Life cycle assessment of the comprehensive utilisation of vanadium titano-magnetite

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list of abbreviations

LCA: life cycle assessment

VTM: vanadium titano-magnetite

LCI: life cycle inventory

LCIA: life cycle impact assessment

Pan. Steel: Panzhihua Iron and Steel Co. Ltd.

BF: blast furnace

GWP₁₀₀: global warming potential for the time horizon of 100 years

AP: acidification potential

EP: eutrophication potential

PCOP: photochemical ozone creation potential

HTP: human toxic potential

ADP: abiotic depletion potential

BOF: basic oxygen furnace

COG: coke oven gas

BFG: blast furnace gas

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Abstract: This study describes the LCA of the comprehensive utilisation of VTM through the integrated steel production and valuable element (V and Ti) extraction route. The major sources of environmental impacts are described and pollution prevention methods are proposed. The LCA methodology is based on the ISO 14044 standard, which uses GaBi 6.0 software and the Ecoinvent database, and the LCI data (input and output) are from Pan. Steel. Impact assessment results indicate that production of pig iron in BF exerts the most extensive impacts on GWP₁₀₀ and fossil fuel consumption. By contrast, iron ore mining dressing and sintering contribute the most to AP, EP and PCOP because of dust and pollutant gas emissions. When indicator contributions are considered, the observed impacts on AP (50.88%), GWP₁₀₀ (24.25%) and POCP (19.51%) are higher than those on EP, HTP and ADP. Therefore, when processes with environmental impacts are taken into account, the iron mining and dressing, iron ore sintering and BF iron-making processes must be considered, when category indicators are taken into account, AP, GWP₁₀₀ and POCP must be considered.

Keywords: VTM; LCA; Category indicator; Pollutant gas emissions

1. Introduction

China, South Africa, Russia and the USA are rich in VTM resources; in fact, the potential reserves of these countries respectively account for 36%, 31%, 18% and 10% of the world's total reserves. Compared with other iron ore resources, VTM has much higher comprehensive utilisation value because it can associate with many other valuable elements, such as iron, vanadium and titanium. VTM is mainly used in China to produce crude steel, vanadium pentoxide and ilmenite through the BF iron-making → BOF vanadium extraction → semi-steel smelting route ([Chen and Chu, 2014a, b](#)).

Since the 2000s, rapid increases in the comprehensive utilisation of VTM have been observed in China. For example, the yield of crude steel derived from VTM was as high as 18.53 million tonnes in 2013; this figure is 2.4 times the crude steel yield in 2004 (**Fig. 1**). Production of steel, which is an important raw material for national economic development, is associated with resources, energy and environment ([Bieda, 2012a](#); [Price et al., 2002](#); [Worrell et al., 2001](#)). Thus, comprehensive utilisation of VTM is a long process that requires environment impact assessment.

Fig. 1 Crude steel production from 2004 to 2013

1 LCA is an environmental assessment method used to evaluate the impacts a process may
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3 exert on the environment over the entire period of its life, from raw material extraction to its
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5 manufacturing, use and end-of-life processes ([Burchart-Korol, 2011](#)). An increasing number
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7 of researchers in many countries, such as Poland, Australia, Japan and the USA, amongst
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9 others, have focused on the steel industry and stressed the importance of LCA in
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11 environmental assessment. Burchart-Korol (2013) conducted a case study to define the major
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13 sources of environmental impacts and proposed pollution prevention methods for the steel
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15 industry of Poland ([Burchart-Korol, 2013](#)). Bieda (2012) presented LCI data from Arcelor
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17 Mittal and analysed the results of environmental impacts on iron-making and steel-making
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19 plants ([Bieda, 2012a, b](#)). In Australia, Norgate et al. used the LCA to estimate the
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21 environmental impacts of ferroalloy and metal (copper, nickel, aluminium, lead, zinc, steel,
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23 titanium) production processes ([Haque and Norgate, 2013](#); [Norgate et al., 2007](#)). To address
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25 climate change and the energy shortage, a several LCAs have discussed the energy and carbon
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27 emission reduction potential of steel industries around the world ([Iosif et al., 2008](#); [Tongpool](#)
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29 [et al., 2010](#); [Yang and Chen, 2014](#)). In China, however, no related studies on the use of a
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31 thorough life cycle method to assess the environment impacts of the comprehensive utilisation
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33 of VTM have been reported.
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47 In this paper, a cradle-to-gate life cycle study is conducted using averaged data from Pan.
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49 Steel, the world's largest comprehensive user of VTM (10 million tonnes per year). After
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51 defining the goal and scope of the study and performing LCI analysis and LCIA,
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53 environmental assessments of the process and cumulative environmental performance of Pan.
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55 Steel are carried out and compared in detail.
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2. Case Study

2.1. Introduction of the Pan. Steel process

In this study, Pan. Steel is chosen as the research object. The main process of mining and dressing, sintering, pelleting, BF iron-making, BOF vanadium extraction and semi-steel smelting consists of five steps. The raw materials are VTM, limestone, coal and coke.

After mining, VTM is transformed to produce VTM concentrate and ilmenite. The VTM concentrate obtained from mining and dressing is partly mixed with coal, coke and limestone to produce sinter ores, and the rest of the material is mixed with bentonite to produce pellet ores. Next, pig iron is manufactured in BF through combustion of sinter ores, pellet ores, lump ores and coke. Coal powder is also co-fired with the coke. After these processes, Pan. Steel employs a characteristic two-step pre-treatment process called preliminary desulphurisation and BOF vanadium extraction to obtain pig iron and vanadium-bearing slag with acceptable quality. This process requires three ladles with average capacity of 140 tonnes each, five desulphurisation setups and two vanadium extraction BOFs. The sulphur content of the pig iron after processing is less than 0.005%, and the recovery of vanadium is about 85%. Finally, crude steel is manufactured from the pig iron and vanadium pentoxide is manufactured from the vanadium-bearing slag.

2.2. Goal and scope of analysis

The LCA method follows the ISO 14040 standard and includes four stages: determination of the goal and scope, inputs and outputs inventory analysis, environmental impact assessment, and results interpretation with proposals for improvement ([ISO, 2006](#)).

The goals of this study are as follows:

1. Quantitatively describe the environmental loads and analyse and compare the environmental impacts of different indicators including GWP₁₀₀, ADP, EP, AP, POCP and HTP on steel production and valuable element extraction.

2. Illustrate the cumulative environmental performanc of the Pan. Steel process for comprehensive utilisation of VTM.

1-Raw materials, 2-Fuels, 3-Additives, 4-Electricity,

5-Dust and gas emissions, 6-By-products, 7-Co-products, 8-Wastewater

Fig. 2 System boundary and process flow diagram of the Pan. Steel process

The scope of this study includes the preparation of auxmary materials (i.e., lime production, coal washing and coke production) and steel manufacturing (i.e., ore mining and dressing, iron ore sintering and pelleting, BF iron-making and BOF steel-making) to valuable element extraction (i.e., ilmenite production and vanadium pentoxide production). The system boundary and process flow diagram are shown in **Fig. 2**. The functional unit ([Yu and Zhang](#)) of this study is one tonne of crude steel produced in steel plants.

2.3. LCI

The LCI for the main process is obtained from Pan. Steel in China and the time horizon is from 2005 to 2007. Data of other stages, such as quicklime production, coal washing and coke production are based on the literature and GaBi 6.0 software ([Ai et al., 2006](#); [Cai et al., 2012](#); [Hu et al., 2007](#); [Luo et al., 2008](#)). The data inventory used to assess environmental impacts and pollution prevention includes raw material consumption, energy consumption, by-products recycling and environmental discharge (i.e., atmosphere discharge and waste discharge) analysis results.

Table 1 Materials flow of the Pan. Steel process

Plants	Raw materials, additives, fuels /kg·FU ⁻¹	Electricity /kwh·FU ⁻¹	By-products, Products /kg·FU ⁻¹
Coke plant	Coal (867), COG (23.1), BFG (365)	20.5	COG (117.5), Coke (586)
Dress plant	Iron ores (4533), Steel (2)	74.0	Concentrate (1971), Tailing (2200)
Sinter plant	Coal (59.4), Common concentrate (279), VTMC (1241), Limestone (185.3), Quicklime (96), Coke (86.0), COG (6.3)	92.1	Siter ores (1718)
Pellet plant	VTMC (451), Bentonite (7)	13.7	Pellet ores (458)
Lime plant	Limestone (159.2), Coke (12.3)	0.2	Quicklime (95.5)
BF	Lump ore (114), Sinter ores (1718), Pellet ores (458), Coal (138), Coke (488) COG (3.3), BFG (1061),	21.2	Pig iron (1080), BF slag (702), BFG (2910)
BOF	Alloys (15), Fluorspar (6kg), pig iron (1080), Limestone (65.0), COG (0.16), BFG (2)	20.0	Vanadium-bearing slag (28), Crude steel (1000), Slag (120)
Ti extraction plant	Coal (15), Tailing (2200)	15.3	Ilmenite (89), Iron (25.8), Deposit (2114)
V extraction plant	Vanadium-bearing slag (28), COG (3.8), Ammonium sulfate (1.868), Salt (1.389), Sulfuric acid (1.653), BFG (17.9), Soda (3.569)	6.2	V ₂ O ₅ (2.395), Iron (2.874), Slag (25.44)

In this study, all of the raw materials and energy required to operate the process are considered in system boundaries, and a detailed LCI of the main input and output (materials and energy) flows required to produce one tonne of crude steel is presented in **Table 1**. As shown in **Fig. 2**, recycled fuels and materials (COG, BFG and iron-bearing materials) are also considered. Solid residues mainly include tailings, high titanium slag ($22\% \leq \text{TiO}_2 \leq 24\%$) and vanadium-bearing slag. The tailings and vanadium-bearing slag are used to produce ilmenite and vanadium pentoxide. Although many studies have reported the utilisation of high titanium slag ([Ai et al., 2006](#); [Bonsack and Schneider, 2001](#); [Han et al., 2012](#); [Sui et al., 2014](#)), no research applying this material in industrial production is yet available. Therefore, during LCA evaluation, the high titanium slag is discharged as solid waste alongside the Jinsha River.

Table 2 Environmental discharge inventory of the Pan. Steel process.

Plants	CO ₂ /kg·FU ⁻¹	SO ₂ /kg·FU ⁻¹	CO /kg·FU ⁻¹	NO _x /kg·FU ⁻¹	CH ₄ /kg·FU ⁻¹	NMVOC /kg·FU ⁻¹	Dust /kg·FU ⁻¹
Electricity generation	230.8	2.116	0.329	1.669	0.697	0.104	4.29
Coal production	131.4	0.471	0.267	1.214	3.821	0.111	0.50
Coke plant	246.8	1.249	0.176	0.217	-	-	0.38
Mining, Dressing	362.6	30.824	226.65	14.506	10.426		149.59
Limestone production	10.8	0.007	0.009	0.026	0.019	0.003	0.0024
Quicklime production	75.1	0.056	0.143	-	-	-	2.04
Sinter plant	389.1	16.461	53.48	6.112	-	-	45.64
BF	870.1	6.822	-	6.104	-	-	10.9
BOF	166.0	1.032	8.012	-	-	-	26.21
Ti extraction	39.5	0.165	-	-	-	-	5.34
V extraction	12.2	0.051	-	-	-	-	0.94

The data show that raw material with the highest consumption is iron ore (4533 kg/FU), followed by coal (1079.4 kg/FU) and limestone (409.5 kg/FU). As well, the electricity consumption is 263.2 kwh/FU.

The environmental discharge inventories for electricity generation ([Di et al., 2007](#)), coal production, coke production, limestone production, quicklime production, and main process are shown in **Table 2**. In this study, the atmospheric discharge, including dust discharge and gas emissions, is emphasized; these discharges mainly originate from burning of fuels, generation of electricity and physiochemical reactions, amongst others ([Huang et al., 2010](#); [Zhang et al., 2012](#)).

2.4. LCIA

LCIA of the Pan. Steel process is carried out using the GaBi 6.0 software ([GaBi Education, 2009](#); [GaBi software](#)) and the CML2001 (University of Leiden) database ([Guinée, 2002](#); [Guinée et al., 2001](#)).

Only six midpoint impact categories are taken into consideration in this analysis: depletion of abiotic resources, climate change, acidification, eutrophication, creation of photochemical ozone and human toxicity. The measured impact potentials of these six impacts are reasonably close to the corresponding real potentials. Differences can be attributed to several influences with subtractive or additive effects on the measured potentials. Freshwater and marine aquatic ecotoxicity are omitted from the LCIA indicators because of inherent uncertainties in fate-exposure-effect modelling of emissions that contribute to freshwater and marine pollution. The impact assessment method consists of three steps: characterisation, normalisation and weighting.

2.4.1. Characterisation

After classifying the results of impact assessment, characterisation and quantitative analysis are performed on the results given as equivalent values, e.g., GWP₁₀₀ is measured in CO₂-equivalents. The characterisation factor of CO₂ emission is 1, the characterisation factor of CH₄ emission is 25, and the characterisation factors of N₂O emissions is 298. The same procedure may be easily adopted to obtain the detailed characterisation factors of AP, EP, POCP, and HTP ([Guinée et al., 2001](#)). However, the characterisation factor of ADP cannot be obtained through this procedure because the resource availability and importance of this factor in China differ from those in other countries. Instead, the characterisation factor of ADP can be calculated based on data of resource reserves and extraction ratios from Chinese mining industry and its statistical characteristics ([Gao et al., 2009](#)).

Table 3 Characterisation of each impact categories

Impact categories	Unit	Major parameters
ADP	kg Sb eq	Iron ore, coal, oil, natural gas (Gao et al., 2009) limestone (Guinée et al., 2001)
GWP ₁₀₀	kg CO ₂ eq	CO ₂ = 1, CH ₄ =25, N ₂ O =298
AP	kg SO ₂ eq	SO ₂ = 1, NO _x = 0.7
EP	kg PO ₄ ³⁻ eq	NO _x = 0.13, N ₂ O = 0.27
POCP	kg Ethene eq	SO ₂ = 0.048, NO _x = 0.028, CO = 0.027, CH ₄ = 0.006, NMVOC = 0.364
HTP	kg DCB eq	SO ₂ = 0.096, NO _x = 1.2, Dust = 0.82, NMVOC = 0.0585

Tables 3 and **4** show the potential of each parameter in different impact categories and the characterisation results of the Pan. Steel process.

Table 4 Characterisation results of the Pan. Steel process

Plants	ADP /kg Sb eq	GWP ₁₀₀ /kg CO ₂ eq	AP /kg SO ₂ eq	EP /kg PO ₄ ³⁻ eq	POCP /kg Ethene eq	HTP /kg DCB eq
Total values	0.181	2845.83	121.05	3.11	3.11	366
Coking	0.00128	423	3.03	0.17	0.17	23.8
BF	3.85E-4	941.11	7.38	0.05	0.05	29
Mining, Dressing	0.07482	703.58	43.12	2.01	2.01	210.2
Sintering	1.14E-4	405.52	65.43	0.8	0.8	52.2
Quicklime	2.41E-5	79.44	0.14	0.02	0.02	2.1
BOF	0.104	186.23	1.12	0.01	0.01	28.1
V extraction	2.96E-4	26.57	0.13	0.01	0.01	4
Ti extraction	3.96E-5	67.18	0.51	0.03	0.03	16.2
Others	4.18E-5	13.2	0.19	0.01	0.01	0.4

2.4.2. Normalisation and weighting

The normalisation and weighting factors are calculated through the CML and analytical hierarchical process methods to perform accumulative environmental assessment. Communicating the results in an LCA becomes easier when a set of impacts is whittled down to a single number - after normalisation, weighting and aggregation. The normalisation factor of each impact category is calculated by using Equation 1:

$$N_i = \frac{C_i}{NF_i} \quad (1)$$

where N_i is the normalisation result per FU for impact category I, C_i is the characterisation result per FU for impact category I and NF_i is the normalisation factor for impact category I. In this study, the normalisation factors of GWP₁₀₀, AP, EP, POCP, and HTP are obtained from GaBi 6.0 software (CML2001, world) ([Guinée et al., 2001](#)) and the normalisation factor of ADP is based on Chinese resource conditions and the literature ([Gao et al., 2009](#)).

After normalisation, the weighting factors are calculated through an analytical hierarchical process, which is a matrix-based approach that measures impact priorities in a hierarchical structure to represent the relative importance of the total environmental impact. The relevant quantified judgment on the impacts is given by a 6×6 matrix (A).

$$A = \begin{matrix} & \begin{matrix} \text{GWP} \\ \text{EP} \\ \text{AP} \\ \text{POCP} \\ \text{HTP} \\ \text{ADP} \end{matrix} & \begin{bmatrix} 1 & 2 & 3 & 4 & 5 & 7 \\ \frac{1}{2} & 1 & 2 & 3 & 4 & 5 \\ \frac{1}{3} & \frac{1}{2} & 1 & 2 & 3 & 4 \\ \frac{1}{4} & \frac{1}{3} & \frac{1}{2} & 1 & 2 & 3 \\ \frac{1}{5} & \frac{1}{4} & \frac{1}{3} & \frac{1}{2} & 1 & 2 \\ \frac{1}{7} & \frac{1}{5} & \frac{1}{4} & \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix} \end{matrix}$$

The eigenvector, the largest eigenvalue and the consistency ratio are calculated using MATLAB software. The results show that the eigenvector is [0.3865, 0.2474, 0.1592, 0.1015, 0.0649, 0.0416], the largest eigenvalue is 6.1046, the consistency ratio is 0.0169. Therefore, the weight factors of GWP₁₀₀, EP, AP, POCP, HTP and ADP are 0.3865, 0.2474, 0.1592, 0.1015, 0.0649 and 0.0416, respectively.

Table 5 shows the normalisation and weighting factors used in this study. **Fig. 3** shows the normalisation and weighting results of the Pan. Steel process.

Table 5 Normalisation and weighting factors adopted for the LCA analyses

Impact classification	Equivalent unit	Normalisation factors	Weighting factors
ADP	kg (Sb) yr ⁻¹	2.14E+10	0.0416
GWP ₁₀₀	kg (CO ₂) yr ⁻¹	4.45E+13	0.3865
EP	kg (PO ₄ ³⁻) yr ⁻¹	1.29E+11	0.2474
AP	kg (SO ₂) yr ⁻¹	2.99E+11	0.1592
POCP	kg (C ₂ H ₄) yr ⁻¹	4.55E+10	0.1015
HTP	Kg (DCB) yr ⁻¹	4.98E+13	0.0649

Fig.3 Normalisation and weighting results of the Pan. Steel process

2.4.3. Sensitivity analysis

Sensitivity analysis investigates how much the output is changed by a small variation of a random input around a reference point. In this study, the ordering of significance of the six midpoint impact categories during weighting is obtained from GaBi software (CML2001, Dec. 07, Experts IKP(Europe)) and other references ([Gao et al., 2009](#)); thus, the orders may be considered reliable and objective. Thus, sensitivity analysis is conducted mainly to evaluate the weighting results through the use of a different judgement matrix A.

The results of sensitivity analysis are compared with the reference point and shown in

Fig. 4.

1-ADP, 2-GWP₁₀₀, 3-EP, 4-AP, 5-POCP, 6-HTP

Fig. 4 Sensitivity analysis using different judgement matrix A

The reference point obtained using reciprocal matrix A is [1, 2, 3, 4, 5, 7], and the weighting results are shown in **Fig. 3**. When judgement matrix A is changed, the weighting results fluctuate within a small range. Thus, the cumulative environmental performance of the AHP method for comprehensive utilisation of VTM is considered acceptable.

3. Results and discussion

3.1 process contribution

Fig. 5 Process contribution of each each category in the Pan. Steel process

Fig. 5 shows the process contribution of each category in the Pan. Steel process. Iron ore mining and dressing, iron ore sintering, coking and BF iron-making yield the highest contributions to environmental impacts. In the iron ore mining and dressing process, the largest environmental impacts on EP, POCP and HTP are determined using direct emissions of CO₂, SO₂ and dust (PM₁₀) during the mining process. A large amount of iron ore used increases contributions to ADP and the solid waste produced after mining occupies land.

In the sintering process, the impact on AP shows a maximum of 54.052%. Impacts on

POCP and EP also showed significant percentages of 33.115% and 25.723%. This phenomenon is attributed to emissions of SO₂ and NO_x from the sintering materials, including VTM concentrate, fuels and electricity.

The contribution of GWP₁₀₀ is the main consideration in the coke production and BF iron-making processes. In the coke production process, greenhouse gas mainly originates from two sources: direct emission from coke production and indirect emission from coal washing. In the BF iron-making process, the highest contribution to CO₂ emission is combustion of fuels including coke, COG and BFG, amongst others. A large amount of high titanium slag, at about 3 million tonnes per year, is produced and accumulated alongside Jinsha River. This process is not only wasteful but also exerts broad environmental impacts on both health and the ecology.

Therefore, when processes with environmental impacts are taken into account, the iron mining and dressing, iron ore sintering and BF iron-making process must be considered.

3.2 Environmental impact

The indicator contributions of the Pan. Steel process are shown in **Fig. 6**.

Characterisation, normalisation and weighting results reveal that the environmental impacts of AP (50.88%), GWP₁₀₀ (24.25%) and POCP (19.51%) are higher than those of EP, HTP and ADP. Therefore, when category indicators are taken into account, AP, GWP₁₀₀ and POCP must be considered.

The results of comprehensive analysis including process contributions and environmental impacts show that extensive effective measures must be taken to meet the requirements of energy savings and emission reduction. Several studies ([He et al., 2014](#);

[Mukherjee, 2011](#); [Nikiforov, 1993](#); [Yu and Zhang, 2007b](#)) have proposed a number of new methods to improve the beneficiation technology. As large contributions of AP, EP and POCP, the CO₂ and SO₂ emitted during the sintering process must be reduced and recycled ([Hartig and Reufer, 2011](#); [Hofstadler et al., 2001](#); [Keddeman and Oosterhuis, 1993](#); [Pak et al., 1998](#); [Wang et al., 2013](#); [Yu and Zhang, 2007a](#); [Zhang et al., 2009](#)). In addition, emissions of pollutant gases and consumption of fuels and electricity must also be reduced or a clean substitute must be found ([Price et al., 2002](#)).

Fig. 6 Indicator contributions of the Pan. Steel process

4. Conclusions

Steel production, specifically the iron-making process, is a highly energy-intensive industry. The application of environmental LCA allows steel producers to improve the manufacturing process by reducing environmental impacts. This paper discussed the environmental impact of iron and steel technologies and is the first study to perform an LCA of steel production and valuable element extraction using VTM. LCA was performed based on inventory data obtained from Pan. Steel. The environmental impacts of VTM utilisation were estimated using a cradle-to-factory gate boundary. Results show that production of pig

1 iron in BF_s exerts extensive impacts on GWP₁₀₀ and fossil fuel consumption, and that the iron
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3 ore mining dressing and sintering processes present the largest contributions of AP, EP and
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5 PCOP because of dust and gas emissions. When indicator contributions were considered, the
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7 impacts of AP (50.88%), GWP₁₀₀ (24.25%) and POCP (19.51%) were observed to be higher
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9 than those of EP, HTP and ADP. As such, when process environmental impacts are taken into
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11 account, the iron mining and dressing, iron ore sintering and BF iron-making processes must
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13 be considered, when category indicators are taken into account, AP, GWP₁₀₀ and POCP
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15 must be considered.
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