metals

Article

Contribution of CO_2 Emissions from Basic Oxygen Steelmaking Process

Nirmal Madhavan *, Geoffrey Brooks, M. Akbar Rhamdhani and Adam Bordignon

Fluid and Process Dynamics (FPD) Group, Department of Mechanical and Product Design Engineering, Swinburne University of Technology, Hawthorn, VIC 3122, Australia; gbrooks@swin.edu.au (G.B.); arhamdhani@swin.edu.au (M.A.R.); adam-343@hotmail.com (A.B.)
* Correspondence: nmadhavanpillaisajee@swin.edu.au

Abstract: The steelmaking process is an energy-intensive multi-stage process, and the step involving the conversion of molten iron to steel, commonly performed in a basic oxygen furnace (BOF), makes an important contribution to greenhouse gas generation. The effective utilization of energy is one of the major challenges in the process, as minor variations of operational parameters can have significant negative effects on the converter in terms of CO_2 emissions. A recent study published by the same authors analyzed the BOF process by developing a general mass and energy balance model. The present study utilizes these models to quantify the contribution of global warming potential (GWP) from the BOF and analyses its sensitivity with the parameters such as hot metal composition, the temperature of hot metal, tapping temperature, scrap quantity, and levels of post-combustion. The term GWP in this study refers to the quantified CO_2 values obtained by summing up the carbon dioxide associated with the production of CaO associated with the mass of flux and carbon dioxide generated from the off-gas (considering C in hot metal is completely oxidized to CO_2). The results from the analysis indicates that for a tapping temperature increase from 1650 °C to 1683 °C, the percentage change in the global warming potential (GWP) was found to be approximately 1%. The study identified that increasing the scrap percentage in the feed would be the most effective approach to effectively utilizing chemical energy from the process and reduce CO_2 emissions. However, increasing scrap above 30% of the total feed is likely to raise issues around: (a) the presence of residual elements in scrap affecting the quality of liquid steel, (b) the effective utilization of post-combustion heat within the furnace, and (c) the recovery of off-gas heat for scrap preheating (assuming no steam recovery from the off-gas system). If these issues could be addressed at the industrial level, a significant reduction in CO_2 emissions from the BOF process could be achieved.

Keywords: environment; basic oxygen steelmaking; energy balance; mass balance; optimization; slag formation; heat loss; dephosphorization; global warming potential

Citation: Madhavan, N.; Brooks, G.; Rhamdhani, M.A.; Bordignon, A. Contribution of CO_2 Emissions from Basic Oxygen Steelmaking Process. *Metals* **2022**, *12*, 797. https://doi.org/10.3390/met12050797

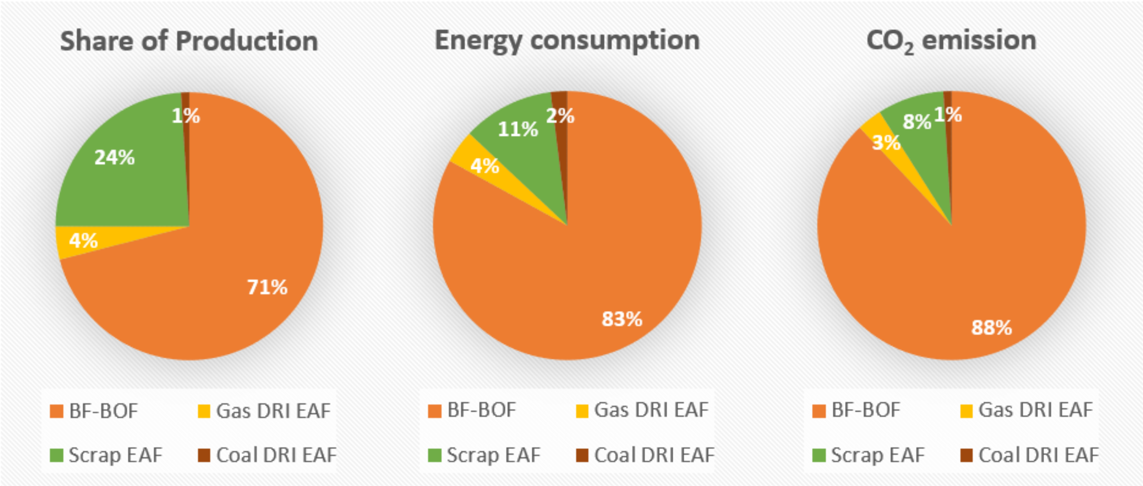
Academic Editor: Henrik Saxen

Received: 2 February 2022
Accepted: 28 April 2022
Published: 5 May 2022

1. Introduction

The steelmaking industry is under some pressure to lower the environmental impact of production but also meet the expected future steel demand. By 2035, the growth in steel demand is expected to be between 1.4% per annum [1]. Therefore, the industry is focused on formulating strategies to improve the performance of the iron and steelmaking process with respect to environmental aspects. Presently, the steelmaking process is mainly carried out through either an integrated blast furnace-basic oxygen furnace (BF-BOF) or a DRI/scrap EAF route. The significance of BF-BOF over other steelmaking routes in terms of the share of production is shown in Figure 1a. From the environmental perspective, the energy consumption, as well as CO_2 emission from the same, are shown in Figure 1b,c. In 2020, around 1.8 billion tonnes of steel were produced, and it was estimated that among all the metallurgical industries the iron and steelmaking industry emits the largest CO_2 (~9%

of the global greenhouse gas emission in 2019 [2]) and consumes the largest energy (over 25 EJ/year in 2017) [3].



(**a**) (**b**) (**c**)

Figure 1. Share of worldwide (**a**) production, (**b**) energy consumption, and (**c**) CO_2 emission percentage via different steelmaking processes. Data from [2].

As the integrated BF-BOF route depends on coke and carbon containing reducing agents, the world steel organization estimates that CO_2 generation from BF-BOF steelmaking accounts for around 1.77 tCO2/tCS [4], of which 80% to 90% is from the blast furnace. Considering climate change, it is estimated that 14% of global steel companies' potential value is at risk if the GHG emission levels are not lowered. It widely thought that the current technologies will not serve as a feasible solution to address the GHG challenges faced by the steel industry [3]. The study conducted by the Voestalpine group [5] (focused on reducing the CO_2 emission in the EU steel industries) highlights that breakthrough technologies such as carbon capture and usage, carbon direct avoidance, incorporating renewable electrical power in basic steelmaking (hydrogen-based), utilizing CO_2 as raw material, and effective chemical conversion of CO_2 from the industrial plant are required to be considered for improving the environmental performance of the plant. However, the study also mentions that these technologies will likely only be available after 2035 [3]. The efficient utilization of renewable sources also raises the challenge of technical and economic feasibility. For example, large-scale green hydrogen is still expensive, and the current technology production rates are well below what is required to match ironmaking technology [2]. Therefore, the steel industries are looking for a more comprehensive understanding of their processes to achieve cleaner steel production to reduce energy consumption and emissions by 30% in the next 30 years [3].

Considering the current scenario, it is important to analyze the CO_2 emissions contributed by individual processes in the steelmaking route. The BOF is the dominant steelmaking process and the CO_2 emissions of oxygen steelmaking is generally incorporated into CO_2 assessment of the integrated BF-BOF route. Previous studies conducted have represented the overall environmental performance of the process. Analysing the overall process of steelmaking, the major sources of CO_2 emission are coming from the production of coke and hot metal in the blast furnace. Table 1 lists the total and direct CO_2 emission contributed from each step in a steelmaking process [6]. The direct CO_2 emission refers to only the CO_2 emission to air of a specific installation. The total CO_2 emission represents the direct CO_2 emission to air due to use of a material together with the upstream emissions (emitted by suppliers).

Table 1. Average CO_2 emissions per tonne of product for the Iron & Steel production in Europe [6].

Process	Total CO_2 Emission (Tco$_2$/T of Liquid Steel)	Direct CO_2 Emission (Tco$_2$/T of Liquid Steel)
Coke plant	0.824	0.794
Sinter plant	0.211	0.200
Pellet plant	0.075	0.057
Blast furnace	1.279	1.219
BOF plant	0.202	0.181
Electric arc furnace	0.240	0.240
Bloom, slab and billet mill	0.125	0.088
Hot strip mill	0.120	0.082
Plate mill	0.133	0.098
Section mill	0.127	0.084
Pickling line	0.016	0.004
Cold mill	0.075	0.008
Annealing	0.070	0.049
Hot dip metal coating	0.104	0.059
Electrolytic metal coating	0.208	0.046
Organic coating	0.074	0.003
Power plant	1.989	1.989

Lin and Polenske illustrated the environmental impact of steelmaking in terms of disposal cost by analyzing the process data through an input/output model [7]. Similarly, Spengler et. al. [8] carried out an environmental performance study of recycling measures in the steelmaking industry. The method devised by Xiu et. al. [9] mainly focused on how to compute the pollution rates from the iron and steelmaking process. By using the fuzzy logic technique, Vahdat et. al. [10] developed a model to understand the emissions from the iron and steelmaking industry in Iran. Furthermore, several studies [11–15] have used the life cycle analysis (LCA) technique to evaluate and develop cleaner production strategies for the steelmaking industry. LCA considers the overall impact of the process or product on the environment during its life cycle (i.e., from cradle to grave). Xu et. al. [12] conducted LCA to determine the greenhouse gas emission from steelmaking. By integrating the physicochemical aspects with LCA, Losif et. al. [13] studied the life cycle inventory (LCI) of the steel industry to optimize the process. An LCA assessment from Li et. al. [15] suggested that every steelmaking industry should consider the environmental parameters while planning the initial process design. This will help in understanding the crucial parameters and provide scope for improving environmental performance. It should be emphasized that in the open literature, the studies conducted based on BOF environmental aspects were focused on (a) reuse and recycle of slag [16–18], (b) disposal of dust [19], (c) removal of dust alkalis [20,21], (d) recovery of elements from the dust [22,23], (e) recovery of heat from off-gas and slag [24–26], and (f) energy consumption and economical aspects [27–29].

The other pollutants contributed by the oxygen steelmaking process are iron dust, slurry, SO_2, NO_x, fluoride dust, wasted water, and so on. In general, the fume sources from a BOF process are categorized as primary and secondary emissions. Primary emissions are generated during the stage of oxygen blowing into the furnace. The compounds emitted are the dust of iron oxides, heavy metals, and fluorides. Moreover, the charging emission will depend on the quantity and quality of the scrap metal charge and the scrap pouring rate. The secondary emission from the process is contributed during the stages of hot metal transfer, desulfurization, iron-ladle skimming, furnace scrap, and hot metal charging, tapping, and, to a lesser extent, slagging and turndown.

In this paper, the authors analysed and made an assessment of the effect of key operational parameters on the specific CO_2 emission from a BOF. It needs to be emphasized that the study considers the CO_2 emission caused by BOF as a stand-alone process. Through this study, the contribution of greenhouse gases from BOF and how it is interlinked with the parameters such as hot metal composition, the temperature of hot metal, tapping temperature, scrap quantity, and levels of post-combustion is evaluated. Of particular importance is control of phosphorous because the quality of steel is greatly affected by even small increases in that element. The removal of phosphorous is sensitive to temperature and the addition of fluxes, which all significantly affect the heat balance. In addition to that, the sensitivity of parameters in optimizing the energy consumption of the process is also discussed. The paper can be used by steelmakers to provide some estimate of the degree of carbon footprint reduction through fine tuning their process parameters.

2. Methodology

To estimate the greenhouse gas emission and energy consumption of the BOF process, it is essential to conduct a mass and energy balance. In the current research, recently developed static mass and energy balance models by the same author [30,31] are used for establishing the relationship between different operating parameters that affect the energy consumption and GWP contributed by BOF. The overall balance is conducted by considering the properties and reaction enthalpies of the input and output components from the data available in the literature. The static mass balance is carried out by forming a series of simultaneous elemental balance equations. These elemental balance equations were then coupled by empirical relations represented as distribution equations (Equations (1)–(8)). The distribution equations used for developing the model are of 3 types: empirical relations (Equations (1) and (2)), thermodynamic relations (Equation (4)), and equilibrium phase diagram relation (Equations (6) and (7)). The calculations are carried out until the iteration loop is converged to balance the mass input (hot metal, scrap, flux + coolant, oxygen, refractory) to the mass of the product (liquid steel) and by-products (slag, flue gas, dust + splashes). The details on the selection of distribution equations and algorithm development are discussed in the recent paper [31]. With respect to the global warming potential, the quantification of values was carried out by summing up the carbon dioxide generated from the off-gas (considering C in hot metal is completely oxidized to CO_2) and carbon dioxide associated with the production of CaO (i.e., for every 1 ton of CaO produced 785 kg of CO_2 is generated) associated with the mass of flux which are considered to be the major contributors of CO_2 for the oxygen steelmaking process. In the analysis, the mass of flux is calculated as the sum of lime and dolomite. The flux calculation details are described in the recent paper [31]. However, it needs to be acknowledged that CO_2 resulting from other sources (CO_2 emissions from imported material, CO_2 emissions during the production of oxygen, argon, processing of scrap, and CO_2 emissions during the off-gas recovery.) [32] are not considered in the present calculations. Similarly, to generate silicon from silica in the blast furnace requires energy and CO_2 associated with it, which is acknowledged in the subsequent section.

$$(\%\ \mathrm{FeO})\ \sqrt{[\%\mathrm{C}]} = 4.2 \pm 0.3, \text{ for BOF with C} < 0.1\% \text{ at Tap Temp. } 1610 \pm 20\ ^\circ\mathrm{C} \tag{1}$$

$$\frac{[\%\mathrm{Mn}]}{(\%\mathrm{MnO})}\frac{1}{\sqrt{[\mathrm{C}]}} = 0.1 \pm 0.02, \text{ for BOF with C} < 0.1\% \text{ at Tap Temp. } 1610 \pm 20\ ^\circ\mathrm{C} \tag{2}$$

$$\mathrm{Lp} = \frac{(\%P)}{[\%P]} \tag{3}$$

$$\log\mathrm{Lp} = \frac{22350}{T(K)} + 2.5\log(\%\mathrm{Fe}_t) + 0.08(\%\mathrm{CaO}) - 16 \pm 0.4 \tag{4}$$

$$\mathrm{Lp}_{\mathrm{industrial}} = 0.09934\ \mathrm{Lp} + 30\ (\text{Top Blown}) \tag{5}$$

$$\left(\%\mathrm{MgO}_{\mathrm{s},1600}\right) = 0.23\mathrm{B}^4 - 3.16\mathrm{B}^3 + 16.4\mathrm{B}^2 - 40\mathrm{B} + 45.2, \text{ where } \mathrm{B} = \frac{(\%\mathrm{CaO})}{(\%\mathrm{SiO}_2)} \tag{6}$$

$$\%\mathrm{MgO}_{\mathrm{sat},\ T(K)} = \left(\%\mathrm{MgO}_{\mathrm{s},1600}\right)\cdot \mathrm{e}^{\left(5.5478 - \frac{10391}{T(K)}\right)} \tag{7}$$

$$PCR = \frac{\%CO_2}{\%CO + \%CO_2} \tag{8}$$

GWP = CO_2 from off-gas + CO_2 emissions during CaO production (Kg CO_2 produced/tonne of product) (9)

where:

[%C]: Wt % of C in Steel
[%P]: Wt % of P in Steel
[%Mn]: Wt % of Mn in Steel
(% FeO): Wt % of FeO in Slag
(% MnO): Wt % of MnO in Slag
(% MgO): Wt % of MgO in Slag
(% CaO): Wt % of CaO in Slag
(% SiO_2): Wt % of SiO_2 in Slag
CO_2 from off-gas refers to C in hot metal is completely oxidized to CO_2
PCR: Post Combustion ratio
GWP: Global warming potential
B: Basicity
Lp: Phosphorus partition
T: Tap Temperature

Following the mass balance, the static energy balance computes the heat associated with the different output (heats of steel, slag, flue gases, the heat of scrap melting) and input (sensible heat of liquid hot metal and heat of reaction) components. The overall heat balance is given by Equation (10). It needs to be mentioned that for the present calculation the average post-combustion ratio is considered to be 0.12 [30,31]. Other details pertaining to the formulation and calculation of individual mass and heat components are discussed in more detail in another paper by the author [30,31].

From the perspective of environmental impact assessment, the energy balance quantifies the heat available for scrap melting when the overall heat loss percentage is assumed or computes overall heat loss when scrap fed into the system is known. Therefore, by conducting a sensitivity analysis with these two parameters (heat of scrap melting and overall heat loss), an optimum amount of scrap and minimum range of overall heat loss percentage can be computed. The repercussion of this study provides the possibilities for reducing the global warming potential and improving the effective utilization of energy

Sensible heat of liquid hot metal + Heat of Reactions = Sensible heats of Steel + Sensible heats of Slag + Sensible heats of Waste Gases + Heat of Scrap melting + Excess Heat or Overall Heat Loss (10)

$$\text{Scrap } \% = \frac{\text{Mass of Scrap}}{\text{Mass of Hot Metal} + \text{Mass of Scrap}} \times 100 \tag{11}$$

To execute the mass and energy balance model several simplifications and assumptions are considered, namely:

- silicon in the hot metal is completely oxidized;
- degree of scrap oxidation and fume/dust losses are not considered;
- effect of sulfur in the hot metal is neglected;
- oxygen blown via lance is completely utilized;
- temperature of slag is assumed to be 100 °C greater than steel temperature;
- coolant considered for calculation is Fe_2O_3 alone;
- turn down heat loss is neglected;
- heat associated with loss on ignition is neglected;
- calculation assumes no presence of undissolved fluxes or solid precipitates in slag such as C_2S ($2CaO{\cdot}SiO_2$), C_3P($3CaO{\cdot}P_2O_5$); and
- effect of residual heat used for heating the scrap is not considered.

Based on the data of hot metal mass and composition, end composition of steel, tapping temperature, and mass of scrap, the static mass balance model [31] computes the amount of flux to be added/slag generated, CO_2 generated, and oxygen required for chemical reactions. The results from the static mass balance model were used for the static heat balance model [30] to compute heat input, heat of reaction, heat output, and excess heat or overall heat loss. As the present study is analysing the CO_2 emissions of a BOF process, the values of parameters (hot metal composition, the temperature of hot metal, tapping temperature, scrap quantity, and levels of post-combustion) are varied within the range of industrial limit to capture the CO_2 emissions and energy consumption or requirement.

3. Results and Discussion

The developed model was validated against 35 heat set data from Tata Steel [30,31]. The Tata Steel BOF shop operates a 330-tonne capacity converter integrated with combined blowing technology. The oxygen is delivered through a 6-hole lance at supersonic speed and bottom stirring is achieved via injecting Ar/N_2. Along with the hot metal, fluxes in the form of lime, raw dolomite, burnt dolomite, and coolants, such as recycled slag and iron ore, are also added during the blowing period. The details pertaining to the validation have been described in previous papers [30,31,33].

As carbon present in the hot metal constitutes the highest percentage of impurity and provides essential heat via exothermic reaction, it is essential to analyze the impact of hot metal carbon on global warming potential, heat loss, and heat of flue gases. If the carbon in the hot metal is increased, then more carbon dioxide emissions will be expected to achieve the same end composition in steel as shown in Figure 2. Similarly, when the scrap percentage is not increased with increased C in hot metal, then the excess heat generated from the increased carbon oxidation goes in the form of heat loss given by Figure 2. The temperature of off-gas determines the capacity of heat recovery. The increment of carbon in the hot metal results in a higher amount of CO_2 in the off-gas resulting in the increase in heat of flue gas as illustrated in Figure 2.

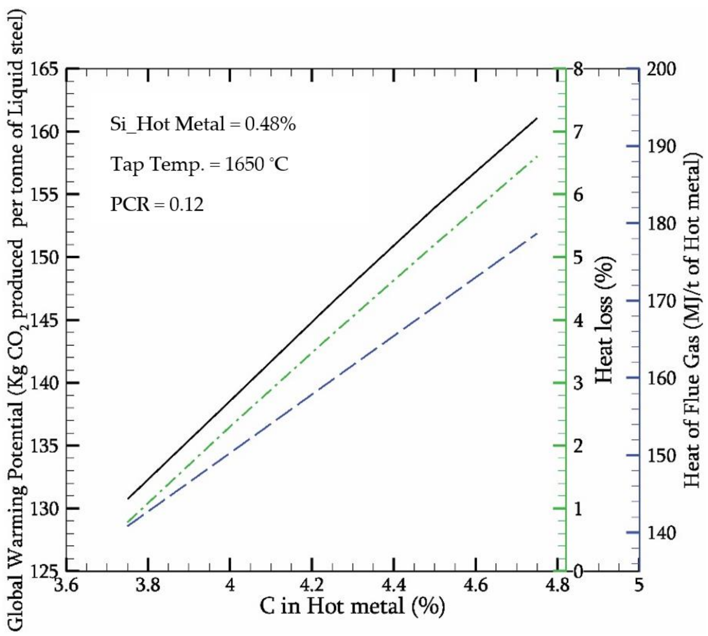


Figure 2. Effect of C in hot metal on GWP, heat loss, and heat of flue gas.

As the refinement of the steel takes place via oxidation of impurities, it is relevant to understand how the percentage change in the composition of hot metal and steel affects the carbon dioxide emission from the process. The graphs are constructed by changing the parameters Si, P in hot metal (increasing) and final C composition in steel (decreasing) one at a time keeping the other reference values listed in Table 2 to be constant. It needs to be acknowledged that generating silicon from silica in the blast furnace requires the energy and CO_2 associated with it. A previous study on "Effect of silicon content in molten iron on carbon emission in blast furnace" [34] quantifies that when the silicon content is increased by 0.1%, the coke rate will increase by 4.54 kg/t. This is equivalent to a carbon emission increase of 7.46 m^3/t. In the present study, the CO_2 emission from the blast furnace is not considered. Therefore, it needs to be highlighted that for the cases where the Si percentage in the BOF input is varied, the change in CO_2 contributed by the blast furnace is not considered (i.e., the effect of Si on global warming potential is only calculated from the BOF process). This is because the intention of the current study is to understand the CO_2 emission from one process BOF that contributes to the overall process.

Table 2. Reference values considered for sensitivity analysis.

Parameters	Ref. Values
Mass of hot metal (t)	276
Si_hot metal wt %	0.45
C_hot metal wt %	4.5
PCR (assumed)	0.12
[% C]	0.048
[% P]	0.006–0.016
P_ hot metal wt %	0.055
Tap Temp (°C)	1650

With the increment of Si or P content in the hot metal, the mass of slag required to achieve the desired end composition will also increase. As mentioned previously, the increase in the mass of slag means a greater amount of CO_2 is generated for producing the required mass of CaO in the flux added. Figure 3 shows that the consumption of mass of slag is higher for complete oxidation of Si compared to P. Therefore, the Si content in the hot metal is more sensitive to generating greenhouse gases providing the hot metal mass remains constant. However, when more C is retained in the final composition of steel, the net CO_2 emission from the process also decreases as shown in Figure 4. It needs to be mentioned that with the increase of C in steel, the mass of slag decreases (due to lower FeO), and it leads to less heat for scrap melting due to reduced C oxidation from hot metal to steel.

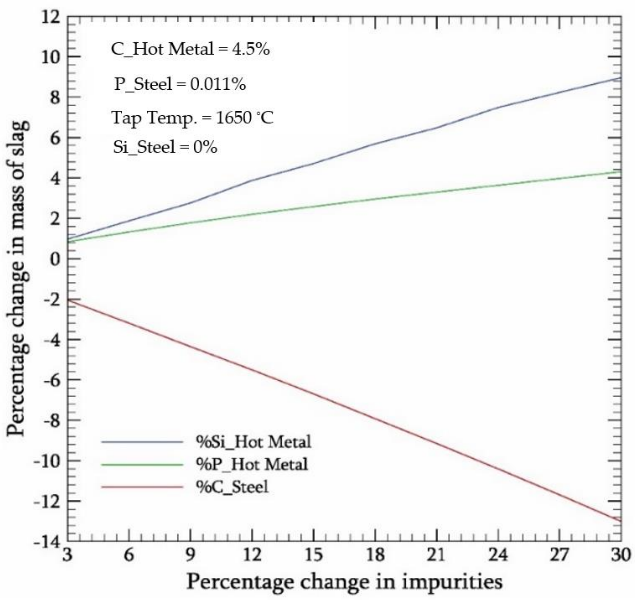


Figure 3. Sensitivity of impurities on mass of slag required for the process.

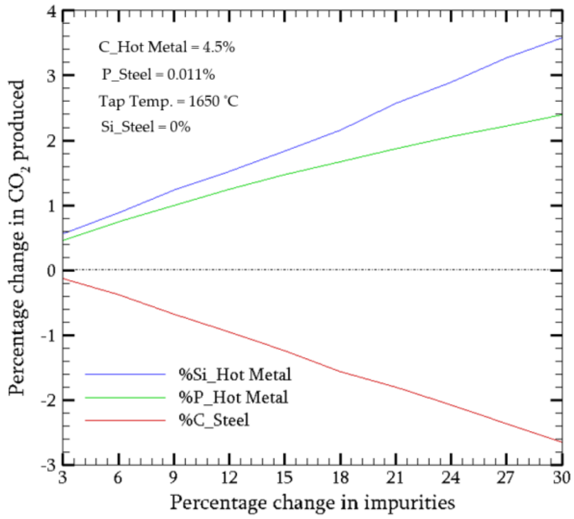


Figure 4. Sensitivity of impurities on CO_2.

Previous studies have shown that tapping temperature is a crucial parameter in the steelmaking process that needs to be controlled based on the required end composition of steel from the BOF process and further processing in downstream operations (secondary metallurgy and casting). Hence, it is quite relevant to understand the sensitivity of tapping temperature on environmental aspects expressed through flux added, global warming potential, and heat loss. The graphs shown in Figure 5 are constructed similarly to Figures 3 and 4 (considering the reference values listed in Table 2). Increasing the limits of tapping temperature favors P reversion, this will result in more flux being added to the system as shown in Figure 5. As global warming potential is calculated based on the CO_2 generated from the CaO production in the flux, the global warming potential from the BOF will also increase with more flux added to the system. Figure 5 highlights that for every 1% increase in the tapping temperature, the mass of flux added and GWP was found to increase by ~4% and ~0.6% respectively. However, the increase in the mass of flux results in retaining more heat within the BOF (due to increased heat taken up by the mass of flux). Therefore, the percentage change in heat loss percentage follows a declining trend with the increase in the tapping temperature as illustrated in Figure 5. Practically, the metal could also get hotter (i.e., the heat is not lost) which would affect the P reversion.

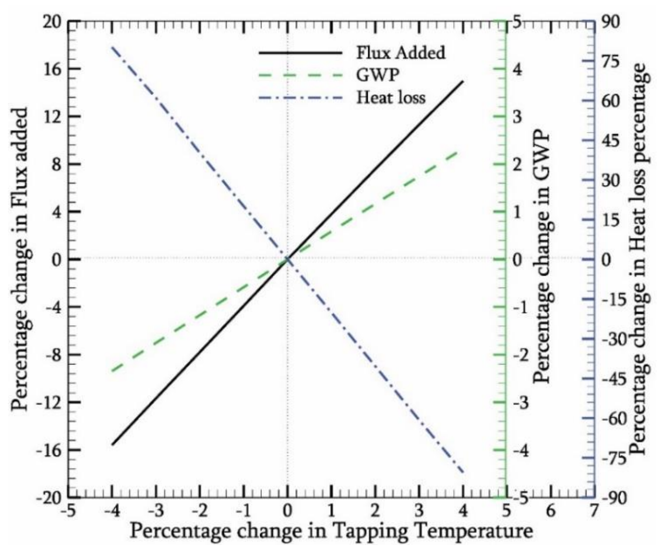


Figure 5. Effect of change in temperature on flux added, change in GWP, and change in heat loss percentage.

From the environmental perspective, it is useful to understand the dependence of scrap addition, mass of slag generated, and CO_2 emission (global warming potential) on the Si in hot metal and final P in steel. The ideal way to reduce CO_2 emissions is by decreasing the mass of slag, increasing the scrap input, energy recovery from off-gas, and reducing the CO_2 emission. The mass of slag and global warming potential is calculated and expressed in terms of kg per tonne of hot metal and kg CO_2 produced per tonne of liquid steel, respectively.

As shown in Figure 6a, when the Si in Hot metal is increased considering a fixed P in steel, the mass of slag generated increases (to refine the excess Si). On the other hand, as Si oxidation is exothermic, it provides additional heat for which extra scrap is shown in Figure 6b. However, due to the increased mass of slag, an additional amount of CO_2 is also generated from the process as depicted by Figure 6c.

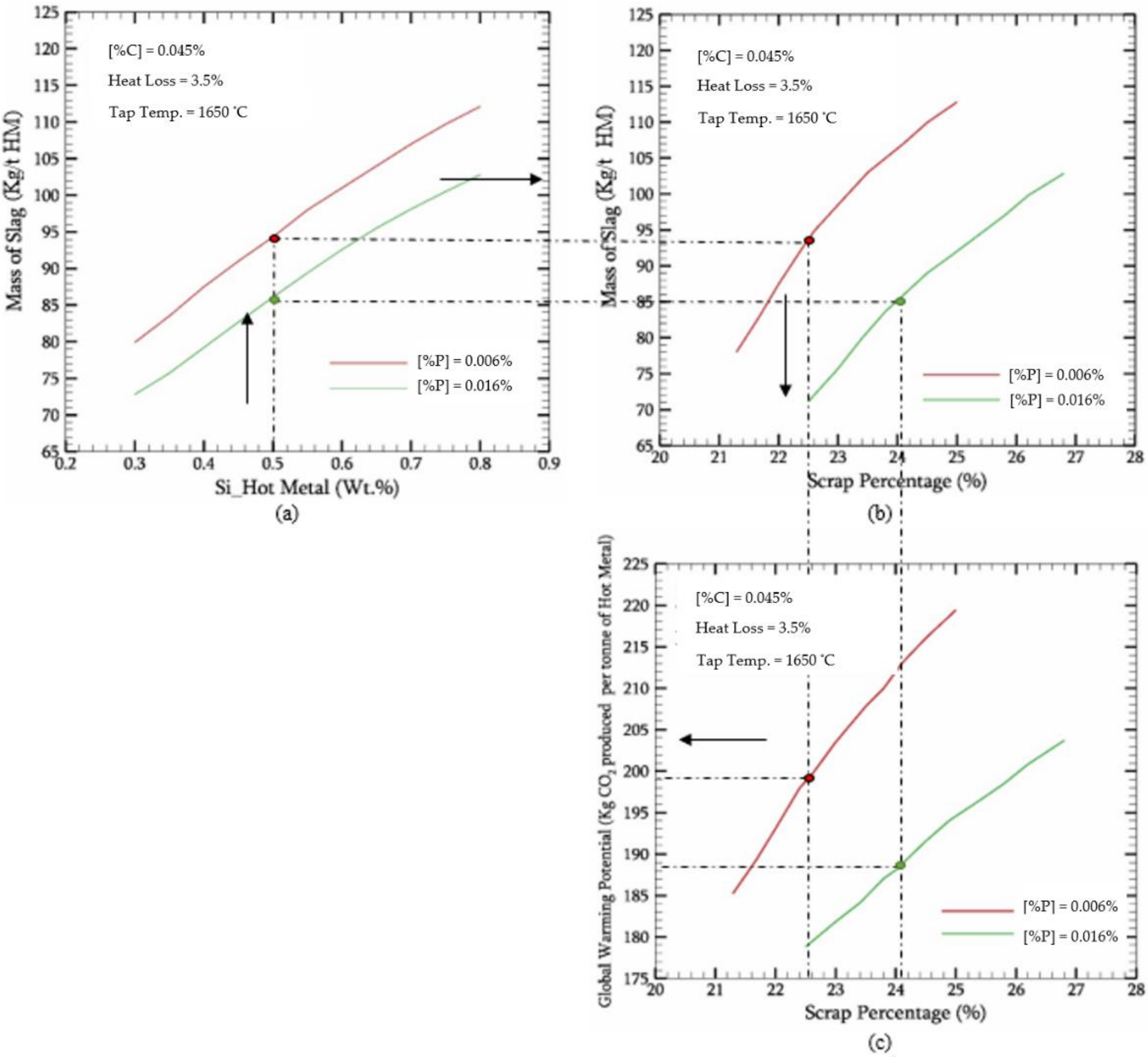


Figure 6. Nomogram from static balance model for top blow bottom stir technology with tap temperature of 1650 °C and assumed heat loss of 3.5%. (**a**) slag mass increase due to Si in Hot metal; (**b**) extra scrap due to additional heat; (**c**) additional amount of CO_2.

A similar trend of increase in the mass of slag is observed from Figure 6a when Si in hot metal is fixed and P removal in the steel is increased from 0.016% to 0.006% (green to red line). In this case, as the P oxidation reaction is not highly exothermic, the scrap that can be fed to the system decreases due to an increase in slag quantity (Figure 6b) that increases the heat content associated with the slag. Furthermore, the increased slag quantity results in increased global warming potential as shown in Figure 6c due to CO_2 generated from the CaO production in the flux. From the environmental perspective, the best combination to optimize the process is listed in Table 3. It needs to be mentioned that from a steel target grade production point of view, low P is also an important requirement. To achieve low P, it costs lot of energy and CO_2 emission.

Table 3. Effect of different combinations on mass of slag, scrap percentage, and global warming.

Parameters	Composition			
	[% P] Fixed & % Si in Hot Metal Increasing	**[% P] Fixed & % Si in Hot Metal Decreasing**	**% Si in Hot & Metal Fixed [% P] Decreasing**	**% Si in Hot Metal Fixed & [% P] Increasing**
Mass of slag	Increases	Decreases	Increases	Decreases
Scrap Percentage	Increases	Decreases	Decreases	Increases
GWP	Increases	Decreases	Increases	Decreases
Best combination preference	3	2	4	1

Input to any BOF comprises of hot metal from the blast furnace and scrap quantity based on the heat available in hot metal and aim steel temperature. The temperature of the hot metal depends on the composition of hot metal, the operating condition of the blast furnace, and on-site logistics. The typical range of hot metal temperature in a BOF ranges from 1300 °C to 1350 °C [35]. Figure 7 highlights how hot metal temperature influences the amount of scrap added and global warming potential. For a fixed composition of hot metal, tapping temperature, and assuming a constant heat loss of 3.5%, if the temperature of the hot metal is increased, more heat will be available in the system that can be effectively utilized for melting more amount of scrap as shown in Figure 7. Furthermore, higher scrap in the BOF input conveys reduced CO_2 produced per tonne of liquid steel. Therefore, from CO_2 emissions perspective, it is favorable to have a higher hot metal temperature that results in reduced GWP and increased productivity.

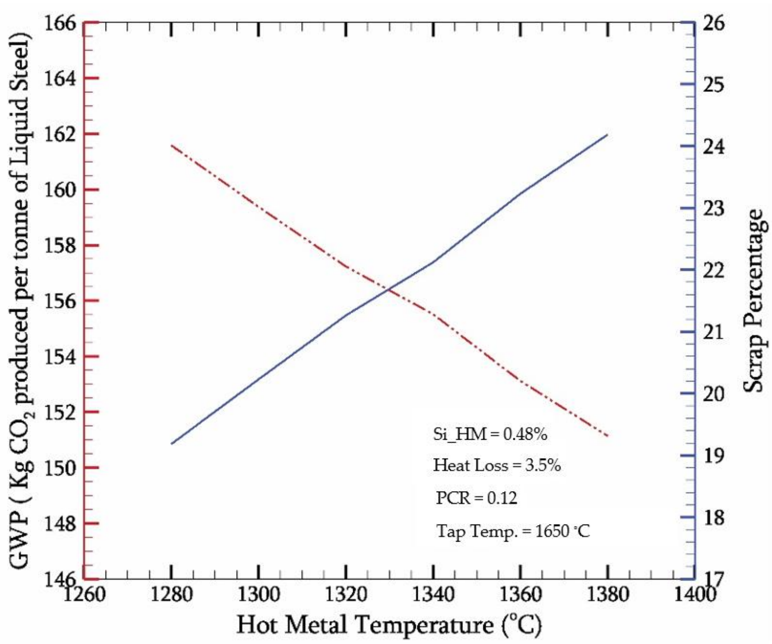


Figure 7. Effect of hot metal temperature on GWP of the process for a given PCR = 0.12, tapping temperature, silicon level, and heat loss.

One of the most effective ways to reduce CO_2 emissions from an oxygen steelmaking process is by reducing the hot metal ratio by increasing the use of scrap fed into the converter. Previous studies have shown that a higher scrap percentage serves the purpose of suppressing the excess heat that goes in the form of heat loss [36]. To determine the amount of scrap that needs to be fed into the converter before starting the blow, the available percentage heat for scrap melting as a function of post-combustion ratio and silicon level in hot metal for an assumed heat loss needs to be known. The industrial Si level and post-combustion ratio generally range from 0.3% to 0.8% and 0.08 to 0.22 respectively. The calculation assumes that all the heat generated from post-combustion is utilized inside the furnace. Figure 8a highlights that for a fixed mass of hot metal, by raising the level of silicon in hot metal from 0.3% to 0.7% and post-combustion ratio from 0.07 to 0.2, the predicted percentage heat for scrap melting was found to increase from 15% to 19.5%. The typical value of scrap melting heat observed from the dynamic heat flow study ranges from approximately 1.2 GJ/t scrap to 1.4 GJ/t scrap [37]. Similarly, Figure 8b highlights that if we can cross the present industrial limit of PCR % i.e., beyond 22%, then increased PCR% from 22% to 40% will aid in more increased scrap percentage i.e., around ~31% scrap and decreases the GWP from 148 Kg/t of liquid steel to 130 Kg/t of liquid steel. This will in effect increase BOF productivity through improved energy consumption. It needs to be emphasized that various operations are aiming for a higher post-combustion ratio to utilized heat available for more scrap melting but there are engineering challenges associated with implementing this strategy (which will be discussed below). From the industrial perspective, a higher Si in HM costs a high coke rate in BF; so it is not always a favourable solution for scrap melting. In addition to that, to generate silicon from silica, the blast furnace requires energy and the CO_2 associated with it. Therefore, it is feasible to deliberately increase post-combustion in the BOF and make this heat available for scrap melting thereby reducing greenhouse gas emissions.

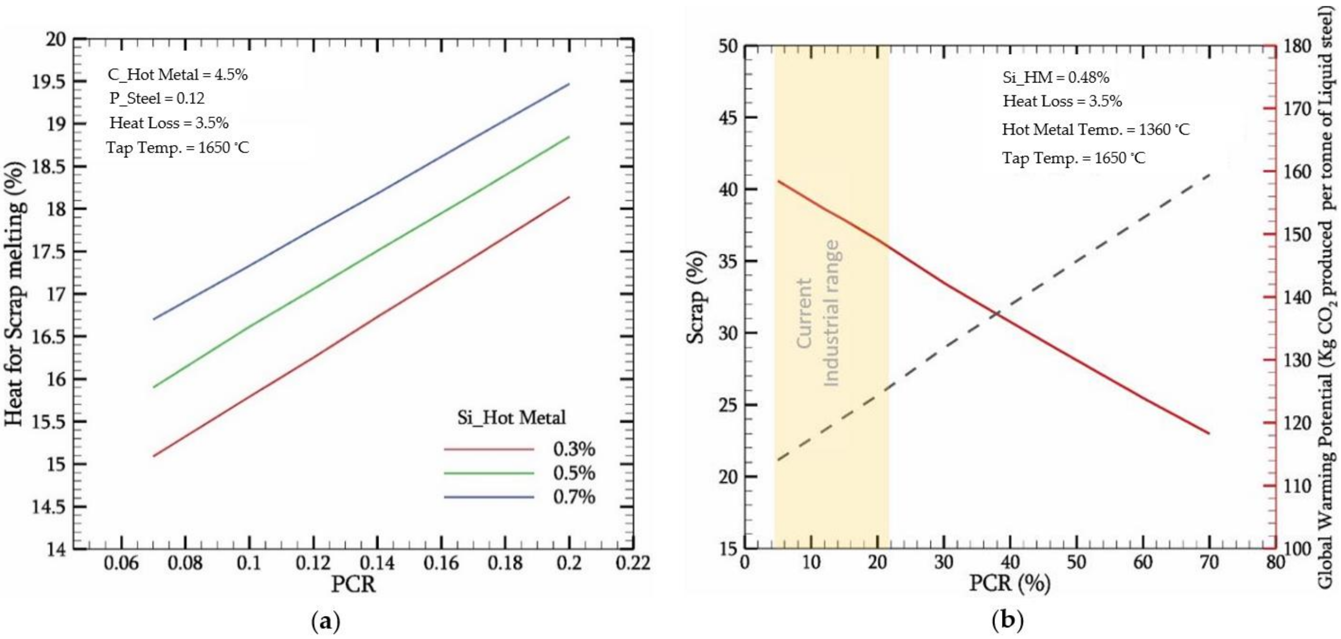


Figure 8. (**a**) Influence of PCR and Si in hot metal (%) on Heat of scrap melting (**b**) Effect of PCR (%) on scrap percentage and global warming potential.

Possibilities of Improving the Process Performance

The results based on the analysis show that there exist different possibilities to improve the environmental performance of the BOF. According to this analysis, maximizing the scrap in the reactor will be the most feasible solution to effectively utilize the chemical energy from the process and reduce greenhouse emissions. However, there exist practical limitations in having a higher percentage of scrap in the oxygen steelmaking furnace as explained below.

(a) Currently, there are no practical ways to check (other than visual inspection) the quality of scrap in the industry [38]. Visual inspection does not provide information about the scrap composition or impurities present in the scrap. A low-grade scrap, having some residual elements, fed into the converter can therefore affect the quality of liquid steel produced from the BOF process. The common residual elements found in the steel scrap are copper (Cu), tin (Sn), antimony (Sb), zinc (Zn), tungsten (W), cobalt (Co), nickel (Ni), and molybdenum (Mo). Of these, Cu and Sn are the main residual elements contributed by electrical, mechanical, and municipal solid waste [39]. The residual elements do not undergo oxidization and thus tend to remain in liquid steel. Therefore, in general, the composition of residual elements are detected at the end of the steelmaking process rather than before or during the selection of scrap [38]. A recent study conducted by Miranda et al. [38] has discussed various techniques like optical emission spectrometry (OES), X-ray fluorescence (XRF), laser-induced breakdown spectroscopy (LIBS), and prompt gamma neutron activation analysis (PGNAA) to detect and quantify the residual elements in steel scrap, and commercial development of these techniques would help address this issue. It needs to be mentioned that many plants use random sampling and statistical models for estimating scrap properties based on the evaluation of historical process data. The results highlight that the partial least squares (PLS) model provides estimates of the levels of impurity (Cu, Sn, As) and alloy content (Cr, Ni, Mo) in scrap grades. The PLS model reports an accuracy of 40% to 70% in predicting the level of impurity and 70% to 100% for predicting the alloy contents in scrap [39].

(b) If the heat from the post-combustion is not utilized effectively then feeding the scrap beyond a limit will increase the blowing time and results in iron yield loss. This will have implications on the economic and productivity aspects of the process. Different studies have previously discussed the limits of scrap percentage that can be fed into the converter based on the levels of post-combustion ratio. According to Holappa et al. [40], when the CO is completely burned to CO_2 and if the complete energy is utilized, this will facilitate the scrap level to increase by 55% of the total charge. In another study by Holappa et al. [41] it was reported that by increasing the post-combustion ratio by 10%, the scrap ratio can be increased by 3.4%. Typically, in a BOF technology, the maximum scrap input has been around 25% of the total charge [42]. Reports from Primetals [43] suggest that incorporating a scrap preheating lance and dual flow post-combustion lance can serve the purpose of increasing scrap melting in a BOF. However, in an industrial BOF, the maximum scrap rate was found to be approximately 30% due to inefficient mixing between the hot gases and the feed materials [43]. Moreover, if post-combustion energy is not directed toward the bath, then the high heat released from PC ends up heating the refractories or off-gas. Therefore, it is important to direct the heat of post-combustion to the metal bath for scrap melting, thereby increasing high heat transfer efficiency. To study the heat transfer aspects, Farrand et al. [44] developed a model that predicts that in a KOBM converter (which utilizes bottom blowing of oxygen), if the heat transfer efficiency (from post-combustion to metal bath) is 100%, then liquid steel temperatures increase by 10 °C for every 1% increase in post-combustion. However, in practice for a 1% increase in in-vessel post-combustion, the steel temperature was found to rise by 4.9 °C, which accounts for a heat transfer efficiency of 44% (one would expect different results for heat transfer efficiency in a BOF compared to a KOBM, but this study is at least indicative for a BOF). A mathematical model (theoretical jet model) developed by Kato et.al. [45] analyzed the characteristics of various designs of secondary oxygen lance on post-combustion and heat-transfer efficiency. The results highlight that to maximize the post-combustion, an optimal oxygen flowrate through a secondary lance is required that can be expressed as a function of lance height, nozzle diameter and nozzle angle. A similar investigation was carried out by Takashiba et al. [46,47], and the results indicate that the location of the in-vessel combustion zone determines the heat-transfer efficiency. The study recommends the optimum location of the combustion zone is just above the hot metal bath 1 m from the refractory wall and a short distance from lance tip.

According to Primetals technologies, the jet process technology that uses a bottom blowing technology is a feasible option to melt higher amounts of scrap [40]. With the jet process, the maximum scrap rate limit was noted to be around 50% of the total, and this would bring around a 40% decrease in GWP [43]. It has been tested at POSCO (Korea), and the results indicate significant improvement in the recovery of energy from the post-combustion. However, this technology is not commercially available. From the industrial perspective, the iBOF technology launched by Tenova [48] is designed to enhance "in-BOF" post-combustion to increase the scrap melting capacity. The iBOF technology uses an optimized post-combustion module to control the lance height based on the off-gas analysis and controls the oxygen flow rate independently for decarburization and post-combustion through primary and secondary lances, respectively, as shown in Figure 9. With the implementation of this module, the scrap usage increased by 3 to 5% and reduces the GHG by ~7%. [48]. However, it needs to be highlighted that the quantified values of the maximum post-combustion ratio achieved at the industrial level were not available in the open literature.

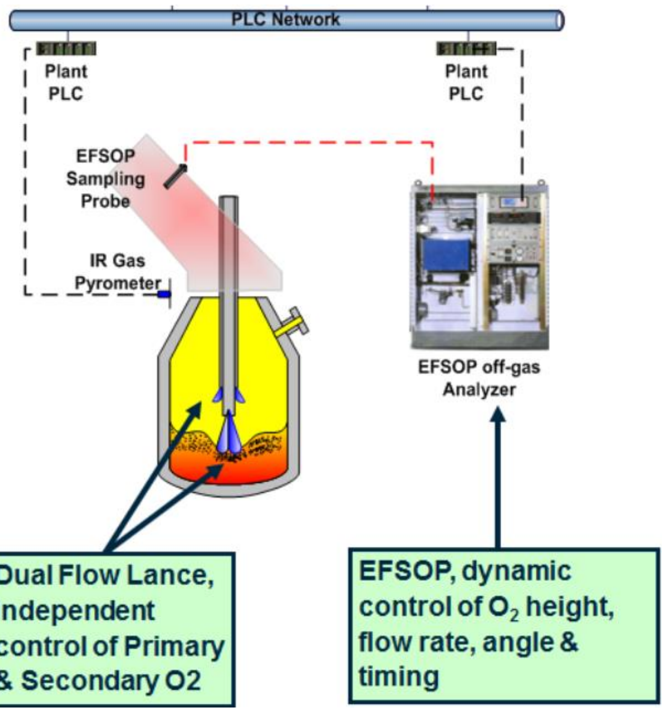


Figure 9. iBOF optimized post-combustion module, adapted from [48].

(c) Inefficient utilization of off-gas results to be another factor that limits a higher amount of scrap addition in the converter. Previous studies [49–58] have suggested that scrap preheating is one of the feasible options to recover the heat from the off-gas. The most common and commercial scrap pre-heating processes in an EAF technology are DANARC [49], Consteel [58] and the Consteel Evolution process [54], the Finger and Double Shaft Furnace system [55], Twin-Shell technologies [56], the EPC system [52] and the Ecoarc furnace [57] process. Summary of these technologies employed in the EAF scrap preheating is given in Table 4. The preheating of scrap in BOF technology has not been developed as much as EAF technology, in part reflecting concerns of costs associated with electricity. Also, EAF technology has very high heat losses compared to BOF technology, and it is estimated that 20 to 30% of all energy in an EAF is lost as heat losses [59,60], compared to less than 10% of energy in a BOF [30]. Thus, providing greater incentive for investment in preheating technology.

Table 4. Scrap pre-heating technologies used in steelmaking process. Data from [49–53].

Technologies	Pre-Heat Temperature (°C)	Energy Savings (kWh/T)
Consteel	300	40
Finger Shaft	500	60
Twin-Shell technologies	200	17
EPC system	800	100
Ecoarc furnace	800	90
DANARC	500	57
EOF	800–1200	-

The recovered off-gas could be utilized to produce electric energy through a Rankine cycle process. However, these various preheat techniques cannot provide a constant supply of off-gas heat to generate power. This limitation has been addressed in a study by Magro et.al. [51] and a system based on phase change materials (PCM) was incorporated to accumulate and release a large amount of energy that facilitates a smooth supply of off-gas energy for either generating electricity or preheating the scrap [51]. The results indicate that for steel production ~57 kWh/t of energy can be recovered [51]. However, studies have not reported these technologies being employed in an industrial BOF process. This may due to (a) the fact that the EAF can operate semi-continuously whereas BOF is a batch process, and (b) fluctuation in off-gas flow rate.

The present study would suggest the use of a phase change material (that is simple, low cost of operation, and high heat recovery system due to smooth supply of off-gas energy) as one of the feasible options that can be incorporated in BOF for scrap preheating. In addition, EOF (given in Table 4) is another batch oxygen steelmaking process with a combination of a high degree of post-combustion and scrap preheating that allows scrap to be charged up to 100% [50] theoretically. However, in practice the EOF operates with a scrap charge of 40–60% with a blowing period of 30 to 35 min, and steels of different grades can be produced competitively compared to other processes [50]. It has been estimated that for scrap to hot metal ratio of 50/50, the EOF requires 64 m^3/t of oxygen with one-third directed toward the bath and two-thirds used for post-combustion that further preheats the scrap to 800–1200 °C [50]. A recent study reports that only 5 EOF plants exist around the world with a total steelmaking capacity of approximately 2.9 million metric tons [61].

(d) Parameters such as scrap quantity, temperature, size, shape, and scrap feeding time determine the rate of scrap melting [62]. The recent study on dynamic heat flow [37] in the oxygen steelmaking process suggests that during the middle of the blow there exists unutilized excess heat that is considered as heat loss. Therefore, it would be an effective method to adopt intermittent feeding of scrap through a bunker feeding system (as incorporated in an EAF) [63] in BOF as a way to utilize the excess heat for increasing the scrap melting rate and thereby increasing the productivity. Another way to increase the melting rate is by optimizing the scrap mix. The ratio of heavy to light scrap matters because heavier scrap is more difficult to melt compared to light scrap. As scrap melting rate is a function of post-combustion, heat-transfer efficiency, scrap size, and feeding rate, it is anticipated that melting rate can be improved by intermittent feeding of preheated optimized scrap mix with higher levels of post-combustion and increased heat transfer efficiency. Therefore, further studies are required to understand how melting rate during the blow can be expressed as a function of scrap parameters (scrap quantity, temperature, size, shape, and feeding interval) to optimize the process and thereby improving the environmental aspects of the BOF.

In addition to scrap, the other main parameters studied were the composition of the hot metal, tapping temperature, post-combustion ratio, and hot metal temperature. The predictions on how global warming potential changes with the mentioned parameters have not been tested rigorously against plant data. Therefore, conducting industrial trials or pilot plant experiments would strengthen and bring more justification to these claims. It should be highlighted that there are engineering challenges which include the utilization of post-combustion heat, scrap preheating via off-gas or bunker feeding systems due to economic reasons such as the fact that pre-processing, sorting, and scrap sizing add costs to the steel production.

4. Conclusions

The following conclusions can be inferred from the present study.

- The mass and energy balance models developed in this study predict that when Si in hot metal is increased, considering a fixed % P in steel, the heat available for scrap melting is increased, thus improving productivity. Moreover, when the final P concentration in the steel is decreased from 0.016% to 0.006% keeping the Si in hot metal fixed, then the scrap percentage decreases from 24% to 22.5% due to an increase in slag quantity.
- Sensitivity analysis shows that an increase in impurity (Si and P) concentration in the hot metal generates more slag to achieve the required end composition. The additional slag results in the increase of greenhouse gas emissions because of CO_2 generated from the CaO production in the flux.
- In the current BOF process, neither the post-combustion nor the Si in hot metal can be precisely controlled. The study predicts that if the Si level in hot metal is increased from 0.3% to 0.7% and by raising the post-combustion ratio from 0.08 to 0.20, the percentage heat available for scrap melting was found to increase from 15% to 19.5%. However, it is recommended that the provision of improving post-combustion within the converter is a more feasible option for increasing available heat for scrap melting because to generate silicon from silica in the blast furnace requires energy. Moreover, for every 0.1% increase in silicon content in the blast furnace, the carbon emission increased by 7.46 m^3/t. Therefore, for Si increase in hot metal we could anticipate that the CO_2 reduction by melting more scrap will disappear from the extra carbon required in the blast furnace to make the Si and the extra lime that is required for slag making.
- From the environmental aspect, the increase in hot metal temperature or lowering the taping temperature reduces the CO_2 emissions and favors productivity through improved energy consumption.
- If the BOF is to be developed as a scrap melting technology, both increased post-combustion and preheating of feed will be necessary. Previous work suggests that approximately 40% scrap feed is possible, but this will require capital investment in PC and preheating equipment, and close attention to scrap chemistry and sizing leading to a large capital investment overall. However, comparing the energy utilization to EAF steelmaking, the BOF route has some advantages as a scrap melting technology because heat loss from a typical BOF varies from 2% to 8% [30], whereas in EAF the heat loss varies in the range of 20% to 30% [59,60]. Therefore, from an environmental perspective, optimizing the chemical energy from the BOF serves for scrap melting is an attractive option.

Author Contributions: Conceptualization, N.M. and G.B.; methodology, A.B.; software, N.M. and A.B.; validation, N.M. and G.B.; formal analysis, M.A.R.; investigation, N.M. and A.B.; writing—original draft preparation, N.M.; writing—review and editing, G.B., M.A.R.; supervision, G.B., M.A.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Van Audenaerde, T. Steel Demand Beyond 2030: Forecast Scenarios. Tech. rep., Accenture Strategy Presentation to OECD, Paris. 2017. Available online: https://www.oecd.org/industry/ind/Item_4b_Accenture_Timothy_van_Audenaerde.pdf (accessed on 15 January 2022).
2. Venkataraman, M.; Csereklyei, Z.; Aisbett, E.; Rahbari, A.; Jotzo, F.; Lord, M.; Pye, J. Zero-carbon steel making: The opportunities and role of Australia. *Energy Policy* **2019**, *163*, 112811. [CrossRef]
3. Cavaliere, P. Efficient technologies for greenhouse emissions abatement. In *Clean Ironmaking and Steelmaking Processes*; Springer Nature: Cham, Switzerland, 2019; pp. 1–33. ISBN 978-3-030-21208-7.
4. Janjua, R. Energy Use in the Steel Industry Brussels: World Steel Association (2014). Available online: https://iea.blob.core.windows.net/assets/imports/events/185/8_Session2_B_WorldSteel_231014.pdf (accessed on 15 January 2022).
5. Prammer, J. Energy in Future Steelmaking. In *EU Seminar "European Steel: The Wind of Change"*; Voestalpine AG: Brussels, Belgium, 2018.
6. Pardo, N.; Moya, J.A.; Vatopoulos, K. *Prospective Scenarios on Energy Efficiency and CO_2 Emissions in the EU Iron & Steel Industry*; Publications Office of the European Union: Luxembourg City, Luxembourg, 2012; ISBN 978-92-79-26971-4.
7. Lin, X.; Polenske, K.R. Input—output modeling of production processes for business management: Structural Change and Economic Dynamics. *Struct. Chang. Econ. Dyn.* **1998**, *9*, 205–226. [CrossRef]
8. Spengler, T.; Geldermann, J.; Hähre, S.; Sieverdingbeck, A.; Rentz, O. Development of a multiple criteria based decision support system for environmental assessment of recycling measures in the iron and steel making industry. *J. Clean. Prod.* **1998**, *6*, 37–52. [CrossRef]
9. Xiu, C.H.; Zhang, Y.; Li, H.Q. Integrated Assessment on Pollution Contribution in Iron and Steel Manufacturing Process. *Res. Environ. Sci.* **2008**, *21*, 207.
10. Vahdat, S.E.; Touhidi, N. Sustainable development in environment for iron and steel making in Iran by fuzzy logic. *J. Environ. Stud.* **2009**, *35*, 111–122.
11. Scaife, P.; Nunn, J.; Cottrell, A.; Wibberley, L. Towards sustainable steelmaking–an LCA perspective. *ISIJ Int.* **2002**, *42*, s5–s9. [CrossRef]
12. Xu, H.C.; Zhang, C.X. Research of LCA Application in Steelmaking. *China Metall.* **2007**, *10*, 33–36.
13. Iosif, A.M.; Hanrot, F.; Ablitzer, D. Process integrated modelling for steelmaking life cycle inventory analysis. *Environ. Impact Assess. Rev.* **2008**, *7*, 429–438. [CrossRef]
14. Tongpool, R.; Jirajariyavech, A.; Yuvaniyama, C.; Mungcharoen, T. Analysis of steel production in Thailand: Environmental impacts and solutions. *Energy* **2010**, *35*, 4129–4200. [CrossRef]
15. Li, G.F.; Kong, J.Y.; Jiang, G.Z.; Zhang, H.; Zhao, G.; Xie, L.X. Optimization of production procedure in iron and steel enterprise for green manufacturing. *Key Eng. Mater.* **2011**, *460*, 631–636. [CrossRef]
16. Arcelor Mittal: Sustainability of Steel World's Report. 2011. Available online: https://www.silgancontainers.com/wp-content/uploads/2014/05/Sustainability-of-Steel.pdf (accessed on 5 January 2022).
17. Baricová, D.; Pribulová, A.; Buľko, B.; Demeter, P. Recycling of the Steelmaking by-products into the Oxygen Converter Charge. *New Trends Prod. Eng.* **2019**, *2*, 1–11. [CrossRef]
18. Aula, M.; Haapakangas, J.; Heikkila, A.; Iljana, M.; Kemppainen, A.; Roininen, J.; Sulasalmi, P.; Visuri, V.V. *Some Environmental Aspects of BF, EAF and BOF*; Department of Process and Environmental Engineering, University of Oulu, Faculty of Technology: Oulu, Finland, 2012.
19. Sun, W.; Zhou, Y.; Lv, J.; Wu, J. Assessment of multi-air emissions: Case of particulate matter (dust), SO_2, NOx and CO_2 from iron and steel industry of China. *J. Clean. Prod.* **2019**, *232*, 350–358. [CrossRef]
20. Gomes, H.I.; Mayes, W.M.; Rogerson, M.; Stewart, D.I.; Burke, I.T. Alkaline residues and the environment: A review of impacts, management practices and opportunities. *J. Clean. Prod.* **2016**, *112*, 3571–3582. [CrossRef]
21. Kelebek, S.; Yörük, S.; Davis, B. Characterization of basic oxygen furnace dust and zinc removal by acid leaching. *Miner. Eng.* **2004**, *17*, 285–291. [CrossRef]
22. Stewart, D.J.; Barron, A.R. Pyrometallurgical removal of zinc from basic oxygen steelmaking dust–A review of best available technology. *Resour. Conserv. Recycl.* **2020**, *157*, 104746. [CrossRef]
23. Trung, Z.H.; Kukurugya, F.; Takacova, Z.; Orac, D.; Laubertova, M.; Miskufova, A.; Havlik, T. Acidic leaching both of zinc and iron from basic oxygen furnace sludge. *J. Hazard. Mater.* **2011**, *192*, 1100–1107. [CrossRef]
24. Carpenter, A. CO_2 Abatement in the Iron and Steel Industry, January 2012, ISBN 978-92-9029-513-6. Available online: https://usea.org/publication/co2-abatement-iron-and-steel-industry-ccc193 (accessed on 5 January 2022).

25. Moon, J.W.; Kim, H.S.; Sasaki, Y. Energy Recuperation from Slags. In Proceedings of the First International Slag Valorisation Symposium, Leuven, Belgium, 6–7 April 2009.
26. Sun, Y.; Zhang, Z.; Liu, L.; Wang, X. Heat recovery from high temperature slags: A review of chemical methods. *Energies* **2015**, *8*, 1917–1935. [CrossRef]
27. Fujii, T.; Nozaki, H.; Yamagishi, Y. Energy saving in steelmaking processes. *Trans. Iron Steel Inst. Jpn.* **1980**, *20*, 40–53. [CrossRef]
28. International Energy Agency. *Tracking Industrial Energy Efficiency and CO2 Emissions*; International Energy Agency: Paris, France, 2007. [CrossRef]
29. Bradarić, T.D.; Slović, Z.M.; Raić, K.T. Recent experiences with improving steel-to-hot-metal ratio in BOF steelmaking. *Metall. Mater. Eng.* **2016**, *22*, 101–106. [CrossRef]
30. Madhavan, N.; Brooks, G.A.; Rhamdhani, M.A.; Rout, B.K.; Overbosch, A. General Heat Balance for Oxygen Steelmaking. *J. Iron Steel Res. Int.* **2021**, *28*, 538–551. [CrossRef]
31. Madhavan, N.; Brooks, G.A.; Rhamdhani, M.A.; Rout, B.K.; Schrama, F.N.H.; Overbosch, A. General mass balance for oxygen steelmaking. *Ironmak. Steelmak.* **2020**, *48*, 40–54. [CrossRef]
32. Calculation Method of Carbon Dioxide Emission Intensity from Iron and Steel Production. Guidance for using the ISO 14404 Series. Available online: https://www.iso.org/obp/ui/#iso:std:iso:14404:-4:e (accessed on 20 November 2021).
33. Madhavan, N.; Brooks, G.A.; Rhamdhani, M.A.; Rout, B.K.; Overbosch, A. Application of mass and energy balance in oxygen steelmaking. *Ironmak. Steelmak.* **2021**, *48*, 995–1000. [CrossRef]
34. Ding, J.K.; Gao, B.; Wang, S.; Zhang, Q. Effect of silicon content in molten iron on carbon emission in blast furnace. *Res. Iron Steel* **2011**, *39*, 1–3.
35. Snigdha, G.; Bharath, B.N.; Viswanathan, N.N. BOF process dynamics. Miner. Process. *Extr. Metall. Trans. Inst. Min. Metall.* **2019**, *128*, 17–33. [CrossRef]
36. Madhavan, N.; Brooks, G.A.; Rhamdhani, M.A.; Rout, B.K.; Schrama, F.N.H.; Overbosch, A. *Analysis of Heat Loss in Oxygen Steelmaking*; Association for Iron & Steel Technology: Warrendale, PA, USA, 2021; pp. 1585–1591.
37. Madhavan, N.; Brooks, G.A.; Rhamdhani, M.A.; Rout, B.K.; Overbosch, A. Analytical evaluation of heat flow in oxygen steelmaking. *ISIJ Int.* **2022**. *Manuscript accepted*.
38. Miranda, A.M.; Assis, P.S.; Brooks, G.A.; Rhamdhani, M.A.; Fontana, A.; King, A.; Sanders, G.; Gda Costa Moreira, P. Monitoring of less-common residual elements in scrap feeds for EAF steelmaking. *Ironmak. Steelmak.* **2019**, *46*, 598–608. [CrossRef]
39. Sandber, E.; Lennox, B.; Undvall, P. Scrap management by statistical evaluation of EAF process data. *Control Eng. Pract.* **2007**, *15*, 1063–1075. [CrossRef]
40. Haile, O.; Lauri, H. *Post Combustion in Converter Steelmaking*; NTIS: Springfield, VA, USA, 1997; p. 56.
41. Haile, O.; Lauri, H. *Current Status of Converter Steelmaking*; Government Research Announcements and Index: Helsinki, Finland, 1995; p. 28.
42. De Beer, J.; Worrell, E.; Blok, K. Future technologies for energy-efficient iron and steel making. *Ann. Rev. Energy Environ.* **1998**, *23*, 123–205. [CrossRef]
43. Primetals: One planet. One future. One mission, Metals Magazine, No. 09. 2020. Available online: https://www.primetals.com/fileadmin/user_upload/metals-magazine/2020_01/Metals_Magazine_1-2020.pdf (accessed on 15 December 2021).
44. Farrand, B.L.; Wood, J.E.; Goetz, F.J. *Post combustion trials at Dofascós KOBM furnace, No. EGG-M-92069, CONF-9204236-1*; Dofasco, Inc.: Hamilton, ON, USA, 1992; pp. 173–179.
45. Kato, Y.; Grosjean, J.C.; Reboul, J.P.; Riboud, P. Influence of Lance Design and Operating Variables on Post Combustion in the Converter with Secondary Flow Nozzles. *Trans. Iron Steel Inst.* **1988**, *28*, 288–296. [CrossRef]
46. Takashiba, N.; Kojima, S.; Take, H.; Okuda, H. Post Combustion of Converter Gases. *Steel Technol. Int.* **1989**, 111–115.
47. Takashiba, N.; Kojima, S.; Take, H.; Okuda, H. Lance for blow Refinement in Converter. US Patent 4,746,103, 24 May 1988.
48. Vazquez, A. Tenova's Intelligent I BOF®Technology, A Modular Package for BOF Process Improvement. In Proceedings of the 45th Steelmaking Seminar, Porto Alegre, RS, Brazil, 25–28 May 2014; pp. 2362–2374.
49. Lee, B.; Sohn, I. Review of innovative energy savings technology for the electric arc furnace. *JOM* **2014**, *66*, 1581–1594. [CrossRef]
50. Fruehan, R.J. *Evaluation of Steelmaking processes Topical Report Work Performed under Contract No. DE-FCO7-891D12847 Prepared for the U.S.*; Department of Energy: Washington, DC, USA, 1994; Volume 5.
51. Dal Magro, M.F.; Savino, S.; Nardin, G.; Meneghetti, A. Energy Recovery Systems Based on High Temperature Phase Change Materials. Ph.D. Thesis, University of Udine, Udine, Italy, 2017.
52. Rummler, K.; Tunaboylu, A.; Ertas, D. A new generation in pre-heating technologıy for EAF steelmakİng. *Steel Times Int.* **2011**, *35*, 23–24.
53. Toulouevski, Y.N.; Zinurov, I.Y. *Preheating of Scrap by Burners and Off-Gases. Innovation in Electric Arc Furnaces 2010*; Springer: Berlin/Heidelberg, Germany, 2010.
54. Memoli, F.; Giavani, C.; Malfa, E.; Rondini, N. Consteel®evolution, the second generation of Consteel®technology. In Proceedings of the ABM 2013 Conference, Araxa, MG, Brazil, 26–29 May 2013.
55. Schmitt, R.J. *Electric Arc Furnace Scrap Preheating*; CMP the EPRI Center for Materials Production; Electric Power Research Institute, Inc.: Pittsburgh, PA, USA, 1997.
56. Sector Policies and Programs Division Office of Air Quality Planning and Standards. US Environmental Protection Agency (EPA) Research Triangle Park. Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Iron and Steel

Industry. North Carolina. 2012. Available online: https://www.epa.gov/sites/default/files/2015-12/documents/ironsteel.pdf (accessed on 15 January 2022).

57. Yamaguchi, R.; Mizukami, H.; Maki, T.; Ao, N. "ECOARC" Technology. In Proceedings of the 58th Electric Furnace Conference, Orlando, FL, USA, 12–15 November 2000; pp. 325–338.
58. Memoli, F.; Ferri, M.B. New track record for Consteel due to new environment-friendly features. *MPT Metall. Plant Technol. Int.* **2007**, *30*, 58–66.
59. Hilmawan, E.; Palaloi, S.; Rosmawar, E. The Study on Energy Conservation and Efficiency Improvement in the Republic of Indonesia, JICA Project Report. 2011. Available online: https://openjicareport.jica.go.jp/pdf/11949294_03.pdf (accessed on 21 December 2021).
60. Hajidavalloo, E.; Dashti, H.; Behbahani-Nejad, M. Exergy and energy analysis of an AC steel electric arc furnace under actual conditions. *Int. J. Energy* **2013**, *12*, 380–404. [CrossRef]
61. Depledge, J. Latest Developments in Steelmaking Capacity. Environ. Policy Law 2020. Available online: https://www.oecd.org/industry/ind/latest-developments-in-steelmaking-capacity-2020.pdf (accessed on 10 January 2022).
62. Shukla, A.K.; Deo, B.; Robertson, D.G.C. Scrap Dissolution in Molten Iron Containing Carbon for the Case of Coupled Heat and Mass Transfer Control. *Metall. Mater. Trans. B Process Metall. Mater. Process. Sci.* **2013**, *44*, 1407–1427. [CrossRef]
63. Kerimov, R.I.; Shakhov, S.I. Use of metallized raw materials in electric furnace steelmaking. *Metallurgist* **2020**, *64*, 128–135. [CrossRef]