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Original Article

Charcoal injection in blast furnaces (Bio-PCI): CO_2 reduction potential and economic prospects

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ABSTRACT

The steel industry is under pressure to reduce its CO_2 emissions, which arise from the use of coal. In the long-term, the injection of pulverized particles of charcoal from biomass through blast furnace tuyeres, in this case called Bio-PCI, is an attractive method from both an environmental and metallurgical viewpoint. The potential of Bio-PCI has been assessed in terms of its CO_2 abatement potential and economic viewpoint. A cost objective function has been used to measure the impact of biochar substitution in highly fuel-efficient BF among the top nine hot metal producers; estimations are based on the relevant cost determinants of ironmaking. This contribution aims to shed light on two strategic questions: *Under what conditions is the implementation of Bio-PCI economically attractive? Additionally, where is such a techno-economic innovation likely to be taken up the earliest?* The results indicate the potential for an 18–40% mitigation of CO_2. Findings from the economic assessment show that biochar cannot compete with fossil coal on price alone; therefore, a lower cost of biochar or the introduction of carbon taxes will be necessary to increase the competitiveness of Bio-PCI. Based on the current prices of raw materials, electricity and carbon taxes, biochar should be between 130.1 and 236.4 USD/t and carbon taxes should be between 47.1 and 198.7 USD/t CO_2 to facilitate the substitution of Bio-PCI in the examined countries. In regard to implementation, Brazil, followed by India, China and the USA appeared to be in a better position to deploy Bio-PCI.

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 [1]. As it is evident the effects of green house gases (GHGs) on global warming, it becomes mandatory for metallurgists to develop rational initiatives to minimize 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 &

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Steel Institute (currently Worldsteel) made a study on the energy use in the steel production, 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) [2].

1.1. Overview of Bio-PCI: fundaments, advantages and limitations

Historically, charcoal was the only reductant used in BF until 1735, when Darby firstly introduced coke into the ironmaking process [3]. This input led to an important increase in the productivity, since coke presents better mechanical resistance that permitted BF with larger shafts. From that point of time, hot metal (HM) production has been associated with high rates of coke utilization, due to its traditional low cost, large availability and processing benefits.

From the metallurgical viewpoint, coke complies simultaneously with different tasks in the BF operation. Firstly provides the energy for processing (acts as fuel). Secondly serves as a reducing agent for iron ores (acts as a reductant). Thirdly supports the burden (acts as a mechanical stabilizer). To this moment, no other fuel presents similar characteristics. However, cokemaking is a rather harmful process for the environment, as in the manufacture of 1 million tonnes of coke about 7000 tonnes of pollutants are emitted to the atmosphere [3].

Biomass char (biochar[1]) presents attractive characteristics to metallurgists, because char gained from wood, livestock or forestry residues, is regarded as renewable since the carbon cycle via wood growth (biomass generation) is comparatively shorter (5–10 years) than to fossil coal (–100 million years) [4].

In the academic inquiry, researchers have proposed diverse uses to charcoal in the steel process, e.g. as composite with iron ore for BF burden [5,6], steel recarburazer [7–9], pelletizing of charcoal fines for BF feed [10] and injection of grinded particles into the BF via tuyeres [11–15], here coined Bio-pulverized carbon injection or Bio-PCI. However, presently the HM production based on charcoal is limited to Brazil and Paraguay, where furnace sizes and production are capped by the relatively low compression resistance of the charcoal.

From the technical perspective, the proposed Bio-PCI route is quite similar to the well-established pulverized carbon injection (PCI) technology. The basic and key difference is the utilization of a renewable carbon source instead of fossil ones, its fundamental aim is the mitigation of CO_2 emissions from the BF process. Previous works argue that Bio-PCI may be a feasible and sustainable initiative to improve sustainability of ironmaking without compromising the ironmaking process, see works of Gupta [4], Ueada et al. [12,13], Hanrot et al. [14], Gielen and Moriguchi [15].

To this moment, there are few peer-reviewed reports on the Bio-PCI utilization. One case was presented by Nascimiento et al. [16] about the charcoal-BF operation at Gusa Nordeste (Brazil), in which injection rate of 50–160 kg/t HM were reported. Similarly, in Siderurgica do Para (USIPAR) an injection system has been installed in BF1 and BF2, injections rates are expected to be 80 kg charcoal/t HM. The charcoal is obtained from the carbonization of assai seeds, an abundant biomass residue available in the region [17]. Finally, also APERAM is reported to inject charcoal at rates of 117–128 kg/t HM at the BF 2 [18].

The idea of Bio-PCI concords completely with the traditional PCI, as biochar particles have to be grinded to a size of approximately 75 μm, dried and conveyed into the shaft.

Besides the obvious carbon neutrality and its CO_2 abatement potential, the experience of charcoal based ironmaking revels the following benefits to the process:

- Lower impurity content: in charcoal the contents of sulphur and phosphor are substantially lesser than in coke (Table 1). This low impurity content results into a better quality of HM and consequently has higher market value (32–45% higher than coke based HM).
- Ash content: the ash in biochar can be lower than in coke, moreover charcoal charged in BF generates 50% less slag than coke based BF [19].
- High reactivity: biochar is highly porous, with a large specific area, this improves combustion rates. In a series of investigations Ueda et al. [12,13] studied the velocity of reaction of samples of coke, PCI and biochar carbonized at 300 °C and 500 °C, the combustion behaviour of samples was studied under the rapid heating by laser and samples were photographed by a high speed CCD camera. The results showed similar velocity for all samples (250 ms).

Together with the technical advantages, there exist practical limitations to Bio-PCI. Firstly, the low crushing strength of charcoal does not allow a complete substitution of coke in large BFs (>600 m^3). Therefore the maximum injectable value of Bio-PCI in the BF is similar to currently used PCI rates, maximum 220 kg_{PCI}/t HM. Secondly, the low bulk density of charcoal hinders the pneumatic conveying at high rates of injection [20]. Thirdly, in experiments carried out in BlueScope, Australia, difficulties were reported during the milling of charcoal, thus a screening was necessary to concentrate particles under 210 μm. An additional limitation refers to the high alkali content, for instance, charcoal from Malle trees possess 15.4% K_2O and 6.1% Na_2O [19]. Finally, a more determining issue can be the price difference between the fossil and renewables reductants, Section 2 will build on this aspect.

2. Economical constrains of Bio-PCI

While the technical benefits of Bio-PCI have been broadly studied in the metallurgical inquiry, the economic prospects of its deployment have been, to this moment, less analyzed. Starting with the cost of biochar, traditionally biochar has been more expensive than coal. The literature analysis for this work found little peer-reviewed papers. Table 2 [21–25] presents some prices of charcoal available in the literature, as shown, charcoal prices reported varied between 162 and 780 USD/t, while traditionally the prices of metallurgical coal have been 40–50 USD/t. In the opinion of the authors, a further

[1] This work defines biochar as the carbonized biomass gained from sustainable plantations, as from the ecological viewpoint charcoal from deforestation has a more negative impact environmental than fossil fuels.

Table 1 – Composition of coke, coal and biochar [11].

	Fixed carbon Wt.%	Hydrogen Wt.%	Oxygen Wt.%	Nitrogen Wt.%	Sulphur Wt.%	Moisture Wt.%	Ash Wt.%	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	2.31	0.90	0.42	2.30	10.27	8.60
Biochar	91.60	2.27	1.95	0.38	0.02	2.30	0.57	19.10

price increase in the mineral fuel commodities would help to reduce the price difference between bio and fossil fuel.

The gaining of biochar from livestock involves an *energy farming management*. This concept incorporates all the necessary steps to produce biochar (e.g. harvesting, carbonization and later grinding). As shown in Table 2, the biomass source is the biggest single cost associated with charcoal production. In this sense, hardwood from primary sources can represent a relative cost of 35% and 67% of total charcoal production cost, while charcoal from corn stover (forestry residue) is only 30.5%. Therefore, the type and source of used biomass determines the final cost of charcoal.

Chronologically, the first attempt to assess the economic perspectives of charcoal injection in BF was presented by Mathieson [20,26] in a research carried out in BlueScope, Australia. In his contribution, Mathieson proposed an assessment based on a value-in-use (VIU) methodology. For the purpose of the study, VIU was defined as the rational purchasing price for a raw material as compared with a referential coal for PCI.

Under the VIU framework, a qualitative value is estimated for a diverse number of reductants injected in the BF, such as ethanol, torrefied softwood, sub-bituminous lignite (briquettes), biodiesel, coal, charcoal (hardwood, mallee and softwood), polychar, oil, tar and natural gas. The VIU is then evaluated as a function of the cost considering more than 25 factors (costs and penalties). In his findings Mathieson argued that: “the heat and mass balance and VIU studies have established that injection of various charcoal types has favourable thermochemistry and that they have high comparative value” [26].

In another article, Norgate and Langberg [25] used an LCA methodology to indicate the potential reductions in GHG emissions resulting from charcoal substitution in steelmaking. Under the LCA framework, the CO_2 emissions of every single intermediate process of steelmaking were accounted. Additionally CO_2 credits were provided during the growth of wood, based on the life cycle inventory (LCI) proposed by Wu et al. [27] for the growth of Eucalyptus.

Norgate and Langberg estimated that under a carbon trading scheme the economic competitiveness of charcoal compared to coal could be improved. Based on price of $US90/t for coal, a carbon tax in the order of US$30–35/t CO_2 would be required in the integrated route for the overall charcoal and coal costs to be roughly equal, these calculations included charcoal electricity co-product credit [25].

VIU and LCA frameworks offer a tool for analyzing competing injection fuels, nevertheless, both methodologies can present disadvantages, for instance, a key limiting factor for the LCA method is the accuracy and availability of data, since wrong data can also mislead to inaccuracy of results. In this regard, data from generic processes may be based on averages, unrepresentative sampling, or outdated results [28]. In the case of the comparison of different BF operation, the LCA method shows rigid system boundaries that complicates the accounting for individual operation parameters. In the case of the VUI method, it is based on arbitrary provided set of 25 factors values (see original article) [20], they facilitate an analysis of diverse fuel to be utilized in a specific operation; however, the comparison of the economic benefits in different plant with diverse economic conditions makes difficult the assessment.

A third kind of framework is been used by Saxen et al. [29], Helle et al. [30], and Wikulund et al. [31,32] in the assessment of the economic potential of biomass utilization in a steel plant. Originally this method has been used for the analysis of the economic prospects of technological innovations in steelmaking (see Pettersson and Saxen) [33]. To the moment of writing this contribution, the framework proposed by Pettersson and Saxen has been applied in several works, for instance, in the estimation the potential of GHG emissions mitigation in steel production [34], top gas recycling in BF [35], steelmaking with a polygeneration plant [36], optimization of ironmaking in the BF [37,38], and BF Operation combined with methanol production [39].

In the mentioned studies, the economic assessment of the technological innovation is estimated by means of a cost objective function (*F*). *F* accounts the main cost elements involved in the production of HM such as iron bearing materials (lumps ores, pellets and sinter), fuels/reductants (coal, coke, charcoal, electricity), oxygen and carbon taxes. However, other key financial elements taxes are not taken in consideration, we will build more on that topic later.

The findings of the different works mentioned before [33–39] appeared to be more valuable for metallurgists

Table 2 – Charcoal costs reported in literature [21–25].

		Finland Suopajärvi H and Angerman M (2011)	Brazil Noldin (2011)	Brazil Fallot et al. (2008)	Australia Norgate and Langberg (2009)	USA Brown et al. (2011)
Charcoal cost	USD/to	780	254.6	162	386	272
Biomass cost	USD/to	390	91.6		260	83
Biomass type		Timber	Eucalyptus	Eucalyptus		Corn Stover

worldwide than other results based on LCA or VIU, as they take in consideration the actual thermodynamics of the BF operation, leading to a more credible and flexible method. The simulation using F could be in principle applied to any BF process leading to fairly representative and comparable economic scenarios. Consequently, the framework has been largely utilized for the assessment of a wide range of technological innovation in the ironmaking process.

Nonetheless, the method is not exempt of criticisms. Firstly, key financial elements of steel making are ignored in the model, these elements can represent up to 37.8% of the total steel production cost, according to crude steel cost model of *Steelonthenet* [40]. The costs absent in the model are: capital charges, hand labour, ferroalloys, refractories and raw material transportation to the plant. Secondly, in the previous works [29–32], the biomass pyrolysis is performed in the steelwork, while in practice charcoal manufactures are separate entities of production. Finally, the finding of previous authors appeared to be based on arbitrary selected raw materials prices, with no relation to actual raw materials cost.

In the area of bio-fuels there have been numerous investigations during the past years. However, in the opinion of the authors the analysis of the future deployment of Bio-PCI in BF should simultaneously considers its technical and economic feasibility. In this respect, it was considered necessary to complement the metallurgical inquiry with a strategic analysis to generate sustainable policies for HM production, using actual production data and cost information to generate accurate economic scenarios. Unlike the researches on the technical feasibility of Bio-PCI utilization, mostly carried out under laboratory conditions arguably independent of regional and time factors, the economic analysis of the deployment of a bio-reductant industry is closely related to regional circumstances, status of economy and geographical factors.

The review and analysis of previous works on Bio-PCI lead to indicate that it is technically feasible, and may bring benefits in the quality of the HM due to the lower impurity content, with a significant CO_2 abatement. Arguments on charcoal utilization point out the lack of commercial attractiveness when biochar is compared to fossil coal, this has certainly hindered the potential of a wider dissemination of biochar in BF. In this sense, this contribution aims to elucidate *under which conditions can be economically attractive to implement Bio-PCI technology?* And *where is such a techno-economic innovation likely to be taken up earliest?*

3. Methodology and data

For this work, a cost objective function (F) was utilized, this function allows us to measure and compare the economy of ironmaking in BF in terms of the specific costs of raw materials with a compensation for the heat capacity of top gas.

$$\begin{aligned} F = {} & 1.58[(C_{ore} \cdot M_{ore}) + (C_{pellet} \cdot M_{pellet}) + (C_{sinter} \cdot M_{sinter})] \\ & + 1.27[C_{coal} \cdot M_{coal/coke}] + [C_{charcoal} \cdot M_{PCI}] \\ & + [C_{CO_2\,Tax} \cdot M_{CO_2\,fossil}] - [P_{off\,gas} \cdot C_{el}] \end{aligned} \quad (1)$$

Actual charcoal prices were used in the calculation, the model assumes that biomass pyrolysis occurs outside the steel plant.

The model F is aimed to show how principal HM inputs prices can impact production cost, through a cost benchmarking type of approach. The estimated costs generated are not meant to represent any real BF. It is a notional and comparative figure of principal raw materials, albeit one built on representative current input costing data. Other elements such as de-capitalization, hand labour and refractories, have not been accounted in the evaluation of F.

With respect to the data, actual BF operation parameters from highly fuel efficient BF were used. The processing data used comes from the following BF: *Baosteel*, *Nippon Steel*, *NLMK*, *Posco*, *Tata Steel Jamshedpur*, *Gerdau Acominas*, *Severstal Dearborn*, *Alchevsk Iron & Steel & AM Eisenhüttenstadt* [42–49]. The off gas composition and its calorific power were calculated for each case using the BF simulation from Steeluniversity [41], as off gas generates valuable power that can be used in other areas of the steel mills. The parameters used in the calculation of F are posted in Table 3.

For the economical assessment, 29 charcoal producers and traders were consulted for charcoal spot prices in China (8), Japan (4), Russia (1), South Korea (1), India (5), USA (5), Ukraine (3) and Germany (2). The survey was carried out electronically between February and April 2012. From each country, the most representative spot price was considered for calculations. It is important to mention that the authors could not directly obtain any charcoal price from any Brazilian producer, therefore for the calculations a price of 270 USD/t was used, this price was reported by Steel Business Bulletin for charcoal based ironmaking [50]. Iron ore and pellets prices are 2010–2012 (March) average price (Metal Bulletin), while sinter prices were estimated. Industrial electricity costs were obtained from data of the International Agency of Energy [51].

The CT are posted from presently implemented regulations. This is the case of India, Germany, USA,[2] and other values reported in the media likely to be imposed in South Korea, Japan. In the literature review of this work, we could not find any determined value of CT in China, Russia, Brazil or Ukraine.

Calculations consider a complete substitution of PCI by Bio-PCI, 1 kg Bio-PCI offsets 1 kg PCI or NG; with composition of coke, coal and biochar been posted in Table 1. For the calculation a tonne of coke generates 1.18 tonnes of CO_2, while a tonne of biochar would generate 1.128 tonnes CO_2.

4. Discussion of results

4.1. Bio-PCI CO_2 abatement potential

Firstly, it is important to quantify the CO_2 mitigation prospects of Bio-PCI implementation considering a complete substitution of coal. The CO_2 abatement for the selected BF was estimated and results are presented in Fig. 1, CO_2 reduction

[2] No nationwide CT; taxes have been introduced in Colorado, California and Maryland. Value of state of Maryland been used for this paper (5 USD/t CO_2).

Table 3 – BF operational parameters [41–48].

	Unit	Symbol	AM Eisenhüttenstadt [42]	Baosteel BF3 [43]	Nippon Steel Oita [44]	NLMK [44]	POSCO [45]	Tata Steel Jamshedpur BF H [46]	Gerdau Acominas BF 2 [47]	Severstal Dearborn BF C [48]	Alchevsk Iron & Steel BF 1 [49]
Productivity	t/m^3d			2.31	2.19	2.22	2.99	2.55	2.37	3.04	2.04
Coke rate	kg/t HM	M_{coke}	414.5	290	356.3	421	302	380	365	414	477
PCI rate	kg/t HM	M_{PCI}	176.9	208	98.4	0	180	160	140	116	90
NG rate	kg/t HM	M_{NG}	0	0	0	98.7	0	0	0	23	20
Sinter	%	M_{sinter}	79.6	68.89	78.5	80e	75	70	86.9	61	74.8
Pellets	%	$M_{pellets}$	12.8	13.97	7	20e	10	0	0	37	21.4
Lump ore	%	M_{ore}	7.5	17.14	14.5	0	15	30	13.1	2	3.9
O_2 enrichment	%		2.6		0.5	6		4%			3.83
Blast temperature	°C		1150	1248	1268	1155	1196	1200	1200	1065	1037
Working volume	m^3			4350	5245		4350	3230	1750	1793	
Top gas heating value[a]	kJ/t HM		191.0	165.1	149.0	137.1	158.0	173.4	165.5	184.7	184.1

[a] Estimated values.

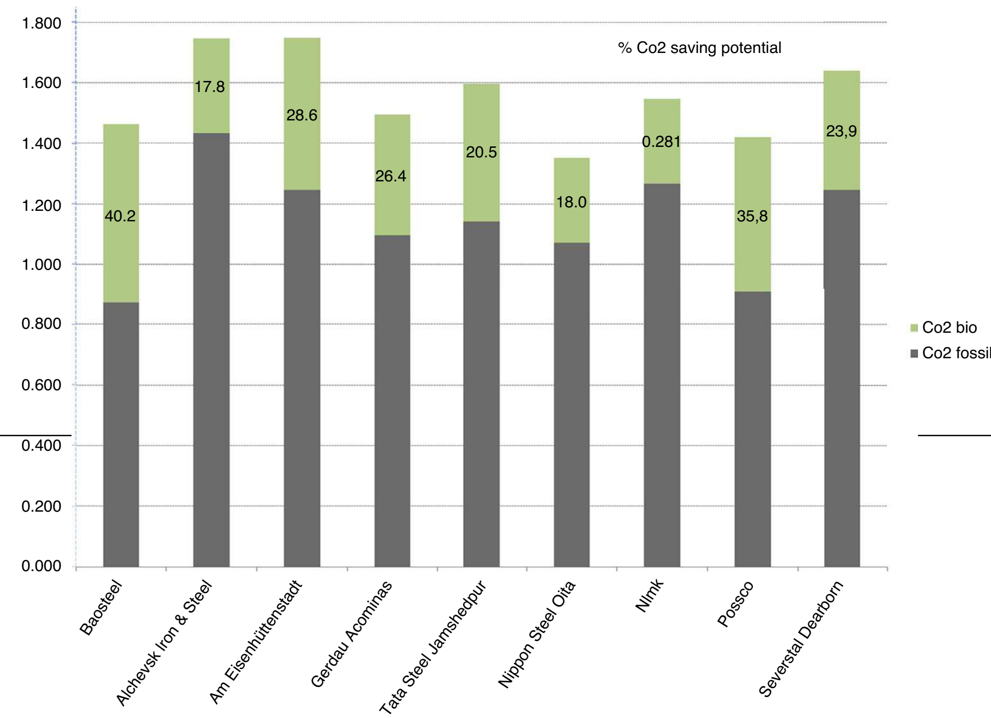

Fig. 1 – CO_2 saving potential using Bio-PCI.

accounts from 0.28 to 0.59 to CO_2/t HM (18.0–40.2%), when Bio-PCI is used instead of fossil coal and natural gas (Russia, Ukraine and USA). Naturally, BF operating with high PCI rates would profit for larger CO_2 reduction, this is the case of Baosteel, Posco and AM Eisenhüttenstadt, where injection rates of 176–208 kg PCI/t HM.

Results posted in Fig. 2, are congruent with previous mitigation values reported by Hanrot et al. [14] and Mathieson [20] 19–28% CO_2 savings. Findings lead to conclude that Bio-PCI may significantly reduce the CO_2 emissions in ironmaking.

4.2. *Cost objective function of Bio-PCI substitution*

Despite the CO_2 saving potential, the Bio-PCI incorporation would have a significant impact on the final cost of HM. When biochar completely substitutes coal as injection fuel, **F** increases between 5.20 and 16.61% as shown in Tables 4 and 5. The **F** value shows a higher dependency to the charcoal cost that to the existing CT.

Gerdau Acominas presents a production cost difference of 5.20% due to a relative low charcoal price in Brazil, this finding is congruent with market price of charcoal based HM in the country, which is 35–45% more expensive than coke based HM [18].

In the case of POSCO, *F* increases in 6.48% due to the CT aimed to be implemented (33.25 USD/t CO_2). On the other hand, NLMK and Baosteel show a large increment in production cost due to the absence of any CT, relatively expensive price of charcoal and low cost of industrial electricity.

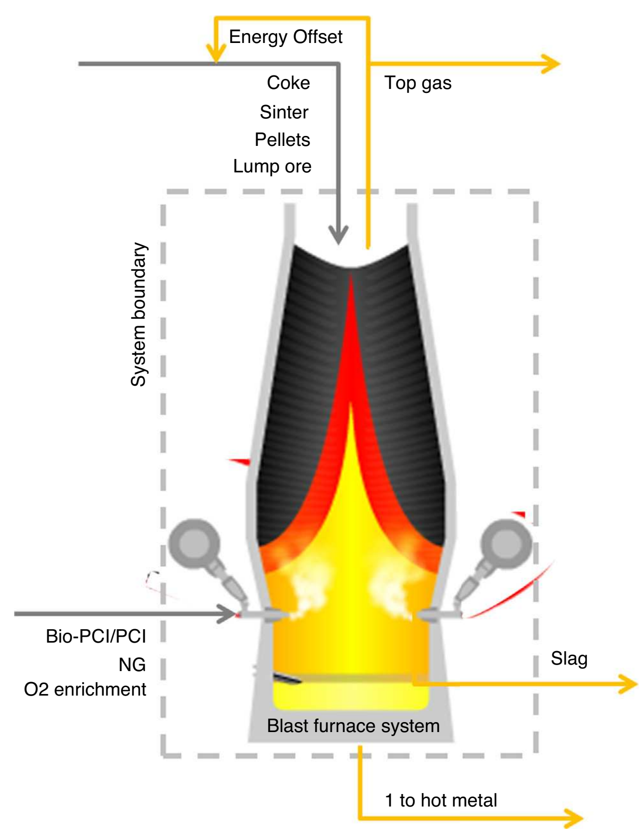

Fig. 2 – Schematic outline of system boundaries.

Table 4 – Cost used in economic objective function [50–56].

Country		Ref	Symbol	China	Japan	Russia	South Korea	India	Brazil	USA	Ukraine	Germany
Coal	USD/to	[52]	C_{coal}	134	135	121	134	120	117	124	121	125
Biochar	USD/to		$C_{biochar}$	330	510	570	375	320	270	360	370	480
Iron ore[a]	USD/to	[53]	C_{ore}	163	163	163	163	163	163	163	163	163
Pellets[b]	USD/to	[53]	C_{pellet}	178	178	178	178	178	178	178	178	178
Sinter[c]	USD/to		C_{sinter}	175	175	174	175	174	174	174	174	157
Lime stone	USD/to	[54]	C_{lime}	125	125	125	125	125	125	125	125	125
Electricity	USD/MWh	[51]	C_{el}	24	232	96	84	123	113	116	40	324
Carbon tax	USD/to CO_2	[55–57]	$C_{O_2\ Tax}$	0.00	20.85	0.00	33.25	1.07	0.00	5.00	1.00	18.62

[a] Daily China import iron ore fines average 2010–2012 March (63.5% Fe) $ per dry metric tonne cfr main port.
[b] China import iron ore pellet 2010–2012 March (65–66% Fe) $ per dry metric tonne cfr main port.
[c] Cost of sinter material was calculated as follows: $C_{sinter} = 0.93[C_{ore}] + 0.14[C_{lime}] + 0.042[C_{coke}]$.

4.3. *Analysis on biochar cost*

Our survey concords with previous findings in the literature (Table 2), in consulted countries charcoal prices ranged between 270 and 570 USD/t, with Brazil showing the lowest cost for charcoal for metallurgical applications. Another factor influencing the cost is the actual charcoal production in each of the evaluated countries. Table 6 presents a comparison between the HM production and the charcoal production, as posted, Brazil is the top charcoal producer with 9,893,000 tonnes of charcoal, followed by India (1,728,000), USA (940,000) and China (122,000) [58]. Brazil presents unique conditions for the development of a charcoal based ironmaking industry: vast arable extensions, abundant mineral resources and few deposits of coking coal.

Countries with small or no charcoal production, such as Germany, Japan and Russia, present the largest price difference (>200%) between coal and charcoal.

In order to be economically competitive biochar prices should range between 130 and 236.4 USD/t under the actual and prospected CT schemes (Table 7). South Korea presents the highest acceptable price for biochar with 236.4 USD/t. Owing to the relatively high CT (33.25 USD/t CO_2), likely to be implemented, Japan can accept an elevated price of biochar due to the cost of industrial electricity, which buffers the price difference with coal.

Three elements may determine the significant difference between renewable and fossil reductants for BF: source of biomass, carbon credits and CT. Firstly, all charcoal prices consulted were produced from hardwood (e.g. oak, eucalyptus), consequently good mechanical properties from their chars can be expected. Nonetheless, hardwood is significantly more expensive than residual biomass, for the purpose of Bio-PCI other biomass resources can be carbonized, for instance, forestry residues. Residual Biomass (e.g. agricultural and forestry residues) present lower prices than hardwood and can produce a charcoal with reasonable quality.

4.4. *Carbon price*

Another feasible alternative to reduce the price difference between renewable and fossil PCI is the implementation of carbon price, by means of carbon credits and/or CT. In a large simplification, we can define carbon credits as allowances generated with the carbon sequestration occurred during the biomass growth. These allowances can later be traded. On the other hand, CT are penalties paid by CO_2 emitters. Arguably, setting a price on CO_2 emission, from fossil fuels may facilitate the substitution of renewable sources fuels and technology. This can motivate a more efficient use of energy and improves efforts in research and development. Several countries have already established carbon taxation. Relevant to this contribution are the cases of Germany, India and USA, while in Japan and South Korea there are discussions on the implementation of CO_2 taxation systems. In our literature review, it was not found any determined figure of CT in China, Russia, Brazil or Ukraine.

According to Bohlin [59], Sweden imposed a CT of 43 USD/t CO_2. Based on the value of Swedish CT, the cost implication on HM production was calculated and this scenario is illustrated in Fig. 3 (dark bars). As indicated in Fig. 3, when Bio-PCI substitutes fossil PCI an increment in the range of 0.42–11.58% in *F* occurs. Countries such as China, Japan, South Korea, India, Brazil, USA and Ukraine present a difference lesser than 7% in the value of *F*, this represents almost 80% of the HM produced worldwide.

The price of carbon emission that could make Bio-PCI economically competitive was estimated, based on the actual processing cost and spots prices of charcoal. Estimations show that CT in the range of 47.1–198.7 USD/t CO_2 are necessary to

Table 5 – Objective function cost (*F*) using PCI and Bio-PCI.

		Baosteel BF3	Nippon Steel Oita	NLMK	POSCO	Tata Steel Jamshedpur BF H	Gerdau Acominas BF 2	Severstal Dearborn BF C	Alchevsk Iron and Steel BF 1	AM Eisenhüttenstadt
FPCI	USD/t HM	347	343	329	385	329	346	345	354	313
FBio-PCI	USD/t HM	387	373	384	410	359	382	369	382	365

Table 6 – Hot Metal and charcoal production [58,59].

Production (year)	Unit	Ref.	China	Japan	Russia	South Korea	India	Brazil	United States	Ukraine	*Germany*
Hot Metal (2011)	TMt	[60]	629,693	81,028	48,120	42,218	38,900	33,243	30,233	28,867	27,795
Charcoal (2005)	TMt	[58]	122	20	60	10	1728	9893	940	22	

Table 7 – Estimated biochar prices necessary to be competitive with coal.

China USD/to	Japan USD/to	Russia USD/to	South Korea USD/to	India USD/to	Brazil USD/to	USA USD/to	Ukraine USD/to	*Germany USD/to*
134.6	207.8	151.7	236.4	133.5	147.9	130.1	140.2	189.3

be implemented. In this sense, the cost of the taxation significantly varies among studied countries, while Brazil, China, USA and India present relatively low values of CT with 47.1, 69.7, 69.7 & 70.8 USD/t CO_2 respectively, the taxes necessary for Russia, Japan and Germany are considerable higher (198.7, 132.9 & 125.4 USD/t CO_2 respectively) Fig. 4.

The present results concord with previous data by Norgate and Langberg [25]. In their assessment, based on a life cycle analysis, it was determined that a CT 95–115 USD/t CO_2 is required to be economically competitive for a complete charcoal substitution.

5. Analysis: where can the bio-pci flourish?

The results posted in the previous sections lead to infer that the Bio-PCI is a feasible initiative to reduce in a quarter the CO_2 emissions in BF (Fig. 1). Nevertheless, to the moment of writing the present work, biochar cannot compete solely on price against fossil coal. A second element in the assessment is the increasing awareness to allocate a price on carbon emission and give credits to carbon sequestration; arguably, the cost of carbon may be the driving force for the emergence of the utilization of renewable fuels in BF.

The results lead to conclude that Brazil possesses the best prospects for the deployment of Bio-PCI, due to the following reasons:

1. Large and consolidated charcoal industry, already the metallurgical industry consumes approximately 90% of local charcoal production. Also, the charcoal fines (considered a low value sub-product) can be used for the purpose of Bio-PCI (in coke and charcoal based BF).
2. The country is the only producer of charcoal based HM, 23% of Brazil's production in 2011 was generated in charcoal based BF.

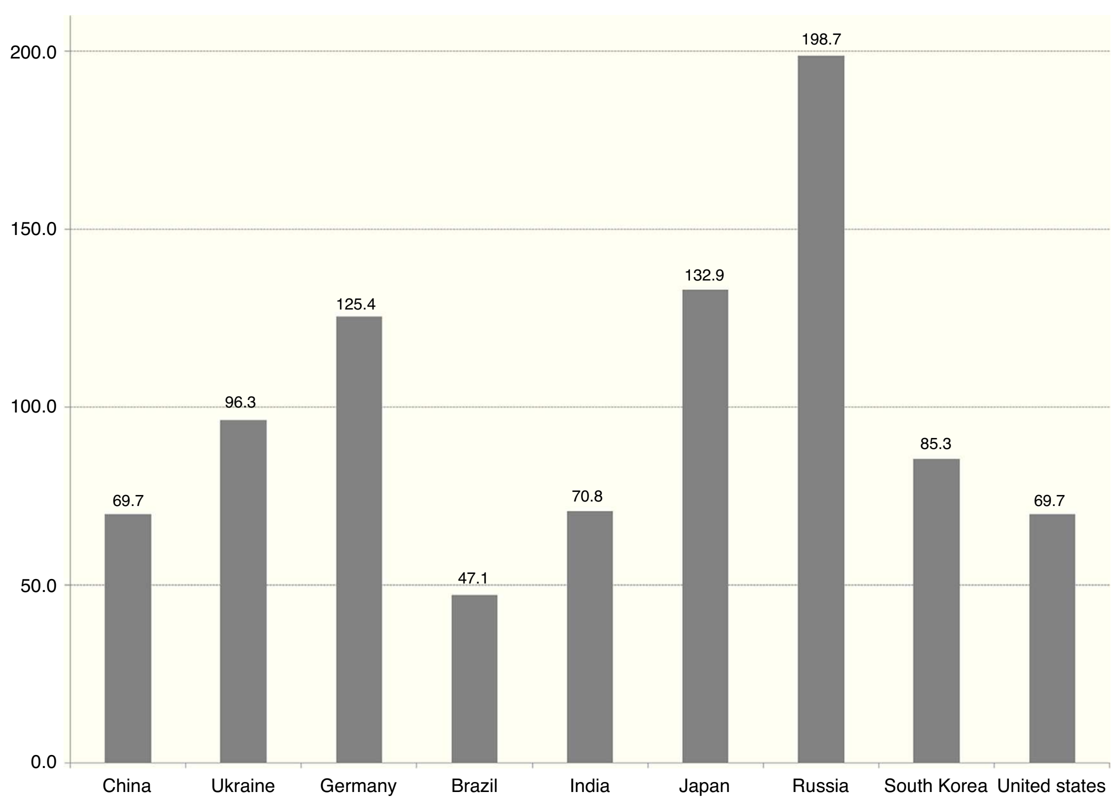

Fig. 3 – Carbon tax level necessary for Bio-PCI to be economically competitive.

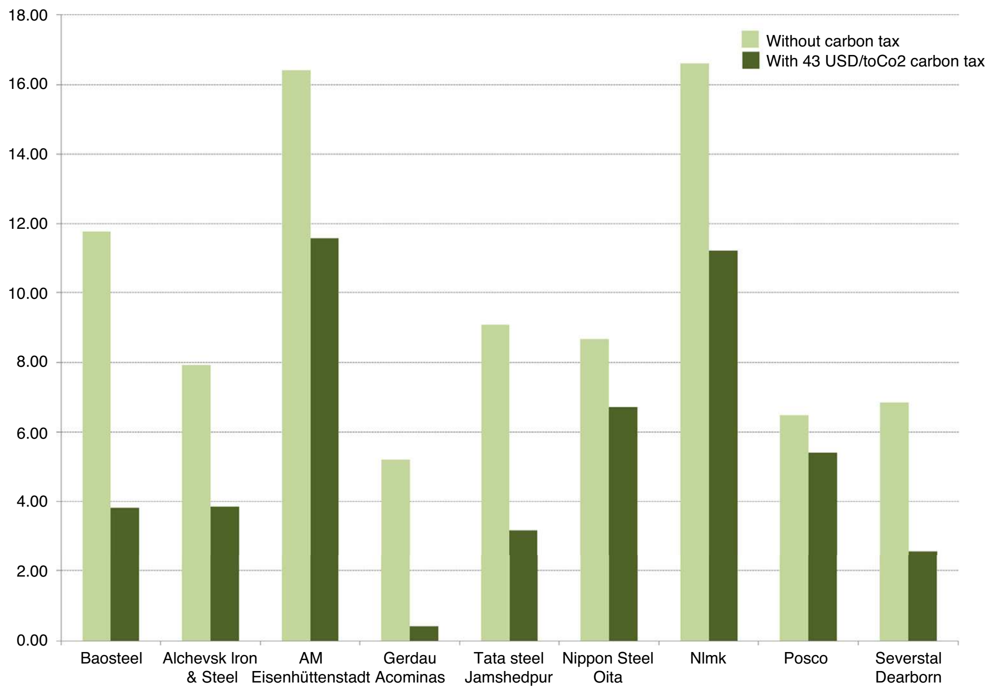

Fig. 4 – Cost difference of Bio-PCI implementation with current carbon taxes (pale green), with Sweden carbon tax (dark green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

3. Vast extensions of land are used for the generation of biomass for charcoal making purposes. According to Melo, 4.87 millions of hectars are dedicated to the cultivation of eucalitus for charcoalmaking [61]
4. No indigenous sources of coking coal (essential for coke-making), thus the country depends on coal and coke imported from overseas.

Nonetheless, a significant challenge in Brazil is the sustainability of charcoal making. In 2005, 52,8% charcoal were produced from deforestation and only 47% from sustainable forestry plantations [62]. The implementation of a CT of 47.1 USD/t CO_2, may as well help to reduce the difference of HM production cost.

Arguably, three other countries present good conditions to incorporate Bio-PCI in their BF processes: India, China and USA, because of the following reasons:

Relative low cost of charcoal: India, China and USA also have a consolidated charcoal industry (Table 6), with relative low cost (320, 330 and 360 USD/t). Thus, the impact of Bio-PCI over F is relatively low, 6.95%, 9.12% and 11.52% for USA, India and China respectively.

Potential growth: the rapid industrialization process of India and China drives a significant consumption of steel, mainly manufactured in integrated mills.

The CT necessary to make competitive the Bio-PCI are below 70 USD/t CO_2, which is low in comparison to Russia, Japan and Germany. Still the efficiency of carbonization and sustainability are to be improved, especially in India and China.

Our assessment leads also to indicate that Japan, Germany and Ukraine have significant lesser prospects to deploy Bio-PCI, due to the elevated cost of charcoal (510, 480 & 370 USD/t respectively), which arises from limited charcoal local production. According to our calculation a rather expensive CT of 132.9, 125.4 and 96.3 USD/t CO_2 are necessary for Bio-PCI to become economically attractive in those countries.

With respect to Russia and South Korea, it is necessary to gather more data regarding charcoal prices in order to be able drop a conclusion.

6. Concluding remarks

The review of existing literature and reported industrial experiences clearly indicates that the injection of pulverized particles of biochar into a BF, here coined Bio-PCI, is a feasible initiative to mitigate a quarter of CO_2 emissions. For the examined cases, abatements were calculated to vary between 18 and 40%. Besides of the obvious ecological benefit, the analysis of previous investigations shows that Bio-PCI would help to reduce the contents of sulphur and slag compared to metallurgical coke.

On the economical perspective, if Bio-PCI would completely substitute coal PCI, an increment between 5% and 16% of cost objective function would occur. Thus, to be competitive either biochar prices should be reduced from present levels or carbon taxes have to be imposed. In respect to biochar, prices should be between 130.1 and 236.4 USD/t, based on present CT schemes. For CT to reduce the difference in cost between Bio and fossil – PCI, values calculated vary from 47.1 to 198.7 USD/t CO_2. Brazil, China, USA and India present levels below 70 USD/t CO_2, while Germany, Japan and Russia are higher than 120 USD/t CO_2.

Based on the analysis of biochar cost and necessary price on carbon, Brazil presents the best prospects for the incorporation of Bio-PCI. Other countries such as India, China and USA present favourable prospects of Bio-PCI implementation.

Conflicts of interest

The author declares no conflicts of interest.

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