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BIO-PCI, Charcoal injection in Blast Furnaces: State of the art and economic perspectives(•)

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Abstract The injection of grinded particles of charcoal through the tuyeres in Blast Furnaces, here coined Bio-PCI, presents as an attractive and plausible alternative to significantly reduce the CO_2 emissions generated during hot metal production. In this contribution a summary of the technological fundaments, benefits and limitations of the incorporation of Bio-PCI is presented. Additionally the principal economic challenges of renewables fuel in ironmaking are exposed, with especial interest in the main productions costs of charcoal making. In this sense, a strategic question arises: can the residual biomass drive the emergence of Bio-PCI?, our analysis leads to conclude that the use of residual biomass (e.g. agricultural and forestry residues) may significantly reduce the production cost in 120-180 USD/t in comparison to primary woods sources, this naturally increment the economical attractiveness of Bio-PCI substitution.

Keywords Bio-PCI; Charcoal; Pulverized Carbon Injection (PCI); Residual biomass.

BIO-PCI, Inyección de carbón vegetal en Altos Hornos: Estado del arte y perspectivas económicas

Resumen La inyección de carbón vegetal por toberas en Altos Hornos, aqui denominada Bio-PCI, se presenta como una forma atractiva y realista de reducir significativamente las emisiones de CO_2 generadas durante la producción de arrabio. En esta contribución se presenta un resumen de los fundamentos tecnológicos, los beneficios y las limitaciones de la incorporación de la tecnología del Bio-PCI. Adicionalmente se exponen los retos económicos que enfrentan los combustibles renovables a los fósiles, con especial interés en los principales costos de producción del carbón vegetal. En este sentido se plantea una pregunta estratégica: ¿puede la biomasa residual impulsar el desarrollo de la Bio-PCI?. Nuestro análisis conlleva a concluir que la utilización de biomasa residual (residuos forestales y agrícolas) puede reducir sensiblemente el costo del carbón vegetal entre 120-180 USD/t en comparación con biomasa primaria, incrementando su competitividad frente al carbón mineral.

Palabras clave Bio-PCI; Carbón vegetal; Inyección de carbón pulverizado (PCI); Biomasa residual.

1. INTRODUCTION

There is a significant pressure over the iron and steel industry to reduce its carbon emissions. Recently it was calculated that the steel making process consumes 20% of the total industrial global demand being also responsible for 30% of the world's CO_2 emissions[1]. As we evidence the effect of Green House Gases (GHG) on global warming, it becomes mandatory for metallurgists to develop rational initiatives to minimized CO_2 emissions and incorporate carbon neutral reductants into the process to substitute other fuels from fossil sources (coke, coal, oil, natural gas, etc.). In 1999 the International Iron & Steel Institute (currently Worldsteel) made a study on the energy use in the steel production[2], the study revealed that 12.2 - 12.3 GJ/t steel from the total energy need of 17.3 - 18.6 GJ/t steel are consumed in the Blast Furnace (BF).

1.1. Bio-PCI: fundaments, benefits and limitations

Recent technological improvements in the ironmaking technology have resulted into a development of diverse

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means to control and minimize heat losses and optimize fuel utilization in the BF, an example is the establishment of the Pulverized Coal Injection (PCI) technology. According to Schmöle *et al.* the coke rate utilization in German BFs decreased from 408 kg/t hot metal (HM) in 1990 to 352 kg/t HM in 2008, through increased coal injection rates from 50 to 124 kg/t HM [3]. The PCI technique basically consists in the injection of grinded particles of carbonaceous content, the injection is not limited to coal or charcoal, other fuels are also been currently used in the industry, for instance oil (e.g. ALGOMA), natural gas (e.g. SEVERSTAL &NLMK) and tar (e.g. JFE Steel Fukuyama)[4 and 5].

Charcoals produced from wood were the sole fuel used in BF until 1735, when Darby developed the process of cokemaking, this technological innovation resulted into a fuel/reductant with greater mechanical resistance and lower kinetic of reaction[6]. The introduction of coke in BF led to a major increase in the productivity, as coke based BF could operate with larger shafts. Since that time the ironmaking process in BF is been associated with high rates of coke and coal consumptions, the key driving forces for the emergence of coke based BF were the relatively low cost of coal, large availability and metallurgical benefits.

Examining the metallurgical benefits of coke, it is acknowledged that it simultaneously fulfils key tasks in the BF operation: delivers the energy for processing (*acts as fuel*), serves as a reducing agent for iron oxides (*acts as a reductant*) and supports the burden (*acts as a mechanical stabilizer*), to the moment of writing this work no other fuel presents similar characteristics. Nevertheless, cokemaking is a rather harmful process for the environment, as in the manufacture of 1 million tons of coke about 7,000 tons of pollutants are emitted to the atmosphere[6].

Focusing on the biomass utilization in ironmaking, it is a sustainable reductant that shows attractive characteristics to metallurgists, principally due to its carbon neutrality; the char gained from wood, livestocks or forestry residues, also known as biomass char, charcoal or biochar, is regarded as renewable due to the carbon cycle via wood growth (biomass generation) which is comparatively shorter (5 to 10 years) than that of fossil coal (around 100 million years)[7]. For the purpose of the present work, biochar is defined as the carbonised biomass gained from sustainable sources, as from the ecological viewpoint charcoal from deforestation has a more negative environmental impact than fossil fuels. Biochar differentiates from the general term: charcoal, as biomass for charcoal production can be sourced out from sustainable plantations or native forest, according to Carneiro 31.5% of the charcoal consumption in Brazil in 2010 use native forest[8].

According to Nascimiento *et al.*[9], in Brazil there are currently 163 charcoal based BF, from their operation it is known that their thermal level is 100-150 °C less than coke based BF, due to their lesser heat losses and lesser refractory wear[9]. Additionally charcoal based BF operated with up to 50% lesser slag volume, which reduces the energy consumption for the slag fusion. Hot metal gained out of charcoal have reduced sulfur content (>0.012%) and generates lesser SO_2 emissions[7]. However, currently the hot metal production based solely on charcoal is only limited to areas with no mineral coal, such as Minas Gerais, Brazil, since furnace sizes and production are capped by the relatively low compression resistance of the charcoal.

Academical researchers have investigated different means to introduce charcoal in the steel process (Fig. 1), e.g. as composite with iron ore for BF burden[10 and 11], substitute of coal for cokemaking[12], steel recarburazer[13-15], pelletizing of charcoal fines for BF feed[16] and more relevant to the present work the injection of grinded particles into the BF via tuyeres[13 and 17-22], here coined Bio-pulverized charcoal injection or Bio-PCI.

The Bio-PCI proposition is quite similar to the well-established PCI technology, the purpose is to inject small particles of charcoal or biochar into the BF though the tuyeres, in order to reduce coke consumption. The basic and key difference is the utilization of a renewable carbon sources, e.g. biomass, instead of fossil coal, coke fines, oil or natural gas. The key purpose of Bio-PCI is to mitigate the CO_2 emissions of the BF process (see next section). Previous contributions argue that Bio-PCI may be a feasible and sustainable initiative to increment the sustainability of ironmaking of without compromising the process, nevertheless to our knowledge charcoal is only been injected at Gusa Norseste, Usipar and CISAM at injection rates of 50-160 kg/t HM in charcoal based BFs[9 and 23].

In the view point of the authors Bio-PCI is in theory and praxis not only plausible, but also would bring additional benefits to the process:

CO_2 abatement potential: there is a consensus in the literature about the potential CO_2 saving of biomass utilization in steelmaking. In this sense Norgate and Langberg[24] using a Life Cycle Analysis assessed the potential of CO_2 mitigation in integrated steel processing, based on their estimation 4.5 kg CO_2/kg steel could be saved, based on a complete fossil fuel substitution by renewable charcoal. Mathieson[13] estimated the net emissions saved with the implementation of Bio-PCI between

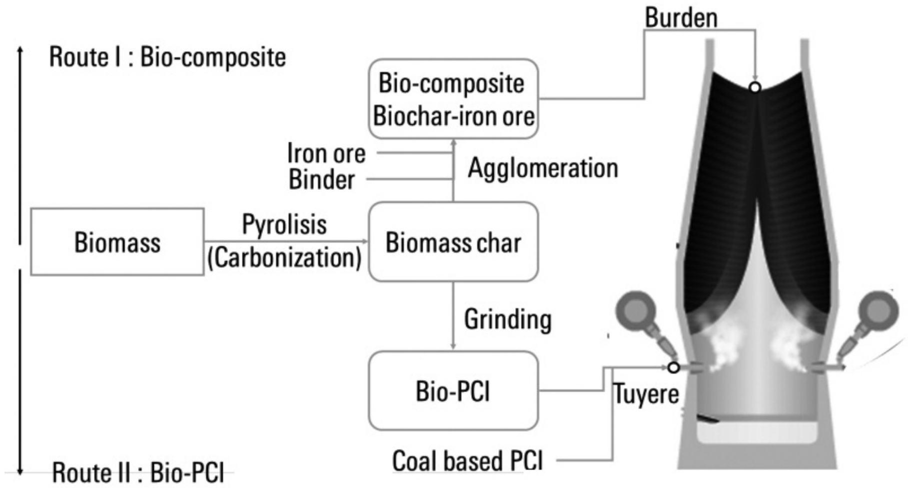

Figure 1. Alternative routes of the biomass utilization in Blast Furnace.

Figura 1. Rutas alternativas para la utilización de la biomasa en Altos Hornos.

0.4-0.6 t-CO_2/ t crude steel (19-25%), while Hanrot *et al.*[25] calculated the mitigation potential in 28% with a rate of 200 kg Bio-PCI /t HM. To illustrate the case of CO_2 abatement, it was calculated a Bio-PCI substitution in BF based on actual processing parameters among selected producers, the results are presented in figure 2, where CO_2 reduction accounts from 0.28 to 0.59 t CO_2/t HM (18.0 to 40.2%), when Bio-PCI are used instead of fossil coal and natural gas[26].

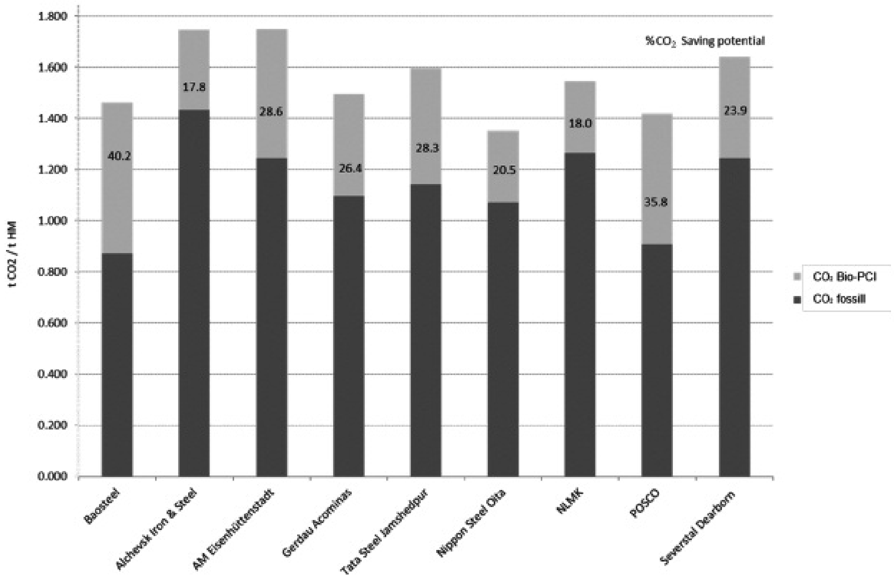

Figure 2. Estimated CO_2 saving potential using Bio-PCI in selected Blast Furnace[i] [26].

Figura 2. Estimación del ahorro potencial de emisiones de CO_2 utilizando Bio-PCI en Altos Hornos seleccionados[i] [26].

i) Alchevsk Iron and Steel BF 1 (Ukraine) & Severstal Dearborn BF C (USA) injects a mixture of NG and PCI, while NLMK (Rusia) injects only natural gas, Feliciano & Matthews[26].

Lower impurity content: in charcoal the contents of sulphur and phosphor are comparatively low, which results into a better quality of hot metal (Table I). Former operations in Wundowie (Australia) reported sulphur (S) and phosphor (P) contents of 0.015% and 0.03%, respectively)[27]. In a visit of the author to ACEPAR (Paraguay), it was verified that hot metal presented a composition of 0.03% and 0.15% of sulphur and phosphor, respectively.

Ash content: previous analysis demonstrate that the ash content in charcoal can be lower than in coke and fossil coal (Table I), moreover industrial experience on charcoal based BF indicates that less than a half slag is generated in this process[28], consequently we estimate that the Bio-PCI may also result in lesser slag generation. The ash in charcoal is highly dependent on the feedstock species, for instance in rice hulls ash content can be 41.34%, while in pine woods is only 0.69% [29]. A report of FAO (1983) [27] on charcoal utilization on BF indicates that the optimum range of ash content should be 0.24-1.5%.

High reactivity: charcoals are highly porous with large specific area, which improves its reaction velocity. In a series of investigations Ueda & Ariyama[19] and Ueda *et al.*[10 and 18] studied the velocity of reaction of samples of coke, PCI and biochar carbonized at 300 °C and 500 °C the combustion, the behavior of the samples was studied under the rapid heating by laser and samples were photographed by a high speed CCD camera. The results showed that similar velocity for all samples, 250 msec, consequently Ueda *et al.* concluded that "the combustibility of the biomass char in the raceway is similar to that of pulverized coal", these results concord with those attained by Machado *et al.* and Mathieson *et al.*[13 and 21].

Together with the technical advantages, there exist practical limitations to Bio-PCI. Firstly it possesses lesser heat capacity than normal coal, due to the higher amount of oxygen compared to coke, however this could be partially adjusted with an increase in temperature or pressure during the pyrolysis. Secondly, the low crushing strength of charcoal does not allow a complete substitution of coke. Therefore the maximum injectable value of Bio-PCI in the BF is similar to currently used PCI rates, 100-220 kg_{PCI}/t HM. Thirdly, as charcoal tends to be porous, this hinders the pneumatic conveying and makes difficult the injection at high rates[30]. Additionally in experiments carried out in Bluescope, Australia, it was reported that the pulverized charcoal from a vertical mill contained a large proportions of coarse grains (3-5 mm), thus a screening was necessary to concentrate particles under 210 μm. An additional limitation refers to high alkali content, for instance charcoal from Malle trees possess 15.4% K_2O and 6.1% Na_2O [27]. The amounts of alkalis (e.g. K_2O, NaO) should be minimized in the blast furnace charge as they evaporate and infiltrate the refractory lining, reducing the campaign of stack. Finally a more determining issue can be the price difference between the fossil and renewables reductants, the next section will build on this aspect.

2. ECONOMIC CHALLENGES OF Bio-PCI DEPLOYMENT

While the technical benefits and limitations of charcoal injection in BF (Bio-PCI) have been subject of analysis in the metallurgical inquiry, the economic prospects of Bio-PCI deployment have been less analyzed. The present section aims to illustrate some of the challenges that bio-fuel may encounter to substitute fossil based fuels in ironmaking.

Starting with the price of charcoal, it has been traditionally more expensive than fossil based coal, in a survey carried out in a previous investigation by the authors among 24 charcoal producers and traders in China, Japan, Russia, South Korea, India, Brazil,

Table I. Chemical composition of coke, coal and charcoal[17]

Tabla I. Composición química del coque, carbón mineral y carbón vegetal[17]

	Fixed carbon	H	O	N	S	Moisture	Ash	Volatile Matter
				Wt.%				
Coke	88.00	0.35	0.50	0.40	0.60	4.94	9.63	3.00
Coal	82.80	2.31	3.30	0.90	0.42	2.30	10.27	8.60
Charcoal	80.30	2.68	-	0.38	0.02	2.30	0.57	19.10

Table II. Cost of coal and charcoal per country[26]

Tabla II. Coste del carbón mineral (coal) y vegetal (charcoal) por país[26]

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

USA, Ukraine and Germany (the top 9 hot metal producing countries)[26], it was revealed that charcoal prices ranged between 270-570 USD/t (posted in Table II), while the prices of coking coal have been 117-135 USD/t. Nevertheless, the cost of most of the commodities fuels have importantly rise in the last years, reaching record prices of 151 USD/t in the 3th quarter of 2009 for coking coal and 192.9 USD/t for thermal coal in 2008, similarly the price of iron ore has increased in the past decade.

The price increment observed in recent years (mainly between 2004-2008 and after 2009) has been associated with the growing appetite for energy of emerging countries, principally China and India. To illustrate the price difference between charcoal and coal, the table II depicts the price of fossil coal and charcoal among the largest iron producing countries in the world[26], in practical terms the charcoal is approximately between 130-370% more expensive than mineral coal, with Brazil showing the lowest cost for charcoal for metallurgical applications.

In our viewpoint the utilization of fossil or renewable fuels in the BF process is ultimately an economic decision, thus the significant price difference between mineral coal and charcoal, may have hindered a broader utilization of charcoal in ironmaking applications. This consequently urges to look for alternative and rational options to reduce the cost of production of charcoal for BF injection, according to previous calculations when charcoal are injected instead of coal, the cost of hot metal production increases between 5-16% [26].

Previous analyses of the economic prospects of charcoal utilization in ironmaking has focused on cost of carbon taxes to make the renewable fuel substitution feasible, in this respect based on a price of 90 USD/t for metallurgical coal, Norgate and Lamberg[24] argue that carbon tax in the order of 30-35 USD/t CO_2 would be required. Focusing on the perspectives of Bio-PCI among top iron producers, the authors determined that a carbon tax between 47-199 USD/t CO_2 would be needed for Bio-PCI to be competitive. In this investigation it was found that lower carbon tax cost would be necessary in Brazil, India and China, due to low cost of charcoal[26].

Yet another alternative to reduce the price difference between charcoal and coal lays on the charcoal production. There are few peer-reviewed articles available on the subject of production cost of charcoal; in a large simplification the production cost structure of charcoal can be summarized in three mayor parts: biomass cost, carbonization/pyrolysis costs and transport cost. This may prove to be simplistic, and a further elaboration of the production cost of charcoal would be needed, taking into account the electricity co-product credit and capital expenditures.

Focusing on the transport cost, they directly depend on the distance of charcoal production to the iron mills, for instance in Brazil sustainable plantations of eucalyptus exist in the vicinity of iron plants to provide charcoal to the local hot metal production in Minas Gerais[25]; this is however relative minor cost in comparison to biomass and pyrolyzation costs, previous study cases indicate a cost of transport between 13-20 USD/t [24 and 31].

There are different carbonization processes available for the charcoal making, their features vary according the conditions of the applications. Table III presents a summary of a broad review and critique made by García-Pérez *et al.*[32] of the principal characteristics of the pyrolysis reactors used presently in the production of charcoal. For instance earth kilns are traditional, robust, simple, *homemade* options for carbonization, with a relatively low capital investment. But the attainable charcoal yield in earth kiln is quite limited. On the other hand, retorts provide good productivity with continuous feeding (e.g. *wagon retorts*), nonetheless the capital investment for such kilns tends to be prohibitive for rural charcoal producers. Finally there are available portable converting technologies (e.g. *small retorts*), which conveniently permit to bring the furnace to the plantation areas. Two other important parameters in the selection of the carbonization process are the heat transfer rate (slow and fast pyrolysis) and raw material usable (primary wood or biomass residues).

References on production of charcoal in continuous retorts reported that carbonization accounts of 27-33% of total production cost[24 and 31].

However, the last and arguably most significant expenditure in charcoal making is represented by the biomass cost. The table IV posts some reported charcoal cost and their respective biomass cost and source, the next paragraph builds on this topic.

As table IV shows, between 10.9-67.6% of the total charcoal production cost is represented by biomass, the biomaterials use in the carbonization can come from primary (logs) or from secondary sources (agricultural and forestry residues). Although the charcoal cost structures posted in references A, B, F & G date from 1985 and cannot be directly compared in price with others more recent references (C, D & E), it is important to notice the actual relative biomass cost in the charcoal production. In this sense, lower relative biomass cost arise from charcoal manufactured out of secondary sources (forestry and agricultural residues), this means a relative biomass cost ranging between 10.9-32.9%, references F, G & H in table IV;

Table III. Characteristics of pyrolysis reactors[32]

Tabla III. Características de los reactores para pirólisis[32]

				Retorts			Wood logs Converters	
	Earth kiln	**Cinder Block**	**Large Kilns With Recovery of Pyrolitic Vapors**	**Small retorts**	**Retorts with By-product recovery**	**Wagon Retort**	**Rechert converter**	**SIFIC process**
Final Product	biochar	Biochar	Biochar, bio-oil and gases	Biochar	Biochar, bio-oil and gases	Biochar, bio-oil	Biochar	Biochar
Heat transfer rate	slow pyrolysis	slow pyrolysis	slow pyrolysis	slow pyrolysis	slow pyrolysis	slow pyrolysis	slow pyrolysis	slow pyrolysis
Mode of operation	batch	batch	semi-batch	semi-batch	semi-batch	Continous	semi-batch	Continous
Heating method	auto-thermal	partial auto-thermal	partial combustion, contact with gases	indirect heat	indirect heating thorugh the walls	indirect heat	Direct contact with hot gases	Direct contact with hot gases
Construction material	earth	cinder, bricks, concrete and steel	bricks and steel	bricks and steel	bricks and steel	Steel	steel	steel
Portability	built in place	stationary	stationary	portable	stationary	stationary	stationary	stationary
Reactor Position	horizontal/vertical	horizontal	horizontal	horizontal	horizontal	horizontal	vertical	vertical
Raw Material	Primary wood	Primary wood & Biomass Residues	Primary wood	Biomass residues	Primary wood & Biomass Residues	Primary wood	Primary wood	Primary wood
Loading and discharge	manual	manual, mechanical	manual, mechanical	manual	manual	use of wagon	mechanical	mechanical
Size of kiln	small/medium	small/medium	Large	small	small	small to large	large	large
Ignition method	small kindled	small kindle wood, burning oil	small kindle wood, burning oil	external combustion with leaves and bark	external cosbustion chamber	heating with external combustion chamber		hot gases in an external oven
Process control	observing color of produce vapors	observing color of produce vapors or temperature measurements	observing color of produce vapors or temperature measurements	observing color of produce vapors	direct measurement of temperature	direct measurement of temperature	direct measurement	direct measurement of temperature

	Wood chips Converters					
	Herreshoff multiple-hearth furnace	**Rotary Drums**	**Auger reactor**	**Moving agitated bed**	**Shelf reactors**	**Paddle pyrolysis kiln**
Final Product	Biochar	Biochar, heat	Biochar, bio-oil and gases	Biochar, bio-oil	Biochar, bio-oil	Biochar
Heat transfer rate	slow pyrolysis	slow pyrolysis, fast pyrolysis	slow pyrolysis, fast pyrolysis	slow pyrolysis, fast pyrolysis	slow pyrolysis, fast pyrolysis	slow pyrolysis
Mode of operation	Continous	Continous	Continous	Continous	Continous	Continous
Heating method	Direct contact with hot gases	Direct contact with hot gases	heating through walls	Indirect heating	Indirect heating	indirect heat
Construction material	steel	steel	steel	steel	steel	steel
Portability	stationary	stationary	stationary	stationary	stationary	stationary
Reactor Position	vertical	Horizontal	Horizontal	Horizontal/vertical	Horizontal/vertical	horizontal
Raw Material	Biomass residues	Biomass residues	Biomass residues	Biomass residues	Biomass residues	Biomass residues
Loading and discharge	mechanical	mechanical	mechanical	mechanical	manual, mechanical	mechanical
Size of kiln	large	small	small	medium, large	small	small
Ignition method	external combustion chamber to produce hot gases		external combustion chamber	external oven		external heater
Process control	direct measurement of temperature	direct measurement of temperature	direct measurement of temperature	direct measurement of temperature	direct measurement of temperature	direct measurement of temperature

Table IV. Charcoal production cost analysis[24, 31 and 33]

Tabla IV. Análisis de los costes de producción de carbón vegetal[24, 31 y 33]

Reference (year)	A [31] (1985)	B [31] (1985)	C [33] (2011)	D [33] (2011)	E [24] (2009)	F [31] (1985)	G [31] (1985)	H [33] (2011)
Carbonization unit	Brick Kiln	* retort			* retort	* retort	Brick	
Biomass source	Primary Wood	Primary Wood	Primary Wood	Primary Wood	Primary Wood	Forest residue	Forest residue	Agricul. residue
Biomass USD/t	65	43.4	390	91.6	260	13.4	30	83
Relative biomass cost (%)	47.7	27.6	50.0	36.0	67.4	10.9	32.9	30.5
Total charcoal cost USD/t	136.1	157.1	780	254.6	386	122.6	91.1	272
	Cells in gray: Primary wood					Cells in white: biomass residues		

* Continuous

while in the cases charcoal produced from primary wood sources the relative cost of biomass is significantly higher: 27.6-67.4%, references A, B, C, D & E. This leads to indicate that biomass from secondary sources may help to reduce the price difference between fossil coal and charcoal, in the following part this hypothesis will be studied in detail.

The review and analysis of previous works on Bio-PCI leads to indicate that the injection of charcoal particles into BF is not only technically feasible, but it may bring benefits to the quality of the hot metal due to the lower impurity content, with a significant CO_2 abatement to the ironmaking process. Arguments on charcoal utilization point out the lack of commercial attractiveness when renewable charcoal is compared to fossil coal, in our viewpoint this lack of competitiveness has certainly hindered the potential of a wider use of charcoal in BF, and however charcoal from biomass residues can substantially reduce the total production cost of charcoal. In this sense, the next section provides arguments about the usage of residual biomass in ironmaking.

3. ANALYSIS: CAN THE RESIDUAL BIOMASS DRIVE THE EMERGENCE OF BIO-PCI?

The production of iron utilizing BF and coke as major reductant is one of the most intensive carbon-emitting industrial processes on the planet. Even with innovations such as PCI, the level of carbon emissions remains unacceptably high. Substituting bio-derived charcoal for coal-derived coke presents itself as an important alternative, because the charcoal so introduced can be carbon neutral, and the carbon emissions from the steelmaking process merely replace the carbon absorbed as the biomaterial grows. In this regard, biomass based energy (bioenergy) is called to offset some part of the energy portfolio currently occupied by fossil fuels in iron and steelmaking, the automobile and transportation industry is well advanced in the utilization of biofuels.

According to figures of Worldwatch institute, in 2010 the total world ethanol production was estimated in 86 bn. liters, with USA and Brazil as the world's top producers (about 90% of global production). The European Union is largest biodiesel producer, accounting for 53% of all biodiesel production in 2010 [34]. The International Energy Agency has an objective to reduce the dependence on fossil fuel for transportation, by the replacement of 25% of global energy demand with biofuels[35].

Conversely the response to the climate change demands a restructuration of the fuel portfolio in ironmaking, with biomass and charcoal likely to play a more determining role in the future, thus recent investigations has focused on proving the feasibility of biomass utilization in BF (see 1st section of the present work).

While the use of biomass in BF can provide a significant CO_2 abatement, the biofuels are not absented of criticism. Profound concerns exist about the potentially negative consequences of biofuel use and their exploitation. For instance it is argued that food price has increased due to bioenergy demand[36 and 37]. Additionally, it is feared that an increment of biomass crops could results into an increase in the conversion of natural areas to agricultural use, with a consequent lost in biodiversity[38].

Large plantation areas would be required if charcoal replaces partially coal in the ironmaking process. In order to provide a guideline, an estimation was made on the total plantation areas needed to replace completely fossil coal injected in BF. The estimations on table V were issued under the assumption of an injection rate of 150 kg $_{charcoal}$/t HM, a charcoal yield of 8.6 $t_{biomass}/t_{charcoal}$ and a biomass yield of 30 $t_{biomass}$/ha/y. Under these constrains, it was calculated that 165.1x10^3 Mt of charcoal would be necessary to completely replace fossil PCI by Bio-PCI (Table V). Additionally around 80x10^3 km^2 hectares of plantation area would be needed for biomass generations (Table V last column right), in comparative terms this is an area larger than Australia. To dedicate such vast arable areas, fertilizer and water to the production of charcoal instead of food presents a significant economical challenge and ethical dilemma.

In our view, some of the criticism and skepticism against biofuels, might be offset to a certain degree with the use of agricultural and forestry residues, instead of primary wood sources. 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 to produce multiple products with a reduce demand for land[40].

Considering the worldwide amount of residual biomass, which mainly arises from agriculture and forestry production, it can be argued that residual biomass a potentially large and under-utilized resource. Gregg and Smith[40] estimated that residual biomass can supply nearly 50 EJ/yr to the global energy market (Table VI), if all sustainably collectable residues in 2005 were converted into energy. Logically, major agricultural producers such as China, USA, India & Brazil possess a large energy potential from residual biomass (Table VI), coincidentally these countries also account for the 67% of the total global iron production using BF. This together with the relative low cost of charcoal lead us to conclude that Brazil, India and China were in prime position to incorporate the Bio-PCI into their production[41].

In our point of view, the use of Bio-PCI is ultimately an economic decision, influenced by competing coal prices. Therefore, the authors electronically consulted 77 producers and traders of primary wood and biomass residues, in order to assess the market price of the principal raw material for charcoalmaking. Table V presents the prices reported, the bands varies from minimum to a maximum offered price, and an average price of primary wood (Eucalyptus, Hardwood, etc.) and biomass residue (biomass briquettes, palm kernel, sawdust, etc.).

As shown in table VII, primary wood prices ranks between 303-395 USD/t, while biomass residues prices were between 72-155 USD/t, thus residual biomass costs are approximately 50% of primary woods, without dedicating large extensions of arable land to its development.

It is acknowledged that previous contributions recommend to use hardwood from primary sources to produce charcoal for BF applications[7 and 31], because direct feed of charcoal in the BF burden (from throat not through tuyeres) requires to use lump pieces of char with high mechanical resistance. In

Table V. Hot Metal production[39], Bio-PCI utilization and plantation areas

Tabla V. Producción de arrabio[39], utilización de Bio-PCI y áreas de plantación

Country	China	Japan	Russia	South Korea	India	Brazil	USA	Ukraine	Germany
Hot Metal TMt (2011)	629,693	81,028	48,120	42,218	38,900	33,243	30,233	28,867	27,795
Bio-PCI § TMt	94,454	12,154	7,218	6,333	5,835	4,986	4,535	4,330	4,169
Plantation area (Km^2) §§	45,782	5,891	3,499	3,070	2,828	2,417	2,198	2,099	2,021

§ Bio-PCI calculation based on injection rates of 150 Kg/ton HM.
§§ Plantation areas calculated under followings constrains: 8.6 ($t_{biomas}/t_{biochar}$), biomass yield of (0.3 t $_{biomass}$/km^2/y.

Table VI. Potential residue biomass energy for 2005 (EJ/yr)[40]

Tabla VI. Potencial energético de biomasa residual para 2005 (EJ/yr)[40]

Residue Source	Wheat	Corn	Rice	Other Grain	Oil crops	Sugar crops	Misc crops	Forest	Mill	Total
China	1.31	0.76	2.07	0.10	0.92	0.41	0.45	0.35	0.77	7.13
USA	0.49	2.39	0.12	0.15	0.53	0.13	0.10	0.47	1.07	5.44
India	0.45	0	1.31	0.08	0.28	1.10	0.24	0.64	0.77	4.86
Brazil	0	0.01	0.13	0.02	0.20	1.97	0.30	0.51	0.59	3.73
Global total	5.58	4.16	6.51	2.01	7.41	6.17	3.89	5.14	7.85	48.71

this sense, we don't recommend using residual biomass for direct burden feeding either, however, for the purpose of Bio-PCI (small particles of charcoal injection), no significant compression strength resistance is required. In addition to this, it is certainly recognized that a number of logistical and technological challenges will need to be addressed in order to use residual biomass, for instance, when the principal characteristics of primary and residual biomass are compared (Table VIII), it is noticed that Eucalyptus and Acacia present larger density and higher calorific values, nevertheless the calorific value is still sufficiently attractive (>15.9 MJ/kg) for the objective of charcoal making.

The present work intends to be of indicative nature of the directions for future research in the deployment of Bio-PCI, we believe this is important to generate prudent strategic decisions to shift the structure of fuel utilization in ironmaking. In the present contribution, no particular consideration was given to the specifics of individual companies and countries; instead our analysis is based upon a set of

Table VII. Survey on biomass costs

Tabla VII. Encuesta sobre costos de biomasa

Type of Biomass	No. Consulted	Minimum Price	Maximum Price	Average Price
		USD/t FOB		
Primary wood				
Diverse woods species	20	188	565	303
Eucalyptus	5	176	588	380
Hardwood	4	235	529	353
Timber	3	190	700	395
		Biomass residues		
Biomass briquettes	22	50	180	125
Palm kernel	5	45	100	72
Coconut shell	5	120	300	155
Saw dust and wood chip	4	40	160	85
Wheat straw hay	3	115	160	128
Corn straw pellets	3	110	160	144
Rice husk briquettes/pellets	3	60	100	78
Cells in gray: primary wood			Cells in white: biomass residues	

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Table VIII. Primary and residual biomass properties

Tabla VIII. Propiedades de biomasa primaria y residual

Biomass residue	Density (kg/m³)	Ash (wt%)	Caloric Value (MJ/kg))	Volatile matter (wt%)	Moisture Content (wt%)
Eucalyptus[5]	1.510	1.2	20.3	82.4	5.2
Acacia[5]	1.440	1.0	19.2	84.0	5.9
Peanut Shell pellets	900 - 1.100	<7	17.6 - 18.8	–	11.0
Saw dust pellets	–	1.00	18.8	83.5	45.0
Biomass briquettes	–	6.9	17.6	62.0 - 68.0	7.2 - 8.0
Rice husk briquettes	–	12.50	16.7	4.3	–
Wood pellets	1.100	0.50	19.2	8.0	4.5
Corn Straw pellets	1.100 - 1.300	8.00	15.9 - 17.6	–	9.0

Cells in gray: primary wood   Cells in white: biomass residues

general rational assumptions. Thus, our analysis leads to infer that the utilization of residual biomass may assist to reduce the production cost of charcoal in about 120-180 USD/t with respect to the charcoal produce with primary wood, this certainly would help to alleviate the price difference between coal and charcoal. Residual biomass combined with a carbon price to CO_2 emmision in ironmaking and electricity co-product credit during charcoalmaking may drive the emergence of the Bio-PCI.

As indicated in previous works, emerging countries with increasing iron and agricultural production, such as Brazil, India and China seem to appear as prime candidates to a broader implementation of the Bio-PCI. The amount of residual biomass likely to be used logically depends on the cost associated with collection and carbonization the residues, in this sense it has to be acknowledge that proper, well-managed structures need to be developed to create a charcoal industry to support hot metal production. An additional element is represented by the capital expenditures of the converting technologies, and the establishment of environmental incentives, i.e. carbon taxes.

4. CONCLUSIONS

— The analysis of the existing literature and industrial experiences on Bio-PCI clearly indicates the feasibility to mitigate a up to 40% of CO_2 emissions per tonne of hot metal. Besides of the obvious ecological benefit, the analysis of previous investigations shows that Bio-PCI would help to reduce the contents of sulphur in the hot metal and slag in the process compared to coke based BF ironmaking. Based on current processing conditions the maximal substitution rate can be estimated in 200-220 kg Bio-PCI/t hot metal.

— The significant difference between charcoal and coal can be reduced or alleviated by the utilization of biomass residues instead of primary wood as main raw materials for charcoalmaking, since the cost of residual biomass is approximately half of primary wood. Residual have certainly lesser density but sufficient calorific value for carbonization. With the use of biomass residues instead of primary wood, no vast extensions of land are required to sustain the charcoal production.

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