Slab Casting and Continuous Casting all benefit from significant amounts of annual operation and maintenance savings to become the cost-effective technology options.

In addition to capital and annual O&M costs, the share of technology applied in steel production (below using implementation rate) also has major impacts on the total costs of carbon abatement.

![Figure 4. Technologies distribution by implementation rate and marginal abatement cost](image-url)
The results of implementation rate and marginal abatement cost is shown in Figure 4. When the implementation rate of a technology is over 50%, the technology is assumed to be mature. Automated Monitoring and Targeting System in Rolling Process and Hot Delivery and Hot Charging of Continuous Casting Billet have good economic efficiency but low implementation rate, and are thus worthy of being further promoted. Also, there are five cost-effective technologies being successfully promoted at scale, of which Continuous Casting, Thin Slab Casting, Pulverized Coal Injection and Oxygen Enrichment, TRT and Thick Layer Sintering have been thoroughly implemented.

Carbon abatement costs and potential also vary amongst different steelmaking processes. Figure 5 shows the carbon abatement potential proportion of the seven aforementioned main iron- and steel-making processes along with the general technical option. The greatest three carbon abatement potential opportunities come in iron making-BF, casting and rolling processes, where the capacity for carbon emissions reduction from the selected technologies themselves and their adoption rate have influenced the final cumulative carbon abatement potential and efficiency.

![Figure 5. Comparison of carbon abatement potential in different processes](image)

The cumulative carbon abatement potential and energy saving potential per tonne crude steel in the sintering process are 50.45 kgCO₂/t and 0.56 GJ/t respectively. The abatement technologies in the sintering process have relatively high carbon abatement costs. However, Waste Heat Recovery from Sinter, though with a relatively high carbon abatement cost of 1.55 CNY/kgCO₂, has been promoted by the Chinese government. Considering the projected rising trend in future energy and carbon prices in the Chinese market, the carbon abatement cost
of Heat Recovery from Sinter Cooler is very likely to become negative and therefore cost-effective in future.

The cumulative carbon abatement potential and energy saving potential per tonne crude steel in the coking process are 54.05 kgCO$_2$/t and 0.60 GJ/t respectively. Coke Oven Rising Tube Heat-recovering Technology is a relatively new option with less than 5% implementation rate in China’s iron and steel industry. The other two technologies, CMC and CDQ, are promoted by the Chinese government. However, they all have poor economic efficiency in this model. CMC has a relatively high carbon abatement cost (1.29 CNY/kgCO$_2$) but a low carbon abatement potential (12.61 kgCO$_2$/t crude steel), with only 15% implementation rate.

The cumulative carbon abatement potential and energy saving potential per tonne crude steel in the iron making-blast furnace process are 240.52 kgCO$_2$/t and 2.67 GJ/t respectively, making this the process with the largest carbon abatement potential. There are two cost-effective options - Pulverized Coal Injection and Oxygen Enrichment and TRT, and four non-cost-effective options. Pulverized Coal Injection and Oxygen Enrichment, CCPP and TRT were all promoted by the Chinese government in the 12$^{th}$ Five Year Plan. Pulverized Coal Injection and Oxygen Enrichment has a high carbon abatement potential (55.85 kgCO$_2$/t) and a low carbon abatement cost (-2.73 CNY/kgCO$_2$ in this MACC model). CCPP and Blast Furnace Control also have high carbon abatement potential (81.07 kgCO$_2$/t and 32.43 kgCO$_2$/t) and potentials to become cost-effective. However, Blast Furnace Control currently has a low implementation rate and might be worth promoting in the future.

The cumulative carbon abatement potential and energy saving potential per tonne crude steel in the steelmaking-BOF process are 57.65 kgCO$_2$/t and 0.64 GJ/t respectively. Neither of the selected technologies for BOF (Heat Recovery of BOF Gas and LT-PR of Converter Gas) are cost-effective in the model.

The cumulative carbon abatement potential and energy saving potential per tonne crude steel in the steelmaking-EAF process are 119.81 kgCO$_2$/t and 1.33 GJ/t respectively. EAF Process Optimization is a cost-effective option. Eccentric Bottom Tapping and Waste Heat Recovery both have positive carbon abatement costs but potentials to become cost-effective. Of these technologies, Waste Heat Recovery is recommended by the Chinese government. A comparison of the selected technologies for EAF and BOF shows that those for EAF normally have better performance in carbon abatement and energy savings than those for BOF. The application rate of the EAF process itself as well as the carbon abatement technologies for it
are still low, but it renders the shift in the steel production structure from a BOF-based route to an EAF-based route all the more worthwhile.

The cumulative carbon abatement potential and energy saving potential per tonne crude steel in the casting process are 167.55 kgCO₂/t and 1.84 GJ/t respectively, making this the process with the third largest carbon abatement potential. Both two cost-effective measures, Continuous Casting and Thin Slab Casting, have already been 100% adopted in China. The other two options were assessed to be non-cost-effective, but have nevertheless already been highly implemented in China’s iron and steel industry.

The cumulative carbon abatement potential and energy saving potential per tonne crude steel in rolling and finishing process are 176.56 kgCO₂/t and 1.75 GJ/t respectively. Three of the selected technologies are cost-effective, including Regenerative Reheating Furnace, Hot Delivery and Hot Charging of Continuous Casting Billet and Automated Monitoring and Targeting System. Both Hot Delivery and Hot Charging of Continuous Casting Billet and Automated Monitoring and Targeting System have only about 5% implementation rate at present.

The cumulative carbon abatement potential and energy saving potential of the other general technical option (Energy Management System) are 31.53 kgCO₂/t and 0.23 GJ/t respectively. The selected technology is promoted in the 12th Five Year Plan for its high carbon abatement potential, and already has a very implementation rate (90%).

According to this study’s MACC model, over half of the selected technologies that are promoted by the 12th Five Year Plan are not cost-effective options for carbon abatement. However, the study’s results could be biased due to limitations in modelling and data collection and the use of average values across the whole iron and steel industry. Different companies have varying production structures that will have influence on their own operation and maintenance costs. Perhaps more pertinent to these limitations is the energy price that has and will continue to fluctuate (the coal price in China has exhibited marked fluctuations in recent years). In addition, with China having just launched a national emissions trading scheme, some of those promoted technologies featuring positive carbon abatement costs may still become cost-effective in the near future.
6. Conclusions

The study reviews existing low-carbon technology options for the steel sector, excluding fuel switching and carbon capture and storage. The carbon abatement costs and potentials for the 33 selected technical options assessed in this study have been estimated based on a bottom-up Marginal Abatement Cost Curve (MACC) model. This study first determined a wide range of energy-efficient and carbon abatement technologies for different iron- and steel-making processes promoted by the Chinese government and in other countries. Data was collated on their capital costs, operation and maintenance costs, energy-saving capacity, carbon abatement capacity and the current share of technologies applied in the iron and steel industry.

All technologies were assessed based on an assumed lifetime of 15 years with a fixed discount rate of 15%, and their carbon abatement costs were noted accordingly. Every technical option’s carbon abatement potential and cost is presented in the form of the carbon abatement cost curve. 9 technologies were found to exhibit negative carbon abatement costs.

The average carbon dioxide emissions are approximately 2.1 tonnes CO\(_2\) per tonne crude steel (Hasanbeigi et al., 2015). If all 25 abatement options were adopted, this would have the potential to reduce emissions by about 50%, or 898 kgCO\(_2\)/tcs in China. The cumulative carbon abatement potential of the 9 most cost-effective technologies could reduce emissions by 426 kgCO\(_2\)/tcs, about 20% of the average CO\(_2\) emissions per tonne of crude steel produced. Over half of the selected technologies promoted by the 12\(^{th}\) Five Year Plan were found not to be cost-effective, but may still become cost-effective technologies in the future, when considering the bias of this model and the projected increase in energy and carbon prices, as well as future policy interventions in the Chinese iron and steel industry.

Further studies on abatement options in the steel sector could improve these cost estimates. The assumed 15-year lifetime may be too short for some technologies and too long for others, resulting in over- or under-estimation of marginal abatement costs. Costs may vary from industry averages, and change with different energy prices. There may also be synergies between different options, and/or barriers to implementing multiple options in parallel, which more sophisticated modelling could seek to address.
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