Int J Life Cycle Assess (2012) 17:787–794
DOI 10.1007/s11367-012-0422-y

LCI METHODOLOGY AND DATABASES

Life cycle inventory processes of the Mittal Steel Poland (MSP) S.A. in Krakow, Poland—blast furnace pig iron production—a case study

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Received: 17 February 2012 / Accepted: 27 March 2012 / Published online: 20 April 2012

Abstract

Purpose The goal of this paper is to describe the life cycle inventory (LCI) approach of pig iron produced by Mittal's Steel Poland Blast Furnace (MSPBF) in Krakow, Poland. The present LCI is representative for the reference year 2005 by application of PN-EN ISO 14040: 2009 (PN-EN ISO 2009). The system boundaries were labeled as gate-to-gate (covering a full chain process of pig iron production). The background input and output data from the blast furnace (BF) process have been inventoried as follows: sinter, several types of pellets, ore (from Brazil or Venezuela), limestone, coke, and from 2005 coal powder, pig iron, blast furnace gas, blast furnace slug, consumption of energy and fuels, including: pulverized coal, natural gas, blast furnace gas and coke oven gas, and emission of air pollutants.

Main feature LCI energy generation was developed mainly on the basis of following sources: site specific measured or calculated data, study carried out by Mittal Steel Poland (MSP) Environmental Impact Report, study carried out by the Faculty of Mining Surveying and Environmental Engineering of the AGH University of Science and Technology in Krakow, literature information, and expert consultations. The functional unit is represented by 1,504,088 Mg of pig iron, produced BF process. Time coverage is 2005. Operating parameters as well as air emissions associated with the BF process were presented. The production data (pig iron) was given. The emissions of SO_2, NO_2, CO, CO_2, aliphatic hydrocarbons, dust, heavy metals (Cr, Cd, Cu, Pb, Ni, and Mn), and waste are the most important outcomes of the pig iron process.

Results With regard to 1,504,088 Mg of pig iron produced by MSP, the consumption of coke, pulverized coal, sinters, pellets, and natural gas were 808,509, 16,921, 1,669,023, and 914,080 Mg, respectively. Other material consumption, industrial water, was 1,401,419 m^3/year.

Conclusions The LCI study is the first tentative study to express pig iron production in Poland in terms of LCA/LCI for the pig iron in steel industry. The results may help steel industry government make decisions in policy making. Presentation of the study in this paper is suitable for the other industries.

Recommendations and outlook The LCI offers environmental information consisting on the list of environmental loads. The impact assessment phase aims the results from the inventory analysis more understandable and life cycle impact assessment will be direction for future research. Another issue to discuss is integration of LCA and risk assessment for industrial processed.

Keywords Air emissions · Blast furnace · Blast furnace gas · Life cycle inventory (LCI) · Pig iron · Poland

1 Introduction

This paper describes a life cycle inventory (LCI) study of pig iron produced by the Mittal's Steel Poland Blast Furnace (MSPBF) in Krakow, Poland. The framework of the study was originally carried out for 2005 data because important statistics are available for this year and also because it represents the data, which are the foundation for the Mittal Steel Poland (MSP) Environmental Impact Report, annually collected (2005) and evaluated (Mittal 2007).

Responsible editor: Zbigniew Stanislaw Klos

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Because no LCA has ever been conducted on the pig iron production in steel plants in Poland, this study is the first work about LCI of energy process. The LCI study was conducted according to the requirements of the International Standards PN-EN ISO 14040: 2009 (PN-EN ISO 2009). The paper is organized as follows: introduction is presented first. Next, the goal and scope of the study are stated. Thereafter main features including LCI of MSPBF installation are developed. Then data analysis on emission results and conclusions are performed.

1.1 Introduction to AMPBF

The raw materials are raw ore, several types of pellets, sinter, limestone, and coke. These materials are transferred to the MSPBF Department by conveyor belts (sinter and coke) and railway cars (pellets and limestone).

These materials after have been unloaded are transferred to the dump yard or direct to the blast furnace (BF) storage bins by grab buckets or by conveyor belts. The raw materials are dumped according to desired sort recipes. Sinter and coke are then fed to stockhouse complex (BF-5) or dumped into a weigh wagon (BF-3). Then (next), formed there materials called “ore and cock cartridges” were transferred by the skip cars at the top of the furnace. Since 2005, pulverized coal can also be injected into the BF-3 and BF-5, to replace part of the expensive cock, using the pulverized carbon blow facility (auxiliary equipment).

The main chemical reaction producing the pig iron is based on the using the CO and H_2 as the reducing agent for the iron ore (Fe_2O_3). The reduction was carried out in the shaft furnace built in the form of a huge, steel stack lined with refractory brick. Counter-current process was employed to flow the raw materials and reduction gases. The raw materials pass to the bottom of the BF. The final products of the process are liquid slag, pig iron, and BF gas. Pig iron is transferred to blast oxygen furnace (BOF), using pig iron ladles, blast furnace gas is passed through pipeline to Gas Department, as well as to Power Plant, and liquid slug is delivered, using the slug ladles, in Granular facility.

The pig iron process in MSPBF is manufactured in two blast furnaces (BF-3 and BF-5) through combustion of sinter, several types of pellets, ore (from Brazil or Venezuela), limestone, coke, and in addition, from 2005 coal powder is also co-firing together with coke. MSP consisted of four plants located in Dąbrowa, Krakow, Sosnowiec, and Swietochłowice. It boasts a full production system—from pig iron to final, highly processed steel products—producing. Today, ArcelorMittal Poland S.A. (Mittal Steel Poland was merged with Arcelor in 2006, and the new company was called ArcelorMittal) is the world’s leading steel company, with operations in more than 60 countries. In 2010, AM had revenues of $78.0 billion and crude steel production of 90.6 million tonnes, representing approximately 8 % of world steel output (Mittal 2011).

By the end of 2005, the size of the total pig iron production (two blast furnaces) had reached the amount of 1,504,088 Mg (Mittal 2006). MSPBF has two (BF-3 and BF-5) blast furnaces. The average efficiency of BF-3 and BF-5 are 770,000–875,000 and 910,000–1,295,000 Mg/rok, respectively (Mittal 2007).

Pulverized coal flow through the two of the 800-m^3 capacity silos up to the distribution tanks containers, were weighed according to the ration designed to the desired pig iron brand (sort). Finally pulverized coal is injected into the BFs using compressed nitrogen N through collinear, coaxial lances. Pulverized coal and oxygen are blown by internal and external conduit, respectively.

The operating parameters of the MSPBF are summarized in Table 1.

2 Goal, scope, terminology, and definitions

The goals of this study were to:

- develop generic Polish LCA method limited to LCI data for MSPBF input/output datasets in the steel production case study with the view to facilitating the range of emerging impact assessment methods in future studies, covering the year 2005;
- produce national and regional LCI data suitable for the steel industry as well as other industries;
- promote the development of LCI and/or LCA research in Poland.

The data used in the study is obtained from the following sources:

- site-specific measured or calculated data (Mittal 2007);
- value based on literature information;
- LCA study carried out on behalf of the Management Department at the Polish Academy of Sciences in Krakow, the AGH University of Science and Technology (Kulczycka and Henclik 2009);
- study carried out by the Faculty of Mining Surveying and Environmental Engineering of the AGH University of Science and Technology in Krakow (Mazur et al. 2006);

Table 1 Operating parameters of the MSP blast furnaces

Blast furnaces number	Start [year]	Rebuilding [year]	Nominal productivity [Mg/year]	Totall productivity [Mg/year]
3	1958	1992	1,075,000	980,000
5	1966	1997	1,540,000	1,330,000

- MSP Environmental Impact Report (Mittal 2007);
- company's internal information (data obtained from personal communication with AMP Environmental Department director);
- expert consultation.

Data represent the integral MSPBF situation with global coverage of pig iron process. The functional unit (FU) is 1,504,088 Mg of pig iron. The system boundaries, which define the scope of the study appear in Fig. 1. It covers all operations required for pig iron production in MSPBF from upstream raw materials (i.e. the gate) to finished product-pig iron ready to be shipped from the blast furnaces (i.e., gate). Raw fuels mining and means of external transportation of raw coal, manufacture of downstream products, their use, and end of life were not included. Internal transport was not included and land using was not taken into account. The internal consumption of electricity is covered by properly produced electric energy. The importation electricity is necessary only in cases of an operational stop. Production data of main energy carriers is given in Bieda (2011).

3 LCI methodology

An LCI requires a lot of data (Finnveden et al. 2009). Full publication of the inventory data are documented in Kulczycka and Henclik (2009). In this case study, the system evaluated does not include anything upstream from the pig iron production. The complete data inventory is documented and presented in Mittal (2007). The main properties of fuels used in MSPBF, as well as air emissions associated with pig iron process in MSPBF have been shown in Table 2.

4 Air pollutants

4.1 CO_2

In 2005, CO_2 emission was estimated on the following formula under the European Commission's 2004/156/EC Decision pursuant to Directive 2003/87/EC of the European Parliament and stated in the Council Decision on 18 July 2007 (Official Journal of the European Union 2007):

$$CO_2\text{emission} = \text{Activity data} \times \text{Emission factor} \times \text{Oxidation (conversion) factor} \qquad (1)$$

CO_2 emissions are in line with the emission credits for MSP. Monitoring and standard criteria for CO_2 emissions were specified in the Decision of Małopolska Provincial Office in Krakow dated 11 April 2006 (Decyzja 2006). This decision also set forth legal emission limits for the maximum CO_2 emissions in 2005 (Journal of Laws 2005). Detailed

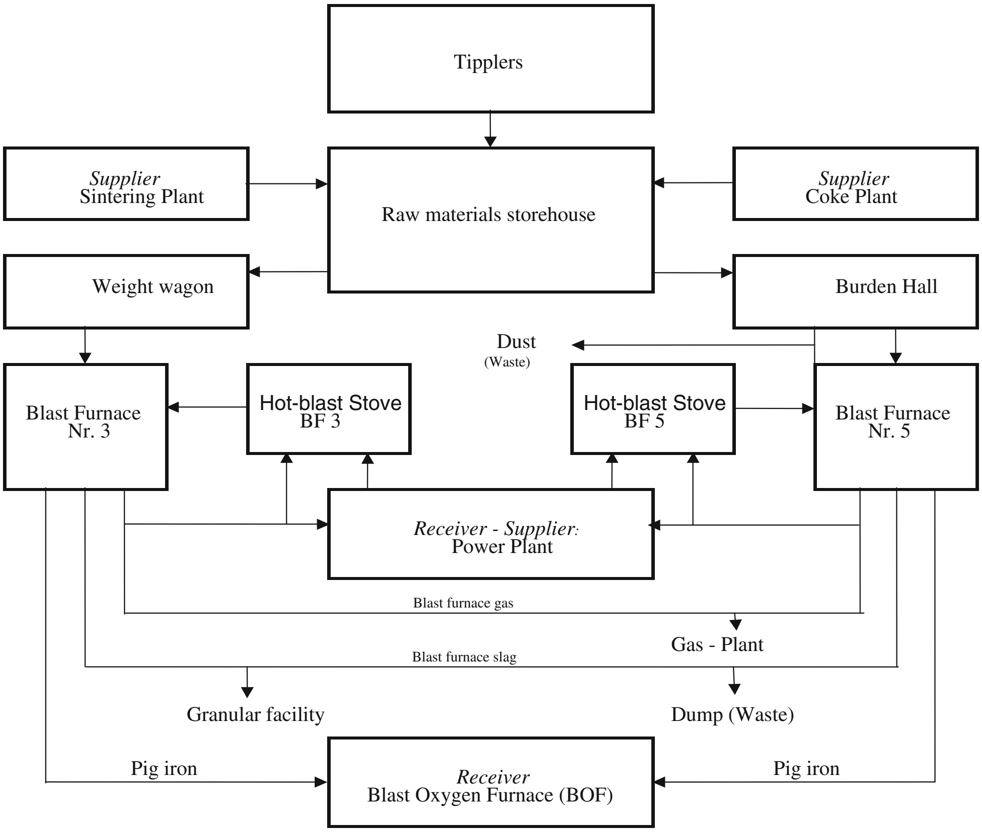

Fig. 1 System boundary of BF process—different processes investigated for the energy production chain of power plant installed in MSP

Table 2 Life cycle inventory for MSPBF generation process (2005)

Flux	Quality	Units
Input		
Energy and fuels		
Coke	808,509	Mg
Pulverized coal	16,921	Mg
Materials		
Industrial water (for pig iron production)	1,401,419	m^3
Industrial water (for pig iron production and slug granular facility)	98,552,175	m^3
Industrial water for 1 Mg of the pig iron	1,03	Mg/m^3
Sinters	1,669,023	Mg
Pellets	914,080	Mg
Raw materials (total)	2,583,103	Mg
Output		
Product		
Pig iron	1,504,088	Mg
Slug	408,000	Mg
Blast furnace (crude, unrefined)	3,818,658	Mg
Blast furnace (crude, unrefined-30 % CO)	3,114,311,200	m^3
Emissions to air		
SO_2	66.352	Mg
NO_2	84.566	Mg
Dust	532.232	Mg
Cr	0.0372	Mg
Cd	0.0009	Mg
Cu	0.0198	Mg
Pb	0.0160	Mg
Ni	0.0236	Mg
Mn	1.8415	Mg
CO	8,472.05	Mg
CO_2	1,185,611	Mg
HCl	N/A	Mg
Aliphatic hydrocarbons	6,224	Mg
Waste		
Slug	408,500,300	Mg
Other metals	1,390,400	Mg
Municipal solid waste, MSW	6	Mg
Waste (total)	443,685,185	Mg

Flows are representative for the production of 1,504,088 Mg of pig iron

description of the CO_2 emissions, as well as emission credits for MSP for the year 2005 was reported in Bieda (2011; 2012).

5 Water pollutants and particulate air pollution

In 2005, 443,685.185 Mg waste produced during the pig iron process in BF plant were sorted and recycled. Generally, the infrastructure for waste recycling is well-established. Waste is transferred either to BOF steelmaking routes or to other MSP installations. If a recycling operation is not available in MSP, the waste is fed to external units for such treatment (recycling). Otherwise, the waste is landfilled.

6 Discussion

Fuels and energy indicators for the production of 1 Mg of pig iron according to the MSPBF model covered 2004 and 2006 are given in Table 3 because of the lack of fuels and energy datasets for the year 2005. MSPBF indicators for the production of 1 Mg of pig iron in 2006 and 2007–2016, as

Table 3 Fuels and energy indicators for the production of 1 Mg of pig iron in the MSPBF model: forecast

Fuels	Unit	Year		
		2004	2006	2007–2016
Cock	kg/Mg pig iron	546	483	302
Coal	kg/Mg pig iron	N/A	72	117
Blast furnace gas	m^3/Mg pig iron	745	745	745
Coke oven gas	m^3/Mg pig iron	11.41	11.41	11.41
Natural gas	m^3/Mg pig iron	0.10	0.10	0.10
Electric energy	kWh/Mg pig iron	26.82	37.1	37.1
Steam	kg/Mg pig iron	37.5	N/A	N/A
Air	m^3/Mg pig iron	17.2	N/A	N/A
Heat	GJ/Mg pig iron	0.03	N/A	N/A

well as limits specified by the European Union (EU), are presented in Table 4.

Industrial water for pig iron production and slug granular facility reach 98,552,175 m^3. The Vistula and Dlubnia rivers serve as industrial water supply sources for the MSP (see Bieda 2012).

The multidimensional blast furnace system is one of the most complex industrial systems and, as such, there are still many unsolved theoretical and experimental difficulties, such as silicon prediction and blast furnace automation. For this reason, Gao et al. (2011) apply data-driven models based on the Volterra series for this complex system. Three kinds of different low-order Volterra filters are designed to predict the hot metal silicon content collected from a pint-sized BF, in which a sliding-window technique is used to update the filter kernels timely. Authors show that the sliding-window linear Volterra filter is full of potential for multidimensional blast furnace system.

To get the modification method of BF gas reburning technology on one 75-t/h stoker boiler, the effect of some key factors such as stoichiometric coefficient, residence time, temperature, and heat ratio input on NO_x formation regulation was studied on a one-dimensional test system with fuel reburning (Zhou et al. 2011). The results showed that prolonging the reburn zone residence time can help to lower the NO_x emission and the best time was 0.8 s. There existed an optimum value 1.0 for reburn zone stoichiometric coefficient. The NO_x reduction efficient increased with the increase of the reburn heat input and the reburn zone temperature. The use of blast furnace gas reburning technology has been successfully implemented during the modification of stoker boiler, the NO_x reduction rate was over 50 %.

Table 4 Fuels and Energy Indicators for the production of 1 Mg of pig iron according to the European Union (EU) and the MSPBF models

Fuels	Unit	EU	MSPBF	
			2006	2007–2016
Cock	kg/Mg pig iron	280–410	546	302
Coal powder	kg/Mg pig iron	0–180	N/A	117
Heavy oil	kg/Mg pig iron	0–60	N/A	N/A0
Blast furnace gas	MJ/Mg pig iron	1,050–2,700	2,405	1,978
Coke oven gas	MJ/Mg pig iron	90–540	172.3	239
Natural gas	MJ/Mg pig iron	50–230	3.57	0.14
Electric energy	MJ/Mg pig iron	270–370	133.6	133.6

The BF requires large amounts of metallurgical coke as a fuel, reductant, and internal structural support to provide stable passages for the furnace hot blast (Riley 2011). In recent years, BF operators have added high levels of oxygen enrichment to the hot blast. The highly enriched blast increases productivity and allows operators to replace part of the expensive coke with secondary fuel, such as pulverized coal and natural gas, injected in the blast. Secondary fuels injection lowers temperatures in the furnace, and blast oxygen enrichment raises furnace productivity and raises temperatures in the furnace. The rates of oxygen enrichment and secondary fuel injection must be closely linked and are used together because the temperature profile in the furnace must be kept within a narrow window (Carpenter 2006; Hyle 2008). Riley (2011) has shown that under normal operating conditions, ironmakers minimize costs. They use the highest fuel injection rate and the lowest blast oxygen enrichment level that will support that amount of injected fuel. When higher productivity is required, ironmakers increase blast oxygen enrichment beyond the minimum required. When total production falls sharply, fuel injection must be lowered to allow the contracted amount of coke to be consumed. Lower fuel injection rates may be more economical than heating unused coke ovens or rebuilding cooled ovens. Operating data for North American BFs supplied by Praxair have been presented in 2007 Blast Furnace Roundup (2007), AIST (2010), and Blast Furnace Roundup (2010).

Strassburger et al. (1969) show that the pig iron produced by the BF has a relatively high carbon content of around 4–5 %, making it very brittle, and of limited immediate commercial use. They note that according to the American Iron and Steel Institute: “BFs will survive into the next millennium because the larger, efficient furnaces can produce hot metal at costs competitive with other iron making technologies”.

The challenge set by the greenhouse gas emissions of the BF is being addressed in an ongoing European Program called ULCOS-Ultra Low CO_2 Steelmaking (van der Stel 2008). The author presents the ULCOS BF process at Luossavaara-Kiirunavaara Aktiebolag Experimental BF in Luleå. The objective of the project is modification of the conventional BF to reduce the CO_2 emission to 50 % per tonne steel. Results indicate that the first Experimental BF campaign in autumn 2007 generated considered success: (1) safe operation and (2) carbon saving up to 24 %.

Several new process routes have been proposed and investigated in depth to cut specific emissions (CO_2 per tonne of steel) by at least 50 %. In the nearer term, a technology that incorporates capture and further storage of CO_2 into the BF process itself is called the Top-Gas Recycling BF and is under development, with a scale-up to a commercial size BF under way. The technology should be fully demonstrated by the end of the 2010s, in line with the timeline set, for example, by the EU to cut emissions significantly. Broad deployment could take place from 2020 on (Strassburger et al. 1969).

Currently, the BF dominates the production of pig iron and is the most important unit in the steel industry from the viewpoint of energy consumption and CO_2 emmisions (Man-sheng et al. 2011). Green et al. (1996) present Ereğli Iron and Steel Works Inc., known as "Erdemir", a modern integrated iron and steel works on the Black Sea coast of Turkey, producing flat steel plate. The by-product gases of the BFs, coke ovens, and basic oxygen furnaces represent a considerable share of the consumed energy in an integrated iron and steel works. A typical BF gas analysis and heating value provided by Erdemir's laboratory is presented in Table 5.

BF higher heating value was 3,623.344 KJ/Nm^3 (866 Kcal/Nm^3). Based on an estimate of the natural gas saved by the burning of the wasted BF gas, Erdemir considers that they recovered their capital cost of the installation in less than a year of operation.

Ironmaking in BFs produces between 1,500 and 1,700 Nm^3 of gas per tonne of hot metal. This gas has a calorific value as high as 3,500–4000 KJ/Nm^3 (Ghost and Chatterjee 2008). The properties of BF gas depend on the fuel rate in the furnace, extent of oxygen enrichment of the blast, amount of indirect reduction in the furnace shaft, and other operating conditions.

Jian et al. (2011) show that BF is a highly complex nonlinear system characterized by high temperature, high pressure, strong noise, and distributed parameters. Generally, the variables related to the raw material and the blast are often taken as input while the variables associated with the hot metal and the in-furnace thermal state are regarded as output (Agarwal et al. 2010). A typical analysis of BF slag is given in Table 6.

The role of BF slag in reducing CO_2 emissions during cement production (BF slag is the additive for blast furnace cement, which accounts for almost all of the blended cement used in Japan) can be found in Japan Iron and Steel Federation presentation (Example 2011). Kunitomo et al. (2006) consider BF ironmaking system using pre-reduced ore in a two-stage ore reduction system that consists of a process for pre-reducing iron ore by using natural gas or some other suitable energy containing a comparatively small amount of carbon and BF process for further reducing and melting the pre-reduced iron ore. Manufacturing pre-reduced ore and using it in the BF is considered one of the promising technologies to be developed to dramatically improve existing ironmaking technology (Hayashi 1968). Shigemi (1979) considers that using pre-reduced ores as a raw material in the BF is effective in increasing the BF productivity and decreasing the reducing agents rate in the existing BF process and thereby save energy. The use of pre-reduced ore in a BF will make it possible not only to save energy in the conventional BF process but also to reduce the total consumption of energy and the total emissions of CO_2 in the entire hot metal production process, including pre-reduced ore production process. For Japan, which has limited natural resources, development of innovative new ironmaking process that makes most effective use of existing equipment and infrastructure are important and solvable issues, as described for example by Kunitomo et al. (2006).

Table 5 Erdemir BF gas volumetric analysis (% by volume)

H_2	N_2	CO	CO_2	CH_4
4.0	54.2	23.0	18.0	0.8

Table 6 A typical analysis (percent) of BF slag

CaO	SiO_2	MgO	AL_2O_3	FeO
40–45	35–40	5–12	12–20	1–2

The BF steelmaking process is presented by Iosif et al. (2009) in the assessment study of environmental impact of the classical steelmaking route. The objective of the above-mentioned work was to develop a new way of carrying out the LCI of the classical steelmaking route. In this framework, models for the Direct Reduction route are currently elaborated, on the basis of MIDREXTM process, in order to draw a comparison with the BF route, in terms of CO_2 emissions.

In recent years, great progress is made in technical equipment of large BF in China. A series of new process, technologies, and equipment are applied on newly built large BFs and have been proved to be highly effective (e.g., fully dry impulse bag filter dedusting technology of BF gas). Integrated innovative high-efficiency long-life high-temperature technology, through applying high-temperature preheating technology of combustion air, improving heat transfer efficiency of hot blast stove and optimizing structure of the hot blast stove system, enables the blast temperature to reach 1,250°C with BF gas as fuel. (Zhang 2012).

Gruyaert et al. (2012) presented a study about replacement of ordinary Portland cement by BF slag alters the durability behavior of concrete. In this research, the influence of BF slag on the concrete's acid or sulfate resistance is investigated. A significant reduction of acid deterioration was recorded for BF slag concrete, which is mainly attributed to the different chemical composition of the binder.

In the study carried out by Bilim and Ati (2012) investigation of some properties of alkali-activated mortars containing slag at different replacement levels was discussed. Ground granulated BF slag was used at 0, 20, 40, 60, 80, and 100 % replacement by weight of cement, and liquid sodium silicate having three different Na dosages was chosen as the alkaline activator. Portland cement/slag mortars activated by liquid sodium silicate exhibited lower strength than the slag alone activated by the same activator.

7 Conclusions

The LCI of pig iron production in MSPBF is focused on the production and operation results in 2005 as defined in the goal and scope. The output of the MSPBF pig iron LCI study is a set of gate-to-gate LCI data for steel production in BF technology. This is the first tentative study to express steel production in Poland in terms of LCA/LCI in the steelmaking industry. The production of 1,504,088 Mg of pig iron in 2005 was the selected FU. The quality of data input in this LCI study is very good. The rules were used in accordance with ISO standards. The methodological approach, boundaries that were made are transparent and fully documented. The purpose of this study is to help steel industry authorities to solve environmental and technical aspects, as well as to train steel industry people in the field of life cycle assessment. In addition, this study can be extended to other processes involved in steelmaking route (via sintering plant/hot rolling plant). Moreover, these results move the LCI study on the steelmaking process one step forward.

In conclusion, the LCI step was carried out in order to provide data for further LCA process. These data will be available for LCIA step. The LCIA provides the analysis of collected data to evaluate contributions to various environmental impact categories. Thus, the LCIA will be introduced as the next step of LCA methodology. These data is available for interpretation—the final step of the LCA method, where the collected data is analyzed in the context of methodology, scope, and study goals and where the quality of study outcomes is assessed. Finally, a complementary paper will be produced and submitted to this journal in which LCIA will be discussed.

8 Recommendations and outlook

The research described in this paper can also serve as the basis for future work. The potential direction for future research is to develop the LCI datasets for the classical route of steel production. The study should cover the foreground processes: coking plant, sintering plant, blast furnace, BOF, and hot rolling plant. A complementary paper will be produced and will be submitted to this journal in which LCIA will be discussed.

Acknowledgments The present scientific research was granted by science financial support for the years 2011-2013. The author would like to thank Mrs. J. Kulczycka and Mrs. A. Henclik from the Polish Academy of Science for invaluable discussions.

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