ECONOMIC ASSESSMENT OF CHARCOAL INJECTION IN THE IRONMAKING PROCESS (BIO-PCI): METHODOLOGY AND DATA

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(Recibido Enero 2014 Aceptado Febrero 2014)

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Abstract: There is a growing awareness of the necessity to reduce the utilization of fossil fuels in the ironmaking process, in this respect, the injection of small particles of charcoal (Bio-PCI) has been regarded as a feasible and practical way to reduce the in 25% the CO2 emission of hot metal production. Despite the positive outlook, there is a significant price difference between charcoal and coal that may deter the prospects of Bio-PCI deployment. This contribution builds on the methodology proposed to assess the economic impact of charcoal injection, based on a blast furnace simulation and a cost objective function. For the simulation, actual processing parameters of 9 fuel-efficient Blast Furnaces were used and current pricing data for the economic assessment. The work begins defining the advantages and limitations of charcoal use in ironmaking, continues with an analysis of diverse frameworks proposed in the literature for the prediction of the impact of Bio-PCI over the economy of the ironmaking in BF. Results show that prices of residual biomass (107-133 USD/t) are substantially more economical than primary biomass (310-400 USD/t), thus the use of residual biomass would help to significantly reduce the cost of charcoal production.

Keywords: Bio-Pulverized Coal Injection (Bio-PCI)/ Charcoal/ Sustainable Iron Production

Resumen: Existe un creciente interés sobre la necesidad de reducir la utilización de combustibles fósiles en el proceso de la producción de arrabio, a este respecto la inyección de pequeñas partículas de carbón vegetal (Bio-PCI) ha sido reconocida como una fórmula factible y práctica de reducir en un 25% las emisiones de CO2 en la producción de arrabio. A pesar del panorama alentador, existe una diferencia de precio significativa entre el carbón fósil y el carbón vegetal que ha desalentado los prospectos de la implementación del Bio-PCI. Esta contribución trata sobre la metodología propuesta para medir el impacto económico de la inyección de carbón vegetal, según la base de la simulación del Alto Horno y la utilización de una función objetiva de costos. Para la simulación han sido utilizados parámetros de procesos reales de 9 Altos Hornos con consumo energético eficiente, y así mismo, los precios actuales fueron utilizados para la evaluación económica. Este trabajo comienza definiendo las ventajas y limitaciones del uso del carbón vegetal en los altos hornos, continúa con el análisis de las diversas metodologías propuestas en la literatura para la predicción del impacto del Bio-PCI sobre la economía del proceso. Los resultados muestran que los precios de la biomasa residual (107-133 USD/t) son sustancialmente más económicos que los de la masa primaria (310-400 USD/t), por lo que el uso de biomasa residual puede ayudar a reducir significativamente el costo de la producción del carbón vegetal.

Palabras claves: Bio-Pulverized Charcoal Injection (Bio-PCI)/ Carbón Vegetal/ Producción de Arrabio Sostenible

I. INTRODUCTION

The ironmaking industry is one of the most carbon intensive industries in the world, the table 1 presents a comparison of the energy consumption of most disseminated ironmaking processes in the world, for instance processes such as MIDREX, HyL III, FINMET, present an energy consumption of less than 14 GJ/t iron, however their total output (by 2010) did not surpassed 52 MMt iron, while the BF with a higher specific energy consumption of 16.25 GJ/t iron, dominates the global production of iron (Zhou et al. 2009)[ ].

In the past years the introduction of numerous technological innovations to the ironmaking process in BFs, have led to a significant reduction of the coke consumption, e.g. ore beneficiation, O2 enrichment and burden distribution, Figure 1 shows the reduction of coke use in the blast furnace process due to process improvements and auxiliary reductants in Germany (Dahlman et al. 2010) [2]. However the establishment of the Pulverized Coal Injection (PCI) technology has significantly helped to reduce the fuel consumption in BF. According to Schmöle et al. the coke rate utilization in German BFs decreased from 408 kg/t 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 being 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 ,5].

Despite the positive fuel reduction caused by the

Table 1: Chemical composition of Coke, Coal and Charcoal used in the BF simulation. Source: Zhou et al. 2009

Process		MI-DREX	HYL III	FIN-MET	DRYI-RON	FASTMET	IN-MET-CO	4000m^3 BF	CO-REX	DRC rotary kiln	SL/RN Rotary Kiln	Tunnel kiln
Reducing agent		Natural gas	Natural gas	Natural gas	Natural gas / Coal	Natural gas / coal	Natural gas / Coal	Coke / Coal	Coal / Coke	Coal	Coal	Coal
Reactor type		Shaft furnace	Shaft furnace	Fluidi-zed bed	Rotary hearth furnace	Rotary hearth furnace	Rotary hearth furnace	Shaft furnace	COREX	Rotary kiln	Rotary kiln	Rotary kiln
Energy Conmsuption	GJ/t	11	11	14	15	15	16	16.25	17	20	18	25 - 30
Single Furnace capacity	Mt/a	1.80	1.90	0.50	0.14-0.50	0.14-0.51	0.10	3.20-4.00	1.50	0.15	0.15	0.01-0.04
General Capa-city (2010)	Mt/a	37.92	11.70	2.00	1.00	0.80	0.03	900.00	5.00	0.40	14.00	0.20

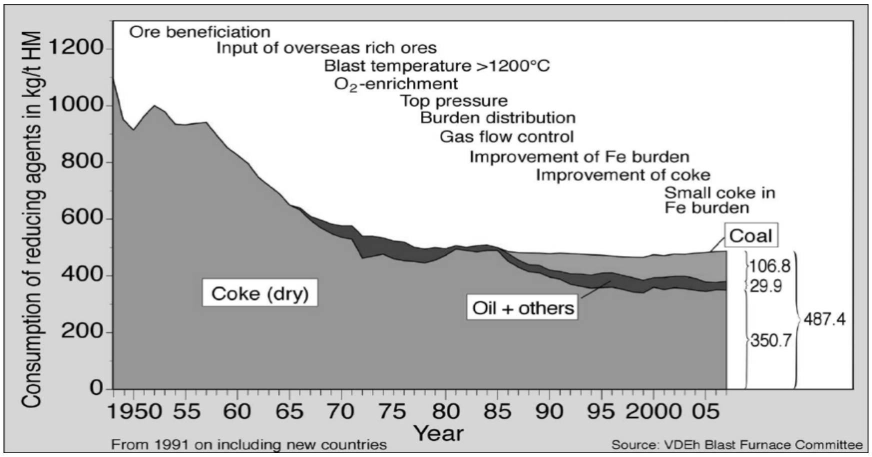


Figure 1. Consumption of reducing agents in Germany (coke, coal and oil) and main technological innovations in BF. Source: Dahlman et al. 2010

injection of auxiliary fuels, e.g. coal, tar, oil and natural gas, still most of the commonly injected carbonaceous elements come from mineral endowments, which contribute to the emission of CO2. In this sense great interest has been generated in the introduction of renewable fuels to the ironmaking process. Particularly the role of charcoal in ironmaking has been re-evaluated, and the injection of small particles of charcoal, here called Bio-PCI, appears as a feasible alternative to reduce the carbon intensity of ironmaking.

The Bio-PCI can be pneumatically conveyed through the injection rigs currently used for coal injection. Presently there are two principal paths of utilization of charcoal that have been currently under investigation, on one hand there is the bio-composites in which charcoal is mixed with iron ore and is fed into the burden of BF. There are some references about the use of charcoal charged in BF burden [6,7], as substitute of coal for cokemaking[8], and pelletizing of charcoal fines for BF feed [9]. The second route of charcoal utilization proposes the charcoal injection via tuyeres (Bio-PCI).

The technical feasibility of charcoal injection has been demonstrated by numerous of researches, in the academia many investigations focused on the assessment of the reaction velocity of charcoal in BF. Ueda & Ariyama [10] and Ueda et al. [11,12] studied the velocity of reaction of coke, PCI and biochar carbonized at 300°C and 500°C. In the mentioned works the combustion behavior of samples was studied under the rapid heating by laser, 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 Babich et al. [13], Machado et al. [14,15], Pohlman et al. (2010) [16] and Mathieson et al. [13,21].

In addition to the previous works, other investigations have also examined the potential utilization of residual biomass. For instance Chen et al. (2012)[17,18]examined the torrefaction and burning characteristics of bamboo, oil palm, rice husk, bagasse, and Madagascar almond. The findings lead to conclude that the torrefaction temperature of 300 °C is a feasible operating condition to transform biomass into an alternative fuel to coal injected in BFs.

A report of industrial scale trials has been presented by Mathieson (2007;2011;2012)[19,20], about a research carried out in Blue Scope, Australia. In an initial assessment based on a Value-In-Use (VIU) methodology, 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”[20]. Later industrial trials revealed that combustion of charcoal samples was stable and smooth. The combustion behavior was comparable to the high-VM PCI coal[21].

To this moment, there are few peer reviewed reports on the Bio-PCI utilization. One interesting case was presented by Nascimiento et al (2009)[22] about the Charcoal-BF operation at Gusa Norseste (Brazil), where charcoal is injected at rates of 50-160 kg/t HM. Similarly in Siderurgica do Para (USIPAR) an injection system has been installed in BF1 & BF2, injections rates are expected to be 80 kg charcoal/ tHM. The charcoal is obtained from the carbonization of Assai seeds, an abundant biomass residue available in the region[23]. Also CISAM (Brazil), also have Bio-PCI to inject fine particles of charcoal generated during screening[24].

Many researchers agree on the CO2 mitigation potential of Bio-PCI, this subject has been analyzed from diverse perspectives. For instance, Norgate and Langberg [25] using a Life Cycle Analysis assessed the potential of CO2 mitigation in integrated steel processing, based on their estimation 4.5 kg CO2/ kg steel could be saved, provided a complete fossil fuel substitution by renewable charcoal. Mathieson et al. [19] estimated the net emissions saved with the implementation of Bio-PCI between 0.4-0.6 t-CO2/ t crude steel (19-25%), while Hanrot et al[26] calculated the mitigation potential in 28% with a rate of 200 kg Bio-PCI /t HM. To illustrate the case of CO2 abatement, the authors calculated a Bio-PCI substitution in BF based on actual processing parameters among selected HM producers, the results are presented in Figure 2, where CO2 reduction accounts from 0.28 to 0.59 t CO2/t HM (18.0 to 40.2%), when Bio-PCI are used instead of fossil coal and natural gas [27].

Numerous evidence seems to demonstrate the feasibility of Bio-PCI to reduce the CO2 emissions associated with iron production, arguably to this moment the significant price difference between mineral coal and renewable charcoal may have deter a proliferation of charcoal use in iron and steel making. In this sense, the authors consider necessary to build a methodology to assess the economic impact of charcoal introduction in ironmkaing. The following sections build upon this subject.

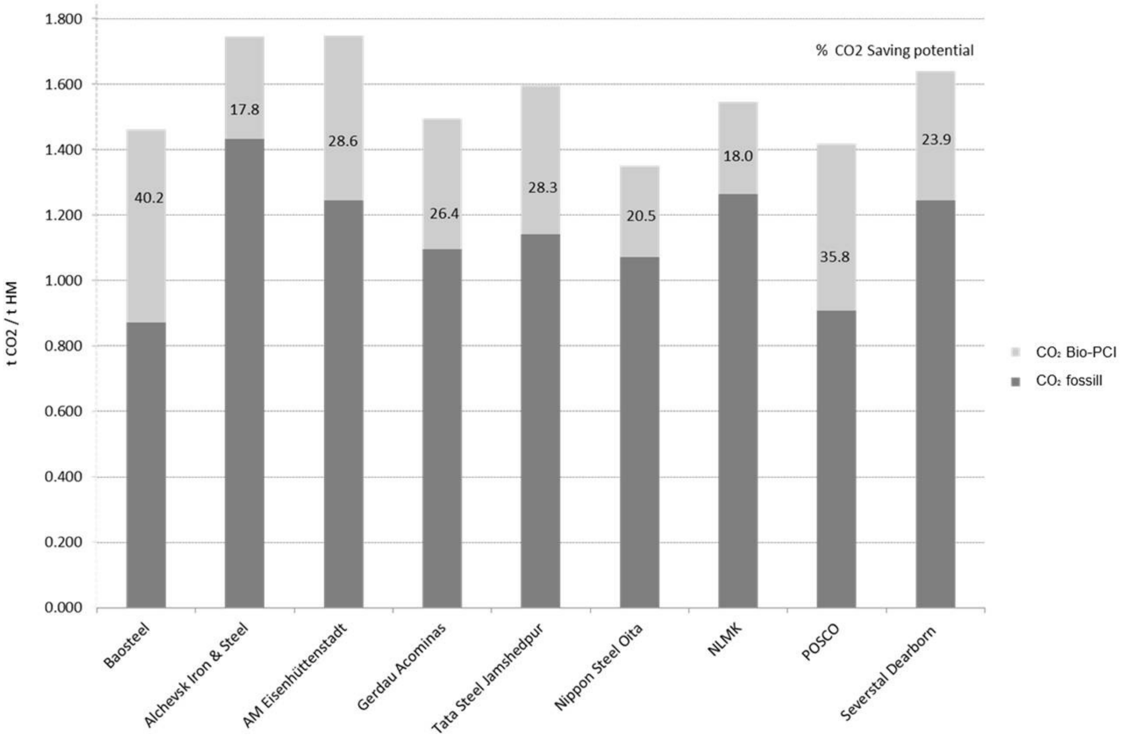


Figure 2: Estimated CO2 saving potential using Bio-PCI in selected BF . Source: [26]

II. METHODS FOR THE ECONOMIC ASSESSMENT OF INNOVATIONS IN IRONMAKING

While there are available numerous investigations about the injection of charcoal in blast furnaces, few peer reviewed works focused on the economic prospects of Bio-PCI deployment. Chronologically, the first attempt found in the literature was presented by Mathieson (2007;2011) [19,20] in a research carried out in Blue Scope, Australia. In his contribution Mathieson proposed an assessment based on a Value-In-Use (VIU) methodology, the schematic outline of the model is posted on Figure 3. 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

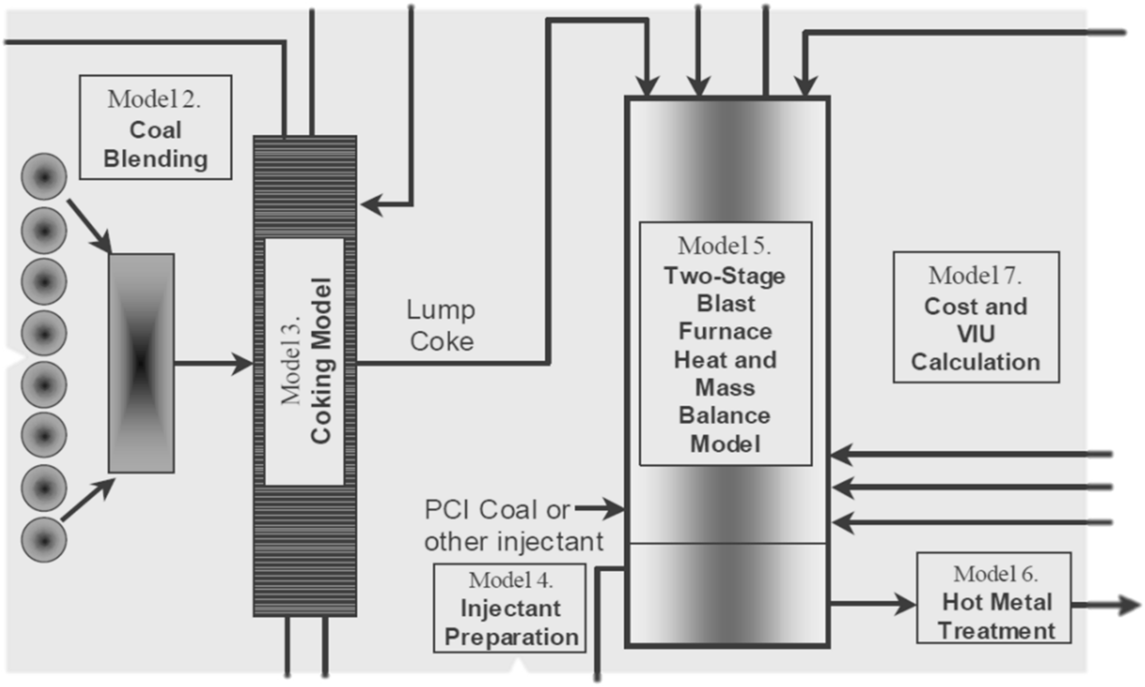


Figure 3: Schematic Outline of the VIU Model. Source: Mathieson (2007)

is estimated for a diverse number of reductants injected into the BF, such as ethanol, torrefied softwood, sub-bituminous lignite (briquettes), biodiesel, coal, charcoal (hardwood, mallee & 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"[20].

In a widely celebrated article, Norgate and Langberg (2009)[25] used a LCA methodology to indicate the potential reductions in GHG emissions resulting from charcoal substitution in the integrated, direct smelting and mini-mill routes for steelmaking. Under the LCA framework, the CO2 emissions of every single intermediate process of steelmaking were accounted. Additionally CO2 credits were provided during the growth of wood, based on the Life Cycle Inventory (LCI) proposed by Wu et al (2005)[ ] for the growth of Eucalyptus.

Norgate and Langberg estimated that under a carbon trading scheme the economic competitiveness of charcoal compared to coal can be improved. Based on a historical price of $US90/t for coal, a carbon tax in the order of US$30–35/t CO2 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].

Both VIU & 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 (Nadav, 2005)[ ]. 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 is based on an arbitrary provided set of 25 factors (see original article)[20], they facilitate an analysis of diverse fuels to be utilized in a specific operation, however the comparison of the economic benefits in different plants with diverse economic conditions makes the assessment difficult.

A third kind of framework has been used by Saxen et al. (2009)[ ], Helle et al. (2009)[ ], Wikulund et al. (2012 & 2013)[,], and Feliciano & Mathews (2012 & 2013)[28,] in the assessment of the economic potential of biomass utilization in a steel plant. Originally this method was developed in the Åbo Akademi, Finland, for the analysis of the economic prospects of technological innovations in steelmaking (see Pettersson & Saxen, 2006)[ ]. To the moment of writing this contribution, The framework proposed by Pettersson & Saxen has been applied in several works, for instance: in the estimation of the potential of GHG emissions mitigation in steel production (Riesbeck & Larsson 2012)[ ], Top Gas Recycling in BF (Helle et al. 2010; Helle et al. 2010; Mitra et al. 2011)[33, ,], Steelmaking with a Polygeneration Plant (Ghanbari et al. 2012)[ ], Optimization of Ironmaking in the BF (Pettersson et al. 2009; Helle et al. 2011)[ ], BF Operation Combined with Methanol Production (Ghanbari et al. 2011)[41].

In the mentioned studies the economic assessment of the technological innovation is estimated by means of a Cost Objective Function (F). F accounts for 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 are not taken into consideration; we will build more on this topic in a later paragraph.

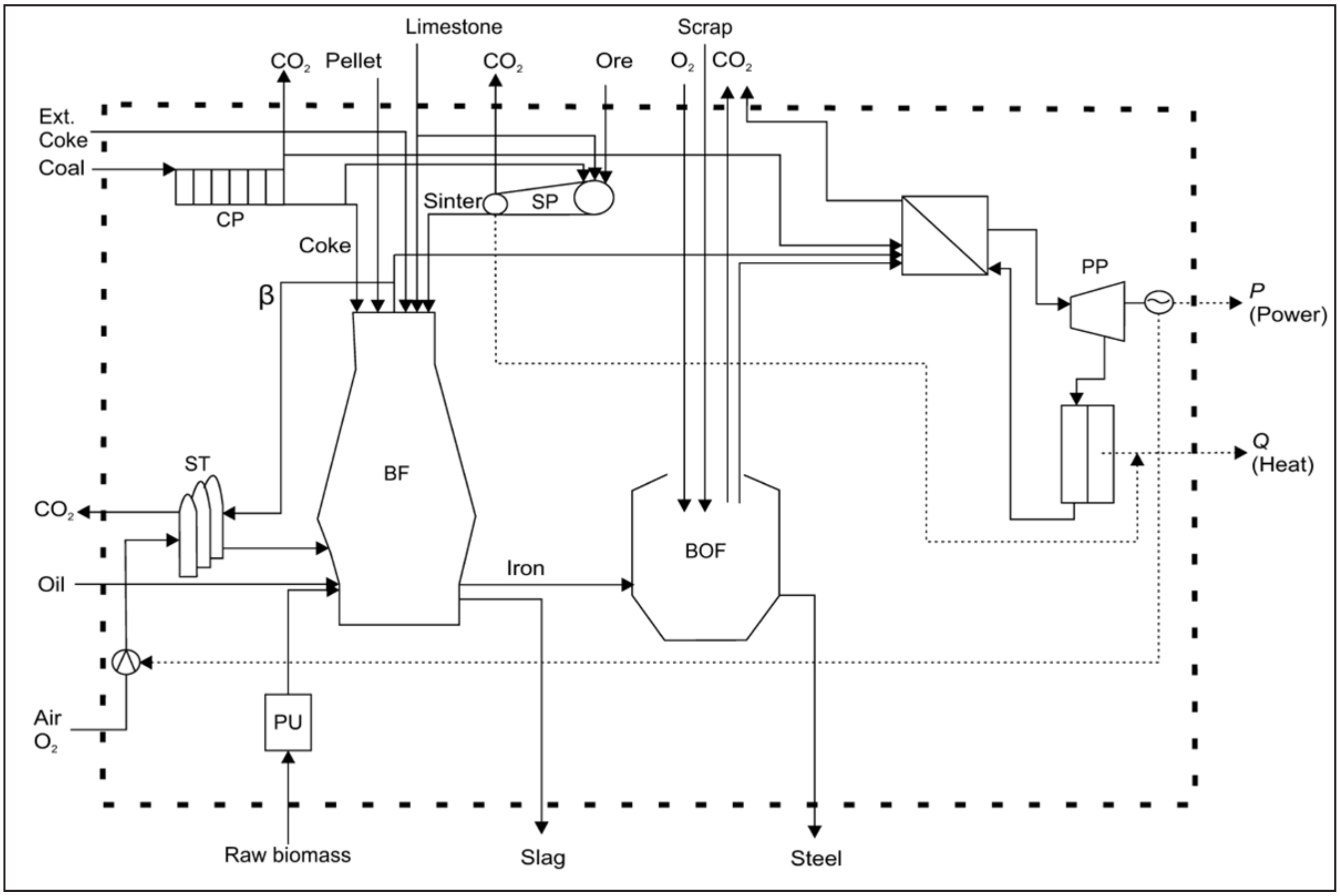


Figure 4. Schematic of the system studied by Helle et al. (2009). CP: coke oven, SP: sinter plant, ST: hot stoves, PU: biomass pyrolysis unit, BF: blast furnace, BOF: basic oxygen furnace, and PP: power plant.

The findings of the different works mentioned before[30-41] appeared to be more valuable for metallurgists worldwide than other results based on LCA or VIU, as they take into consideration the actual thermodynamics of the BF operation, leading to a more credible and flexible method. The simulation using F could in principle be 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[ ]. The costs absent in the model are: capital charges, hand labour, ferroalloys, refractories and raw material transportation to the plant. Secondly, in previous works by Saxen et al., Helle et al., Wikulund et al. [30-33], 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 an arbitrary selected raw materials prices, with no relation to actual raw materials cost.

This contributions aims to respond to an original strategic question: Which economic conditions may facilitate the deployment of Bio-PCI?, in this respect our viewpoint clearly differentiates from previous works, as the focus is given to the iron making in BF (not in the whole steel process). We also identify the Bio-PCI as the most feasable way to replace fossil based coals and its derived product coke, as we judge that the complete replacement of coal by biochar is not technically feasable. It is aimed to measure the impact economic impact of charcoal injection based on actual processing parameters and ironmaking cost.

III. SYSTEM BOUNDARIES

The selection of the proper limits of the system, system boundaries, is essential in order to adequately assess the impact of different reductants in the BF. According to Churchman (1968)[ ], variables inside the system are those that can be affected and those that might be affected by the system, in the present case burden materials, oxygen and fuels. Outside the system are those variables that influence the system, but conversely are not influenced by the system, for instance carbon credits, raw material prices and energy prices. As the purpose of the present work is to evaluate the economic impact of Bio-PCI in BF, we define the system boundaries as schematically depicted in figure 1, gray lines represent material introduced to the system (e.g. coal, charcoal, oxygen, coke, sinter, pellets and lump ores), while yellow lines represent the products and by products (e.g. hot metal, off gas, slag). Contrasting to previous works by Saxen et al., Helle et al., and Wikulund et al. [30-33], the present contribution only considers input and output elements to the BF, while all other aggregates in steel plant are excluded from the present work (coke ovens, BF stoves, steel shop, rolling mill, etc.).

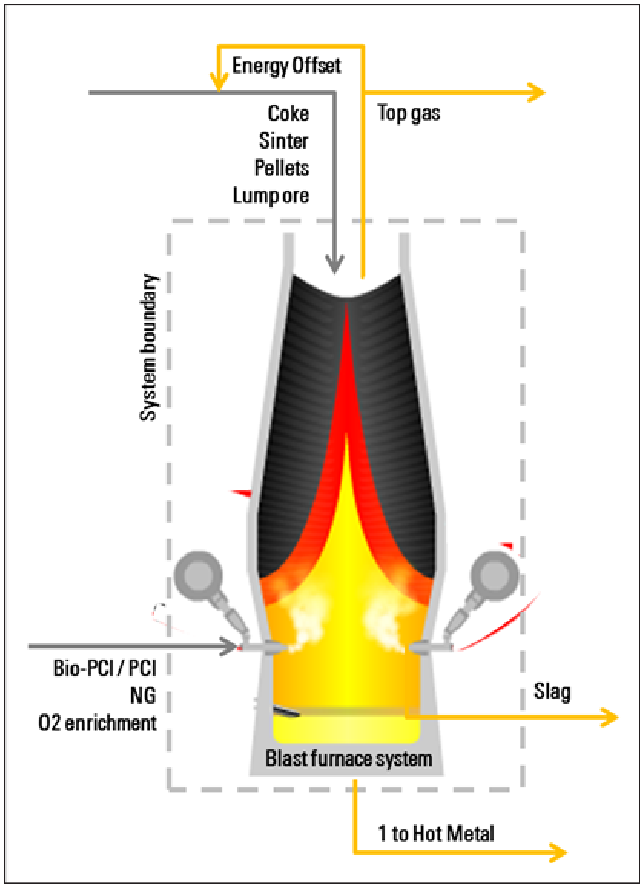


Figure 5, schematic outline of system boundaries for this study and list of symbols used

Some other assumptions underlying in the present contribution are that coke and charcoal used in the BF are completely provided from external sources, while coal and charcoal are only use for injection through tuyeres (PCI / Bio-PCI). Additionally in the calculations credits are provided by electricity generation due to top gas calorific power. With respect to slag, the authors acknowledge that it can be sold as raw material for other applications, for instance cement, motorways pavement, and pH modifier in agriculture (Feliciano 2005)[ ], however in the present investigation no credits are given for the commercialization of slag.

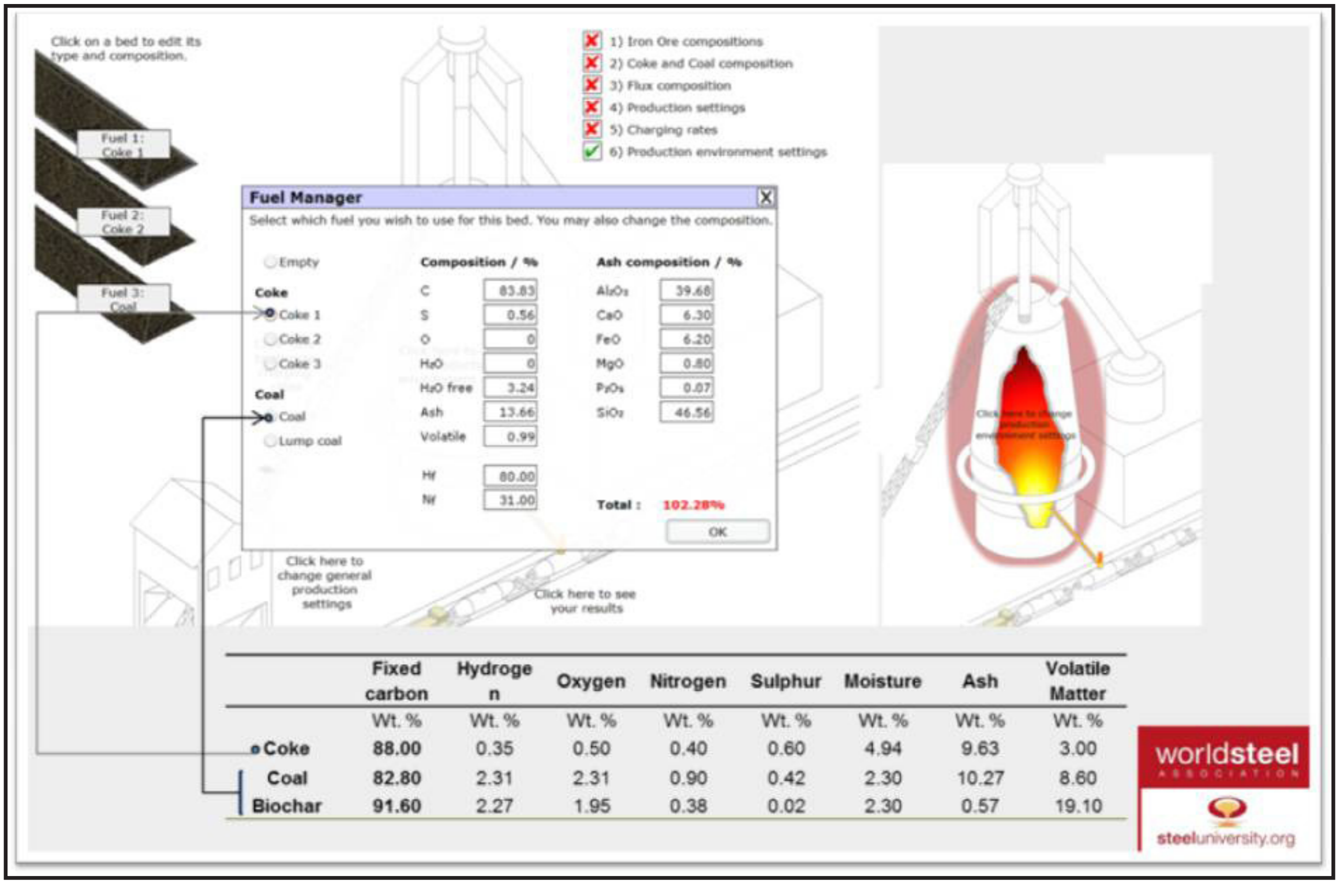
IV. BF PROCESS SIMULATION

To our knowledge, only few plants around the world actually inject charcoal via tuyeres, some industrial cases are Siderurgica do Para (USIPAR), Gusa Norseste and CISAM [,]. However it is known that a vast majority of large size BF does use PCI technology. In this respect, it was necessary to simulate the effects of charcoal injection (Bio-PCI) over the BF process. The presents work used the interactive simulation of Steeluniversity to assess the technical influence of charcoal substitution, this freely available simulation tool has been designed as an educational and training tool for both students of ferrous metallurgy and for steel industry employees[47].

The basic aim of the simulation was to verify the variations in the operational parameters in BF, when charcoal replaced coal as auxiliary injecting fuel. The table 2 shows the chemical compositions of coke, coal and charcoal used in the simulation (after Babich et al, 2010)[13]. In order to simulate the scenarios of replacement, it is necessary to adapt the interphases of the BF simulation: chemical composition of raw materials, production settings, charging rates and production environmental parameters. Once all interphases were successfully reviewed and adjusted, the system delivered the results based on the parameters conditions given.

Table 2: Chemical composition of Coke, Coal and Charcoal used in the BF simulation. Source: Babich et al. (2010)

	Fixed carbon	**Hydrogen**	**Oxygen**	**Nitrogen**	**Sulphur**	**Moisture**	**Ash**
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
Coke	**88.00**	0.35	0.50	0.40	0.60	4.94	9.63
Coal	**82.80**	2.31	3,30	0.90	0.42	2.30	10.27
Charcoal	**91.60**	2.68	-	0.38	0.02	2.30	0.57



☒ 1) Iron Ore compositions
☒ 2) Coke and Coal composition
☒ 3) Flux composition
☒ 4) Production settings
☒ 5) Charging rates
☑ 6) Production environment settings

Fuel Manager

Select which fuel you wish to use for this bed. You may also change the composition.

○ Empty

Coke
● Coke 1
○ Coke 2
○ Coke 3

Coal
● Coal
○ Lump coal

Composition / %
C: 83.83
S: 0.56
O: 0
H_2O: 0
H_2O free: 3.24
Ash: 13.66
Volatile: 0.99
Hf: 80.00
Nf: 31.00

Ash composition / %
Al_2O_3: 39.68
CaO: 6.30
FeO: 6.20
MgO: 0.80
P_2O_5: 0.07
SiO_2: 46.56

Total : 102.28%

OK

	Fixed carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Moisture	Ash	Volatile Matter
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	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

Figure 6, process simulation by Steeluniversity

With respect to the selection of raw materials the specific rate of charge was adjusted to the actual patterns of charge of the 9 BF selected for the study (see table 3), however the chemical composition of sinter, pellets and lumps ores was used according the default values present in the simulation.

Table 3: Chemical composition of sinter, pellets and lump ore used in the cost objective function

	Fe_2O_3	FeO	CaO	SiO_2	MgO	Al_2O_3	MnO	P_2O_5	FeS
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
Sinter A	77.25	5.75	7.25	4.39	1.32	0.97	0.57	0.11	0
Pellets B	92.16	0	0.50	2.51	0.55	0.25	0.08	0.06	0.01
Lump Ore A	91.93	0	0.10	3.61	0.01	1.46	0.04	0.11	0.07

Similarly to the charge of the iron bearing elements (sinter, pellets and lumps ores), the feed rate of fuel utilization was adjusted according to the actual consumption of coke and coal for PCI. Then the PCI content was recalculated substituting the exact amount (in kg/t HM) by charcoal. The chemical composition used for coke, coal and charcoal are posted in the table 2 (Babich et al, 2010)[ ].

With respect to the process parameters used in the BF simulation, processing data from highly fuel efficient BF available on literature was selected: Baosteel (China), Nippon Steel (Japan), NLMK (Russia), Posco (South Korea), Tata Steel Jamshedpur (India), Gerdau Acominas (Brazil), Severstal Dearborn (USA), Alchevsk Iron & Steel (Ukraine) & AM Eisenhüttenstadt (Germany)[49-56]. The actual top gas composition and its calorific power were calculated for each case using the BF simulation from Steeluniversity[42], it is important to notice that BF off gas generates valuable power that can be used in other areas of the steel mills, this is schematically illustrated in the figure 3 (System boundaries). The parameters used in the estimation are presented in Table 4.

Table 4: Parameters used in the process simulation. References: [, , , , , , , ,]

			AM Eisenhü-ttenstadt	Baosteel BF3	Nippon Steel Oita	NLMK	POSCO	Tata Steel Jamshedpur BF H	Gerdau Acominas BF 2	Severstal Dearborn BF C	Alchevsk Iron & Steel BF1
	Unit	Simbol									
Productivity	t/m3d			2.31	2.19	2.22	2.99	2.55	2.37	3.04	2.04
Coke rate	kg/thm	Mcoke	414.5	290	356.3	421	302	380	365	414	477
PCI rate	kg/thm	MPCI	176.9	208	98.4	0	180	160	140	116	90
NG rate	kg/thm	MNG	0	0	0	98.7	0	0	0	23	20
Sinter	%	MSinter	79.6	68.89	78.5	80e	75	70	86.9	61	74.8
Pellets	%	Mpellets	12.8	13.97	7	20e	10	0	0	37	21.4
Lump ore	%	More	7.5	17.14	14.5	0	15	30	13.1	2	3.9
O2 enrichment	%		2.6		0.5	6		4%			3.83
Blast temperature	°C		1,150	1,248	1,268	1,155	1,196	1,200	1,200	1,065	1,037
Working Volume	m3			4,350	5,245		4,350	3,230	1,750	1,793	

The resulting BF top gas compositions of the 9 BF selected is shown in table 4, additionally information about the heating value and CO2 emissions are provided.

Table 5: Estimated top gas composition

		AM Eisenhüttenstadt	Baosteel BF3	Nippon Steel Oita	NLMK	POSCO	Tata Steel Jamshedpur BF H	Gerdau Acominas BF 2	Severstal Dearborn BF C	Alchevsk Iron & Steel BF 1
Top Gas Compositione	Unit									
CO2	%	17.29	20.73	23.89	24.94	21.84	20.83	20.62	18.2	18.4
CO	%	27.12	23.02	20.42	25.54	22.3	26.17	23.12	24.73	27.73
H2	%	3.35	4.05	2.89	2.97	3.82	3.47	3.21	3	2.75
N2	%	51.76	51.71	52.31	45.99	51.54	49.02	52.57	53.6	50.62
CH4	%	0.49	0.49	0.5	0.56	0.49	0.52	0.49	0.47	0.5
Top Gas heating valuee	kJ/tHM	191.0	165.1	149.0	137.1	158.0	173.4	165.5	184.7	184.1
CO2 emissionse	tCO2/ tHM	1.749	1.463	1.351	1.546	1.420	1.598	1.496	1.640	1.747

It is also important to mention some of the underlying assumptions of the simulation. Firstly the model estimates that a part of the material is lost during charging due to the mechanical degradation and powder formation, values account from 0.01-0.03%. Secondly the model takes into considerations the free H2O of the charged materials.

V. COST OBJECTIVE FUNCTION

As earlier mentioned, at the Heat Engineering Laboratory in the Åbo Akademi a numerical model was developed for the assessment of techno-economic impact of innovations in the BF ironmaking process. The economic part of such model, also known as Cost Objective Function (F), takes into consideration the primary costs of BF operation, such as iron bearing materials (pellets, lumps and sinter), reductants (coke, coal and charcoal) and even carbon taxes, which are evaluated based on utilisation rates, product and by-products. The F provides an indication of the production cost of HM when fossil based coal for PCI is substituted by charcoal (Bio-PCI). The results applied in the present work aim to shed light on the influence of charcoal prices and emission rights over the optimal economy of hot metal production.

F is aimed to show how principal raw materials prices used in hot metal production (coke, coal, charcoal, sinter, lump iron ore, Pellets and limestone) can impact over the BF economy, through a cost benchmarking type approach. The estimated costs generated are indicative in nature (rather than specific) and calculations are not meant to represent any specific BF. It is a notional and comparative figure of principal raw materials, albeit one built on representative current input costing data. It is also important to mention that the following costs are not accounted in the model, for instance capital charges, hand labour, ferroalloys, refractories and raw material transportation to the plant.

In the present case, we aimed to measure the effect of Bio-PCI incorporation in the process and the simplified F in our case can be represented as follows:

$$F = 1.8\left[(C_{ore}.M_{ore}) + (C_{pellet}.M_{pellet}) + (C_{sinter}.M_{sinter})\right] + 1.2\left[C_{coal}.M_{coal/coke}\right] + \left[C_{charcoal}.M_{PCI}\right] + \left[C_{O_2Tax}.M_{O_2fossil}\right] \quad \text{Eq. 1}$$

Where:

Coke rate	M_{coke}	Coal cost	C_{coal}
PCI rate	M_{PCI}	Charcoal cost	$C_{charcoal}$
Sinter fraction	M_{Sinter}	Iron ore cost	C_{iron}
Pellets fraction	$M_{pellets}$	Pellets cost	C_{pellet}
Lump ore fraction	M_{ore}	Sinter Cost	C_{sinter}
		Lime Stone cost	C_{lime}
		Carbon Tax	C_{O2Tax}

For the economical assessment a survey was done to identify representative raw material prices. The next section builds on the data collection of prices used in the cost objective function.

VI. ECONOMIC DATA USED IN THE COST OBJECTIVE FUNCTION

Little peer-reviewed data is available on the costs of charcoal and biomass, table 5 presents some values found in the literature. However, the prices of charcoal and biomass show a significant variation according to the source consulted, for instance Suopajärvi & Angerman (2011) report charcoal prices of 780 USD/t in Finland, while Fallot et al (2008) prices of 162 USD/t in Brazil.

Table 6: Charcoal costs reported in literature.

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

In order to create rational economic scenarios it is important to utilize the most accurate economic data possible, in this sense the authors consulted the biomass prices of 37 producers and traders in over 19 countries to assess the market price of primary biomass. Survey took place between April to September 2012, a summary of the results is posted on table 6.

Table 7: Prices consulted for primary biomass

Consulted	Producer	Product	Country	Price	Minimum Price	Maximum Price
				USD/m³	**USD/t**	**USD/t**
04/06/2012	Guangzhou Jingsenhuang Import And Export Trading Co., Ltd.	Natural Wood Veneer	China	500-1000	588	1176
04/06/2012	Ocean East Co. Ltd.	Eucalytus	Thailand	198 - 470	233	553
04/06/2012	WATA CI Sarl	Hardwood	Cote D'Ivory	200 - 450	235	529
04/06/2012	Perspekta	Siberian pine	Rusisia	160	188	188
04/06/2012	Khafaga tropical Woods	Bubinga Logs	Cameroon	180 - 200	212	235
04/06/2012	World Wood Export	Greenheart	Guayana	200	235	235
04/06/2012	World Wood Export	Darina	Guayana	200	253	253
04/06/2012	World Wood Export	Tatabu	Guayana	215	253	253
04/06/2012	World Wood Export	Purpleheart	Guayana	280	329	329
040/6/2012	World Wood Export	Jatoba	Ecuador	290	341	341
04/06/2012	World Wood Export	Mascarey	Ecuador	290	341	341
04/06/2012	World Wood Export	Saligna	Angola	320	376	376
04/06/2012	World Wood Export	Ipe	Ecuador	480	565	565
04/06/2012	Shandong Huaxin Jiasheng Wood Co., Ltd.	Eucalytus	China	200 - 500	235	588
040/6/2012	Veritas International	Eucalytus	Zambia	385 - 400	453	471
28/08/2012	KM Korea	Acacia Timber	Vietanam	190-235	233	276
28/08/2012	Kwa Zulu timbers	Teak	South Africa	375-500	441	588
28/08/2012	TKL Sawmill Sdn. Bhd.	Keruing	Myanmar	380-450	233	529
28/08/2012	Khafaga tropical Woods	Padauk logs	Cameroon	180-200	212	235
28/08/2012	Ace Link Pte Limited	Azobe	Liberia	190	224	224
28/08/2012	Nis Limitada	Hardwood	Mozambique	250-300	294	353
28/08/2012	Nicewood Company Ltd	Balau	Vietnam	400-480	471	565
28/08/2012	Evergreen Hardwoods, Inc.	Pine	Vietnam	200-220	235	259
28/08/2012	D & W Agencies	Turpine logs	South Africa	200-220	235	235
28/08/2012	Hoang Hai SX & XNK Co. LTD	Keruing	Vietnam	320-380	376	447
28/08/20012	Pro Forestry	Eucalytus	South Africa	150	176	176
28/08/2012	Kwanita Import & Export Co.	Hickory	USA	350-400	235	471
28/08/2012	Fidelity Group Ltd	Kayno Hardwood	Gambia	200-220	235	259

28/08/2012	ionel baluta	whitewood	Romania	200	235	235
28/08/2012	thetaj	Kwila hardwood	Australia	300-400	453	471
28/08/2012	Veritas International	Eucalytus	India	385-400	453	471
28/08/2012	IEL International LTD	Lumber	Papua New Guinea	185-220	353	259
28/08/2012	Charles Thom	Wamara	Guyana	300-350	353	412
28/08/2012	Ultrawoods Ent.		Guyana	100-350	118	412
28/08/2012	Green Farms LLC	Timber	USA	300-450	353	529
28/08/2012	Alpha Farmers LTD	Timber	Cameroon	500-700	588	824
28/08/2012	Abdullahoglu Orman Urunleri Mobilya Insaat Ithalat Ihracat Sanaya Ve Ticaret Limited Sirketi	Oak	Bulgaria	125	147	147

Additionally histograms of consulted prices of primary biomass (minimum and maximum price) have been issued using the statistical tool MINITAB®14 (see figures 7). The results show that the mean of minimum price is 310 USD/t (with a standard deviation of 121 USD/t), while in the case of maximum price the mean is 400 USD/t (with a standard deviation of 201 USD/t).

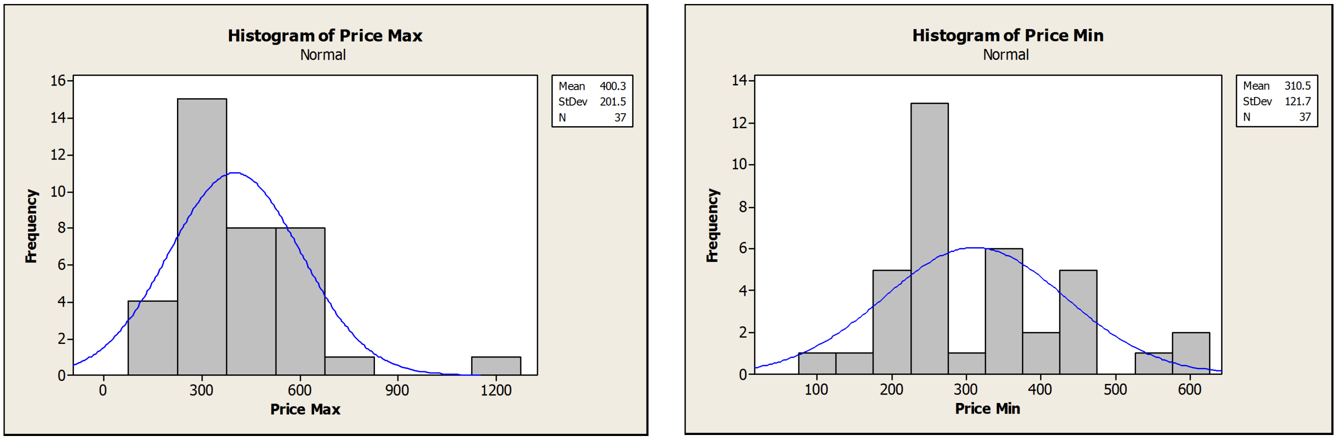


Figure 7, histogram of minimum (right) and maximum (left) price for primary biomass

Residual biomass, such as biomass briquettes, palm kernel, coconut shell, wood chip, wheat straw hay, corn straw pellets, rice husk pellets, are forestry and agricultural wastes that can be used for the purposes of charcoal making with a significant cost abatement.

Similarly to the cases of primary biomass and charcoal the authors consulted the biomass prices of 48 producers and traders in over 19 countries, survey took place between April to September 2012, a summary of the results is posted on table 6.

Table 8: Prices and characteristics for residual biomass

Consulted	Producer	Country	Product	Price	Density	Fixed carbon	Ash	Caloric Value	Vo-latile matter	Moisture Content	Size
				USD/t	Kg/cm3	(%)	(%)	Mj/kg	(%)	(%)	(mm)
23/08/2012	M.Ali & CO.	Pakistan	Wheat straw hay	115-120							

23/08/2012	M.Ali & CO.	Pakistan	Sugar cane Bagasse	85-90								
24/08/2012	Zigma International	India	Coconut shell	150-300								
24/08/2012	Galavin Trading	Philippines	Coconut shell	120-130								
24/08/2012	Live-Ex Resources	Kenya	Coconut shell	130								
24/08/2012	Zakza Utama Enterprise	Malaysia	Coconut shell	120								
24/08/2012	Truong Kim Trading and Investment JS Co	Vietnam	Cashewnut shell	220-240								
24/08/2012	Speedway Marketing	Malaysia	Palm kernel shell	95-100								
24/08/2012	IBIC Ghana Limited	Ghana	Coconut shell	150-200								
24/08/2012	Evergreen Multi Resources	Malaysia	Palm kernel shell	65-85								
24/08/2012	CV. Prima Desain Widya Adicipta	Indonesia	Palm kernel shell	70-75								
24/08/2012	Taito Energy SDN BHD	Malaysia	Palm kernel shell	45-60								
24/08/2012	JPG Continental Link Ltd	Nigeria	Palm kernel shell	50-55								
24/08/2012	Dalian Minglu International Trade Co., Ltd.	China	Peanut Shell Pellets	138-145	0.9-1.1		7 max	17.5-18.8		11 max	8 mm	
24/08/2012	Dalian Minglu International Trade Co., Ltd.	China	Peanut Shell Pellets	140-190								
24/08/2012	Dalian Minglu International Trade Co., Ltd.	China	Corn Stalk pellets	110-150	0.9-1.1		7 max	17.5-18.8		11 max	8 mm	
24/08/2012	Nong Trai Xanh Co. LTD.	Vietnam	Pine Wood Shavings	130								
24/08/2012	Vietwoodee Joint stock Co.	Vietnam	sawdust	55-90								
24/08/2012	Vietwoodee Joint stock Co.	Vietnam	Wood chip	120-135								
27/08/2012	Binh Ühoc Export Import Joint Stock Co.	Vietnam	Acacia Sawdust	40-100								
24/08/2012	Bioenergy Machinery SDN. BHD.	Malaysia	Saw dust pellets	100-140			1	4500 kcal/kg		4.50%	6 x 30	
24/08/2012	Qingdao Aibang International Trading Co., Ltd.	China	Wood Sawdust	110-160				4501 kcal/kg		6-8%	6 mm	
24/08/2012	Vietwoodee Joint stock Co.	Vietnam	Wood Sawdust	50-70								
24/08/2012	Qingdao Chengyang Xingwang Charcoal Mechanism Factory	China	Biomass briquette	150-250			5%	4500		10%	50*500	
24/08/2012	Matsuri International CO. LTD.	Thailand	Biomass briquette	120		16.19		2000 J		6.83	50*400	
24/08/2012	Dalian Minglu International Trade Co., Ltd.	China	Biomass briquette	120-150								
24/08/2012	Xinxiang Yitong Machine Co., Ltd.	China	Biomass briquette	180-280			6%	1340000		12%	18*60	
24/08/2012	Jinan Jutao Bioenergy Technology Co., Ltd.	China	Biomass briquette	68 - 120								
24/08/2012	RAM EXPORTS	India	Biomass briquette	100-105	1.0		7%	4200 J		10%	90 mm	
24/08/2012	Gordie Global	Ireland	Biomass briquette	125-180				17.76 Mj/kg		10-12%		
24/082012	Natural Enviroment Company	Vietnam	Biomass briquette	85 - 100		16.91	8.96%	4491		6.43%	85*350	
24/08/2012	AADITYA IMPEX	India	Biomass briquette	110-150			7.00%	4000		8.00%	90	

24/08/2012	FiberTay	Malaysia	Biomass briquette	50-100				3500 kcla/ kg		<10%	
24/08/2012	Sri Balaji Bio Fuels	India	Biomass briquette	95	0.8-1.2			> 4200			90
24/08/2012	SC Adelphin Boys Impex SRL	Romania	Biomass briquette	110-156							
24/08/2012	eClouds	India	Biomass briquette	125-130							
24/08/2012	JSC Agrostilplus	Ukraine	Biomass briquette	65-104							
24/08/2012	Nguyen Brothers Company	Vietnam	Rice Husk briquette	90-100			8.96%	4491		6.43%	85*350
24/08/2012	Brazil Biomass and Renewable Energy - Exports Wood Chips	Brazil	Wood briquette	156	1.4		1.50%			<10%	60*150
24/08/2012	Century Biomass	Malaysia	Rice Husk briquette	60-70			14.50%	3900-4300		9.48%	95*270
24/08/2012	EMSI	India	Biomass briquette	77-88							
24/08/2012	PELLETFARM SDN. BHD.	Malaysia	Biomass briquette	130-133			2.00%	19		6.00%	8*50
24/08/2012	Fuel India Agrinergy Syndycateicate	India	Biomass briquette	125-150		47.1	6.78%	4200		7.2-8%	
24/08/2012	MADEIRAS GOEDE LTDA - EPP	Brazil	Biomass briquette	147							
24/08/2012	Agro-Foresty Waste Management	Bangladesh	Biomass briquette	110			6.00%	4200			
24/08/2012	Ralm Inc.	Vietnam	Rice Husk briquette	75-78			12.50%	4000	4%		3000*90
24/08/2012	Yew Hoe Heng Oil Palm Sdn Bhd , Eco Earth Resources	Malaysia	palm briquette	120-140							
24/08/2012	K + LFW	Singapore	Biomass briquette	140-160	1.200			4400		7.80%	
24/08/2012	wood trading exporters	Cameroon	Wood pellets	45-60	1.100		0.50	4600	8%	4.50%	8*40
24/08/2012	Americanstone Contractors	USA	mesquite fuel chip	54			10.0			15.00%	
24/08/2012	Archana Enterprises	India	Bio-fuel	175-200	0.8-1.2	40-55	3-7%	4200-4600		<5	
24/08/2012	Jinan Jutao Bioenergy Technology Co., Ltd.	China	Biomass briquette	68-120				3500-5000			
24/08/2012	MUSAAB MOOSA ENTERPRISES	Pakistan	Wheat straw hay	120-130							
24/08/2012	ASK Enterprises	India	Wheat straw hay	125-160							
28/08/2012	Liaoning Modern Agricultural Machine Equipment Co., Ltd.	China	Corn Straw pellet	138-158	1.1 -1.3		8.00%	3800-4200		9.00%	8 mm
28/08/2012	Dalian Minglu International Trade Co., Ltd.	China	Corn Straw pellet	150-160	0.9-1.1		7.00%	4200			8*15

As in the case of primary biomass (figure 7), histograms of consulted prices of residual biomass (minimum and maximum price) have been issued using the statistical tool MINITAB®14 (see figures 7). The results show that the mean of minimum price is 107 USD/t (with a standard deviation of 39 USD/t), while in the case of maximum price the mean is 133 USD/t (with a standard deviation of 52 USD/t). As clearly indicated by the results, residual biomass is significantly less expensive than primary biomass.

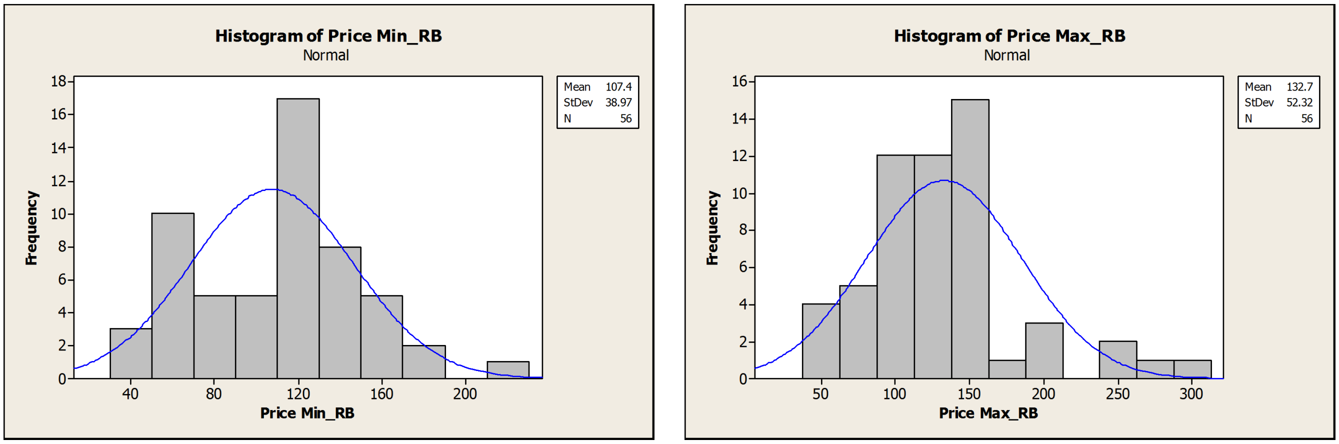


Figure 8, histogram of minimum (right) and maximum (left) price for residual biomass

Similarly, the prices of charcoal were consulted to 29 producers and traders in 8 countries, survey took place in April 2012, a summary of the results is presented in table 7. It is important to mention that no information was available with regards to the sustainability of the biomass and charcoal, thus we cannot distinguish if the biomass or the charcoal posted in table 6 & 7 come from well managed plantations.

Table 9: Prices and characteristics of charcoal

Consulted	Producer	Country	Product/raw material	Price	Fix Carbon	Ash	Caloric Value	Volatile matter	Moisture Content
				USD/to	%	%	MJ/kg	%	%
15/04/2012	Ganzhou Yaxin Trading Co., Ltd.	China	Briquettes from coconut	650 - 750	87	5	7500		6
15/04/2012	Jianyang Eagle Bamboo And Wood Products	China	Lump from bamboo	20 - 50					
15/04/2012	Gongyi Xiaoyi Hongji Machinery Factory	China	Hardwood charcoal	290 - 320		0.3	7800		
15/04/2012	Yongkang Harvest Industry & Trade Co., Ltd.	China	Coconut shell lump	350 - 500	85 - 90	4	8000	2	4
15/04/2012	Jiangxi Taisheng Charcoal Industry Co., Ltd.	China	Bamboo lump charcoal	200 - 250		8	7000		
15/04/2012	Yongkang Harvest Industry & Trade Co., Ltd.	China		350 - 500	85 - 90	4	8000	2	5
15/04/2012	Ying Lan Sawdust Charcoal Manufacture	China	Lumps from hardwood	400 - 600		3	7500 - 8000	2.5	4
15/04/2012	Gongyi Xiaoyi Hongji Machinery Factory	China	Lumps from hardwood	270 - 340		3	8200		
15/04/2012	Nanchang Twin Win Import & Export Trade	China	Bamboo	300 - 700		2	8500		
15/04/2012	Ganzhou Yaxin Trading Co., Ltd.	China	Bamboo lump	450	75 - 85	4.0 - 8	7000 - 7500	15 - 20	8.0 - 13
15/04/2012	Publiaromas	Bolivia	Hardwood charcoal	350	85	5			5.0 - 7
15/04/2012	Baikal Herbs trade	Russia		505 - 638					
15/04/2012	Oconee Eenergy inc	USA	Hardwood charcoal	550 - 600	76 - 89				
15/04/2012	Carlos Augustin	USA		300 - 400	75 - 85	1.3			6.5
15/04/2012	Aldana’s Corp	USA		300					
15/04/2012	Consto traders, LLP	USA	From Iroko, Oak, Mahogany	207 - 255	78 - 80	3	7400	12 - 13	1

15/04/2012	SMI International Inc	USA	Hardwood charcoal	250 - 300					
16/04/2012	Sindicarv	Brazil	Charcoal for BF	251 - 288					
16/04/2012	Climsy Agro International company	Germany	hardwood charcoal, coconut	450 - 500					
16/04/2012	Cocofire Kokoskohle	Germany	Coconut shell lump	980 - 990	75	4	7650		7
16/04/2012	Pt Indo Jaya Terigu	Germany	hardwood charcoal	428	72 - 84	2.0 - 5	6500 - 7200	7 - 17	4 - 8
16/04/2012	Olypian protect product manufacture	S.Korea	Coconut shell lump	350 - 380					
17/04/2012	Gongyi Xiaoyi Hongji Machinery Factory	Japan	hardwood charcoal	430 - 530	77.6	1 -2	7440		4.8
17/04/2012	Ganzhou Eastern Dragon Household Articles	Japan	Bamboo lump charcoal	499 - 749		5 max	8500		
17/04/2012	Nanchang Twin Win Import & Export Trade	Japan	Saw dust briquette	500 - 800	85 - 90	5 – 10	7800 - 8900	3	5 - 10
17/04/2012	Gongyi Xiaoyi Hongji Machinery Factory	Japan	Oakwood charcoal	380 - 450		0-1	7800		
17/04/2012	Jier leh ting industrial co., ltd.	Taiwan	Mangrove charcoal	430 - 460					
15/04/2012	Universal Enterprises	India	tyre pyrolysis black charcoal	330					
15/04/2009	Sairam Charcoal Export and Consultants	India	Lump charcoal	600 - 650	70 - 75				10
15/04/2010	Sikumar Trading and Service Co.	India	hard wood charcoal	300 - 400					
15/04/2011	Maruthi Prasad	India	hard wood charcoal	400 - 500					
15/04/2012	M/S Kilanga enterprises	India	hard wood charcoal	225					
15/04/2012	VKN Groups	India	Babul hardwood charcoal	250 - 280	65 - 75	< 1	> 6500		5 - 10
15/04/2011	EUROWOOD Ltd	Ukraine	hard wood charcoal	380 - 400					
15/04/2011	El-fut	Ukraine	hard wood charcoal	360 - 380			7500 -8120		
15/04/2012	Ukrainian charcoal holding	Ukraine	hard wood charcoal	332 - 400	82 - 86	< 3			< 6

To recreate scenarios of raw material cost for the 9 BF selected, most relevant charcoal prices were used, these prices are posted in the table 8.

Table 10: Cost used in economic objective function.

Country		**Ref**	**Simbol**	**China**	**Japan**	**Russia**	**South Korea**	**India**	**Brazil**	**USA**	**Ukraine**	**Germany**
Coal	USD/t		Ccoal	134	135	121	134	120	117	124	121	125
Charcoal	USD/t		Ccharcoal	330	510	570	375	320	270	360	370	480
Iron Ore	USD/t		Core	163	163	163	163	163	163	163	163	163
Pellets	USD/t		Cpellet	178	178	178	178	178	178	178	178	178
Sinter*	USD/t		Csinter	175	175	174	175	174	174	174	174	157
Limestone	USD/t		Clime	125	125	125	125	125	125	125	125	125
Electricity	USD/ MWh		Cel	24	232	96	84	123	113	116	40	324
Carbon Tax	USD/t CO2		CO2Tax	0.00	20.85	0.00	33.25	1.07	0.00	5.00	1.00	18.62

**Cost of sinter material was calculated as follows:* $C_{\sin ter} = 0.93.[C_{ore}.] + 0.14.[C_{\lim e}] + 0.042.[C_{coke}]$

Some of the other cost in table 8 come from the following sources:

Cost	Source	Reference
Coal	International Coal Report by Platts, Issue 1030 (July 11, 2011)	[60]
Iron Ore	Daily China import iron ore fines average 2010 – 2012 March (63.5% Fe) $ per dry metric tonne cfr main port (Metal Bulletin).	[61]
Pellets	China import iron ore pellet 2010 – 2012 March (65-66% Fe) $ per dry metric tonne cfr main port (Metal Bulletin).	[62]
Limestone	Mineral Commodity Summaries: Lime, by US Geological Survey (September 2011)	[63]
Electricity	2011 Key World Energy Statistics by International Energy Agency (2012)	[1]
Carbon Tax	Analyse van de CO2-markt, Emissierechten Reuters, Thomson (October 27, 2005). “Japan should introduce Carbon Tax in 2007-Ministry”. Planet Ark World Environment News. Kim, Y. (March 30, 2010). “Carbon tax plan floated”. The Korea Herald.	[64-66]

With resepct to the values of iron ore and pellets used in the cost objective function, the present work calculated the average values of iron ore fines average 2010 – 2012 March (63.5% Fe) $ per dry metric tonne cfr main port (Metal Bulletin) and Pellets China import iron ore pellet 2010 – 2012 March (65-66% Fe) $ per dry metric tonne cfr main port (Metal Bulletin), see figure 5.

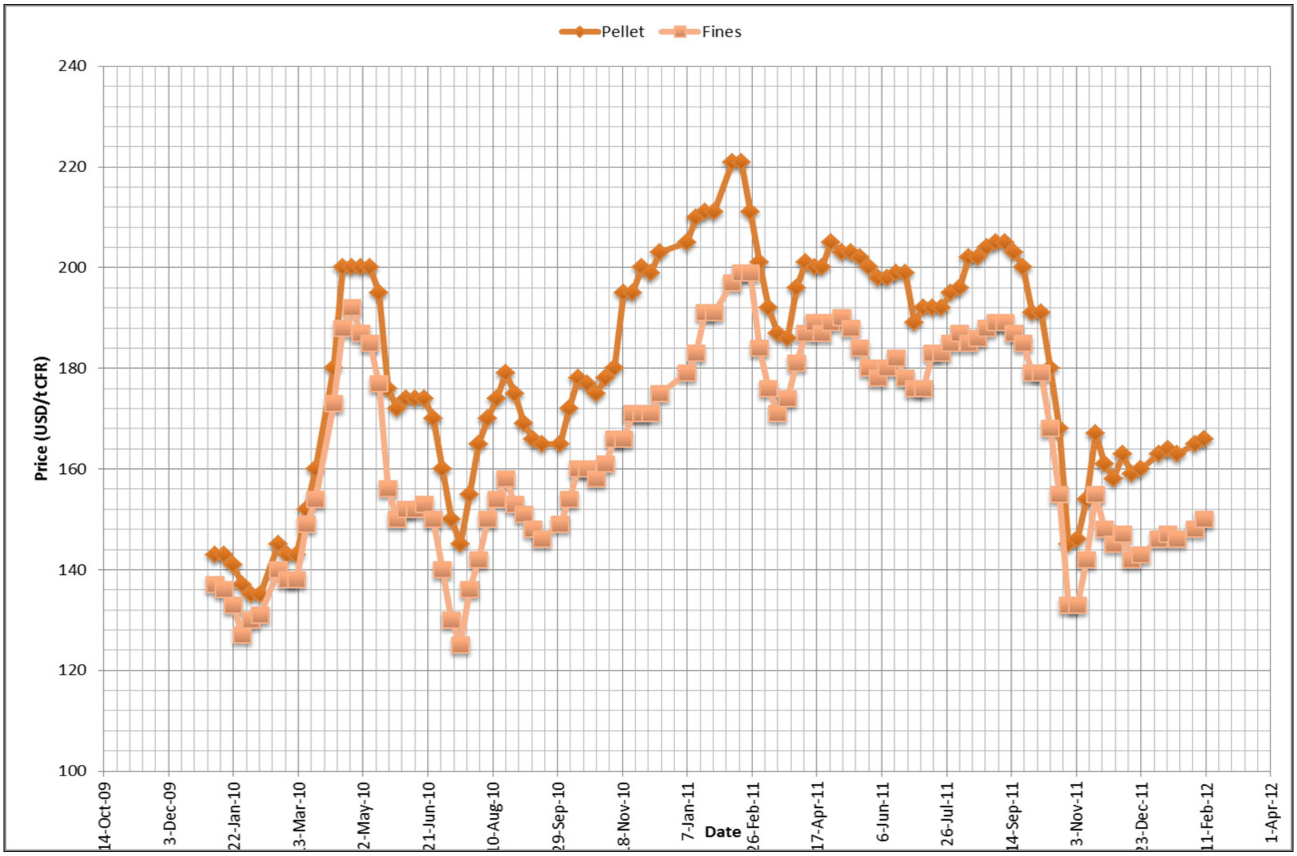


Figure 9, Price development of Iron ore fine and pellets (China) January 2010- February 2012, Source: Metal Bulletin

VII. CONCLUDING REMARKS

1. The analysis of the literature concerning the injection of small particles of charcoal to blast furnaces (Bio-PCI), leads to indicate a potential CO2 emission reduction of 19-40% without any major affectation to the actual BF operation.

2. A BF process simulation has been used for the estimation of off gases and other process parameters, the off gas presents a valuable heat capacity that can be used in other areas of the iron plant and may reduce the need for external power sources.

3. In the methodology a cost function objective has been used to assess the impact of Bio-PCI over the economy of the ironmaking in BF. The cost objective function takes into consideration the principal cost elements in the ironmaking productions: iron bearing materials, fuels, fluxes and oxygen.

4. A survey on prices of charcoal, primary biomass and residual biomass has been performed to asses actual market prices, such prices were used in the cost function objective.

5. Prices of residual biomass (107-133 USD/t) are substantially more economical than primary biomass (310-400 USD/t), thus the use of residual biomass would help to significantly reduce the cost of charcoal production.

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