Assessing the economics of CO2 capture in China's iron/steel sector

Citation for published version:
Liang, X, Lin, Q, Muslemani, H, Lei, M, Liu, Q, Li, J, Wu, A, Liu, M & Ascui, F 2019, 'Assessing the economics of CO_2 capture in China's iron/steel sector: A case study', *Energy Procedia*, vol. 158, pp. 3715-3722. https://doi.org/10.1016/j.egypro.2019.01.886

Digital Object Identifier (DOI):
10.1016/j.egypro.2019.01.886

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Energy Procedia

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 158 (2019) 3715–3722

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Assessing the Economics of CO_2 Capture in China's Iron/Steel Sector: A Case Study

LIANG Xi[a,b], LIN Qianguo[a,c], MUSLEMANI Hasan [a]*,LEI Ming[d], LIU Qiang[e], LI Jia[b], WU Alisa[c], LIU Muxin[a,b], ASCUI Francisco[a]

[a] *University of Edinburgh Business School, Edinburgh, UK*
[b] *UK-China (Guangdong) CCUS Centre, Guangzhou, China*
[c] *North China Electric Power Design Institute, Beijing, China*
[d] *Peking University Guanghua School of Management, Beijing, China*
[e] *National Center for Climate Change Strategy and International Cooperation, Beijing, China*

Abstract

Global crude steel production reached 1.6 billion tonnes in 2015, registering an increase of 41% from 2005 levels, half of which is produced by China alone. Amongst other low-carbon technologies, Carbon Capture and Storage (CCS) is identified as a key technology that will help achieve the much-needed emission reductions in the iron/steel sector. This paper delineates a techno-economic analysis of a hypothetical first-of-its-kind CO_2 capture and storage project with a 0.5-million tonne of CO_2 per annum capture capacity, using amine capture technology, in a generic Chinese steel plant. The technical configuration of the project was modelled using the Advanced System for Process Engineering (ASPEN) accompanied by a financial model analysis. The cost of CO_2 avoidance for the modelled project with transport and storage was estimated at CNY448/tCO_2 (USD65.2/tCO_2). The cost of CO_2 avoidance is sensitive to a number of assumptions, including the discount rate and the cost of CO_2 transportation and storage. There is also potential for cost reductions in transport and storage if the project were to share infrastructure with large stationary emission sources.

Keywords: CO_2 Capture; Iron/Steel Sector; Economics; China

1. Introduction

The 2015 Paris Agreement set out a global action plan to avoid dangerous climate change by limiting long-term global warming to levels below 2°C compared to pre-industrial levels, while pursuing best efforts to limit this increase

* MUSLEMANI Hasan Tel.: +441316508074
E-mail address: H.Muslemani@ed.ac.uk

10.1016/j.egypro.2019.01.886

to 1.5°C [1]. In practice, the 2°C target reflects an urgent need for a deep and rapid reduction in global emissions per capita – from the current average of $7tCO_2$ per annum to $4tCO_2$ in 2030 and $2tCO_2$ in 2050 [2]. The International Energy Agency (IEA) projects Carbon Capture and Storage (CCS) technologies to contribute towards 13% of greenhouse gas emission reductions between 2010 and 2050 [3].

Providing a fundamental structural component to society, the steel sector remains one of the most energy- and carbon-intensive industrial sectors and therefore a major contributor to global anthropogenic carbon dioxide emissions [4]. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the production of steel generated more than 2.6 billion tonnes of carbon dioxide ($GtCO_2$) in 2006, equivalent to approximately 5% of global anthropogenic carbon dioxide emissions per year [5].

Global crude steel production reached 1.6 billion tonnes in 2015, of which China alone produced around half (804 million tonnes). The application of environmentally-friendly and low-carbon technologies is anticipated to become a major trend within the global steel sector [6-11]. The EU Commission's Low Carbon Roadmap aims for the sector to reach, by 2050, a global emission intensity of less than 0.2 tCO_2 per tonne of crude steel produced – a significant reduction from the current global average (which is above $1.3tCO_2$ per tonne of steel produced) and China's average sector in 2014 (around 2.18 tCO_2/t). The Roadmap expects Carbon Capture and Storage (CCS) to play a key role in achieving the much-needed emission reductions in the iron/steel sector.

There are currently only two large-scale integrated iron/steel CCS projects under development in the world: the Ultra-Low CO_2 Steelmaking (ULCOS) Blast Furnace Project and the Emirates Steel Industry CCS Project [12]. The ULCOS project aims to capture up to 700,000 tCO_2/year from a blast furnace gas-fired boiler located in France. The Emirates Steel Industry CCS Project aims to capture 800,000 tCO_2/year from a Direct Reduced Iron (DRI) facility. Although China is the largest global producer of crude steel, it does not yet have any steel sector CCS demonstration projects. In this, the Asian Development Bank (ADB) suggested that new-build steel mills in China should be designed to be CCS-ready [2]. This paper provides a techno-economic analysis of CO_2 capture technologies at a hypothetical generic Chinese steel plant, preceded by an overview of typical steel manufacturing processes and routes to emissions reduction.

2. Process of steel manufacturing and mechanisms for emissions reduction

2.1. Steelmaking processes

Steel is produced from iron ore via two major stages: 1) the *ironmaking* stage where raw iron is extracted from the iron ore and 2) the *steelmaking* stage where raw iron is purified to produce crude steel. The two stages can be further sub-categorised into four steps [3], as illustrated in Figure 2.

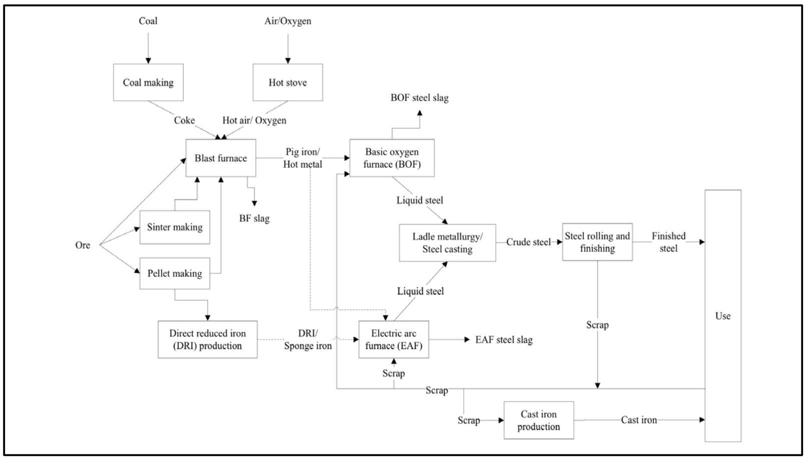

Fig. 1. Typical steel production processes

There are two types of iron ore preparation plants: sinter and pellet plants. Pellets are almost always made of one well-defined iron ore or concentrated at the mine to be transformed into this form. Sinter is generally produced at the ironworks from pre-designed mixtures of fine ores, residues and additives [13]. During the past two decades, around 60% of steel has been derived from hot metal/pig iron, although the share of steel produced from DRI has steadily increased. Today, 5% of global steel is produced from DRI and around 35% is derived from steel scrap. These developments are important as they significantly affect energy use and CO_2 emissions [3].

Globally, there are two main routes for the production of steel: the blast furnace-basic oxygen furnace (BOF) route and electric arc furnace (EAF) route. The key difference between them is the type of raw materials they consume. For BOF, these are predominantly iron ore, coal, and recycled steel, while the EAF route produces steel using mainly recycled steel (scrap). Based on plant configuration and availability of recycled steel, other sources of metallic iron such as DRI or hot metal can also be used in the EAF route. The BOF route always uses some scrap (up to 30%), while an EAF can be charged with 100% steel scrap. Another steelmaking technology, the open-hearth furnace (OHF), accounts for about 1% of global steel production. The OHF process is highly energy intensive and is in decline owing to its environmental and economic disadvantages. The majority of steel plants in China apply the BOF route.

2.2. CO_2 emission sources

Steel manufacturing contributes the largest share of CO_2 emissions of all global manufacturing sectors. The high CO_2 emissions are due to the energy intensity of steel production, its reliance on coal as a main energy source and the large volume of steel produced [14]. The average CO_2 intensity for the steel industry is 1.9 tCO_2 per tonne of steel produced [3, 15-16]. The carbon intensity of iron and steel production varies considerably between the production routes, ranging from around 0.4 tCO_2/t crude steel for scrap/EAF, 1.7-1.8 tCO_2/t crude steel for the integrated BF-BOF, up to 2.5 tCO_2/t crude steel for coal-based DRI processes [14,17].

The ironmaking process is the most emissions-intensive part of steel production, contributing 70-80% of the carbon dioxide emitted. Producing iron involves reacting iron ore with a reducing agent – such as coking coal – which produces a large volume of CO_2. There are several main streams featuring high concentrations of CO_2 in a steel plant. The system boundary consists of the following processes: coking plant, sinter plant, ironmaking, steelmaking and rolling mills. Additionally, the system boundary of the site includes the energy unit producing electricity, process steam and heat at the mill site as well as the purchase and sale of energy. Process gases, such as coke oven and blast furnace gases, are used for energy production at the mill site [18-20]. Here, we do not account for other emissions that occur off-site, but a further consequential analysis for CO_2 emissions from the steel sector would be beneficial.

CO_2 is emitted at a variety of points in the iron and steel production processes including: 1) direct emissions from on-site combustion of fossil fuels; 2) process-related (i.e. non-energy) emissions; and 3) indirect emissions from electricity consumed during the production process (Table 1). The main equipment resulting in direct CO_2 emissions includes the sintering machine, coke oven, dry quenching furnace, blast furnace, converter, continuous casting machine, rolling mill, shaft kiln and rotary kiln, and power generation boiler.

Table 1. Primary CO_2 sources in the steel production process

Processes	**CO_2 Source**
Sintering/ Pelletizing	Solid fuel, Ignition gas, Calcination
Coking	Washed coal, Coke oven heating fuel, etc.
Ironmaking	Coke reduced iron process, Consumption of hot blast stove
Steelmaking	Molten iron decarbonization
Continuous casting – cold/hot rolling	Heat treatment using fuel

2.3. CCS as an emission reduction technology

The pathways to emission reduction in the steelmaking process can be categorised based on their sequence of occurrence: ***1) Carbon source,*** i.e. switching to a fuel and/or reducing agent with lower carbon content. Carbon dioxide can be prevented from being emitted by using zero-carbon – or lower carbon – energy carriers (such as wind energy, nuclear energy, water power, biomass, fuel cells, etc.) instead of fossil fuels; **2) *carbon emission minimization*** i.e. to minimize the CO_2 emitted from steel plants by employing energy saving technologies. This involves improvements in the efficiencies of energy conversion, transportation and utilisation [16]. The principal measures for improving energy efficiency include enhancing continuous processes to reduce heat loss, increasing the recovery of energy and process gases, utilisation of by-product fuels and implementation of efficient design [14]; and **3) *Carbon sink*** i.e. where the emitted CO_2 can be either captured or recycled, then stored in permanent carbon sinks instead of being released back to the atmosphere. Beyond the aforementioned routes to emissions reduction, there is substantial potential for further reductions that could only be achieved by equipping plants with carbon capture and storage [21].

Applying CCS to all the stacks in a steel works is possible, provided there is space. This would not interrupt upstream and downstream processes but the cost for transporting and storing CO_2 remains relatively high. This study assumes the employment of an amine-based technology for CO_2 capture in a steel blast furnace. The amine-based technology remains one of the most popular global carbon capture technologies and is also recognised as a cost-efficient method. It has been established for over 60 years in oil and chemical industries – for removal of hydrogen sulphide and CO_2 from gas streams. Commercially, it is the most well-established of the techniques available for carbon capture, although practical experience exists mainly in gas streams (which are chemically-reducing as opposed to the oxidising nature of a flue gas stream). By using this technology, CO_2 recovery rates of 98% and product purity in excess of 99% can be achieved [22]. There are other potentially-disruptive technologies investigated by researchers, such as ammonia capture, water gas shift technology, modified blast furnace with pre-combustion capture and calcium looping. However, the amine-based technology remains the best option for carbon capture in the steel sector, not only for its capture efficiency, but also its economic efficiency.

3. Case study

3.1. Technical assumptions

The study assesses the economics of CCS in a generic crude steel production plant that uses the BF technology, aided by process and financial assumptions from Bao Steel's Zhanjiang plant [23]. The hypothetical retrofit project is assumed to capture 0.5 $MtCO_2$/year from a slip stream from the BF. The study assumes the application of a mature amine CO_2 post-combustion capture technology, and the major equipment of the hypothetical project are listed in Table 2. The blast furnace integrated steel-making process is assumed to include six modules, and ASPEN, a state-of-the-art process simulator and economic evaluation package designed for use in engineering fossil energy conversion processes, was used to evaluate the project's financial parameters. The methodology employed in this assessment is derived from IEAGHG [24-25] and Tsupari et al. [26-27] studies where modules were coded for simulation and cost analyses purposes. It is worth noting that the study did not assume an engineering design for CO_2 storage.

The study assumes a 20% CO_2 concentration from the blast furnace flue gas [28]. The CO_2 flue gas from the top of the blast furnace enters a gas cleaning process. 'Clean' flue gas enters the amine base chemical absorption module and the captured high-purity CO_2 is compressed before being transported for storage. The remaining flue gas rich with H_2 and CO is recycled to the bottom of the blast furnace via a gas heater. The composition of gas from the BF is listed in Table 3.

Table 2. Major equipment and facilities of the hypothetical project

Equipment	Scale	Number of Units
High Furnace	5050 m^3	2
Rotary Furnace	350t	3
Two-strand Continuous Slab Casters	2300mm	1
Two-strand Continuous Slab Casters	1650mm	1
Hot Strip Mill	2250mm	1
Hot Strip Mill	1780mm	1
Think Board Casting Plant	4200mm	1
Cold Strip Mill	2030mm	1
Cold Strip Mill	1550mm	1
Raw Material Loading Terminal	300,000t loading capacity	1
Lime Plant	2 x rotary mills and 1 x fixed mill, 0.84 million tonne	1
Coal and flue gas fired Power Plant	350MW subcritical	2
Air Separation Unit	60,000 Nm^3/h	3
Sea Water Desalination	15,000 tonne / day	2

Table 3. Estimated composition of Blast Furnace Flue Gas Stream

Treated BF Gases	Units	Composition
CO_2	% (v/v) dry basis	20%
CO	% (v/v) dry basis	25%
H_2	% (v/v) dry basis	3%
N_2 /Air	% (v/v) dry basis	49%
H_2S	mg/Nm^3	10
Particulate Matter	mg/Nm^3	5
Mn	mg/Nm^3	0.2
Pb	mg/Nm^3	0.05
Zn	mg/Nm^3	0.05

3.2. Economic assumptions

The economic analysis focuses on the computation of two main outputs:

a) Cost of CO_2 Avoidance (CNY/tCO_2), denoted COA, and is given by equation (1):

$$COA = \frac{\sum_{n=0}^{T} \frac{(I_n + O_n + F_n + S_n)}{(1+r)^n}}{\sum_{n=0}^{T} \frac{(Q_n - A_n)}{(1+r)^n}} \qquad (1)$$

Where I_n *is* the investment cost at year n, O_n the fixed operating and maintenance cost at year n, F_n the variable costs (incl. fuel and solvent) at year n, S_n the transport and storage cost at year n, Q_n the total amount of CO_2 captured from the project at year n, A_n the total amount of CO_2 generated from an auxiliary power plant for supplying steam and electricity for capturing and compressing CO_2 at year n, r the discount rate (i.e. the required rate of return), and T the lifetime of the project.

b) Incremental Cost for Steel Product (CNY/t), denoted CFP, is given by equation (2):

$$CFP = \frac{\sum_{n=0}^{T} \frac{(I_n + O_n + F_n + S_n)}{(1+r)^n}}{\sum_{n=0}^{T} \frac{\theta \cdot Y_n}{(1+r)^n}} \qquad (2)$$

Where Y_n is the total amount of crude steel produced at year n and θ the percentage representing the fraction of CO_2 avoided divided by the steel total CO_2 emissions from the steel plant without capture.

The capital cost of the capture plant is estimated at CNY360 million with an additional 7% margin for owner's cost. An additional CNY20 million is assumed for working capital for a company to oversee the development of the project and a CNY2 million as a one-off start-up cost. The modelling results show an electricity output penalty for the auxiliary power plant (to generate steam and electricity for capture, compression and storage) of 142kWh/tCO_2 captured. The coal price is assumed to be CNY27/GJ (approximately US$4/GJ), and the electricity price for calculating the cost of using auxiliary power is CNY0.48/kWh, approximately 10% above the benchmark wholesale electricity price in Guangdong Province. The cost of purchasing the solvent is CNY 40,000 per tonne of amine. The fixed O&M cost is assumed to be CNY 12 million per year.

The discount rate of the capture project is assumed to be 12%. A sensitivity analysis was also conducted for 11% and 13% discount rate scenarios. The plant is currently assumed to emit 1.65tCO_2/tonne steel produced as an average of reported emissions from major steel plants, with total CO_2 emissions of 15.5MtCO_2 per year. The auxiliary power plant has an emission factor of 743 gCO_2/kWh. The total amount of CO_2 avoidance capacity is 394,494 tonnes per annum with a CO_2 capture capacity of 500,000 tonnes CO_2 per annum.

4. Results & Discussion

The assessment estimates the cost of CO_2 avoidance for the project at CNY448/tCO_2 (USD65.2/tCO_2) (Table 4). The project would capture 0.45MtCO_2/year over 25 years, totaling 11.25MtCO_2. However, this is offset by emissions from increased energy consumption so the project would only reduce aggregate emissions by 0.36 MtCO_2/year, or a total of 8.88 MtCO_2 over its lifetime. When the cost of the project is apportioned only to the amount of steel associated with 8.88 MtCO_2 (2.5% of total steel production), the cost is CNY740 (USD 107.7) per tonne of steel produced. However, if the cost is spread over the entire production of the plant, the cost per tonne of total steel production is only CNY21/tonne (~USD 3).

Table 4. Economic analysis results for a hypothetical 0.5 MtCO_2 CCUS project in China

Outputs	**Results**
Intermediate Outputs	
Discounted Quantity of CO_2 Avoidance (t)	2784664
Discounted Quantity of Zero Carbon Steel Production (t)	1685171
Discounted Total Steel Production (t)	59590602
Discounted Cost Cash Flow (million CNY, before tax)	1247
Discounted Cost Cash Flow (million CNY, after tax)	1441
Key Final Outputs	
Cost of CO_2 Avoidance (CNY/tCO_2)	448
Incremental Cost for Zero Carbon Steel Production (CNY/tonne steel)	740
Incremental Cost for Total Steel Production (CNY/tonne steel)	21

The cost of CO_2 avoidance is sensitive to a number of assumptions, including the discount rate and the cost of CO_2 transportation and storage. If a project is considered as a moderate-risk investment applying an 8% discount rate, the cost of CO_2 avoidance (i.e. the abatement cost) would be reduced from CNY448/tCO_2 to CNY417/tCO_2. In contrast, the abatement cost would increase to CNY479/tCO_2 at a 16% discount rate. If the CO_2 storage and transport cost increased from CNY112/tCO_2 to CNY123/tCO_2, the abatement cost would be CNY449/tCO_2 at an 8% discount rate.

A study of CCS in the Australian steel sector [29] suggests that the cost of avoidance with conventional amine CO_2 capture technology could range from AU$70 to AU$250 excluding transportation and storage costs. In contrast, the estimated cost in China is significantly lower. The lower cost per tonne of CO_2 abated is mainly due to the lower capital costs in China. Guangdong is China's largest province with demand for more than 1 million tonnes of CO_2 in industry and food processing [30]. Selling CO_2 for local utilization could reduce transportation costs and eliminate storage costs, resulting in a breakeven price for selling CO_2 to the market at CNY299/tCO_2. However, the utilization of CO_2 for local consumption does not reduce anthropogenic CO_2 emissions unless it can be demonstrated that the captured CO_2 replaces naturally-mined CO_2.

Acknowledgements

The authors appreciate the financial support provided through the BHP Industry Carbon Dioxide Capture Project. Thanks to revisions undertaken by Hasan Muslemani and Jiang Mengfei from the University of Edinburgh Business School and to Francisco Ascui and Liang Xi for their helpful inputs and comments.

References

[1] UNFCCC. *Adoption of the Paris Agreement*. Paris, France; 2015.
[2] ADB (Asian Development Bank). *Roadmap for Carbon Capture and Storage Demonstration and Deployment in the People's Republic of China*; 2015. Available at: https://www.adb.org/sites/default/files/publication/175347/roadmap-ccs-prc.pdf [Accessed Jul 14, 2018]
[3] IEA (International Energy Agency). *Tracking Industrial Energy Efficiency and CO_2 Emissions, Chapter 5 (Iron and Steel Industry)*. Paris, France: IEA; 2007; p. 95-138.
[4] Leeson D, Fairclough J, Petit C, Fennell P. *A Systematic Review of Current Technology and Cost for Industrial Carbon Capture*. Grantham Institute, Imperial College London; 2014.
[5] IPCC (Intergovernmental Panel on Climate Change). *Working Group III: Mitigation of Climate Change, Chapter 10 (Industry)*; 2014.
[6] Sodsai P, Rachdawong P. The Current Situation on CO_2 Emissions from the Steel Industry in Thailand and Mitigation Options. *International Journal of Greenhouse Gas and Control*. 2012; 6: 49-55.
[7] Moya JA, Pardo N. The Potential for Improvements in Energy Efficiency and CO_2 Emissions in the EU27 Iron and Steel Industry under Different Payback Periods. *Journal of Cleaner Production*. 2013; 52: 71-83.
[8] Wen Z, Meng F, Chen M. Estimates of the Potential for Energy Conservation and CO_2 Emissions Mitigation Based on Asian-Pacific Integrated Model (AIM): The Case of the Iron and Steel Industry in China. *Journal of Cleaner Production*. 2014; 65: 120-30.
[9] Morfeldt J, Nijs W, Silveira S. The Impact of Climate Targets on Future Steel Production - an Analysis based on a Global Energy System Model. *Journal of Cleaner Production*. 2015; 103: 469-482.
[10] Riccardi R, Bonenti F, Allevi E, Avanzi C, Gundi A. The Steel Industry: A Mathematical Model under Environmental Regulations. *European Journal of Operational Research*. 2015; 242(3): 1017-27.
[11] Tsai IT, Al Ali M, El Waddi S, Zarzour OA. Carbon Capture Regulation for the Steel and Aluminum Industries in the UAE: An Empirical Analysis. *Energy Procedia*. 2013; 37: 7732-40.
[12] GCCSI (Global CCS Institute). *The Global Status of CCS. Special Report: Introducing Industrial Carbon Capture and Storage*. Melbourne, Australia; 2016.
[13] Hidalgo I, Szabo L, Calleja I, Cisar J. C, Russ P. *Energy Consumption and CO_2 Emissions from the World Iron and Steel Industry*. European Commission Joint Research Centre, Institute for Prospective Technological Studies, Spain; 2003, p. 11-18.
[14] Carpenter A. *CO_2 Abatement in the Iron and Steel Industry*. IEA Clean Coal Centre, London; 2012, p. 7-100.
[15] Kundak A, Lazic L, Črnko J. CO_2 Emissions in the Steel Industry. *Metalurgija*. 2009; 48(3): 193-7.
[16] Quader M. A, Ahmed S, Ghazilla R. R, Ahmed S. CO_2 Capture and Storage for the Iron and Steel Manufacturing Industry Challenges and Opportunities. *Journal of Applied Science and Agriculture*. 2014; 9(21): 60-7.
[17] Van Ruijven BJ, Van Vuuren DP, Boskaljon W, Neelis ML, Saygin D, Patel MK. Long-term Model-based Projections of Energy Use and CO_2 Emissions from the Global Steel and Cement Industries. *Resources, Conservation and Recycling.* 2016; 112: 15-36.
[18] Siitonen S, Tuomaala M, Ahtila P. Variables Affecting Energy Efficiency and CO_2 Emissions in the Steel Industry. *Energy Policy*. 2010; 38(5): 2477-85.
[19] Jin P, Jiang Z, Bao C, Hao S, Zhang X. The Energy Consumption and Carbon Emission of the Integrated Steel Mill with Oxygen Blast Furnace. *Resources Conservation & Recycling*. 2017; 117: 58–65.
[20] Lisienko VG, Lapteva AV, Chesnokov YN, Lugovkin VV. Greenhouse-gas (CO_2) emissions in the Steel Industry. *Steel in Translation*. 2015; 45(9): 623-6.
[21] Ghanbari H, Helle M, Saxén H. Optimization of an Integrated Steel Plant with Carbon Capturing and Utilization Processes. *IFAC-Papers Online*. 2015; 48(17): 12-7.
[22] Liang H, Liu Z, Wang L, Li P, Yu JG. Capture of CO_2 from Flue Gases by a Combined Process of Vacuum and Temperature Swing Adsorption using 13X-APG Zeolite. *Chinese Journal of Process Engineering*. 2010; 10(2): 249-55.
[23] Bao Steel. *Bao Steel Limited 2015 Annual Report*. China; 2016.
[24] IEAGHG (International Energy Agency Greenhouse Gas Programme). *Understanding the Economics of Deploying CO_2 Capture Technologies in an Integrated Steel Mill. Report 2013/04*; 2013a.
[25] IEAGHG (International Energy Agency Greenhouse Gas Programme). *Iron and Steel CCS Study (Techno-economics Integrated Steel Mill). Report 2013/TR3*; 2013b.
[26] Tsupari E, Kärki J, Arasto A, Pisilä E. Post-Combustion Capture of CO_2 at an Integrated Steel Mill – Part II: Economic Feasibility. *International Journal of Greenhouse Gas Control*. 2013; 16: 278-86.

[27] Tsupari E, Kärki J, Arasto J, Lilja J, Kinnunen K, Sihvonen M. Oxygen Blast Furnace with CO_2 Capture and Storage at an Integrated Steel Mill – Part II: Economic Feasibility in Comparison with Conventional Blast Furnace Highlighting Sensitivities. *International Journal of Greenhouse Gas Control*. 2015; 32: 189-96.
[28] Zhang C, Sun Z, Chen S, Wang B. Enriching Blast Furnace Gas by Removing Carbon Dioxide. *Journal of Environmental Sciences*. 2013; 25: 196-200.
[29] Wiley DE, Ho MT, Bustamante A. Assessment of Opportunities for CO_2 Capture at Iron and Steel Mills: An Australian Perspective. *Energy Procedia*. 2011; 4: 2654-61.
[30] GCCSI (Global CCS Institute), Guangzhou Institute of Energy Conversion. *Analysis of CO_2 Emission in Guangdong Province, China*. Guangdong, China; 2013, p. 6-9.