

ASSESSMENT OF CO₂ MITIGATION POTENTIAL, BIOMASS USE AND PLANTATION AREAS TO SUSTAIN CHARCOAL-IRONMAKING

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Abstract

Ironmaking is among the most carbon intensive industries in the world, metallurgists are researching for options to replace the use of coke and coal by renewable fuels as such biomass chars. In this respect, the re-introduction of charcoal in blast furnaces appears as feasible alternative to mitigate the CO₂ emission in the process. Nevertheless, for the production of charcoal large extensions of land are required for the generation of wood. In this regard, the present work aims to contribute by assessing the actual CO₂ mitigation potential, as well as the charcoal and plantation areas associated with an increase of charcoal use in blast furnaces. The first sections build on the technical aspects of charcoal blast furnace and the ecological limitations of charcoal production. The methodology shows scenarios in which fossil fuels are replaced by 10-25% charcoal. The results show that the use of charcoal may prevent the generation of 229-572 MMt CO₂ in the ironmaking process, and to achieve this ambitious goal 46-115 MM t charcoal would be required, however plantation areas of 13-33 MM ha should be dedicated to the generation of biomass. Based on the results, it is considered challenging the further proliferation of 100% Charcoal-BF outside Brazil.

Keywords: Charcoal; Blast furnace; Bio-PCI, CO₂ emissions; Sustainability.

1 INTRODUCTION

The proposition of a carbon neutral production of Hot Metal (HM) in Blast Furnaces (BF) has significantly driven the interest to investigate the future role of charcoal in the global ironmaking production. Certainly charcoal and/or biochar may reduce the carbon emissions in the BF process, however a re-introduction of charcoal presents tremendous challenges from the technical, economic and social viewpoints. The present contribution aims to provide an overview of the CO₂ mitigation potential, and to assess the amounts of charcoal, biomass and plantation areas required to sustain an increment of the charcoal-ironmaking.

Besides water availability and CO₂, several other factors intervene in the productivity of biomass generation, Gurumurti and Raturi [2] investigated the biomass generation under Indian constrains, they provide the following relation for biomass productivity (P) (Equation 2):

$$P(\text{ton / ha / yr}) = \frac{I \cdot E}{\left(\frac{A \cdot D}{C}\right)} \quad (2)$$

Where:

I = Intensity of solar radiation (kcal/ha/day)

E = Eco-system efficiency of plant

A = Area of plantation (ha)

D = Solar radiation (expressed in sunshine days per year)

C = Energy stored in dry biomass (kcal/ton)

In this respect, the solar radiation and eco-system efficiency depend directly on the geographical position of the energy farm. For instance in tropical and sub-tropical areas the solar radiation is more abundant than in the rest of the world. Similar to the solar radiation, the eco-system efficiency, also known as photosynthesis efficiency, varies according to the regions, from 0.5-2.5 for tropical plants.

The carbonization process is based on the same fundament of cokemaking, as the charcoal is manufactured through a thermal treatment in a highly reductant atmosphere to provoke a breakdown of the chemical constituents, generating

2 FROM BIOMASS TO CHARCOAL: THE PRODUCTION OF A RENEWABLE REDUCTANT

2.1 Principles of Biomass Char Generation

Similar to the agricultural process of food growing, the biomass generation is based in the natural development of the plants. As the plants grow they require nutrients, water, solar radiation and CO₂. Chemically the wood formation process is summarized in Equation 1 [1], where the plants generate hydrocarbon molecules (CH₂O) and oxygen, and the CO₂ and water are fixed to produce the biomass.



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Table I. Stages of carbonization process [4]. (Unit: Thousand tons)

Stage	Temp	Energy	Observations
I. Drying	20-110°C	Endothermic	Wood is pre-heated to vaporize the moisture. Temperature does rise until the complete charge of wood is dried. Wood moisture is in the range 50 to 70%, depending on the species.
II. Final Drying	110-175°C	Endothermic	The remaining moisture is vaporized, dehydration reactions occur.
III. Pre-carbonization	175-270°C	Endothermic	Velocity of reaction increments, beginning of emission of volatiles and gases. Decomposition of the biomass releases CO, CO ₂ , acetic acid and methanol. Wood becomes scorched (char), dark color.
IV. Transition	270-290°C	Exothermic	Decomposition reactions proceeds, start of exothermic stage.
V. Carbonization	290-380°C	Exothermic	Exothermic reactions begin and the process becomes self-sustainable. The temperature raises, the thermal decomposition process speeds, releasing heat. Important stage of decomposition reactions and gases emissions. The chemical composition of gases changes to less oxygenated gases, with the emission of combustible gases containing CO, H ₂ , CH ₄ with CO ₂ and condensable gases. The emission of vapors of acetic acid, methanol, acetone and other substances reaches a maximum. The final residue of this stage is charcoal.
VI. Carbonization	380-500°C	Exothermic	When the temperature goes over 380°C, wood is almost completely transformed into char, gas emission is reduced. The final charcoal fixed carbon content is a function of the temperature, as shown by Figure 1.
VII. Gasification	>520°C	Exothermic	Heating over 500°C charcoal gasification and degradation is started.

by-products and volatiles. The process is represented in the following reaction (Equation 3: charcoal making):



According to Kumar and Gupta [3] the biomass from wood contains several hydrocarbons (chemical compounds: weight % in wood): cellulose/ (C₆H₁₀O₅)_n: 45-65, lignin/C₃₀H₃₃O₁₁ – 20-40, resin/C₂₀H₃₀O₂ – 0.5-1.5 and Waxes/C₂₉H₆₀O – 0.2-4. The carbonization process (described in Equation 3) liberates humidity, volatile matter (which can be treated to produce oil and gas) and a solid but porous residue with 70-90% carbon content. The carbonization process is summarized in the Table I [4].

The final product of carbonization may significantly vary according to the volatile matter content and processing temperature. In a paper on the optimization of biomass pyrolysis, Ueda et al. [5] argue that charcoal for ironmaking should present low contents of oxygen to achieve sufficient heat capacity.

Carbonization temperature has as well a significant influence on the charcoal yield. Results by Demirbas [6] show that char yield decreases gradually from 47.1% to 31.8% for hazelnuts kernel husk samples, while chars from corncob 31.9% to 19%. According to the results best charcoal yields are obtained at carbonization temperatures below 850 K (577°C), where more of the 25% of the weight of the biomass becomes transformed, beyond 577°C the yield of gas and liquids increments.

2.2 Fundamentals of Charcoal Based Ironmaking

In 2010, it was estimated that there exist 165 Charcoal-BF in the world, 163 in Brazil and 2 in Paraguay [7]. Schrerer and Braga [8] determined that from the total 33,1 MMt Hot

Metal (HM) in Brazil, charcoal based HM represented an output of 23% (7.6 MMt HM), while Paraguay only generated 0.07 MMt HM [9]. Based on total global iron production, the HM output gained in Charcoal-BF represents less than 0.01% of the total global HM production.

While the production capacity of Charcoal-BF has a limited significance in the international trade of pig iron^a, the carbon neutrality of charcoal as fuel and its consequent CO₂ mitigation potential attracts the attention of many researchers worldwide, as a feasible source for reducing the Green House Gas (GHG) associated with ironmaking. In the following some fundamentals differences in the Coke- and Charcoal- based BF operation will be addressed.

Firstly, charcoal is regarded to be a “carbon neutral” fuel, as the carbon cycle via wood growth (biomass generation) is comparatively shorter (5 to 10 years) than that of fossil coal (- 100 million years) [1]. As estimated by Gonçalves et al. [10] with the production of HM in Charcoal-BF 2.42 t CO₂/t HM are sequestered, while with Coke-BF 2.06 t CO₂/t HM are liberated to the atmosphere. Additionally the Charcoal-BF shows a positive balance of oxygen generation (1.56 t O₂/t HM), while Coke-BF consumes 1.41 t O₂/t HM.

Other fundamental differences between Coke-BF and Charcoal-BF in Brazil are schematically depicted in the Figure 1 (after Pfeifer et al.) [11]. Starting with the BF capacity, it is known that working volumes in Coke-BF are significantly higher than in Charcoal-BF. Currently, the biggest Charcoal-BF has 568 m³ working volume at APERAM (Brazil) [10], while the largest Coke-BF is the BF 1 at POSCO (Korea) with 6.000m³ [12]. The difference in working volume is determined by the characteristic compression resistance of coke (130-160 kg/cm²), which

^a Common name used by merchants of iron or hot metal.

Description	Unit	Charcoal (154 BF) Typical values
Working volume	m ³	30 to 550
Production	Kt/a	20 to 500
Cfix	%	75
Volatile matter	%	24
Ashes	%	1
Compression resistance	Kg/cm ²	10 to 50
Reductant consumption	Kg/t HM	570 to 700
Pulverized coal injection	Kg/t HM	100 to 200
Blast temperature	°C	600 to 1100
HM temperature	°C	1300 to 1400
Sulfur in HM	%	0.06 to 0.08

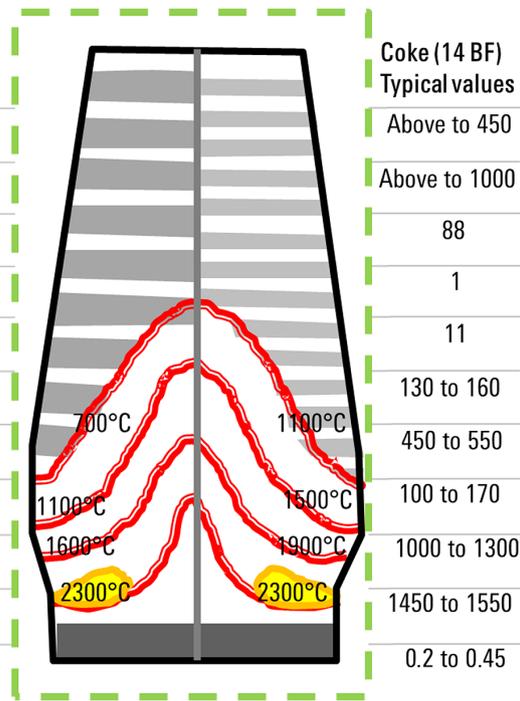


Figure 1. Principal differences of charcoal based and coke based BF.

is 4 times harder than charcoal (compression resistance varies between 10-50 kg/cm²). Consequently, modern Coke-BFs can have production capacities higher than 1.000.000 t HM/year, while Charcoal-BFs have production rates of 20-50.000 t HM / year (Figure 2). The difference in production capacity in coke- and charcoal-BF makes the complete substitution of coke/coal by charcoal technically improbable, however studies have demonstrated that up to 25% of the energy in the BF process can be sourced from biomass chars (see sections 2.3 and 6).

As shown in the Figure 2, the Charcoal-BFs work with a higher volume of reductant (gray stripes in Figure 2) and lower volume of ore (white stripes in Figure 2), such burden distribution leads simultaneously to positive and negative effects. From the negative side, the fast reaction of charcoal may produce a rapid decrease in particle size, this diminishes the permeability of gases in the shaft. From the positive side, the HM in Charcoal-BF has lower residence time, due to the higher iron ore reducibility, this is a direct consequence of the intensive Boudouard reaction^b created by charcoal [11].

The high reaction velocity of charcoal is directly related to its specific surface, which is larger in comparison to that of coal. Ng et al. [14] measured the specific area of charcoal and coal, the results revealed that charcoal has a specific area of 155m²/g, while coal has 89 m²/g. The specific area of charcoal comes from the cellular structure of woody biomass.

^b The Boudouard reaction represents the chemical equilibrium mixture of CO-CO₂ at a given temperature.

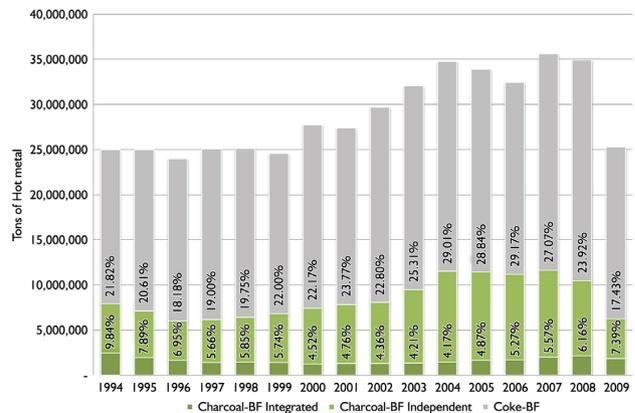


Figure 2. Historical output of charcoal and coke based BF in Brazil (1994-2009) [13].

Additional differences in the Coke- and Charcoal-BF processes are linked to the lower sulfur content in the iron. Normally HM from Charcoal-BF have a sulfur content of 0.06-0.08%, while HM from Coke-BF has 0.2-0.45%. Therefore HM gained from Charcoal-BF requires lesser further processing in the stages of secondary metallurgy, and it is consequently preferred by foundries, where the options for desulfurization are limited. Mainly due to low impurity content, HM produced from Charcoal-BF presents a higher market value, approximately 32-45% higher than Coke-BF HM [13].

It is known from Charcoal-BF operation that their thermal level is 100-150°C lower than Coke-BF, due to their

lesser heat losses and low refractory wear [7]. Additionally Charcoal-BF operated with up to 50% lesser slag volume, which reduces the energy consumption for the slag fusion.

The charcoal based ironmaking flourished in Brazil mainly in areas of *Minas Gerais*, *Maranhão*, *Espírito Santo* and *Pará* [15], due to the simplicity of the aggregate and its operation. The Figure 3 presents a historical development of production of HM using Coke-BF (bars in gray color) and Charcoal-BF (bars in green and light green) in Brazil (from 1994 to 2010) [17], as it can be noticed HM from charcoal-BFs have declined its market participation and this trend is likely to continue in the future.

2.3 Alternatives Uses of Charcoal in the Iron- and Steel-making Process

The potential to mitigate the CO₂ footprint in the whole steelmaking process have motivated the investigation of biomass char in diverse uses such as as steel recarburiser [18-20], cokemaking blend component (McPhee) [21], BF pre-reduced feed [22,23], nut coke replacement, fuel for sintering and BF tuyere injectant (also known as Bio-PCI) [24,25]. The Figure 3 presents an estimation made by Mathieson et al. [16] about the potential CO₂ mitigation of different charcoal applications in steelmaking.

3 ENVIRONMENTAL ASPECTS OF CHARCOALMAKING

In addition to the technical aspects of charcoal-ironmaking addressed in the previous section, there also exist concerns about the sustainability of charcoal production, the following part addresses this subject.

3.1 Charcoal or Biochar?

For the purpose of the present investigation, biochar is defined as the carbonaceous residue of a biomass gained from sustainable biomass sources, while charcoal (commonly used term) can be originated indistinctively from sustainable

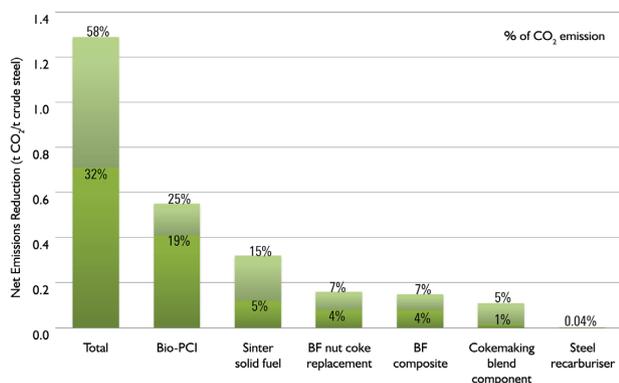


Figure 3. Net emissions reduction by diverse proposed applications for charcoal. After Mathieson [16].

plantations or from deforestation. Thus, the author favors the use of sustainable biomass chars in (biochar) in BFs. Demirbas [26] provides some examples of deforestation and local fuel scarcities in Nepal, parts of India and sub-Saharan Africa.

According to Nogueira et al. [27], in 2005 in Brazil 5.5 Millions of tons charcoal were produced from non-sustainable native forests (52,8%) and sustainable forestry plantations (47.2%). Illegal logging in Brazil for charcoal production was considered responsible for the deforestation of approximately 200.000 hectares per year. However, this situation has significantly improved in the past decade, due to the enforcement of rigorous environmental laws. According to Carneiro [17] in 2010, there was a consumption charcoal from native sources of 31.5%, while planted sustainable forestry plantation accounted for 68.5% of the total charcoal production.

Due to the increasing limitations to produce charcoal from non-sustainable sources, some companies in Brazil have implemented reforestation initiatives using several eucalyptus species (e.i. *Camaldulensis*, *Cloesia*, *Urophylla* and *Pellita*). These species have adapted well to the Brazilian conditions (soil, climate) and present high growing rates [28].

3.2 Efficiency of Charcoal Production

To the moment of writing this work, still a vast majority of charcoal is being produced in rudimentary aggregates with low charcoal yields. Presently 80% of all charcoal production in Brazil is manufactured in beehive kilns, which present dry wood yield of 20 to 25%. Such aggregates certainly require low capital expenditures, but are hand labor intensive and have a strong environmental impact. In the present, there exists alternative industrial processes for the carbonization with charcoal yields above 35% (for instance retort kilns), however they require much higher engineering and capital expenditures.

Other issue challenging the sustainability of charcoal making is the process of wood drying and pyrolysis. Most of the actual charcoal making processes wood without any type of pre-drying of the biomass^c, this reduces the yield of charcoal as a large amount of the energy in the system is utilized for the endothermic evaporation of wood logs (see Table 1, Stages of carbonization process). Recent developments in the process of pyrolysis make use of the off gas to dry out the biomass.

In spite of the efforts to increase self-sufficiency in fuel and local development through charcoal, see reports by FAO [29,30], still the charcoal industry is arguably obsolete with low output capacity, with severe working conditions and in most of the cases lacks of proper infrastructure to deliver the products to the markets with a reasonable transport cost. According to the United Nations, in 2005 the total world charcoal production was 44,113 Tmt charcoal with Brazil (9,893 Tmt), Thailand (3,916 Tmt), Ethiopia

^c For instance, in Brazil most of the wood is pre-drying at natural weather conditions, leaving the logs during some months at site to reduce the humidity.

(3,221 TMt), Tanzania (2,506 TMt) and India (1,728 TMt) as the main producers^d.

In the metallurgical inquiry most of the property assessment of biomass utilization contemplates the use of different species of trees for the charcoal production, for instance eucalyptus (Gupta) and acacia [31]. However, up to this moment few investigations focus on the actual plantation areas needed to support the charcoal production. Charcoal production already represented 13% of round wood industrial consumption from planted forests in Brazil in 2013 [32].

While charcoal-ironmaking presents unique benefits in terms of CO₂ mitigations, the experience of last charcoal-BF show that vast arable land and large quantities of fertilizer are required to sustain the HM production, this leads to question the true sustainability of charcoal-ironmaking in other countries besides Brazil. In the view of the author, it is fundamental to estimate the amount of biomass, charcoal, plantation areas and fertilizer required, if charcoal partially replaces mineral fuel outside Brazil in the ironmaking process. The following part presents a methodology for the assessment of CO₂ reduction, plantation areas and fertilizer required.

4 METHODOLOGY

The present work aims to elucidate the benefits and consequences of using charcoal in ironmaking instead of fossil fuel (coal, coke and natural gas). In this sense a methodology to assess the CO₂ mitigation potential, the charcoal consumption, the required minimum amount of biomass and the plantation areas have been designed.

Based on the assumption of a generation of 2.06 t CO₂ / t HM (Winter 2012), the CO₂ emissions of the ironmaking process in BFs have been calculated as follows (Equation 4):

$$t_{CO_2} = 2.06 * t_{HM} \quad (4)$$

Where:

t_{CO₂}: tonne CO₂ t HM: tonne hot metal

According to Schmoele [33], 416 kg reductant / t HM are the minimum necessary for the production of HM^e, thus the following equation was used for the estimation of charcoal utilization (Equation 5):

^d It is acknowledged that there are significant concerns in the energy statistics community that charcoal production/consumption is inaccurately reflected in national accounts, and thus at the reports of institutions such as Renewables 21, UN and IEA. Critics argue that such figures may probably contain traditional biomass, e.g. firewood for heating and cooking. The present work shows these statistics to illustrate the estimated relative proportion of biomass utilization in energy generation worldwide, but these figures are not use in any further calculation.

^e It is acknowledged that this value is based fuel utilization for coke based blast furnaces, while for charcoal is much higher, however the value of 416 kg reductant / t HM serves to determine the "minimum" of reductant required for the introduction of charcoal in coke-BFs.

$$t_{charcoal} = 0.416 \frac{t_{charcoal}}{t_{HM}} * t_{Hot Metal} \quad (5)$$

Where:

t_{charcoal}: tonne charcoal t HM: tonne hot metal

Biomass is required for the production of charcoal, based on series of industrial assumptions Norgate and Langberg argue that for the production of a tonne of a charcoal 8.6 tonnes of wood are necessary^f. Therefore the tonnage of biomass has been estimated using the following Equation 6:

$$t_{biomass} = 8.6 * t_{charcoal} \quad (6)$$

Where:

t_{biomass}: tonne biomass t_{charcoal}: tonne charcoal

The biomass yield highly depends on the tree species and the geographical position of the plantation, however for the purposes of charcoal making for ironmaking, Eucalyptus seems to be the most widely used tree species in Brazil. The yield of Eucalyptus can also significantly vary from 1 to more than 50 m³/ha/yr, presently in Brazil, advances in plantation management produce a yield of 40 m³/ha/yr and it is expected to reach 50m³/ha/year in the near future [34], thus for the purposes of the present study a rate of 30 t biomass/ HA/y has been used. The formulation for the assessment of the plantations areas is posted below (Equation 7):

$$\frac{A}{y} = 30 * t_{biomass} \quad (7)$$

Where:

$\frac{A}{y}$: Plantation area per year (HA/y) t_{biomass}: tonne biomass

To illustrate the case of charcoal ironmaking, the CO₂ mitigation potential, tonnage of charcoal, tonnage of biomass and plantation areas were calculated for the total iron production in the world and the top 9 producing countries in the world^g (Table 2).

5 RESULTS AND DISCUSSION

As stated previously the principal aim of charcoal utilization is to reduce the CO₂ emission associated with the HM production. In this sense, it is important to assess the possible mitigation achieved when mineral coal is replaced by charcoal.

Based on the production figures of Worldsteel [35], in 2102 together with 1,112,400 tons HM, 2,291,540 tons of

^f Norgate and Langberg assume for their calculations a humidity of 44% in the biomass and a charcoal yield of 23% in retorts.

^g Top 9 iron producers in the world: China, Japan, Russia, India, South Korea, USA, Ukraine, Germany and Brazil. Combine these countries produce 89% of all hot metal in the world.

Table 2. Hot Metal and charcoal production [35,36]

Production (year)	Unit	Ref.	China	Japan	Russia	India	South Korea	United States	Ukraine	Germany	Brazil
Hot Metal (2012)	TMt		657,800	81,400	50,500	48,000	41,700	32,100	28,867	27,000	26,900
Charcoal (2005)	TMt		122	20	60	1,728	10	940	22	-	9,893

Table 3. CO₂ emissions as function of charcoal replacement rate per country. (Unit: millions of tons CO₂)

Charcoal Replacement rate	China	Japan	Russia	India	Korea	USA	Ukraine	Germany	Brazil	Total World
	MMt CO ₂									
100%	1,355.07	167.68	104.03	98.88	85.90	66.13	58.71	55.62	55.41	2,291.54
25%	338.77	41.92	26.01	24.72	21.48	16.53	14.68	13.91	13.85	572.89
10%	135.51	16.75	10.40	9.89	8.59	6.61	5.87	5.56	5.54	229.15

Table 4. Estimated charcoal consumption as function of replacement rate in blast furnaces. (Unit: Millions of tons charcoal)

Charcoal replacement rate	China	Japan	Russia	India	Korea	USA	Ukraine	Germany	Brazil	Total World
	MMt	MMt	MMt	MMt	MMt	MMt	MMt	MMt	MMt	MMt
100%	273.64	33.86	21.01	19.97	17.35	13.35	11.86	11.23	11.19	462.76
25%	68.41	8.47	5.25	4.99	4.34	3.34	2.96	2.81	2.80	115.69
10%	27.36	3.39	2.10	2.00	1.73	1.34	1.19	1.12	1.12	46.28

CO₂ were generated (Table 3). The use of charcoal instead of coke could significantly reduce the CO₂ emission, up to a theoretical 100%^h. However, as previously discussed due to technical and economic reasons the complete substitution of coke it is not feasible, especially in large BFs. Thus the present analysis bases the assessment in the replacement of 10 to 25% of the fossil fuels in the BF process by charcoal.

In the case that 10 to 25% of coke/coal would be replaced by charcoal, this could represent a reduction potential of 229.15-572.89 MMt CO₂ in the BF process globally. Principally, there are two practicable paths for achieving this goal: firstly, using charcoal as nut coke replacement and secondly injecting charcoal as auxiliary fuel in coke-BF (see section 2.3 and 6).

The results of CO₂ mitigation may motivate an increase in charcoal consumption, thus it is important to assess the possible scenarios of utilization as function of the substitution rate. In this respect, some scenarios of charcoal consumption as function of replacement rate are posted in the Table 4.

As indicated in the Table 4, at least 462.76 MM tons of charcoal are required to sustain the current production rate of HM, which is based on a fuel utilization rate of 0.416 t charcoal/t HM, however with an actual fuel utilization in charcoal-BF this figure would have been higher. Moreover, according to the United Nations Statistics Division, only 9.89 MMt charcoal were produced in 2005. Thus the whole present

charcoal production only would suffice to sustain 2.14% of total HM production (approximately 23.77 MMt HM). Based on these results, it can be concluded that a further increase in charcoal-ironmaking would require new additional sources of biochar.

Wood is the primary raw material for charcoal, in this respect, the following Table 5 presents the scenarios of biomass utilization for the production of charcoal.

As shown in Table 5, to completely sustain the present iron production, a minimum of 3,979.72 million tons of biomass are required. In order to generate this amount of biomass large plantations areas are necessary. The next section builds upon plantation areas necessary to sustain charcoal production.

To generate biomass from primary sources (for instance, trees), significant extensions of arable lands are required. In this respect, the Table 6 presents the estimated plantation areas required to sustain the charcoal production.

According to the present estimation, at least 132.66 MM ha are required to sustain current rates of iron production. Under some different assumptions of charcoal yield, Piketty et al. [37], estimated that 1 Mt of HM requires approximately 129,000 ha (1290 km²) of plantation area. Under Piketty et al. assumptions, 143.5 MM ha would be required to sustain the global iron industry. While both calculations may slightly differ (in above 8%), they both show the exorbitant dimension of plantation areas required if charcoal ironmaking would prosper. Even the replacement of 10-25% of fossil fuel by charcoal would require dedicating 13.27 and 33.1 MM ha. The present calculations are based

^h This is based on the assumption that charcoal is gained on sustainable basis.

on conservative production assumption (low reductant consumption, high yield of biomass, etc.), however, if other less beneficial assumptions were to be used the actual values of charcoal utilization and plantation areas would be much higher.

To illustrate the minimum plantation areas required to generate the biomass for ironmaking, the Table 7 show the available arable land in the studied countries, for instance Japan and South Korea have less land than the required to generate the biomass to sustain the present HM production. While other countries present better land availability, for instance Brazil. The substitution of fossil fuel by charcoal made from primary sources (trees) would require vast extensions of arable land, this certainly limits the potential expansion of charcoal-BFs.

6 ANALYSIS, IMPLICATIONS AND ALTERNATIVES

Despite the possible CO₂ mitigation offered by the re-introduction of charcoal in ironmaking, based on the results, the author considers very challenging the further proliferation of Charcoal-BF outside Brazil. On one hand, some countries with significant HM production (e.g. Japan, South Korea and China) lack sufficient arable land to generate the necessary biomass to partially substitute coal. Additionally, in countries such as Russia, India or USA, it is unlikely that vast extensions of arable land will be dedicated to the

growth of trees for charcoalmaking. Still to this moment, Brazil remains to be the last bastion of charcoal-BF and the trend is to reduce its market participation.

As illustrated in the Table 6, for the replacement of coal by charcoal large plantations areas are required. To dedicate such large extensions of arable land, nutrients and water just to grow a fuel, is under the present circumstances in most of the countries economically, politically and ethically challenging. In the viewpoint of the author, it would be more practical, profitable and ethical to dedicate such vast arable areas, water and fertilizer to the production of food, pulp and paper or other agricultural products.

On the economical perspective, there is a significant price difference between charcoal and coal in the studied countries. As shown in Table 8, lowest charcoal prices are found in Brazil, India and China. These countries already possess a relatively large charcoal production (see Table 2: Hot Metal and charcoal production). Using charcoal instead of coal would directly have a negative impact on the production cost of HM.

Finally, as mentioned before it is technically not feasible to completely fuel with charcoal a BF with a capacity exceeding 600 m³, principally due to the poor mechanical resistance of charcoal.

As shown in Figure 3, Mathieson estimates that a net CO₂ emissions reduction of 32-58% (0.70-1.26 t CO₂ / t Crude Steel) can be attained through the incorporation of charcoal to the process. From all investigated propositions

Table 5. Estimated biomass required as function of charcoal replacement rate. (Unit: millions of tons biomass)

Country	China	Japan	Russia	India	Korea	USA	Ukraine	Germany	Brazil	Total World
	MMt	MMt	MMt	MMt	MMt	MMt	MMt	MMt	MMt	MMt
100%	2,353.35	291.22	180.67	171.72	149.19	114.84	101.96	96.60	96.24	3,979.72
25%	588.34	72.80	45.17	42.93	37.30	28.71	25.49	24.15	24.06	994.93
10%	235.33	29.12	18.07	17.17	14.92	11.48	10.20	9.66	9.62	397.97

Table 6. Estimated plantation areas required as function of charcoal replacement rate. (Unit: millions of hectares of plantation)

Country	China	Japan	Russia	India	Korea	USA	Ukraine	Germany	Brazil	Total World
	MMha	MMha	MMha	MMha	MMha	MMha	MMha	MMha	MMha	MMha
100%	78.44	9.71	6.02	5.72	4.97	3.83	3.40	3.22	3.21	132.66
25%	19.61	2.43	1.51	1.43	1.24	0.96	0.85	0.80	0.80	33.16
10%	7.84	0.97	0.60	0.57	0.50	0.38	0.34	0.32	0.32	13.27

Table 7. Available arable land per country [36]. (Unit: Millions of hectares plantation)

China	Japan	Russia	India	Korea	USA	Ukraine	Germany	Brazil
MMha	MMha	MMha	MMha	MMha	MMha	MMha	MMha	MMha
103.4	4.36	121.78	159.65	1.64	174.45	32.45	11.90	59.00

Year of data. 2003: China, Japan and Brazil / 2005: USA, Russia, India, South Korea, Ukraine and Germany.

Table 8. Cost of Coal and Charcoal per country (2012) [38]. (Unit: USD/t Charcoal)

Country		China	Japan	Russia	South Korea	India	Brazil	USA	Ukraine	Germany
Coal	USD/t	134	135	121	134	120	117	124	121	125
Charcoal	USD/t	330	510	570	375	320	270	360	370	480

[16,22-34], the BF tuyere injection (Bio-PCI) appears to be the most feasible alternative to reduce in a quarter the CO₂ emission of the BF process. With the Bio-PCI small grinded particles of charcoal could be injected through the PCI rigs in BF.

As previously mentioned, some limiting factors for a further deployment of charcoal in ironmaking are: availability of large plantations areas, biomass availability and economic factors. Partially all these limitations could be offset to a certain degree with the use of agricultural and forestry residues (residual biomass), in substitution of primary wood (e.g. logs). Sources of residual biomass may include agriculture residues (i.e. stalks, stover, chaff, etc.), forestry residues (i.e. tree tops, branches, slash, etc.), and mill residues (i.e. sawdust, scraps, pulping liquors, etc.). Arguably the residual biomass allows generating multiple products with a reduced demand for land [39].

7 CONCLUDING REMARKS

The low crushing resistance of charcoal makes improbable the complete substitution of fossil fuels by charcoal worldwide. Thus, it is estimated that a feasible rate of charcoal substitution is 10-25% of the total energy utilization in the blast furnace process.

The replacement of 10-25% of the fossil fuels in blast furnaces may assist to reduce the CO₂ emissions in 229-572 MMt CO₂ worldwide. However, to attain these positive results there would be required to produce 46-115 MM t of charcoal.

Additionally, it would be necessary to dedicate 13-33 MM ha of arable land to the production of biomass. The large extension of plantation areas may reduce the attractiveness of charcoal-ironmaking.

Few countries outside Brazil, present similar conditions to allow of blast furnaces based 100% in Charcoal. Therefore, the assessment of alternatives uses of charcoal in the iron-and steel- making process becomes mandatory.

The injection of small biochar particles in the blast furnace PCI rigs appears a feasible and economical future alternative to reduce the CO₂ emissions in the ironmaking process.

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