The Carbon Cost of Slag Production in the Blast Furnace: A Scientific Approach

Karl Buttiens¹ · Joel Leroy¹ · Patrick Negro¹ · Jean-Sébastien Thomas² · Kyle Edwards¹ · Yann De Lassat³

Published online: 5 February 2016
© The Minerals, Metals & Materials Society (TMS) 2016

Abstract The quality of raw materials (iron ore, coal, and coke) has a clear impact on the carbon emissions of the hot metal production in steel making. So far, very little work has been done to measure and quantify this impact. Yet for benchmarking, technology choice and general carbon optimization are important elements. The total slag production of a blast furnace gives an accurate and relevant measure of the raw materials quality and is the main variable on which plant operators have no control. To quantify the impact of a varying amount of slag produced together with hot metal, a method is developed based on a differential approach. For a number of different blast furnaces with different operating points and burden compositions, the carbon footprint or carbon cost of slag production is determined using this method and a robust value for the carbon cost of the slag is derived. This value can also be used in the comparison of the carbon cost of different steel making routes or in life cycle assessments for steel and slag applications.

Keywords Blast Furnace · Hot Metal · Benchmarking · Slag allocation · Carbon efficiency · CO₂ emissions · Granulated blast furnace slag · Life cycle analysis

Introduction

When comparing carbon efficiency of hot metal in a blast furnace, differences in quality and mix of raw materials complicate quantification of the carbon footprint. Lower quality raw materials contain more gangue in the ores and ash in the coal that the furnace must process and in the end, this translates into more blast furnace slag production. This obviously requires energy but no precise estimates could be cited when researching the carbon footprint penalty of lower quality raw material.

It is obvious that hot metal production with a higher slag burden will emit more CO₂ per ton of hot metal. Slag burden is a parameter that is often not under control of the process operator but is rather dictated by local availability of raw materials or sourcing strategies aimed at optimizing cost of hot metal production. In the past, these differences in slag burden were neglected also because the production practices are often regionally similar, leading to insignificant differences in slag burdens. For benchmarks on a larger scale, however, slag burdens can vary between 150 kg/t and 650 kg slag/t hot metal. These differences effectively distort comparison in term of fuel consumption and carbon footprint.

In the literature, no previous work was found in attempting to quantify the energy or carbon impact of slag, so we set out to develop our own method. We incorporated a large set of detailed process data on the 30 blast furnaces of the ArcelorMittal group and also on many more through professional exchanges. First attempts to find correlations

The contributing editor for this article was Bart Blanpain.

Jean-Sébastien Thomas—Deceased Dec 2014.

✉ Joel Leroy
joel.leroy@arcelormittal.com

Karl Buttiens
karl.buttiens@arcelormittal.com

Yann De Lassat
yann.delassat@hotmail.fr

¹ ArcelorMittal Group CTO, Luxembourg, Luxembourg

² ArcelorMittal Maizières Research, Maizières-lès-Metz, France

³ Iron Making Energy Consultant, Metz, France

between carbon consumption and slag burden failed, indicating that many other parameters are significant in the overall performance of a blast furnace. Also, attempts to calculate in a theoretical way the energy need to process slag were not satisfactory. Therefore, a more refined method based on monitored data had to be developed.

Materials and Methods

Method to Determine the Carbon Cost of Slag Production

To determine the part of CO₂ due to the slag production in the BF process route (carbon cost of slag), a differential reasoning can be developed. The difference in overall emissions of an increase of slag quantity while keeping the hot metal production exactly at the same level should give a reliable estimate of the CO₂ impact of the slag quantity. In order to assess the CO₂ due to the production of slag over the range of slag quantities regularly encountered, this differential calculation can be done for several installations with different operating points.

The idea is simple but may be a bit complicated to bring into practice because the slag quantity in the blast furnace has an impact on the overall functioning of the blast furnace process. If the carbon demand of the blast furnace changes, so will be the amount of waste gases produced. Since the carbon in this waste gas is not fully consumed, it is necessary to determine exactly what changes to the blast furnace gases will happen while the hot metal production is being kept constant. It is common practice in carbon accounting for the steel industry to substitute steel waste gases for natural gas when it leaves the shop limits because it hugely simplifies the accounting of waste gases in other activities than the ones where the gases were generated. So a credit for an equivalent quantity of natural gas corresponding to the change in blast furnace gas can be attributed to the process. In LCA terms this can be viewed as “system expansion.”

Next to the changes in the blast furnace itself there is also a need to look at some upstream emissions. To maintain a blast furnace operating well, the chemical composition of the slag needs to meet certain chemical requirements, primarily the basicity of the slag. This determines the capacity of the slag to remove unwanted elements such as sulfur out of the hot metal. It also impacts the melting point of the slag. The gangue of iron ores and the slag are in general acid (higher Si-content), so it is necessary to add limestone or dolomite to adjust this slag chemistry. These fluxes also end up in the slag and are proportional to the slag burden attributed to the raw materials. In general, the emissions related to these fluxes

are found in the sinter plant upstream of the blast furnace but there are other possibilities depending on the hot metal production route as previously discussed. In any case, these fluxes will create CO₂ emissions too which are part of the generation of the slag and caused by the chemistry of the gangue material.

The two aforementioned aspects are considered to be the predominant aspects of the CO₂ emission due to a marginal increase in the quantity of slag. This is an assumption that was tested by the methodology described below. It is expected that other aspects contribute to the carbon footprint, such as total quantity of the gangue, sulfur or phosphorous content, and initial acidity of the gangue; however, it is expected their influence is less significant. The main question to answer is if there exists a single value or a simple relation which can take into account the total slag burden, within a sufficient broad range, and which can predict with an acceptable precision ($\pm 10\%$) the carbon cost of slag in the BF route.

The operation of the blast furnace is modeled using the mathematical model of the blast furnace (MMBF).

The Mathematical Model of the Blast Furnace (MMBF)

The mathematical model of the blast furnace (MMBF) is the standard model used for the ArcelorMittal blast furnaces [1].

The model development started in the middle of the 50's, thanks to the contribution of J. Michard [2], who proposed to divide the blast furnace in two parts which would act as two independent reactors (Fig. 1). This principle was based on vertical probing analysis performed by the former IRSID¹ in operating blast furnaces and was confirmed by the dissection of Japanese and Russian blast furnaces after shut down for relining. After a first mathematical analysis in a graphical form done by André Rist [3], a computer software was released.

The basic principle of the model is the existence in the blast furnace of a thermal reserve zone in which gas and solids have the same temperature fixed by the reactivity of coke in the solution loss reaction. When the quality of iron burden is good, this thermal reserve zone includes a chemical reserve zone in which gas and solids reach a chemical equilibrium ($\text{FeO} + \text{CO} = \text{Fe} + \text{CO}_2$).

Due to these simultaneous equilibriums, the lower part (processing zone) of the furnace sets the important operating parameters (fuel and blast rates) and the upper part recovers the available heat and reducing potential of gas to pre-process the burden.

¹ Institut de la Recherche SIDERurgique, former Name of the ArcelorMittal Global R&D organisation, Maizières-lès-Metz, France.

Fig. 1 Principle of the blast furnace model, from [4]. ① refers to solids temperature; ② refers to gas temperature; ③ refers to iron oxidation index; ω is the gap to ideality for reduction process; solids go down and gases go up

The algorithm adopted in the model is based on the determination of a linear system, which links different types of operational data (see Annex 4).

Fundamentally, the model is a mass and energy balance that ensures the fundamental equilibria of the different chemical reactions and heat transfers in the blast furnace. Given its longevity and widespread use, the blast furnace model has proven to be a capable tool to model the most diverse operating points and successfully predicts that the different output parameters of the BF products give a set of input data. The detailed description of the model is given in Annex 4.

Data and Calculations

For the purpose of analyzing the impact of differential slag burdens, five different existing blast furnaces were considered. Data used are from the year 2012 and come from the European Blast Furnace Committee data exchange and from our internal blast furnaces data collection. Additionally, a theoretical operation was added corresponding to the reference blast furnace used in the ULCOS² project [5, 6] to measure the carbon efficiency of the different break-through technologies studied during this research program. For one blast furnace, an extreme operating condition was added with exceptionally high slag production rate (Table 1). The data had to be checked for consistency with the MMBF model and some minor adjustments were required to guarantee the thermodynamic equilibrium of the process.

In order to determine the slag effect, two operating points are considered for every blast furnace: the first one is

the reference situation with normal operation using the reported slag volume and the second one is calculated one with 50 kg slag/ton Hot Metal more. Since all equations (related to slag) are linear this amount itself is not very important but it needs to be high enough to remain unaffected by the noise of calculation precision.

The increased slag weight is modeled by varying the quality of the minerals used in sinter while the iron entries in the blast furnace remain the same. Also, the consumption ratios of pellets and lump do not change. Calculations were made at a constant flame temperature.

There are three steps in the calculation:

- (1) Blast furnace balance using MMBF to calculate coke consumption. MMBF calculates coke rate at a given coal rate (or the opposite, depending on the fixed conditions).
- (2) Calculation of stove fuel consumption using a simplified stove model. By difference with the first step, this permits to calculate the CO₂ BF credit due to net BF gas export.
- (3) Upstream requirements for coke production and limestone impact are considered. In this paper, adjustments to the carbon input are only via coke, since injected fuels can vary in carbon content (oil, coal, natural gas).

With these three calculations, a global balance of an iron making plant including coke making and sintering was performed to account for cross effects of BF operation on upstream processes. Figure 2 presents the model of such a plant and identifies inputs and outputs used for assessment of slag effect.

The boundary of the model considered includes operations needed for the operation of the blast furnace, i.e., coke plant to transform coal into coke, sinter plant to

² ULCOS stands for Ultra-Low Carbon dioxide (CO₂) Steelmaking; see: http://www.ulcos.org/en/about_ulcos/home.php.

Table 1 Burden composition and fuel rate

Burden in kg per tonne of hot metal	ULCOS (reference)	BFA	BF B	BF C	BF D-1	BF D-2	BF E
Bell sinter	1000	1167	1093	548	1329	1329	1668
Lump ore	150	58	254	8	27	27	14
Pellets	430	392	266	970	441	441	0
Slag volume	260	292	297	213	650	525	391
Coke rate	283	297	334	283	602	573	488
Coal rate	197	183	162	221	31	43	42
T° blast (°C)	1200	1149	1121	1256	969	969	1054
C in hot metal (%)	4.74	4.90	4.80	4.57	4.45	4.29	4.20

Fig. 2 Model of iron making plant for slag effect assessment

prepare iron ores for blast furnace, coal grinding for direct injection into the blast furnace, blowers and stoves to generate hot wind for the blast furnace and the blast furnace itself. Inputs are indicated on the left and output on the right. Outputs from the blast furnace are blast furnace gas, hot metal and gas. Coke gas is also considered to account for the quantity of coke used. Blast furnace gas is used at the stoves and also at the coke plant; coke gas is used at the coke plant and at the sinter plant. Remaining gases are exported to other shops in the plant (or to external power plant). Power consumption and generation are not indicated in the graph.

To produce a BF slag with a sufficiently low viscosity and that is efficient in purifying the liquid hot metal at an optimal temperature, the chemistry of the slag needs to be managed very strictly. Considering main iron ores used in steel industry, a CaO content of about 40 % in weight needs to be aimed for. To achieve this, limestone must be added to the sinter causing an upstream CO₂ emission due to the decarbonation of 315 kg CO₂/t slag; one tonne of CaO produced releases 786 kg CO₂ because there is one mole of CO₂ by mole of CaO (ratio of molar weight):

$$[44/56(\text{CO}_2/\text{CaO}) = > 786 \text{ kg CO}_2/\text{t CaO}]$$

And 40 % of CaO is needed to get the right slag chemistry:

$$786 \times 40 \% = 315 \text{ kg CO}_2/\text{t slag}$$

Replacing part of limestone by dolomite will marginally increase these CO₂ emissions.

The blast furnace model predicts an additional emission of 235 kg CO₂/t slag which in total gives 550 kg CO₂/t slag (see Table in Annex 3).

The CO₂ impact of the slag results from the difference between the reference operation and the newly calculated operation using a different slag volume. The carbon cost of slag is equal to the ratio of the CO₂ balance change and the slag volume change.

Results and Discussion

The calculations were carried out for the five considered blast furnaces, the ULCOS Model and one operation with very high slag burden. The summary of the results is shown in Table 2.

Table 2 Equivalent CO₂ for the production of slag

	ULCOS	BFA	BF B	BF C	BF D-1	BF D-2	BF E
Equivalent CO ₂ for the production of slag (kg CO ₂ /t slag)	540	529	555	551	560	580	532

Fig. 3 CO₂ effect of slag rate

The results of the calculations show a remarkable constant value for the CO₂ cost of treating gangue through the Blast Furnace route independently of the quantity or nature of the slag as well as the operating practices.

Since the blast furnace model is based on a set of linear equations, we expected that for every blast furnace and every working point the impact of a charge of slag impact can be represented by a constant. What is remarkable is that this constant is very similar for all the cases considered with very different operating practices and raw materials quality.

Figure 3 (from Table 2) presents the relation between slag rate and slag rate effect. Slag rate effect seems to be quite constant with an average value of 550 kg CO₂/t slag (Std dev = 18 kg CO₂/t slag, i.e., ± 3 %).

This confirms the hypothesis that the melting of the slag and the basicity correction are the most important energy-related aspects of the processing of slag and are significantly more important than all other aspects like sulfur or phosphorous content, initial acidity, and overall blast furnace performance, which could also have an impact on the CO₂ cost of the slag treatment.

Importance of Assessment of the Carbon Cost of Slag

The identification of this constant which can take the carbon cost of slag into account with sufficient precision allows to benchmark the efficiency of blast furnaces. This constant can be applied in the formulas proposed in the draft CEN standard for greenhouse gas (GHG) emissions in

energy intensive industries (part 2: iron and steel industry) [7].

On top on the importance for process benchmarking, there are three other areas where this assessment of the carbon cost of slag burden could be relevant:

Evaluation of Different Steelmaking Routes

When comparing different steel making routes in terms of carbon footprint (pellet—blast Furnace—basic oxygen furnace; sinter-blast furnace-basic oxygen furnace; pellet-direct reduced iron-electric arc furnace), it is essential to define the system boundaries in a precise way. The total balance of the produced products and by-products (steel, waste gases, and granulated slag) should also be compared. Many studies tend to omit upstream production steps for one or more product streams leading to erroneous answers when carbon footprint of the different routes is compared. This can easily be corrected but also the impact of the by-products needs to be made comparable. Slag produced by direct reduced iron in an electric arc furnace is not comparable to blast furnace slag because it has no latent hydraulic properties. Hence, we need to compare a production route which produces stones as by-product with a production route that produces a cement substitute. To compare carbon footprint of steel produced by both production routes, the blast furnace route should receive a credit which corresponds to the additional value of its by-product.

Moreover, the evaluation of slag valorization methodologies, where with an additional production step electric arc furnace slag is turned into an hydraulic slag, is only possible if there is a criterion to determine the additional value of treated slag such as in the Zero Waste technology for GGBFS [8] (Ground Granulated Blast Furnace Slag).

Evaluation Supply Chain from Extraction to Steel

An important aspect is to know how important the quality of raw materials is in the supply chain up to hot metal. In general, there is a choice between (i) concentrating ores (at the expense of additional energy), by removing as much gangue from the ores as possible (giving rise to tailing ponds which create vast waste lands), while producing concentrated ore pellets and (ii) taking the iron ores and

Fig. 4 Route comparison for low and high slag rate at BF

feed them directly into sinter plants where all the fluxes to create an ideal slag chemistry can be added.

Figure 4 gives a synthetic view of these two approaches. The left side of the figure presents the route where beneficiated iron ore is produced along with tailings; this route leads to a processed iron ore pellet with low gangue. A high rate of pellets in the blast furnace generates a relatively low slag volume that is illustrated in the central graph by the zone “with” (beneficiation). The right part of the figure presents the route where iron ore is used as it is processed in a sinter plant. Sinter has a higher gangue level than pellets and leads to higher slag volume that is illustrated in central graph by the zone “without beneficiation” with higher slag volume.

Unlike the slag of other steel making processes (electric arc furnace, basic oxygen furnace), the blast furnace slag has the right chemistry to become a cement clinker substitute [9] when quenched and ground afterwards and is known as GGBFS. In order for society to decide on the desirability of making granulated slag, the question should be answered whether the CO₂ cost of the production of granulated slag is higher or lower than the production of the cement product it can substitute [10]. If it is lower, there should be no reason to discourage the production of slag. If however more CO₂ is required than for clinker, the pressure to decrease the slag volume produced should be proportional to the additional CO₂ requirement.

Slag Life Cycle Analysis

Another problem that can be dealt with using this carbon cost value is the accounting of GGBFS in Life cycle analysis (LCA). A commonly used method is the system

expansion method where a by-product is attributed an equal impact as the product it replaces and which is used as a credit for the main product of the process [11, 12]. System expansion has disadvantages in that the value depends on an exogenous element and is ultimately linked to the evolution of technologies that have nothing to do with the own activities. Furthermore it allows hot metal production to be credited by non-existing CO₂. The ISO 14,044 standard therefore prefers a direct allocation to sub-processes. The CO₂ value for granulated slag as derived above allows dividing the hot metal production into two sub-processes, one for hot metal and one for slag.

Conclusions

The present analysis shows that the carbon footprint or carbon cost of slag on the Blast Furnace process can be estimated rather precisely by a single value of about 550 kg CO₂/t slag. This value has proven to be rather robust within a wide range of slag burden independent of the nature of the raw materials (sinter, pellets, lump ore) used in the Blast Furnace. By crediting the Blast Furnace process for the production of slag using this value and for the Blast Furnace gas produced using a natural gas equivalent, the inherent efficiency of the hot metal production of every blast furnace operator can be measured and compared. It also allows studying the optimal burden composition—pellets, sinter, lump ore—to have the lowest possible CO₂ emissions. Moreover, it enables to benchmark the blast furnace route with other steelmaking technologies that do not produce valuable by-products that replace valuable products with high CO₂ footprint (cement in this case).

This value finally gives the carbon footprint impact of producing a ton of slag which if it is turned into GGBFS is much lower than the benchmark value of 766 kg CO₂/t clinker for gray cement clinker [13]. This means that the generation of more GGBFS as such is desirable as its production does not cause more emissions than the product it could substitute.

Annexes

Annex 1—Calculations

- MMBF gives fuels balance (calculation of coke or coal rate for energy requirement) with blast furnace gas (BFG) generation.

- A part of BFG is used for blast heating. The rest is exported at natural gas equivalence (MJ exported gas = 0.056 kg CO₂).
- Upstream in CO₂ equivalence is calculated for.
- Coke consumption (simplified CO₂ balance at coke plant).
- Lime needed for slag formation.
- Fuel for sintering.
- Pellet production.
- Electricity consumption.

Annex 2

See Table 3.

Table 3 Main hypothesis for calculations

Gas requirements	
Coke plant heating	4 GJ/t coke
Stove consumption	Stove requirement for hot blast with 85 % efficiency heating
BF gas coal drying	0.32 GJ/t coal
Electricity requirements	
Electricity requirements for Coke plant	50 kWh/t coke
Electricity requirements for Blast compression	0.065 kWh/m ³ N air
Electricity requirements for Oxygen production	0.55 kWh/m ³ N O ₂
Electricity requirements for Coal preparation	30 kWh/t coal
Sinter fuels	
Sinter fuels: coke breeze	Coke breeze = 10 % of total coke production (i.e., BF coke/0.9)
Sinter fuels: anthracite	55 kg/t sinter—coke breeze
Eq CO ₂ inputs Iron making	
Coking coal	1.42 t coal/t coke at 80.5 % C
Tar production	35 kg/t total coke production at 93 % C
Anthracite	80 % C
Injection coal	80.6 % C
Pellets	115 kg CO ₂ /t (upstream)
Limestone	40 % slag volume × 44/56
Electricity	total electricity at 580 kg/MWh

Table 4 Data and calculation results

	Unit	ULCOS	ULCOS + 50 kg slag	BFA	BFA – 50 kg slag	BF B	BF B +50 kg slag	BF C	BF C +50 kg slag	BF D-1	BF D-1 +50 kg slag	BF D-2	BF D-2 +50 kg slag	BF E	BF E +50 kg slag
Omega	atO/atFe	0.005	0.005	–0.014	–0.014	0.044	0.044	0.047	0.047	0.230	0.230	0.260	0.260	0.052	0.052
Bell sinter	kg/t HM	1000	1000	1167	1167	1093	1093	548	548	1329	1329	1329	1329	1668	1668
Lump ore	kg/t HM	150	150	58	58	254	254	8	8	27	27	27	27	14	14
Pellets	kg/t HM	430	430	392	392	266	266	970	970	441	441	441	441	–	–
Slag volume	kg/t HM	260	310	292	242	297	347	213	263	650	700	525	575	391	441
T blast	°C	1200	1200	1149	1149	1121	1121	1256	1256	969	969	969	969	1054	1054
Blast moisture	g/m ³ N	15.0	15.0	18.7	18.7	14.7	14.7	15.8	15.8	12.0	12.0	53.4	53.4	14.4	14.4
Si HM	%	0.35	0.35	0.35	0.37	0.35	0.35	0.35	0.35	0.90	0.90	0.30	0.30	0.61	0.61
P HM	%	0.08	0.08	0.08	0.06	0.08	0.08	0.08	0.08	0.80	0.80	0.65	0.65	0.10	0.10
Hot metal	°C	1500	1500	1493	1493	1500	1500	1497	1497	1480	1480	1480	1480	1492	1492
temperature															
Coke rate	kg/t HM	282.6	286.0	296.7	293.3	333.7	337.4	282.7	286.2	602.0	606.0	573.0	576.9	488.4	491.6
Coal rate	kg/t HM	197.0	197.0	182.9	182.9	162.4	162.4	220.7	220.7	31.0	31.0	42.8	42.8	41.8	41.8
Air rate (dry)	m ³ N/t HM	867.4	889.9	908.5	890.9	935.7	956.7	664.9	674.1	1240.6	1259.1	1032.0	1079.7	1064.9	1258.2
Oxygen rate	m ³ N/t HM	51.1	49.7	46.6	46.9	45.1	44.2	109.1	110.6	82.0	82.0	76.0	69.8	81.5	37.4
Hot blast sensible heat	MJ/HM	1592	1628	1585	1556	1574	1607	1415	1435	1799	1824	1594	1654	1719	1940
Cold blast sensible heat	MJ/HM	157	161	165	162	169	173	120	122	223	226	196	205	192	227
Stove requirements	MJ/HM	1435	1468	1420	1395	1406	1434	1295	1313	1576	1598	1397	1448	1527	1713
Iron input	kg/t HM	954	954	972	972	970	970	939	939	1079	1079	1079	1079	993	993
YzeroP		1.469	1.469	1.465	1.465	1.467	1.467	1.483	1.483	1.464	1.464	1.464	1.464	1.450	1.450
C in hot metal	%	4.738	4.738	4.900	4.888	4.800	4.800	4.570	4.570	4.450	4.450	4.290	4.450	4.200	4.200
Gas generation															
CO gas	MJ/t HM	2543	2574	2670	2639	3003	3036	2544	2575	5418	5454	5157	5192	4395	4425
CO gas eq CO ₂	kg/t HM	117	118	123	121	138	140	117	118	249	251	237	239	202	204
BF raw gas	m ³ N/t HM	1506	1530	1530	1510	1580	1604	1426	1440	2037	2059	1834	1878	1779	1935
BF dry gas	m ³ N/t HM	1424	1448	1439	1419	1501	1521	1306	1320	1956	1977	1754	1798	1698	1840
BF gas ncv	kJ/m ³ N	3389	3370	3267	3273	3383	3373	4255	4246	4050	4036	4507	4428	3620	3391
BF gas energy	MJ/t HM	4827	4880	4701	4644	5078	5129	5558	5604	7922	7981	7905	7960	6145	6238
CO	%	23.11	23.01	22.86	22.88	23.72	23.67	28.23	28.16	29.71	29.62	32.99	32.43	24.65	23.62
CO ₂	%	23.81	23.53	23.49	23.73	22.81	22.64	24.73	24.66	17.29	17.20	17.15	16.83	20.41	18.25
BF gas eq CO ₂	kg/t HM	1312	1323	1310	1299	1372	1383	1358	1369	1805	1818	1727	1739	1502	1512
Gas requirements															
Coke plant heating	MJ/t HM	1130	1144	1187	1173	1335	1349	1131	1145	2408	2424	2292	2308	1953	1967

Table 4 continued

Unit	ULCOS	ULCOS + 50 kg slag	BFA	BFA – 50 kg slag	BF B	BF B +50 kg slag	BF C	BF C +50 kg slag	BF D-1	BF D-1 +50 kg slag	BF	BF D-2 +50 kg slag	BF E	BF E +50 kg slag
Stove consumption	MJ/t HM	1688	1671	1641	1654	1687	1523	1545	1854	1880	1644	1704	1796	2016
BF gas coal drying	MJ/t HM	63	59	59	52	52	71	71	10	10	14	14	13	13
Electricity requirements														
Coke plant	kWh/t HM	14.1	14.8	14.7	16.7	16.9	14.1	14.3	30.1	30.3	28.6	28.8	24.4	24.6
Blast compression	kWh/t HM	56.4	59.1	57.9	60.8	62.2	43.2	43.8	80.6	81.8	67.1	70.2	69.2	81.8
Oxygen production	kWh/t HM	28.1	25.7	25.8	24.8	24.3	60.0	60.8	45.1	45.1	41.8	38.4	44.8	20.6
Coal preparation	kWh/t HM	5.9	5.5	5.5	4.9	4.9	6.6	6.6	0.9	0.9	1.3	1.3	1.3	1.3
Total	kWh/t HM	90.4	90.2	89.2	90.5	91.4	109.8	111.3	126.7	127.9	110.1	109.8	115.3	103.6
Gas exports														
Total export	MJ/t HM	4488	4455	4411	5041	5077	5377	5420	9068	9121	9112	9127	6778	6667
Sinter fuels														
Coke breeze	kg/t HM	31	38	38	41	41	17	17	89	89	85	85	91	91
Anthracite	kg/t HM	24	17	17	14	14	38	38	–34	–34	–30	–30	–36	–36
Eq CO ₂ inputs iron making														
Coking coal	kg/t HM	1184	1243	1228	1398	1413	1184	1199	2521	2538	2400	2416	2046	2059
Tar production	kg/t HM	–37	–39	–39	–44	–44	–37	–38	–79	–80	–76	–76	–64	–65
Injection coal	kg/t HM	575	534	534	474	474	644	644	90	90	125	125	122	122
Anthracite (for Sinter)	kg/t HM	69	48	50	42	41	111	110	–99	–101	–87	–89	–104	–106
Limestone (from sinter)	kg/t HM	82	92	76	93	109	67	83	204	220	165	181	123	139
Pellets	kg/t HM	49	45	45	31	31	112	112	51	51	51	51	0	0
Electricity	kg/t HM	52	52	52	52	53	64	65	73	74	64	64	67	60
Total	kg/t HM	1974	1975	1946	2047	2076	2144	2174	2762	2793	2642	2672	2189	2209
Total gas export	MJ/t HM	4488	4455	4411	5041	5077	5377	5420	9068	9121	9112	9127	6778	6667
Equivalent CO ₂ input	kg/t HM	1974	1975	1946	2047	2076	2144	2174	2762	2793	2642	2672	2189	2209
Export gas credit	kg/t HM	251	249	247	282	284	301	304	508	511	510	511	380	373
Net CO ₂	kg/t HM	1723	1725	1699	1764	1792	1842	1870	2254	2282	2132	2161	1809	1836
Margin effect	kg/t HM	0	0	–26	0	28	0	28	0	28	0	29	0	27
Margin effect	kg/t Slag	540	529	529	555	555	551	551	560	560	580	580	532	532

Annex 3

See Table 4.

Annex 4—Description of the Mathematical Model of Blast Furnace (MMBF)

Description of BF Operation

The blast furnace is a continuous reactor operating at steady state. It allows counter current flows of condensed phases (solids and liquids) and gases which exchange mass and energy. The analysis of these heat and oxygen transfers lead to define three zones which are schematized on Fig. 1:

- An upper zone of intense heat exchange, where cold charge solids (coke and mineral burden) are quickly heated to a temperature of 950 °C. As soon as the temperature reached 450 °C, the reduction of higher iron oxides (hematite and magnetite) starts.
- An intermediate isothermal zone at a temperature of 950 °C covering most of the stack and in which the reduction of iron oxides progresses to the level of wüstite ($\text{Fe}_{0.947}\text{O}$) without noticeable heat transfer. Gas and solids have the same temperature in this “Thermal reserve zone” and, if burden reducibility is sufficient, a “Chemical reserve zone” can develop. This chemical reserve zone is due to a pause of oxygen exchange due to a chemical equilibrium between gases, wüstite and metallic iron nuclei.
- A lower zone of intense heat exchange, where iron oxides coming from the thermal reserve zone are reduced to metal before melting. Pig iron and slag reach their final temperature (1500 °C) while alloy elements (Si, P, Mn) are reduced parallel to carburization of pig iron and slag/pig iron reactions.

The existence of the thermal reserve zone is due to the specific behavior of coke which reacts with the upcoming gas to regenerate its reduction potential through the so called “Solution loss reaction”: $\text{CO}_2 + \text{C} \rightarrow 2\text{CO}$. This reaction is highly endothermic and requires high temperature to evolve with a significant kinetics. The thermal reserve zone is at the temperature when this reaction starts. Metallurgical cokes react above 950 °C but lower temperature (750–800 °C) can be observed in charcoal blast furnaces due to higher reactivity of this material.

The existence of a zone where heat and mass transfers stop is the basis of the blast furnace model which considers a boundary in the lower part of the thermal reserve zone separating the preparation and processing zones which are described below.

Preparation Zone

The preparation zone, in the upper part of the furnace, is characterized by the absence of consumption or formation of carbon by the solution loss reaction or by carbon deposition. Forgetting the gas coming from burden decomposition, the volume of reducing gases ($\text{CO} + \text{CO}_2$ and $\text{H}_2 + \text{H}_2\text{O}$) remain constant all over this zone and there is a simple oxidation of CO to CO_2 and H_2 to H_2O resulting from reduction of higher iron oxides when the gas flows to the top.

The boundary between the preparation and processing zones is defined by the following boundary conditions:

- Identical temperatures of gas and solids at the level of thermal reserve zone;
- Gas composition with an oxidation degree corresponding to the wüstite-iron equilibrium. At 950 °C, this composition is such as

$$\text{XW}_{\text{CO}} = \frac{\text{CO}_2}{\text{CO} + \text{CO}_2} = 0.298$$

$$\text{XW}_{\text{H}_2} = \frac{\text{H}_2\text{O}}{\text{H}_2 + \text{H}_2\text{O}} = 0.382$$

When the reducibility of the burden is sufficient, iron can leave the preparation zone as pure wüstite in equilibrium with the gas and a chemical reserve zone is included in the thermal reserve zone. Usually, the reduction of higher oxide is not fast enough to reach these ideal conditions and when the gas reaches this “equilibrium composition,” the mineral burden still contains some residual magnetite which can be estimated by means of the “Deviation from ideality (Omega)” which measures an excess oxidation of iron as compared to wüstite.

In the preparation zone also occur some reactions with the burden components:

- Evaporation of moisture of coke and mineral burden;
- Decomposition of iron hydrates;
- Decomposition of iron and calcium carbonates.

Finally, the preparation zone can be considered as recovering heat and chemical potential of the gas delivered by the processing zone. The main heat effect is heating of the burden by transfer of sensible heat from upcoming gas. The only limit is that sensible heat exceeds the requirements to keep drying potential through sufficient top gas temperature.

Processing Zone

The lower part of the blast furnace is also a heat and mass exchanger. It receives the prepared materials and processes

the liquid products of the metallurgical operation, pig iron, and slag. In this zone, the gasification of coke and injected reducing agents in the nozzle raceway delivers a gas composed of CO, H₂, and N₂ at a temperature of over 2000 °C and this gas ensures the heat requirements for heating, melting, and final processing of liquids. Due to its reducing potential, it also allows oxygen transfer from solid or liquid oxides.

Looking at the solids leaving the preparation zone, the metallurgical path is as follows:

- Final reduction of iron oxides and heating of solids to melting temperature accompanied by regeneration of reducing gas through the solution loss reaction;
- Melting of the solids in a zone located above the level of nozzles;
- Drainage of liquids to the hearth through a coke bed (the dead man) and final heating to tapping temperature;
- Separation of liquid phases in the hearth and achievement of metal/slag reactions.

Parallel to these four steps, some side reactions occur:

- End of decomposition of calcium carbonate;
- Decomposition of phosphates of the mineral burden.
- Reduction by carbon and dissolution of alloying elements (Si, Mn, P);
- Desulfurization of pig iron by slag/metal reaction with formation of CaS;
- Formation of slag by dissolution of gang material and formation of calcium silicates.

While the gas reduction reactions have very limited heat effect, the regeneration and carbon reduction reactions require a large amount of heat ahead of heating and melting requirements and the heat and mass balance of the processing zone set the operation conditions of the blast furnace.

Mathematical Modeling

The MMBF is mainly a heat and mass balance model which transcribes the assumptions of the metallurgical model. This results in an algebraic model allowing the computation of operating parameters under the following conditions:

- Equilibrium of heat and mass balances of the blast furnace, processing, and preparation zones;
- Achievement of boundary conditions of the processing zone, identical temperatures of gas and solids at the

boundary between zones, gas composition at wüstite-iron-gas equilibrium and iron burden with an oxidation degree equal to $1.056 + \Omega$;

- Achievement of various constraints determined by the operator ahead of those resulting from the above-mentioned ones.

All this results in a set of linear equations solved to give the characteristics of an operating point.

References

1. Burtiaux M, Haut Fourneau, Exploitation, 2.2 Modèle mathématique de l'IRSID: le MMHF, Techniques de l'Ingénieur, M 7 411
2. Michard J (1959) Etude du Haut Fourneau, Cahier II: Cessid
3. Rist A, Meysson N (1964) Recherche graphique de la mise on mille minimale du haut fourneau a faible temperature du vent. Rev de Metall 2:121–145
4. Burtiaux M, Haut Fourneau, Théorie, Techniques de l'Ingénieur, M 7 400
5. Birat JP, Lorrain JP, de Lassat Y (2009) The “CO₂ tool”: CO₂ emissions and energy consumption of existing and breakthrough steelmaking routes. La Rev Metall-CIT 106:325–336
6. Birat JP (2009) Steel and CO₂: the ULCOS Program, CCS and mineral carbonation using steelmaking slag. In: 1st International Slag Valorisation Symposium, Leuven, Belgium, pp. 15–26, 6–7 April
7. European Committee for Standardization, Second Interim Report Mandate (CEN TC264 WG33). https://www.vdi.de/fileadmin/vdi_de/redakteur_dateien/krdl_dateien/2nd_Interim_Report_Man date_M_478.pdf
8. Fleischanderl A, Gennari U, Gebert W, Borlee J, Sorrentino F, Gimenez M (2004) Zero waste steel works: valuable products from by-products, Waste processing and recycling in mineral and metallurgical industries. CIM, Montreal, Canada
9. Cement Technology Roadmap 2009: Carbon emissions reductions up to 2050. International Energy Agency, Paris. <https://www.iea.org/publications/freepublications/publication/Cement.pdf>
10. Birat JP, Delbecq JM, Hess E, Huin D (2002) Slag, steel and greenhouse gases, La revue de Métallurgie-CIT, Janvier, pp 13–21
11. Worldsteel LCA forum, Methodology report Life cycle inventory study for steel products, World Steel Association (worldsteel), extranet worldsteel.org (2011). Brussels, Belgium
12. Environment Management (2006) Life cycle assessment, requirements and guidelines, EN ISO 14040. International Organization for Standardization, Geneva, Switzerland
13. Commission Decision of 27 April 2011 determining transitional Union-wide rules for the harmonized free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC. Official J European Union L130, May 2011, pp. 1–45. <http://faolex.fao.org/docs/pdf/eur102977.pdf>