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The CO₂ mitigation potential, technical and economic viability of biomass char utilization in blast furnaces

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*To my children, Valentina and Samuel,
to my wife Marsha and my mother and father: Gracias!*

*“The clear and present danger of climate change means
we cannot burn our way to prosperity.
We already rely too heavily on fossil fuels.
We need to find a new, sustainable path to the future we want.
We need a clean industrial revolution.”*

Ban Ki-moon

*“Our problems are man-made,
therefore they may be solved by man.
And man can be as big as he wants.
No problem of human destiny is beyond human beings.”*

John F. Kennedy

*“Start by doing what's necessary;
then do what's possible;
and suddenly you are doing the impossible.”*

Francis of Assisi

Abstract

This thesis addresses the issues of climate change mitigation and reduction of carbon emissions within the iron- and steel-making industry, which is responsible worldwide for 5 % of total greenhouse emissions. The problem in mainstream hot metal production is that the principal reductants are coke and coal, which come from fossil endowments. This generates the major portion of the carbon emissions from blast furnaces. In this respect, the re-incorporation of biomass as fuel/reductant in ironmaking may significantly help to reduce the carbon footprint of the industry. The goal of this study is to investigate such a hybrid solution to the problem of carbon emissions in coke-based blast furnaces.

There are fundamental barriers to the wide diffusion of ironmaking based 100 % on charcoal replacement of coke. The most significant of these include the large land areas needed for plantation growing the biomass required, and elevated processing cost. Nevertheless, the partial injection of biomass char fines into blast furnaces as auxiliary fuel, which in this thesis I call **Bio-PCI**, appears to be a favorable, technically feasible and economically viable option to mitigate part of the CO₂ emissions in iron-making. This hybrid solution has been used at industrial scale in small blast furnaces in Brazil for several years. Based on process simulation, results have been generated that indicate the technical and economic feasibility of **Bio-PCI**. In this Thesis a cost objective function was employed to evaluate the variation in production cost when biochar replaces coal as injection fuel.

From the technical perspective, this Thesis presents estimates that the use of biomass chars as **Bio-PCI** may reduce total CO₂ emissions in a coke based blast furnace by between 19 % and 40 %, according to the injection rate. Additionally, its utilization would not alter the quality of hot metal or slag composition. From the economic perspective, I report an increase in the production cost of hot metal when **Bio-PCI** was introduced. Accordingly, two alternative pathways were explored to improve the economic attractiveness of **Bio-PCI** - 1) the introduction of carbon taxes and 2) the utilization of residual biomass for charcoal-making. With respect to carbon taxes, the Thesis estimates that a tax of US\$47.1 to \$198.7 per tonne CO₂ would be needed to enhance the attractiveness of **Bio-PCI** in reducing carbon emissions. With respect to the use of residual biomass, the production cost of biochar could be reduced by US\$120-180 per tonne through the use of agricultural and forestry residues instead of hardwood. From the strategic perspective, the Thesis argues that the use of sustainable

residual biomass, together with the introduction of carbon taxes, can create the economic conditions needed to produce carbonaceous residues at a competitive price in order to reduce CO₂ emissions in coke based blast furnaces with a view to mitigating their impact on climate change.

Keywords: biomass char, blast furnace, Bio-PCI, sustainable ironmaking, CO₂ reduction, carbon tax, auxiliary fuel, residual biomass, climate change mitigation.

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Authorship statement

Paper I was planned and written by the author of this dissertation, John A. Mathews contributed with valuable discussion and comments on drafts. Mr. Ricardo Luchese added some important data about the utilization of charcoal in the Blast Furnaces and iron ore sintering in Brazil.

Paper II was planned and written by the author of this dissertation; John A. Mathews contributed with valuable discussion and comments on drafts.

Papers III and IV were planned and written by the author of this dissertation.

Papers V and VI were planned and written by the author of this dissertation, John A. Mathews contributed with valuable discussion and comments on drafts. The author of this dissertation has been responsible for the literature review, methodology presented, and data collection.

Paper VII was planned and written in co-operation with John A. Mathews and Fernando Garcia-Carcedo.

Related publications by the author of this dissertation

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Abbreviations and acronyms

AISI	American Iron and Steel Institute
BF	Blast furnace
Bio-PCI	Biochar injection through PCI rigs
BOF	Basic oxygen furnace
CCS	Carbon capture and storage
CO ₂	Carbon dioxide
COG	Coke oven gas
COURSE50	Ultimate Reduction in Steelmaking process by Innovative technology for cool Earth 50
CR	Compression resistance
DRI	Direct reduced iron
EAF	Electric arc furnace
<i>F</i>	Cost function objective
GHG	Green house gases
LCA	Life cycle analysis
LCI	Life cycle inventory
HM	hot metal
kg/t HM	kilogram per ton hot metal
M	stoichiometric coefficient
MMt	millions of metric tons
NG	natural gas
PCI	Pulverized coal injection
OHF	open hearth furnace
SNG	Synthetic natural gas
TMt	Thousand of metric tons
V&M	Vallourec and Mannesmann
ULCOS	Ultra-low carbon dioxide steelmaking

1. Introduction

As Western nations became industrialized, they did so with the intense use of resources and fossil fuels, which worked very well in building wealth and raising populations out of poverty. But now these carbon- and resource-intensive industrial systems present a barrier to the further development and spread of industrialization. According to estimations of the IPCC (2011), currently 85 % of primary energy driving global economies comes from the combustion of fossil fuels and consequently consumption of fossil fuels accounts for 56.6 % of all anthropogenic greenhouse gases (GHG) emissions [1]. Certain industries such as cement production, iron and steel, non-ferrous metals and aluminium all now present as highly efficient producers of materials but also as strong sources of carbon emissions. Policy analysts are searching for ways to reduce the carbon- and energy-intensity of these industries, with interventions ranging from carbon taxes (to change cost calculations), circular economy innovations (to link outputs of one process to inputs in another), market expansion initiatives (for less energy-intensive products), and technological innovations.

One of the critical industries that presents major carbon emission problems is iron and steel. Globally the iron and steel industry produced 1.16 billion tons iron and 1.61 billion tonnes steel in 2013 (Worldsteel, 2014) [2], mostly in China, accounting for 2.29 billion tonnes carbon dioxide (CO₂) emissions. Presently there is now an intense search underway globally to find effective ways of reducing the energy and carbon footprint of the iron and steel industry. To this end several CO₂ breakthrough programs have been launched globally, such as the program ULCOS in Europe, the COURSE50 in Japan, the CO₂ Breakthrough in Metal Production Program in Australia, the AISI CO₂ Breakthrough Program in USA and Canada and the POSCO CO₂ Breakthrough Technology Development in South Korea [3,4,5,6]. The approaches and the research focus may vary according to the programs mentioned; however they share the ambitious target of reducing carbon intensity of steel production by 50 % (Jahanshahi, 2015) [7].

This dissertation aims to contribute to this search, by focusing on ways in which biomass inputs might be substituted for coke/coal in iron producing operations. It reviews the experience to date in utilizing such biomass inputs (e.g. charcoal produced from quick-growing trees in Brazil, or recent developments in biochar production from agricultural waste) and analyses the

processes from both a technological effectiveness perspective and from a business/economic analysis. What has to be reported is that there is so far little progress on this front because of the continuing low costs of coal used in blast furnaces and the reluctance of policy makers to introduce carbon taxes that would even the pricing playing field and make low-emission alternative more economically attractive.

The overall conclusion reached in the research that lies behind this thesis is that a hybrid approach might work best as means of introducing a less energy- and carbon-intensive way of producing iron and steel. This is consistent with earlier episodes of introducing new technologies – such as the hybrid electric vehicle as a means of changing the paradigm of private automobiles from fossil fuels to electric traction.

At present, in the value chain of steel production, it is estimated that blast furnaces (BF) consume approximately 70% of the total energy needed in the whole steel production process in integrated plants (Larsson, 2005) [8]. Therefore, BF's are considered the single most carbon intensive contributor in the steel manufacturing process. In this sense, it becomes mandatory for metallurgists to look for feasible options to reduce the utilization of fossil fuels (mainly coke and coal) in iron production. In consequence, the present study focuses on the contribution that the carbonaceous residue of biomass after a carbonization process (biomass char or biochar) provides in replacing part of the fossil fuel requirement in ironmaking, and so to partially mitigate the CO₂ emissions. In summary, the objective of this work is to strategically analyze the present and future role of sustainable biomass char or biochar¹ in BF's.

The role of biomass in ironmaking

Looking back on the history of industry, it can be observed that charcoal from trees played a predominant role in metallurgy over time. Charcoal was the only fuel available for centuries in the reduction and smelting of ores, until Darby introduced the use of coke in BF's in 1709 (Gudenau et al. 2002) [9]. Paradoxically, at the time the introduction of coke was an environmentally positive action, because it helped to overcome the depletion of the native forest in England. After this innovation, the use of coke permitted operations with larger shafts, which led consequently to incremental increase in the iron production capacity. Arguably, the

¹ For the purpose of the present investigation, it is defined biochar as the biomass char gained from sustainable biomass, and carbonized using highly efficient kilns with high char yields (higher than 33 %).

introduction of coke was one of the fundamental conditions that facilitated the beginning of the Industrial Revolution (Sieferle 2002) [10]. Since the decade of 1980, there has been an increasing interest to reduce the coke utilization in BFs by the injection of auxiliary fuels through the so called tuyere rigs or PCI rigsⁱⁱ.

Presently, biomass char is used as fuel in some selected industries, for instance in the production of iron in Brazil (Valladares and Scherer, 2012) [11], or in ferroalloy manufacturing in India (Harman, 2007) [12]. Additionally, it is a key raw material in the fabrication of crystalline silicon solar cells (Ceccaroli and Lohne, 2003) [13]. In ironmaking, the production of hot metal (HM) from charcoal blast furnaces is considered to be carbon neutralⁱⁱⁱ, as trees sequester carbon and liberate oxygen during their growth. To this moment, 172 small BFs in Brazil use charcoal as a fuel in their operation (charcoal-BFs), the larger producers of charcoal-HM are: APERAM, Vallourec & Mannesman and GERDAU Divinópolis (Scherer and Braga, 2012) [14].

Biomass char is not only used as main reductant/fuel in charcoal-BFs in Brazil, it is also currently under industrial utilization in 46 BFs as auxiliary fuel, in which BF charcoal fines or *moinhas de carvão vegetal* (in Portuguese) are injected through the tuyere, also known in this work as Bio-PCI: biochar injection through PCI rigs. In these BFs, it is reported injection rates varying from 60 - 190 kg/t HM, for instance the BF 2 at Aperam and BF 2 Vallourec & Mannesman (both in Brazil) have respectively achieved a maximum injection rate of 160 and 190 kg/t HM (Gonçalves et al. 2012) [15]. According to Luchese (2015) charcoal fines are also used in the process of iron sintering at the iron mills of Viena, Sidepar and Cosipar [16]. Evidence shows that biomass char fines, which is a low value by-product of the charcoal production, is presently in active use in the Brazilian metallurgical industry.

Based on their potential carbon sequestration, in the past decade, the operation of the charcoal-BF has been of great interest to researchers worldwide as a plausible option to reduce the carbon footprint of ironmaking. In addition to the carbon neutrality, the experience of the last charcoal-BFs in Brazil demonstrates that charcoal-HM presents high market value, mainly due to the resulting low content of sulfur (Winter, 2012) [17].

ⁱⁱ Most of the modern BFs worldwide present injection rigs of auxiliary fuels to reduce the use of coke (which is an expensive fuel/reductant), and increase the economic performance of ironmaking. They are commonly known as tuyere or PCI rigs, because initially they were developed in 1837 by Carl Alberts for pulverized coal injection (PCI) (Assis, 2008), however under current industrial practice these rigs can also inject natural gas, tar, oil and biomass char.

ⁱⁱⁱ To attain the benefits of carbon neutrality, the biomass should be farmed in a sustainable manner and the carbonization should be efficient.

Despite the technical benefits, the economic prospects of ironmaking BF_s based on 100 % charcoal are set to progressively disappear, mainly because of the significant price difference between biomass char and fossil coal. The large plantations and resources required for the production of wood are additional barriers at the present moment. In consequence, the re-introduction of biomass as a renewable fuel in ironmaking is not only a technical challenge, but in the absence of a carbon tax it presents a serious economic problem that needs to be overcome.

Besides the industrial practice found in the last 172 charcoal-BF_s at this moment, the prospects of biomass utilization in iron- and steelmaking have been studied in the literature from several perspectives:

- Firstly, other lines of research have concentrated on alternative options of biomass char utilization to replace fossil fuels for specific stages of the steelmaking process to reduce its carbon intensity. For instance in the production of bio-composites (Ueda et al. 2009; Matsui et al. 2009; Lucena et al. 2008) [18,19,20], as a substitute of coal for cokemaking (McPhee et al. 2008, Ng et al. 2011) [21,22], in the injection of biomass-based synthetic natural gas (Bio-SNG) in BF (Suopajarvi et al. 2014) and in reheating furnaces (Johansson 2013) [23,24]
- Secondly, some studies have assessed the potential CO₂ reduction of biomass in the whole steel process (Norgate and Langberg 2009; Mathieson et al. 2011; Suopajarvi and Fabritius 2012) [25,26,27]. These works used life cycle analysis (LCA) in the case of Norgate and Langberg (2009), Mathieson et al. (2011) and Life Cycle Inventory (LCI) in the case of Suopajarvi and Fabritius (2012) to identify areas of improvement in the energy utilization and GHG impacts in the process.
- Thirdly, research focuses on the technical aspect of the torrefaction and burning of diverse residual biomass sources for metallurgical purposes (Chen et al. 2013), examining the technical properties of different sources of carbonization in the process. The results show that residual biomass can be blended and used in BF_s in compliance with the requirement of volatile matter of the application [28,29].

- Fourthly, there have been some investigations assessing by numerical simulation the economic perspectives of the introduction of CO₂ mitigation technologies to the BF process, for instance: *Top Gas Recycling in BF* (Helle et al. 2010; Mitra et al. 2011)[30,31], *Steelmaking with a Polygeneration Plant* (Ghanbari et al. 2012)[32], *Optimization of Ironmaking in the BF* (Pettersson et al. 2009)[33], and *BF Operation Combined with Methanol Production* (Ghanbari et al. 2011)[34].
- Fifthly, studies have looked at the technical aspects of biomass char in blast furnaces. These contributions have determined the viability of coal replacement (Babich et al. 2010; Machado et al. 2009), this has been corroborated by simulation performed by Wijayanta, et al. (2013) [35,36].

All the works mentioned above are fundamental in the field of charcoal use in ironmaking and their contributions are significant to the present dissertation^{IV}. Nonetheless, the literature review of this work has identified several gaps in the body of knowledge, which have motivated and guided the writing of the papers that form the foundations of the present dissertation. The structure of the present dissertation is described below.

Structure of dissertation

The dissertation is structured around a number of peer-reviewed journal and conference papers which build upon other specific research questions related to present and future role of biomass char in BFs. As shown in Table 1, each paper has been designed and written to address specific sets of research questions. Papers I and II explore the current status of charcoal-ironmaking and the limitations for a further increase in the HM production based purely in charcoal-BF. Papers III, IV, and V build on the technical, environmental and economic aspects of biomass char injection in BF or Bio-PCI. Paper VI discusses the utilization of residual biomass as potential source of improving the economic perspectives of biochar in ironmaking. Finally, paper VII (and part of paper IV) presents a discussion of countries with improved prospects of incorporating Bio-PCI in ironmaking.

^{IV} A detailed review of these and other fundamental studies is presented in the literature review.

Table 1. Papers and research questions

<i>Paper</i>	<i>Journal/ Conference Name</i>	<i>Research question(s)</i>
I	In the proceedings of <i>Sustainability in Ironmaking/ Steelmaking, COM 2015</i> , Toronto, Canada	<ul style="list-style-type: none"> • <i>What are the main limiting factors governing the expansion of biomass char based ironmaking?</i> • <i>What are the future prospects for biomass char utilization in ironmaking?</i>
II	Journal: <i>Tecnologia em Metalurgia, Materiais e Mineracao 2015 / 6th Steel Industry Conference and Exposition. AIST</i> , Oct. 2014 Monterrey, México.	<ul style="list-style-type: none"> • <i>What quantities of biomass, plantation area and fertilizer are required for the expansion of biomass char based iron making?</i> • <i>What is the potential CO₂ reduction in the BF process with biomass char utilization?</i>
III	In the proceedings of 23rd <i>International Metallurgical and Materials Conference METAL 2014</i> , May 2014, Brno, Czech Republic	<ul style="list-style-type: none"> • <i>What is the CO₂ reduction of Bio-PCI introduction in a coke-based BF?</i> • <i>What is the effect of Bio-PCI introduction over the operation of a coke-BF?</i> • <i>What is the effect of Bio-PCI introduction over the economy of a coke-BF?</i>
IV	<i>Journal of Materials Research and Technology</i> JMRT 2014 (Journal) / 6th ICSTI'12, Oct. 2012 Rio de Janeiro, Brazil (Conference)	<ul style="list-style-type: none"> • <i>What is the potential CO₂ reduction in the coke-BF process with Bio-PCI?</i> • <i>How can charcoal prices influence the economics of HM production in a coke-BF with Bio-PCI?</i> • <i>How can carbon taxes influence the economics of HM production in a coke-BF with Bio-PCI?</i> • <i>Which countries present best prospects for Bio-PCI deployment in BFs?</i>
V	In the proceedings of <i>Sustainable Development Seminar, IAS</i> , Nov. 2013, Rosario, Argentina	<ul style="list-style-type: none"> • <i>What is the potential CO₂ reduction of co-injection of charcoal and coal?</i> • <i>How does co-injection affect the economy of a coke-BF operation?</i> • <i>How can carbon taxes influence the economics of HM production in a coke-BF with Bio-PCI and coal co-injection?</i>
VI	<i>Revista de Metalurgia 2013</i> (Journal) / <i>5th Steel Industry Conference and Exposition. AIST</i> , Oct. 2012 Monterrey, México.	<ul style="list-style-type: none"> • <i>What is the effect of biomass cost over the biomass char production cost?</i> • <i>How does the use of residual biomass affect the economics of biomass char production?</i> • <i>How does the use of residual biomass affect the technical features of biomass char?</i>
VII	In the proceedings of 4th <i>Baosteel Biannual Academic Conference</i> , Nov. 2010, Shanghai, China.	<ul style="list-style-type: none"> • <i>Which countries are likely to implement Bio-PCI?</i>

The body of research reported in these papers examines and evaluates the biochar option in ironmaking. The analysis suggests that one of the most feasible options to mitigate the carbon footprint of BFs is the incorporation of Bio-PCI or the injection of small particles of biomass char through PCI rigs. There is a consensus in the literature that Bio-PCI is one of the most practicable options to reduce up to 40 % of the CO₂ emissions in the ironmaking process. It is additionally industrially proven, as at the time of writing most this contribution (between January 2010-September 2015) 46 BFs in Brazil inject biomass char in BFs, according to the feedback from Prof. Assis in 2016 the number has reduced to less than 25 BFs injecting charcoal [37].

The present dissertation focuses on four aspects of the technical option of biomass-char injection in BFs: 1) technical feasibility; 2) CO₂ mitigation potential; 3) economic prospects; and 4) strategic analysis of its deployment.

The structure of the dissertation is schematically depicted in Figure 1. Chapter 2 presents a literature review of the fundamentals of BF operation, and introduces the concept of auxiliary fuels. It examines the history and current state of biomass char utilization in ironmaking, and follows with a review of the economic aspects of biomass in ironmaking. Chapter 3 shows the different models for the assessment of technological innovations in BFs and describes the methodologies and data used in the presented articles. Chapter 4 summarizes the main contributions used in the presented papers. Chapter 5 presents the results and discussion. Finally, Chapters 6 and 7 present the conclusions and suggested future research work.

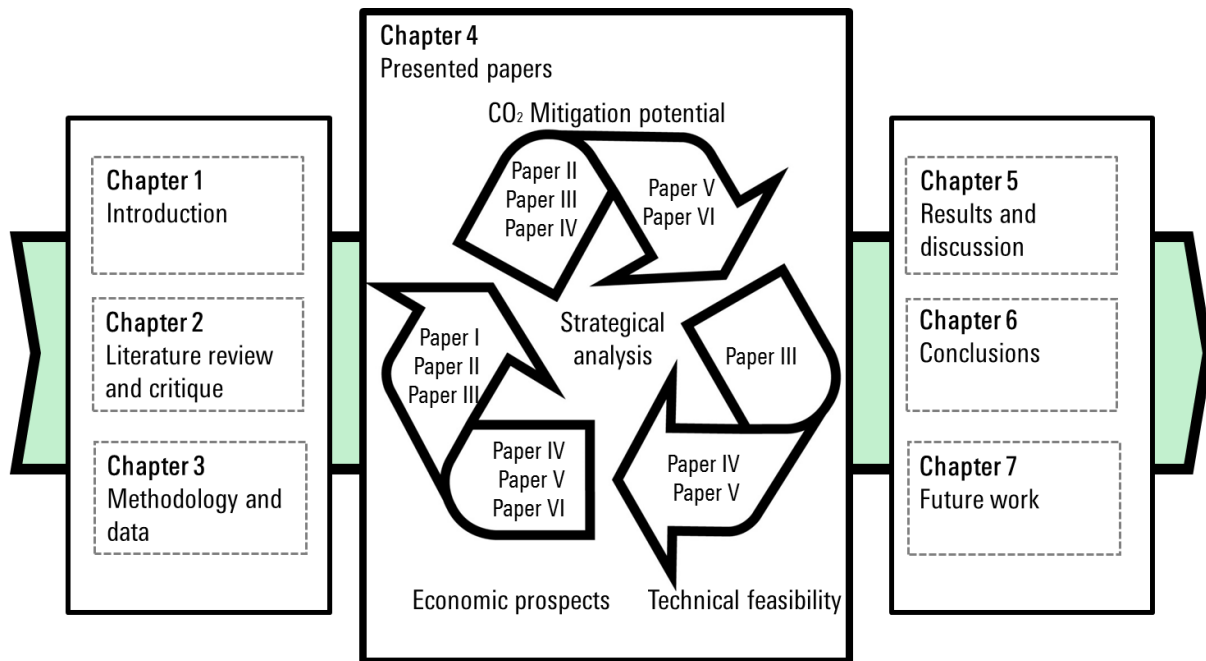


Figure 1. Schematic representation of the dissertation

The present conceptual study sets out to make a distinctive contribution to metallurgical process by assessing the opportunities for introducing biomass char in the professional practice of BF-ironmaking. The present dissertation makes the following distinct contributions.

1. Technical perspective:

- ✓ Based on the results of the process simulation, it is observed that the injection of charcoal in a coke-BF would not negatively influence the quality of HM, slag and top gas.
- ✓ The process simulation indicates that coke-BF operating with Bio-PCI generate less slag than the case of fossil PCI.

2. Environmental perspective:

- ✓ The assessment shows a CO₂ reduction potential as a function of Bio-PCI injection rate. In this respect, prospective users may estimate the level of CO₂ mitigation according to the biomass char injection rate.
- ✓ The assessment indicates that large quantities of biomass and fertilizer and vast plantation areas are required to sustain an increase in biomass char use in BFs.

3. Economic perspective:

- ✓ The assessment shows an increase in the production cost of HM when Bio-PCI is introduced.
- ✓ It estimates the projected level of carbon taxes required to make Bio-PCI economically feasible in a coke-BF.
- ✓ It evaluates the effect of residual and primary biomass costs over the charcoal production costs.

The argument presented is framed to support the technical, environmental and economic justification for introducing biochar into the steelmaking process. The distinctive contributions are indicative (rather than being specific) of a future direction in the biomass utilization in BFs. The main objective of the current dissertation is to indicate a possible partial solution to the very practical problem of CO₂ emissions associated with iron production; the findings are claimed to be relevant for metallurgists, policy makers, managers and scholars. The dissertation provides an indication of the possible benefits, limitations and economic scenarios.

Scope and limitations

The present dissertation is based on the study and analysis of the replacement of fossil fuels in BFs by biomass char with a special focus on the technical, environmental and economic perspectives of the deployment.

From the environmental perspective, the present dissertation focuses exclusively on the mitigation of CO₂, as this is the main GHG emission generated in BFs (Gielen, 2003) [38]. Also the values of biomass yield used for the calculation of plantation areas required for carbonization are based on values attained in well-managed plantations in Vallourec and Mannesmman (V&M) Florestal (Brazil), which is one of the largest Eucalyptus plantations in Brazil (Pfeifer et al. 2012) [39]; however this yield can be significantly lower in other countries in non-tropical areas or lower biomass productivity. In this sense, the present calculation of plantation areas actually would represent the minimum plantation areas required.

From the economic perspective, the main target was to assess the variation in processing cost of main raw materials used in iron production, when biochar substitutes for coal as auxiliary fuel. The target is not to measure the exact production cost of hot metal, which varies according to

the production facility and country. Therefore the assessment does not take account of the cost of hand labor, capital expenditure, refractories, fluxes and oxygen. Additionally, the main costs used in the assessment come from data of actual steelmaking plants in China 2012.

The present work focuses on the use of biomass in blast furnaces, thus technical aspects of the biomass pyrolysis were not assessed and the charcoal making is not considered as part of the BF process.

The social impacts of a wider deployment of biomass in ironmaking were not investigated in this study, as the core of the research is the verification of the environmental, technical and economical feasibility. By contrast, a complete social life cycle assessment is performed by Weldegiorgis and Franks (2014), under Australian conditions [40].

2. Literature review

The present chapter shows the technical fundamentals of blast furnace processes and the introduction of auxiliary fuels; followed by the analysis of current and prospective usage of biomass in ironmaking. The chapter concludes with a review of the economic aspects of biomass and biofuels.

2.1. Principles of ironmaking

Currently two main routes exist to manufacture steel; one is the integrated route (blast furnace with basic oxygen converter) and the other is the remelting route, also known as ‘mini mill’ (using electric arc furnaces). From a total world steel production of 1,606,000 TMt in 2013, the integrated route accounted for 1,143,000 TMt (72.1 %) whereas the mini mills route manufactured 453,000 TMt (28.2 %), according to the estimates of Worldsteel (2014) [2]. Other processing methods such as Open Hearth Furnace (OHF) and Thomas Oxygen Converter have limited industrial application with a production of approximately 96.3 TMt (0.6 %), mainly due to their lack of economic efficiency, with long production times. Figure 2, from Stahl Zentrum (2009) [41], depicts the historical evolution of the diverse steel processing methods during the past 50 years by the 15 initial members of the European Union.

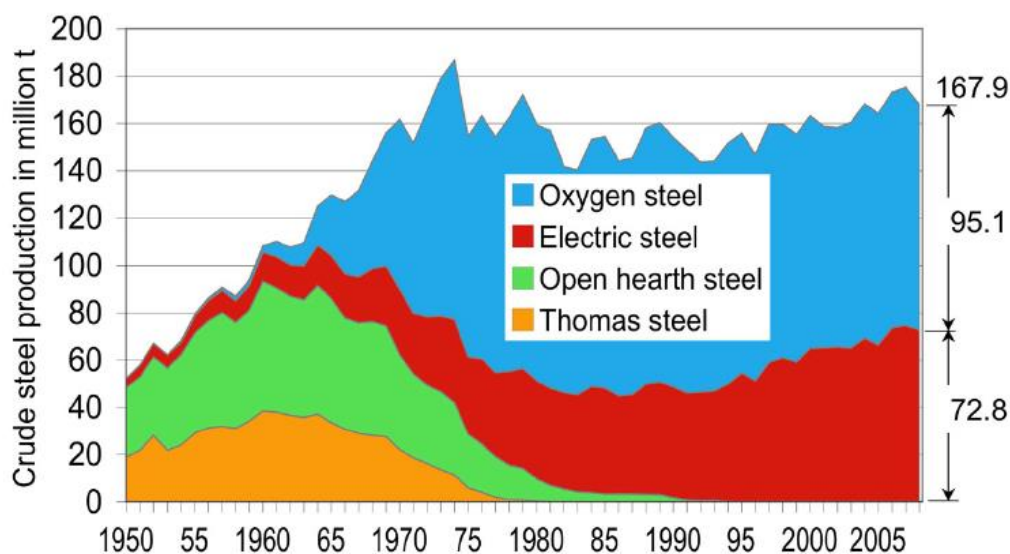


Figure 2. World Steel production by process in EU 15 (1950–2009)
Source: Stahl Zentrum

Steel is a material of key importance for the modern world, as it presents excellent mechanical properties, is relatively easily available and has a low production cost. Currently its usage is mainly in the construction and infrastructure sectors (see Figure 3), while other applications correspond to less than 38 % of total utilization.

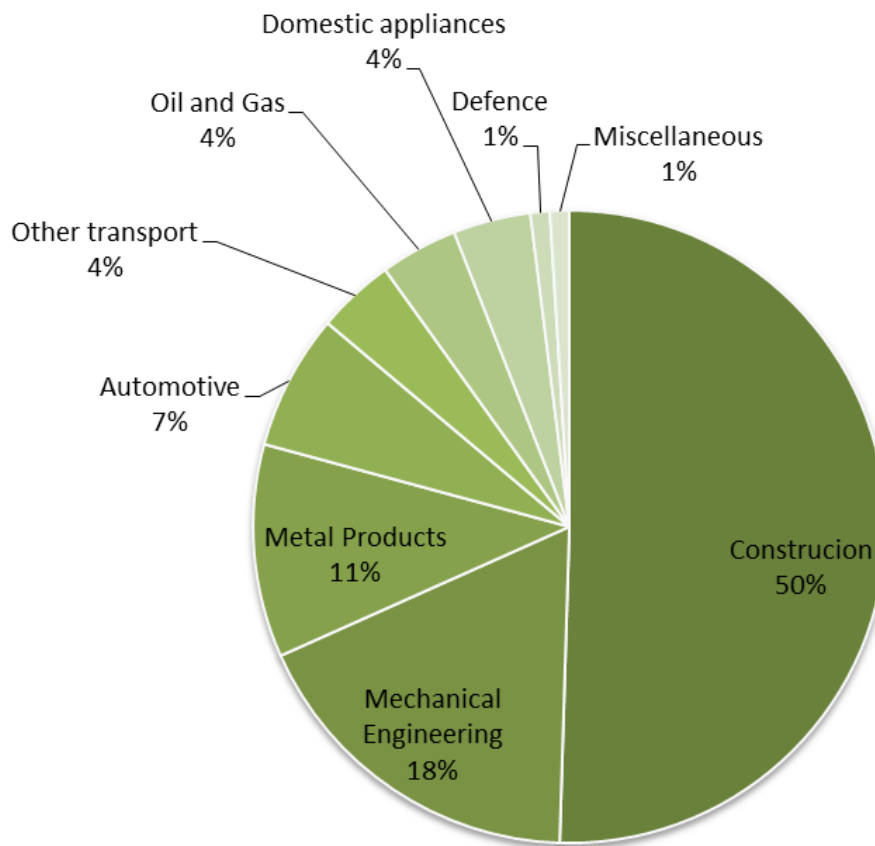


Figure 3. Steel demand by consuming end-use industry
Source Steelonthenet (2008) [42]

Despite the development of a remelting route (based on the electric arc furnace, induction furnace and EOF process), which mainly uses recycled steel scrap as metallic raw material^v, the ironmaking stage is still of strategic importance within the steel production chain. This is because it generates the hot metal (HM) necessary for the further refining at oxygen converters and secondary metallurgy vessels, Figure 4 presents a layout of the steelmaking processes (right) and their individual energy use (left). From an environmental perspective, the ironmaking units are responsible for a large proportion of energy consumption in steel production. In 1999, the International Iron & Steel Institute (currently Worldsteel) carried out a study on energy use in

^v In addition to scrap, the electric arc furnace can also melt direct reduced iron (DRI), pig iron and converter hot metal. However, it is mainly used for the remelting of scrap.

steel production. The study revealed that 12.2-12.3 GJ/t steel of the total energy need in an integrated plant of 17.3-18.6 GJ/t steel are consumed in the blast furnace (BF)[8]. Figure 4 depicts the individual main processing routes of steel and their percentages of total energy utilization; as shown the BF is responsible for 38 % of the total energy usage and is consequently also responsible for a large part of the CO₂ emissions in the whole steelmaking process.

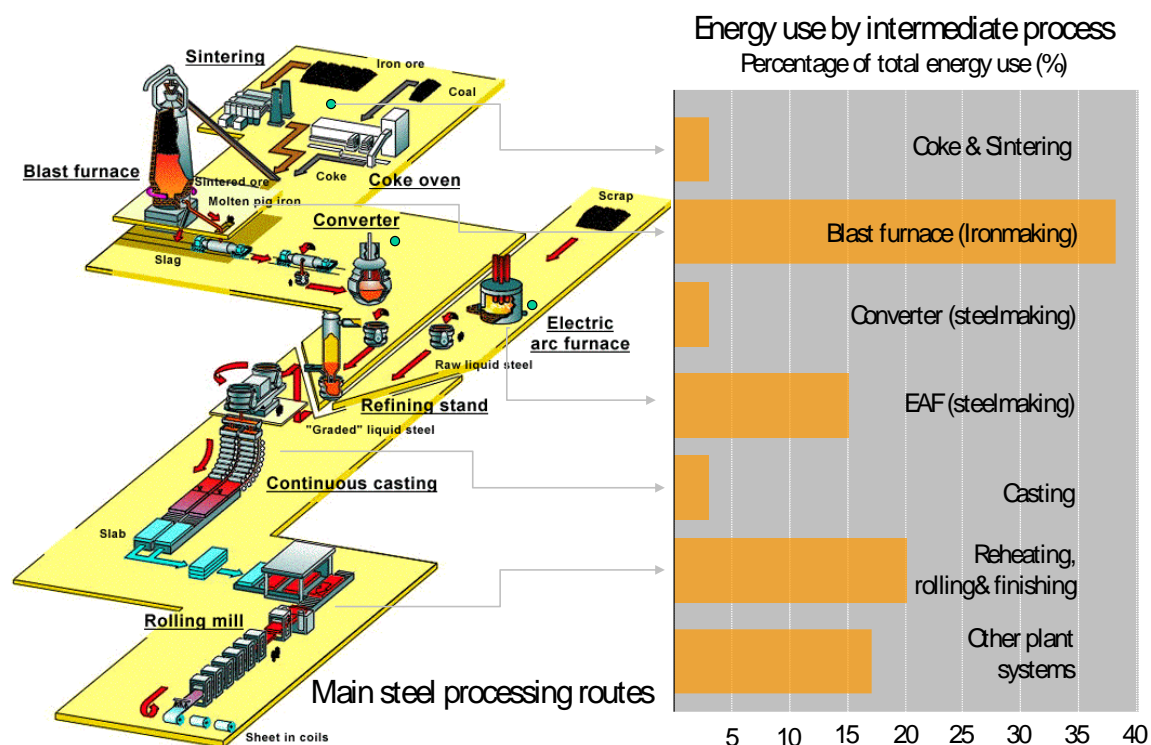


Figure 4. Main processing routes and their energy utilization
Source: American Iron and Steel Institute

Therefore, the reduction of the environmental impact of the ironmaking has become a significant challenge for metallurgists worldwide, as it jeopardizes the sustainability of iron and steel production over time. The following sections address some principles about iron production, development of the BF and current patterns of charge.

2.1.1. Brief history of iron production

As considered previously, the main technology of process currently utilized to produce iron is the BF, and historical evidence shows that these aggregates have been operating since 200 BC,

Table 2 presents a chart of the historic evolution of ironmaking, from the production tools from meteoric iron to the substitution of charcoal for coke, which enable the present BF designs. From 1830 onwards, blast furnaces went through a major phase of evolution that permitted operations with larger shafts (see **Table 2**) [9,43], basically due to the introduction of coke by Darby.

Table 2. Historical evolution of ironmaking (4000BC - present)
Source: Gudenau et al. (2002) and World News

Time period	Location	
4000BC	Egypt	First evidences of iron beads from meteoric iron (7.8 % Ni)
3000BC	Iraq & Egypt	An iron and a steel dagger, found during excavations. Iron replaces bronze as main constituent of weapons and tools, due to higher hardness and resistance
2100BC	Asia	First bloomery hearth
600BC	Spain	Celts in Catalonia were able to smelt iron in charcoal furnaces
> 600BC	Egypt & Europe	Begin of the Iron Age
200BC	China	Evidence of first blast furnaces for iron smelting
8 th Century	Spain	the Catalan furnace replaced the natural draught by pumped air
10 th Century	Switzerland	Oldest known blast furnace in Europe
12 th Century	Europe	The hydraulic wheel came into use for driving bellows
11 th Century	Europe	Blast furnaces are being constructed in Germany (Markische Sauerland) and Sweden (Lapphyttan).
15 th century	Belgium	The forefather to modern blast furnaces is designed in Namur
16 th Century	Europe	The iron production reaches a high level of hot metal production for forges.
1619	England	Later in England the first blast furnace operation using specially prepared coal conducted by D. Dudley. His patents were lost.
1621	Germany	Description of coking of coal by Johann Joachim Becher
1735	England	A. Darby's patent for coke production from coal. First trials of blast furnace operation with only coke as fuel. Promptly hot metal based on coke became more economical than the charcoal-based.
1743	Russia	First use of double-tuyere delivery of blast by Makhotin
1829	Scotland & Russia	J.B. Neilson's patent the preheating of blast. Introduction of hot blast at Clyde plant (Scotland) and Alexandrovsk plant (Russia)
1831	Britain	The Dawes first patent application for coal injection into the blast furnace tuyeres
1838		The Barnet patented application for natural gas and oil injection into the blast furnace tuyeres
1871-1876	Britain	Bessemer's patent for blast furnace operation with high pressure in the inner volume (1871) and patent for blast furnace operation with oxygen enrichment of

		blast (1876)
1877	Germany	C. Alberts's patent for coal injection into the blast furnace tuyeres
1906	USA	Invention of a conveyor sinter machine by A. Dwight and P. Lloyd (USA)
1907		Invention of a rotary distributor for the bell locker by McKee
1950-1957	Ukraine	The first commercial trials for pulverized coal injection and natural gas into the blast furnace at the steel plant in Dneprodzerzhinsk
1960	Canada	The first blast furnace operation with heavy oil injection was adopted by Dofasco No. 3 BF
1964	Ukraine	The industrial trials for hot reduction gas injection into the blast furnace at 'Azovstal' steel plant
1973	World	More than 500 million tons of hot metal was for the first time produced in the world
1974	Ukraine	Blowing in of the blast furnace with inner volume of 5000 m ³ (Krivoi Rog)
1986	Russia	Blowing in of the blast furnace with inner volume of 5580 m ³ (Cherepovetsk)
2013	South Korea	Blowing in of the blast furnace with inner volume of 6000 m ³ , after revamp of BF 1 at POSCO

Nowadays ironmaking through BF is still of key importance within the metallurgical industry, and a series of engineering developments have boosted its efficiency. For instance, from 1960 to the 1980s the hearth diameters have almost doubled, while the inner volume and productivity have incrementally increased by approximately 2.5 and 5 times (Figure 5) [9].

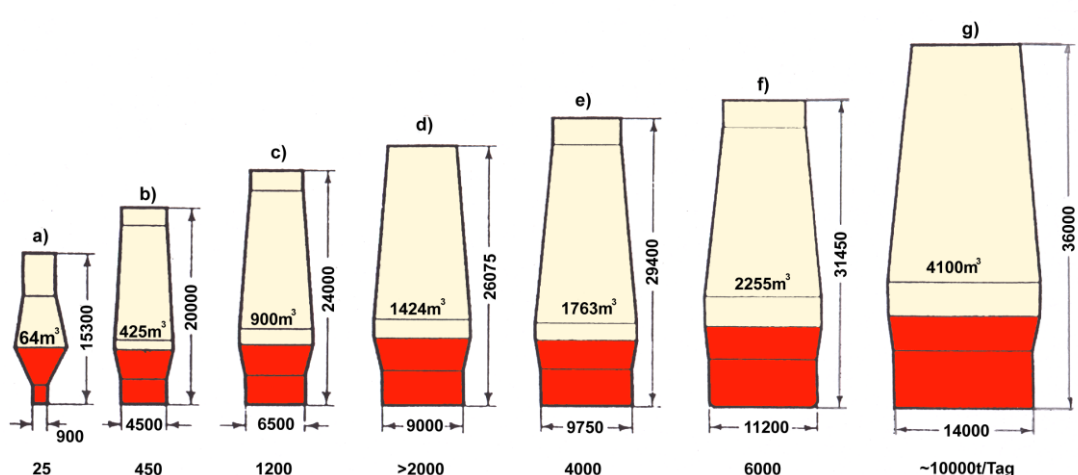


Figure 5. Development of the dimensions of BF shafts
Source: Gudenau et al. (2006)

In the BF process, the following principal raw materials are used: iron ores, fuel/reductant (e.g. coke, pulverized coal, oil, etc.) and fluxing agents (e.g. limestone and dolomite). The basic aim of modern blast furnace is to generate HM, also known as *pig iron*, *liquid* or *molten iron*, with standard levels of iron, carbon and impurities for the later refining stages during steel processing. Worldsteel estimates that in 2013, 1,167.3 million metric (MM) tons of iron (hot metal) that were produced in BFs. In contrast 69.6 MM tons of direct reduced iron were generated through all other processes combined (MIDREX, HyL, SR/LN, etc.). Thus it is important to address the basics of ironmaking in BFs [44].

2.1.2. Fundamentals of ironmaking in blast furnaces

Figure 6 shows a schematic representation of a modern BF. This aggregate operates continuously under a counter flow principle, and the throat of the furnace is fed with iron ores, sinter and pellet, together with fluxes and reductants (top of **Figure 6**). Simultaneously *hot wind* or *hot blast* is injected in the tuyeres (middle of **Figure 6**) into the shaft, to provoke the reduction of the iron oxides (**Figure 6**, left-hand side) (Fruehan 1999) [45].

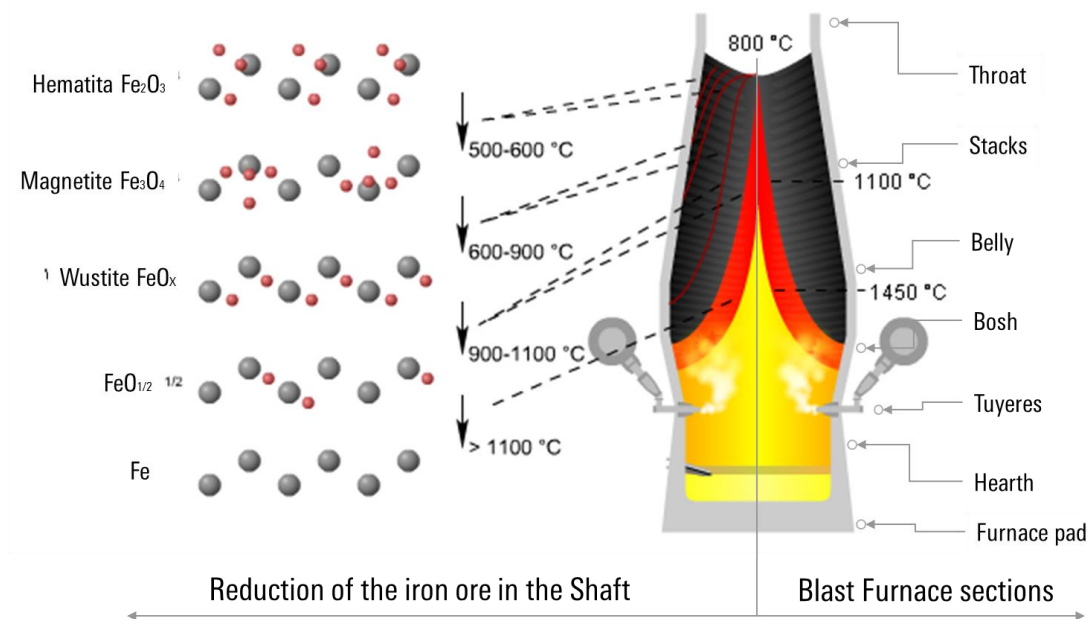


Figure 6. Schematic illustration of iron ore reduction (left) and blast furnace sections (right)
After: Steel University^{VI} and Making, Shaping of Steel

The rising hot reductant gas provides the necessary temperature to the burden to reduce it from hematite (Fe_2O_3) or magnetite (Fe_3O_4) to hot metal (liquid Fe-C). Most of the reactions occurring in the BF processing are endothermic and consume energy (positive enthalpy on

^{VI} Steel University is an educational and training tool for both students of ferrous metallurgy and for steel industry employees

Table 3); therefore the coke oxidation (exothermic reaction) provides the energy necessary to enable BF operation. The main chemical reactions and their energy consumption occurring during BF ironmaking are shown in **Table 3**.

An illustrative mass balance of a modern BF is presented in figure 7^{vii}. In common modern practice, it is calculated that 1.6 tons of iron ore are required to generate a ton of HM. Iron ores in the form of sinter, lumps or pellets are used to feed the BF. Additionally 500 kg/t HM of reductants are necessary to provide the operational energy and reduce the ores; from this generally from 370–450 kg/t HM of metallurgical coke are used, and the carbonaceous input is complemented with 50–200 kg/t HM of pulverized coal injection (PCI). To ensure fuel combustion, 1,100 Nm³ of compressed air is blasted into the furnace at temperatures between 1000–1200 °C. In order to create a slag with the appropriate chemical composition and viscosity, 250 kg/t HM of fluxes are added (mainly limestone and dolomite) (Fruehan 1999) [45].

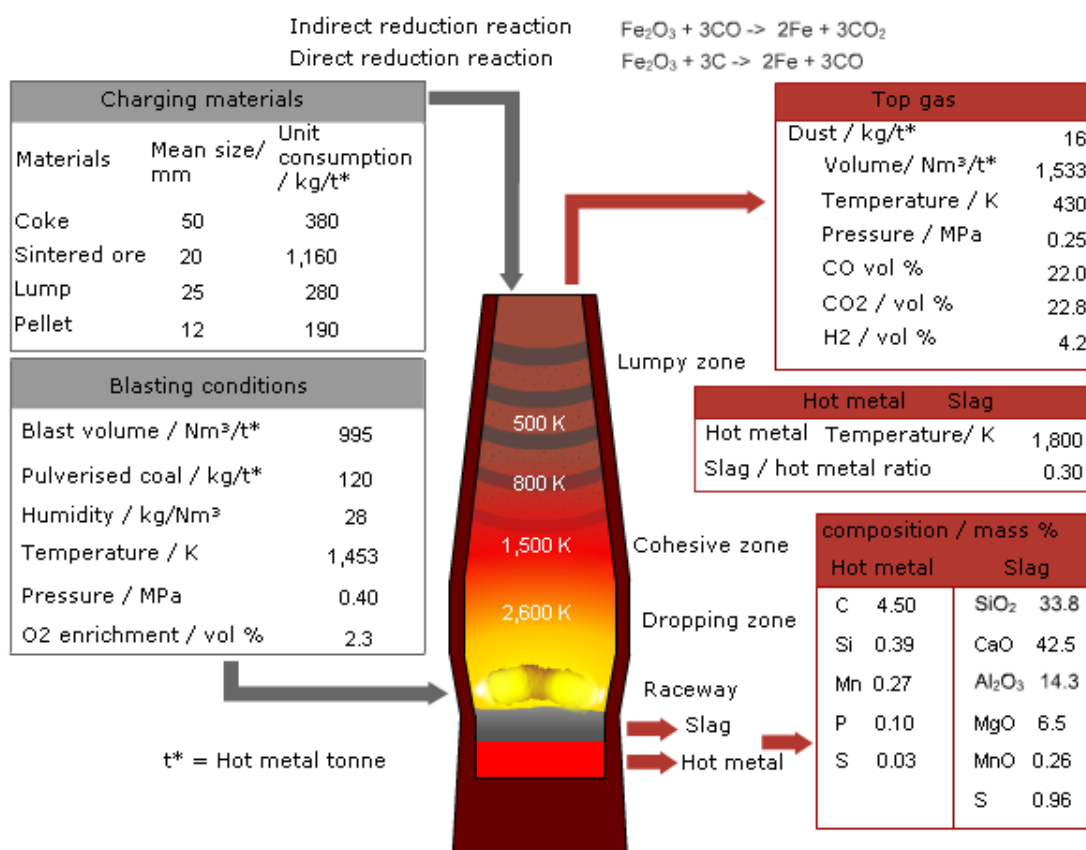


Figure 7. Blast furnace mass balance (per ton hot metal)
Source: Steel University

^{vii} The mass balance is a general guidance as several factors intervene in the mass and energy balance.

Table 3. Main chemical reactions in blast furnace processing
Source: Babich (2006)

Stage of processing	Temperature (°C)	Reaction heat ΔH_r (kJ/kmol)
Evaporation of moisture	100	+ 6.490
Removal of hydrated water	120-300	+ 7.955
Removal of CO ₂ from MnCO ₃ and FeCO ₃ :		
$3 \text{ MnCO}_3 \rightarrow \text{Mn}_3\text{O}_4 + \text{CO}_2 + \text{CO}$	> 525	+ 363.791
$3 \text{ FeCO}_3 \rightarrow \text{Fe}_3\text{O}_4 + \text{CO}_2 + \text{CO}$	380-570	+ 236.973
$\text{FeCO}_3 \rightarrow \text{FeO} + \text{CO}_2$	> 570	+ 112.206
Reduction of Fe ₂ O ₃ to Fe ₃ O ₄ :		
$3\text{Fe}_2\text{O}_3 + \text{CO} \rightarrow 2\text{Fe}_3\text{O}_4 + \text{CO}_2$	400-550	- 52.854
Removal of CO ₂ from MgCO ₃ and MgCO ₃ ·CaCO ₃ :		
$\text{MgCO}_3 \rightarrow \text{MgO} + \text{CO}_2$	400-500	+ 114.718
$\text{MgCO}_3 \cdot \text{CaCO}_3 \rightarrow \text{MgO} \cdot \text{CaO} + \text{CO}_2$	400-750	+ 304.380
CO - splitting		
$2\text{CO} \rightarrow \text{CO}_2 + \text{C}$	450-600	- 172.467
Reduction of Fe ₃ O ₄ to FeO:		
$\text{Fe}_3\text{O}_4 + \text{CO} \rightarrow 3 \text{ FeO} + \text{CO}_2$	570-800	+ 36.463
Removal of CO ₂ from CaCO ₃ :		
$\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$	850-950	+ 177.939
Reduction of FeO to Fe:		
$\text{FeO} + \text{CO} \rightarrow \text{Fe} + \text{CO}_2$	650-T _s	- 17.128
Boudouard-reaction:		
$\text{CO}_2 + \text{C} \rightarrow 2\text{CO}$	≥ 900	+ 172.467
Fusion of primary slag	≈ 1100	+921.1 (kg slag)
Dissolution of CaO in primary slag	≈ 1250	+ 1046.7 (kg Fe)
Combustion of C _{coke} :		
$\text{C}_{\text{coke}} + \text{O}_2 \rightarrow \text{CO}_2$	1800-2000	- 406.120
$\text{C}_{\text{coke}} + \text{CO}_2 \rightarrow 2\text{CO}$	2000-1450	+ 172.467
$\text{C}_{\text{coke}} + 0.5\text{O}_2 \rightarrow \text{CO}$	≈ 1550	- 116.83

As indicated in Figure 7, in addition to HM other by-products are generated, principally slag and top gases. According to the Steel University, 300 kg slag/t HM and 1,533 Nm³ top gas/t HM are created during the HM production [46]. With respect to slag, this residue is normally granulated and quenched with water to generate a solid by-product that can be traded as raw material for other applications, for instance cement, motorway pavements, and as a pH modifier in agriculture (Feliciano 2005) [47]. New environmental developments, point out the use of dry slag granulation by the means of spinning discs with heat recovery, in order to deliver significant savings in capital and operating costs (Jahanshahi et al. 2011) [48].

Liquid iron or HM is the main product of the BF process; it consists of carbon saturated iron with controlled amounts of impurities such as silicon, manganese, sulfur and phosphorus. It is tapped from the hearth at a temperature between 1480–1520 °C. The HM composition may

vary according to its final utilization; typical compositions of different HM qualities can be seen in Table 4. At the time of writing, coke-HM is the most widely produced.

Table 4. Chemical composition of different hot metal composition (and ferro-alloys)
Source: Gudenau et al. (2002)

Type	Weight content (%)				
	C	Si	Mn	P	S
Coke-HM	4.2-4.8	0.4-0.8	0.3-1.0	0.05-0.10	0.02-0.06
Charcoal-HM	3.50-4.50	1.50 max	1.00 max	0.08 max	0.05 max
Foundry	3.5-4.2	2.0-3.0	0.5-1.0	0.07-0.30	0.02-0.06
Spiegel (mirror)	4.5-5.5	1.0-2.0	10.0-25.0	0.1-0.2	0.03-0.04
Ferro-manganese	6.0-7.0	1.8-2.0	75.0-80.0	0.1-0.4	0.02-0.03
Ferro-silicon	1.5-2.0	9.0-14.0	0.5-1.0	0.1-0.2	0.02-0.03

The HM is frequently tapped into transport vessels commonly known as *torpedo cars*, from where HM is transfer to the steelshops for converting processes in basic oxygen furnaces (BOF). Further refining and alloying occurs in the secondary metallurgy stage in ladle or degassers. A complete layout of the steelmaking process is presented in Figure 4. The objectives of the subsequent stages after ironmaking are:

- Steel converting: to reduce the amount of carbon in the HM; thus iron transforms into steel.
- Eliminating impurities: reduce the amount of dissolved phosphorous, sulfur, oxygen, nitrogen and hydrogen in the steel.
- Alloying: adjust chemical composition of bulk (silicon, manganese) and alloying elements (vanadium, molybdenum, titanium, aluminium, niobium, etc.).
- Homogenizing and cleaning: through stirring to eliminate non-metallic inclusions and simultaneously homogenize the bath chemistry and temperature.
- Steel casting: solidification of steel for further processing, normally rolling.

As mentioned previously, the operation of a BF is highly dependent of the patterns of charge; therefore in the following sections the iron and reductants used in ironmaking will be addressed in details.

2.1.2.1. Blast furnace charging materials

2.1.2.1.1. Iron ores

After silicon and aluminium oxides, the iron oxides are the most common substances on the earth's crust (approximately 5 %). There exist different type of iron bearing endowments as such: magnetite (Fe_3O_4), hematite (Fe_2O_3), goethite ($\text{FeO}(\text{OH})$), limonite ($\text{FeO}(\text{OH}) \cdot n(\text{H}_2\text{O})$) or siderite (FeCO_3). The hematitic and magnetitic deposits are the most commonly exploited.

According to USGS [49] in 2009 (see Table 4), China, Brazil, Australia and India rank as the top global producers of iron ore. Different deposits present diverse iron content and impurity concentration; additionally iron content can be increased by using a concentrator. Currently seaborne ores are traded with iron content ranging from 58–65 %. Another factor influencing the value of ores is the grain size. In this respect, the feeding ores are normally classified as:

- *Fine ores*: grain size < 4.75 mm
- *Lump ores*: grain size > 4.76 mm (see Figure 8 c)
- *Pellets* (ores): agglomerates of concentrated fine ore (9.55–16 mm), normally endured through tempering (see Figure 8 d).
- *Sinter*: pre-reduced iron ores (see Figure 8 b).



Figure 8. Main raw materials charged to the blast furnace (common size)

Source: Steel University

According to USGS (2010), world resources are calculated to exceed 800 billion tons of crude ore containing more than 230 billion tons of iron (**Table 5**).

Table 5. World top producers of iron ore (million metric tons of iron ore).

Source: USGS (2009)

Country		China	Brazil	Australia	India	Russia	Ukraine	United States	South Africa	World total
Annual	2008	824	355	342	220	100	73	54	49	2220
Production	2009	900	380	370	260	85	56	26	53	2300

2.1.2.1.2. Reductants/fuels used in blast furnaces

Since Abraham Darcy initially replaced the charcoal for coke in BFs, iron production has been highly associated with major consumption of coke. This permitted in principle the utilization of larger shafts increasing the productivity [9]. Moreover this input lead to an important increase in the iron output, as the coke's heating value was superior in comparison with wooden char and presented superior mechanical strength. Complementing the engineering features, the widespread availability of coal at relatively low cost made economically reasonable the substitution of charcoal by coke (Sieferle 2001) [10]. Table 6 presents a list of the global production of coal by 2007 and the proved reserves. According to this statistics from BP (2008) [50], 82% of the reserves of the world are concentrated in USA (28.6 %), Russia (18.5 %), China (13.5 %), Australia (9 %), India (6.7 %) and South Africa (5.7 %).

Nowadays coal and coke, from fossil non-renewable sources, are still the most utilized reductants in the HM production in BFs; nevertheless, as shown in Table 2, since 1838 it has also been technically feasible to charge other fuel such as oil, natural gas, plastic and biomass. It is the opinion of the author that up until now the utilization of alternative fuel has been mainly limited by economic reasons. This point is addressed in details in the section 2.7.

Coming back to the characteristics of reductants, the 80 % of carbon-bearing elements charged into a BF are used for the reduction of iron ore (Schmole et al. 2009) [51]. Consequently these elements are more likely to be known as 'reductants' than fuels in metallurgical applications. Focusing on the metallurgical benefits of coke, this reductant/fuel complies simultaneously with different fundamental tasks in the BF:

- *Fuel the process:* provides the energy necessary for reactions to occur.
- *Reductant:* serves as reducing agent for iron ores (see **Figure 6**, left-hand side).
- *Mechanical stabilizer:* supports burden and creates cavities burden that permits reducing gases to flow.
- *Carburize the hot metal:* the coke helps to carburize the hot metal to a level of carbon dissolved of 4 to 4,5 %.

Table 6. Coal production and proved reserves (2007)
Source: BP Statistical Review of World Energy, June 2008

	PRODUCTION		PROVED RESERVES 2007			
		Share of total	Anthracite and bituminous	Sub-bituminous and lignite	Total	Share of total
			Million tonnes oil equivalent			
US	587.2	18.7 %	112,261	130,460	242,721	28.6 %
Canada	36.9	1.2 %	3471	3107	6578	0.8 %
Mexico	5.9	0.2 %	860	351	1211	0.1 %
Total North America	629.9	20.1 %	116,592	133,918	250,510	29.6 %
Brazil	2.2	0.1 %	-	7,068	7,068	0.8 %
Colombia	46.6	1.5 %	6,578	381	6,959	0.8 %
Venezuela	5.9	0.2 %	479	-	479	0.1 %
Other Americas	0.6	♦	172	1598	1,770	0.2 %
Total S. & C. America	55.3	1.8 %	7,229	9,047	16,276	1.9 %
Bulgaria	5.1	0.2 %	5	1,991	1,996	0.2 %
Czech Republic	23.6	0.8 %	1,673	2,828	4,501	0.5 %
Germany	51.5	1.6 %	152	6,556	6,708	0.8 %
Greece	8.2	0.3 %	-	3,900	3,900	0.5 %
Hungary	2.0	0.1 %	199	3,103	3,302	0.4 %
Kazakhstan	48.3	1.5 %	28,170	3,130	31,300	3.7 %
Poland	62.3	2.0 %	6,012	1,490	7,502	0.9 %
Romania	7.4	0.2 %	12	410	422	♦
Russian Federation	148.2	4.7 %	49,088	107,922	157,010	18.5 %
Spain	6.0	0.2 %	200	330	530	0.1 %
Turkey	15.8	0.5 %	-	1,814	1,814	0.2 %
Ukraine	39.6	1.3 %	15,351	18,522	33,873	4.0 %
United Kingdom	10.4	0.3 %	155	-	155	♦
Other Europe & Eurasia	16.9	0.5 %	1,025	18,208	19,233	2.3 %
Total Europe & Eurasia	445.4	14.2 %	102,042	170,204	272,246	32.1 %
South Africa	151.8	4.8 %	48,000	-	48,000	5.7 %
Zimbabwe	1.4	♦	502	-	502	0.1 %
Other Africa	1.1	♦	929	174	1,103	0.1 %
Middle East	0.5		1,386	-	1,386	0.2 %
Total Middle East & Africa	154.2	4.9 %	50,817	174	50,991	6.0 %
Australia	215.4	6.9 %	37,100	39,500	76,600	9.0 %
China	1,289.6	41.1 %	62,200	52,300	114,500	13.5 %
India	181.0	5.8 %	52,240	4,258	56,498	6.7 %
Indonesia	107.5	3.4 %	1,721	2,607	4,328	0.5 %
Japan	0.8	♦	355	-	355	♦
New Zealand	2.8	0.1 %	33	538	571	0.1 %
North Korea	-		300	300	600	0.1 %
Pakistan	1.6	0.1 %	1	1,981	1,982	0.2 %
South Korea	1.3	♦	-	135	135	♦
Thailand	5.1	0.2 %	-	1,354	1,354	0.2 %
Vietnam	23.1	0.7 %	150	-	150	♦
Other Asia Pacific	22.1	0.7 %	115	276	391	♦
Total Asia Pacific	1,850.2	59.0 %	154,216	103,249	257,465	30.4 %
TOTAL WORLD	3,135.6	100.0 %	430,896	416,592	847,488	100.0 %

The resistance of the coke to breakage and erosion is likely to be its most outstanding characteristic. To this moment, no other fuel presents similar characteristics, and therefore in large BF's (with shaft larger than 600 m³) it is almost technically impossible to completely substitute coke by any other reductant.

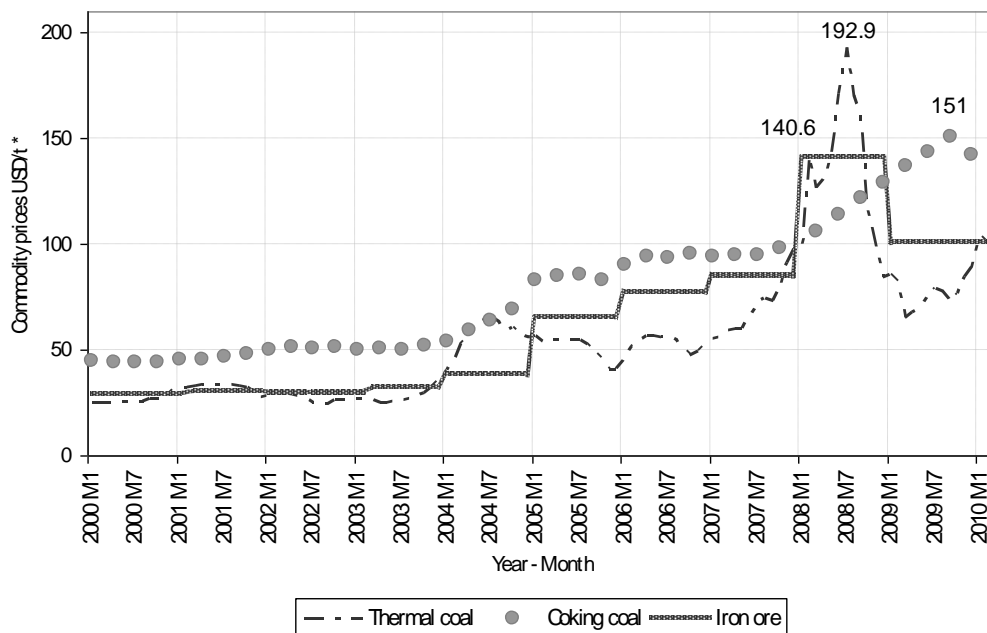
The coke used in BF is known as *metallurgical grade coke* or *met coke*, which comes originally from the thermal transformation of the hard coal in *coke batteries* or *coke ovens*. Coke is classified according to its processing as low-, medium- and high-temperature coke. *Met coke* should be transformed at temperatures from 900–1095°C, in order to possess sufficient mechanical strength (Fruehan 1999) [45]. Presently, also the small size coke, known as *nut coke*, is used in BF's with different amount (10–140 kg/t HM) and different grain sizes (10–40 mm) in the sinter layer to decrease the coke losses (Mousa et al. 2011) [52]

Unfortunately the manufacture of coke generates significant environmental problems. In the generation of 1 million tons of coke about 7000 tons of pollutants are emitted into the atmosphere including dust, H₂S, SO₂, CO, NH₃, NO_x, phenol, CHN, along with an extra 0.5–0.7 million m³ of sewage (Gudenau et al. 2002) [9].

In addition to the environmental problems, two other challenges may reduce the present and future coke utilization – its availability and cost. With respect to availability, it is known that only a few countries in the world have the natural endowments of coking coal (refer to Table 6), the fundamental raw material for *met coke-making*. From the cost perspective, in the past decade there has been a significant increase in the price of principal inputs in the ironmaking process (see Figure 9 [53]).

In summary, in past centuries coke has served to fuel the growth of the ironmaking industry, since it permitted the substitution of rudimentary aggregates for large furnaces with high HM output capacities. Additionally, metallurgical grade coke still presents unmatched characteristics as it provides energy, reduces the ores and supports the burden in the BF's shaft. At this point in time, no other fuel can simultaneously provide such features. Nonetheless, at present it is only possible to produce metallurgical grade coke from non-renewable fossil resources. Additionally, the thermal transformation of coking coal into coke is highly polluting and generates harmful emissions. From the economic perspective, the circumstances that allow

charcoal substitution by coke have changed, as the coking coals have significantly increased in price in the last decade (see Figure 9) and availability has been reduced. All of these circumstances have boosted the development of alternatives fuels to minimize and substitute the coke in BF or the creation of parallel routes to produce iron. The following section builds on the injection of auxiliary fuels.



*Notes: 1) Coal is Australian thermal coal, 2790 kJ/kg less than 1 % sulfur, 14 % ash, f.o.b. Newcastle/Port Kembla, US\$ per metric ton. 2) Iron ore is 67.55 % iron content, fine, contract price to Europe, FOB Ponta da Madeira, US cents per dry metric tonne unit.

Figure 9. Ironmaking raw material and input costs (2000-2010)
Data source: International Monetary Fund (2010)

2.1.2.2. Injection of auxiliary fuels in blast furnaces

The utilization of auxiliary fuels, such as coal injection, to reduce the consumption of expensive types of fuels was initially introduced by the cement industry (Fruehan 1999) [45]. As shown in **Figure 10**, the first patent for its application came in 1831 in Britain from J. S. Dawes, while in Germany the first patent was introduced in 1877 by Carl Alberts (Assis 2008, Assis 2006) [54,55], nonetheless, due to operational inadequacies, injection of auxiliary fuels was not applied industrially until the 1950s when the first commercial trials for pulverized coal injection (PCI) began at the steel plant in Dneprodzerzhinsk, Ukraine. Following the increase in the price of fossil fuels, due to oil crises in 1973 and 1979, many investigations focused on the injection of alternative fuels in BF (Babich et al. 1996) [56] with PCI a major focus of attention.

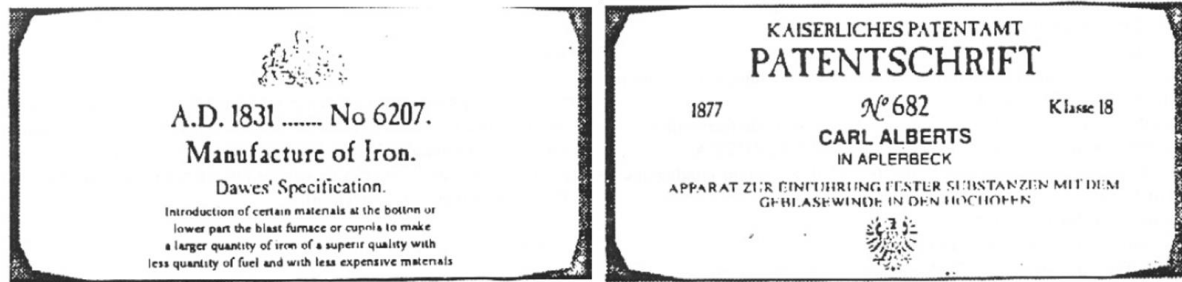


Figure 10. First patent of PCI in England and Germany
Source: Assis (2008) originally from Assis (2006)

According to Babich et al. (1999) [57], auxiliary fuel injection is the most radical method for reducing the consumption coke in BF. PCI has been largely used as an alternative source of fuel for metallurgical purposes in steel plants, such as in open hearth furnace (OHF), reheating, forge and annealing furnaces (Fruehan 1999); presently, it is widely employed as an auxiliary fuel in the BF tuyeres to increase performance and efficiency, and current rates of pulverized carbon injection can vary from 130 up to 250 kg /t HM. Nowadays, most of the BFs around the world have PCI rigs to reduce coke consumption. Table 7 presents some chemical composition of coal used for PCI purposes [45].

Table 7. Composition of coal as auxiliary fuel
Source: Fruehan (1999)

Component	Chemical composition according to source			
	Lohberg	Niederberg	Guasare	Donbass
Proximate Analysis				
Volatile matter	27.7	10.8	37.35	13.1
Ash	9.95	9.03	5.43	11.2
Ultimate Analysis				
Carbon	77.86	82.3	79.57	79.4
Hydrogen	4.73	3.75	5.26	3.7
Nitrogen	1.71	1.6	1.48	1.7
Sulfur	1.03	1.09	0.72	1.14
Oxygen	4.71	2.24	7.54	2.8

Other developments in the technology of injection have permitted substitution of almost 30 % of the fed coke by the injection of auxiliary reductants such as coal, oil, natural gas and more recently charcoal from renewable sources. **Figure 11** shows the reduction of coke use in the blast furnace process due to process improvements and auxiliary reductants in Germany (Dahlmann et al. 2010) [58].

As previously mentioned, coke is an important fuel in the BF process. With the present advancement and deployment of PCI rigs, almost a third of the coke consumption can be reduced. The PCI technology permits the utilization of a broader range of alternative fuels, besides coal. In the literature, there are a large number of references reporting the use of the injection of oil (Andahazy et al. 2006) [59], natural gas (Agarwal et al. 1996; Tovarovski et al. 2003)[60,61], and plastics (Janz and Weiss 1996; Buchwalder et al. 2006; Ziebig and Stanek 2001) [62,63,64]. Currently the use of one or another type of auxiliary fuel depends on the ratio of their prices, their deposits and the peculiarity of the technology [57].

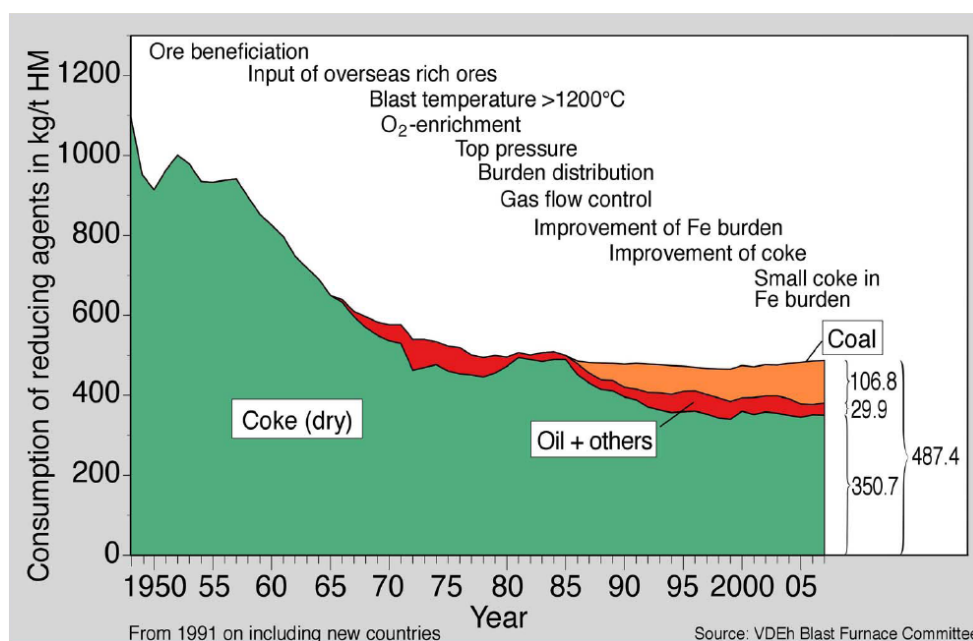


Figure 11. Consumption of reducing agents in Germany (coke, coal and oil) and main technological breakthroughs in ironmaking

Source: Stahl-Zentrum

In general terms, the injection of pulverized coal decreases the coke and coal requirement per ton of HM manufactured^{viii}. Furthermore, the usage of PCI enables a higher blast temperature operation, leading also to an increase in productivity and reducing the cost of BF operation as less coke is required.

^{viii} Metallurgical coke is normally more expensive than hard coal.

2.2. Principles of fuel injection in blast furnaces

When reductants or fuels are injected into the BF shaft, the hydrocarbons present are oxidized by the hot blast and produce gases rich in $\text{CO}_2/\text{H}_2\text{O}$, which react with coke, reducing them to CO and H_2 . See **Table 8** (Garcia et al. 1998) [65].

The combustion of a solid reductant/fuel injected to a BF is a heterogeneous process, as it takes place in the inter-phase between the solid and gas; thus it is controlled by the velocity of burning (kinetics) and the diffusion of gases (O_2 and CO/CO_2) through the product layer. As a general rule, the more the combustion occurs on the outer surface of the fuel (e.g. coal particle, coke) the more stable the temperature and higher reaction rate that are achieved.

Table 8. Reaction of combustion by auxiliary fuels.

Source: Garcia et al. (1998)

	MJ/m ³ gas	MJ/kg C
$\text{C}_{\text{COKE}} + \frac{1}{2}\text{O}_2 \leftrightarrow \text{CO}$	-	9.8
$\text{C}_{\text{COKE}} + \text{H}_2\text{O} \leftrightarrow \text{CO} + \text{H}_2$	-5.56	-10.4
$\text{C}_{\text{COKE}} + \text{CO}_2 \leftrightarrow 2\text{CO}$	-7.39	-13.8
$\text{CH}_4 + \frac{1}{2}\text{O}_2 \leftrightarrow \text{CO} + \text{H}_2$	1.59	3.0
$\text{C}_2\text{H}_6 + \text{O}_2 \leftrightarrow 2\text{CO} + 3\text{H}_2$	6.05	5.7
$\text{C}_3\text{H}_8 + \frac{3}{2}\text{O}_2 \leftrightarrow 3\text{CO} + 4\text{H}_2$	10.1	6.3
$\text{C}_4\text{H}_{10} + 2\text{O}_2 \leftrightarrow 4\text{CO} + 5\text{H}_2$	13.8	6.5
$\text{C}_5\text{H}_{12} + \frac{5}{2}\text{O}_2 \leftrightarrow 5\text{CO} + 6\text{H}_2$	18.05	6.7
$\text{C}_2\text{H}_4 + \text{O}_2 \leftrightarrow 2\text{CO} + 2\text{H}_2$	12.1	11.3
$\text{C}_2\text{H}_2 + \text{O}_2 \leftrightarrow \text{CO} + 2\text{H}_2$	20.0	18.7

In common practice it is known that alternative fuel injection normally increases the top gas temperature and reduces direct reduction, because of the increased volumes of reducing gas (Garcia et al. 1998) [65]. Given the endothermic process of fuels injection of BF^{IX} , in particular natural gas, on occasion the blast should be enriched with oxygen to keep sufficiently high flame temperature in the tuyeres.

^{IX}Fuels injected provide heat, that means, it is exothermic reaction, but when injecting material, like PCI or Natural Gas, the flame temperature only considering the reaction by itself is less than the flame temperature. Therefore, it is endothermic process, but the reaction is exothermic.

The cost saving in auxiliary fuel injection, especially in the substitution of met coke, are highly influenced by reductant quality and operational parameters. Cost saving is characterized by the amount of met coke saved to the amount of reductant injected utilized as substitute, so called *coke replacement ratio* (CRR). This ratio is measured in units of $\text{Kg}_{\text{Coke}} / \text{Kg}(\text{m}^3)$. Figure 12 shows the replacement ratio of coke and coal. This has a value of approximately 0.94; for other reductants the corrected value is 0.8-0.9 for natural gas, 0.4-0.5 for coke oven gas, 1.2-1.4 for oil and 1.0-1.1 for anthracite and 1.0-1.2 for charcoal (Bennet and Fukushima, 2003; Assis 2016) [37,66].

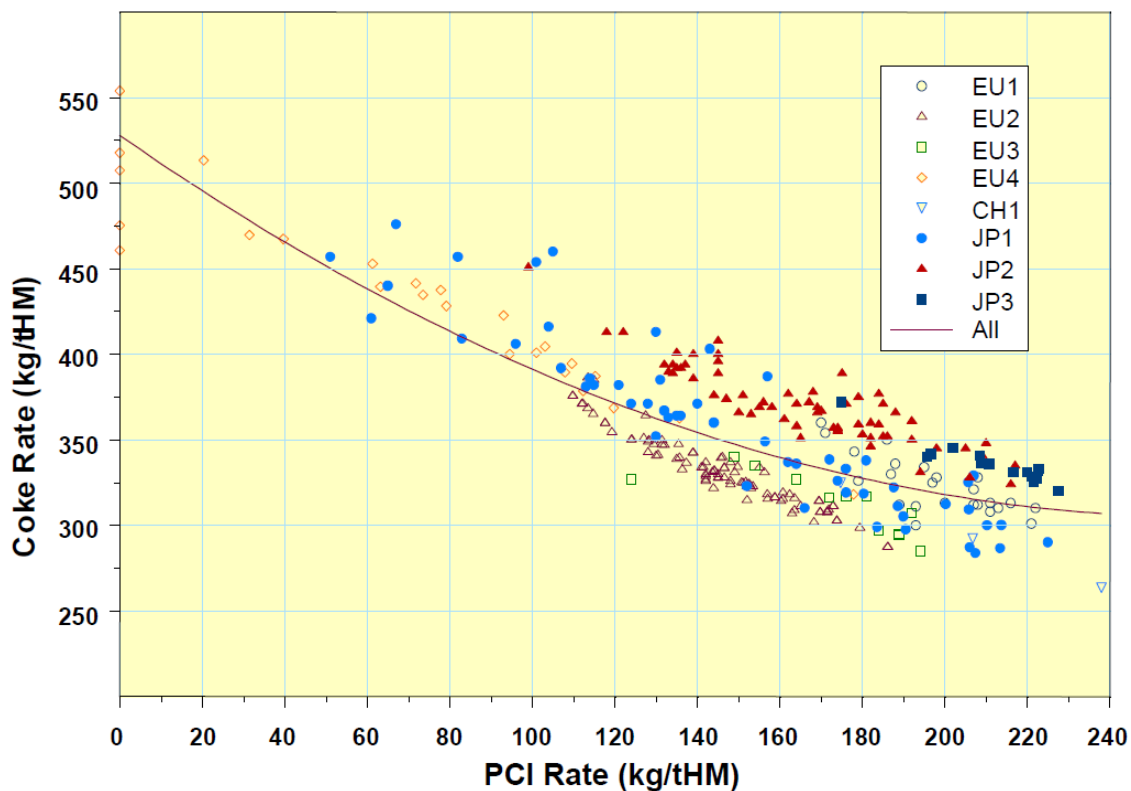


Figure 12. Coke/coal replacement ratio

Source: Bennet and Fukushima (2003)

Prior to the injection coal through the PCI rigs, the following processing is necessary:

- *Pulverization:* A size reduction in a grinding element occurs, reducing the size of coal up to 75 μm .
- *Storage and dosage:* This part consists of different vessels, weighing system and valves. The injected quantities may vary by modifying the pressure or by adjusting the particle concentration in conveying gas (e.g. air, nitrogen). Normally the drying of 8-10 % of the remaining moisture in coal occurs in this stage.

- **Conveying:** The delivery of the fuel from the dosage and storage, usually meters apart is performed pneumatically (see Figure 13). The PCI is injected through the tuyeres, using lances into the blowpipes.

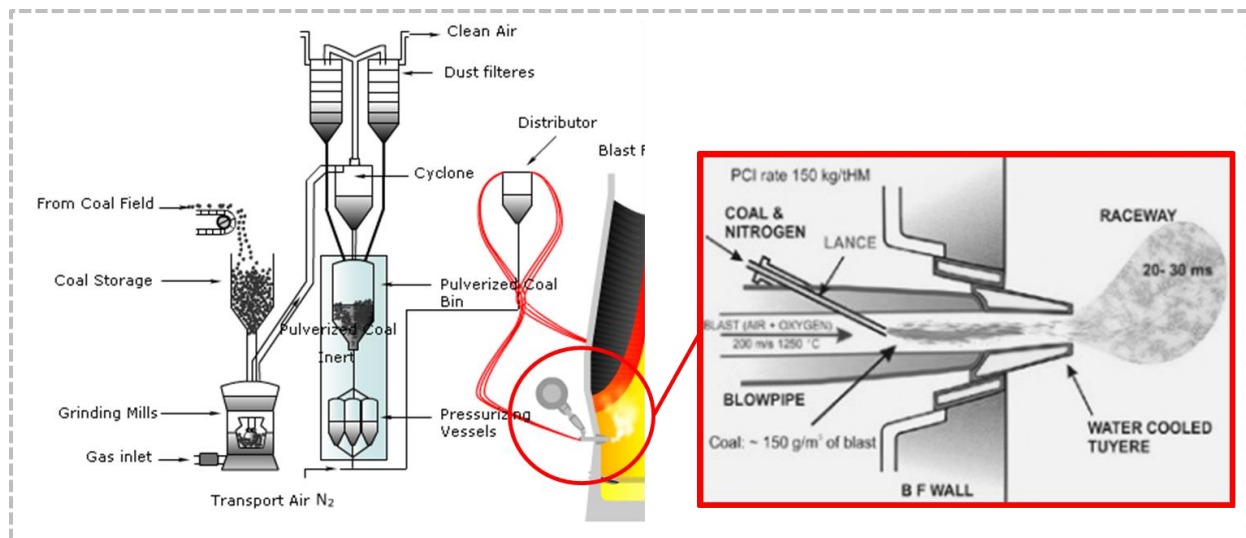


Figure 13. Operation of PCI rigs in blast furnaces
Source: Steel University and Ispatguru [67]

The content of volatile matter, impurities^x and moisture may severely limit the amount of PCI used as they could bring negative consequences to the ironmaking process, such a HM contamination and sticking problems. In this respect, Assis et al. (2003) recommend the pre heating of coal to improve the combustion in the BF [68].

Despite the benefits in terms of cost reduction, the utilization of PCI may also represent some difficulties to the process; in this respect Bennet and Fukushima [66] mention the following challenges:

- The reduction in the size of the raceway, due to the decrease in the permeability of the burden.
- Reduction of permeability of the coke surrounding the raceway.
- Changes in temperature distribution in the raceway.
- Mechanical degradation of coke in the raceway.
- Decrease in *deadman* temperature, which is highly influenced by the the presence of unburnt char and slag chemistry.

^x Mainly alkalis, phosphor and sulfur.

All these factors are interlinked, and they are influenced by the characteristics of fuel and processing conditions. Therefore, common practice is to limit injection at rates of 180–200 kg/t HM (Ichida et al. 2002).

Nevertheless, measures exist to counteract the problems related with injection and to intensify the reaction of PCI in the raceway:

1. *Enrich hot blast with oxygen:* This accelerates the combustion and significantly increases the productivity. However, Babich et al. (2014) mention that higher oxygen flow rates are not necessary beneficial for coal combustion, as too high oxygen rate at a certain lance arrangement may cause ‘punching through’ the coal [69].
2. *Improve tuyere design:* The proper design and arrangement of injection lances are a determining factor to improve the conversion efficiency of auxiliary PCI in the raceway. For instance, the insulating of coal stream with oxygen by using co-axial lances improves the burn out of char, however cold oxygen causes shift of ignition away from the lance tip due to additional time required for its heating.
3. *Adjust fuel blends and mixtures:* Diverse types of coals with different contents of volatile matters are mixed to keep a high ratio of combustion degree and coke replacement.
4. *Optimize grain size:* An increase in the grinding level of coal results in improvements in the combustion velocity as the specific surface area is reduced. However, this also creates problems, as additional grinding is necessary and conveying can become difficult since small particles tends to stick together.

Besides traditional coal, many other alternative fuels can be injected to the BF such as natural gas (NG), coke oven gas (COG), oil and charcoal. All of them present benefits and limitations. **Table 9** presents a comparison of the properties, benefits and limitations of most widely utilized alternative fuels.

As reviewed previously, the development of alternative fuel injection technology has resulted in lower fuel costs, due to the reduction of the amount of coke needed to produce HM; additionally this has reverted into higher productivity. The expansion of auxiliary fuel injection has been also possible due to its flexibility in terms of qualities and quantities charged into the

BF. Several carbonaceous elements such as, oil, natural gas, coke oven gas, coal and **charcoal** can be injected (see **Table 9**). However, currently, coal is preferred due to its large availability and relatively low cost (in the absence of a carbon tax).

Table 9. Comparison of auxiliary fuels injected to BFs
Source: Fruehan (1999) [45]

Component	Natural gas (NG)	Coke oven Gas (COG)	Oil	PCI	Bio-PCI
Principal chemical composition	90-99 % CH ₄	55-60 % H ₂ 22-28 % CH ₄	84-88 % C 10-14 % H	75-85 % C 3-6 % H	70-85 % C 3-7 % H
Calorific power	32,000-46,000 kJ/m ³	18,000-19,000 kJ/m ³	43,000-47,000 KJ/Kg	22,000-28,000 kJ/kg	17,000-26,000 kJ/kg
Advantages	1) low capital investment 2) reduces use of coke	1) COG available in steel work 2) free of cost	1) rise indirect reduction (> H ₂) 2) rise in gas velocity 3) lesser slag volume	1) reduces operational cost 2) largely available	1) reduces charcoal lump consumption in charcoal-BF 2) uses a by-product
Disadvantages	1) high cost of NG 2) Limited to countries/areas with NG	1) lower value of heat released (10-20 lesser than NG) 2) required gas cleaning ^{xi}	1) affects the burden column and descent time 2) decrease in flame temperature 3) Elevated costs	1) reduces permeability of burden 2) heat fluctuation and more slag formation	1) limited availability 2) oxygen enrichment is required to attain high injection rate
Typical injection rate	40-100 Kg/tHM	100-300 m ³ /tHM	20-120 Kg/tHM	50-200 kg/tHM	50-140 kg/tHM
Countries	Ukraine, USA & Canada		Canada, Germany, Japan and USA	World wide	Only in Brazil

Nearly all of the above-mentioned fuels come from fossil endowments and therefore their combustion will eventually contribute to the generation of CO₂ emissions, with their negative influence on the environment, being the main cause of global warming. In this sense, numerous initiatives have been launched to improve the energy-intensity of steel production and to minimize the GHG generation.

2.3. Collaborative initiatives to reduce the CO₂ emission in the steel production

Because of the pressing situation of global warming, it has become of fundamental importance to develop rational use of energy and the introduction of substitutes for fossil fuels in the ironmaking process. In this scenario, strategies range from short- to long-term initiatives. In this sense, different organizations have launched so-called CO₂ breakthrough programs, such as the

^{xi} In order to remove naphthalene, benzene hydrocarbons and hydrogen sulfide.

programs Ultra Low CO₂ Steelmaking^{xii} (ULCOS) in Europe, the CO₂ Ultimate Reduction in Steelmaking process by Innovative technology for cool Earth 50 (COURSE 50)^{xiii} in Japan, The CO₂ Breakthrough in Metal Production Program^{xiv} in Australia, the AISI CO₂ Breakthrough Program^{xv} in USA and Canada and the POSCO^{xvi} CO₂ Breakthrough Technology Development in South Korea [3,4,5,6]. The approaches and the research focus may vary according to the programs mentioned; they all mostly share the target of reducing 50 % of the carbon intensity of steel production (Jahanshahi, 2013) [7].

Within the possible breakthroughs, some new radical technologies have been investigated and developed such as BF top gas recycling, carbon capture and storage, molten salt electrolysis, hydrogen reduction of iron ores, flash smelting of iron oxide and heat recovery from slag – to mention some emerging technologies (Ariyama and Sato 2006) [70]. The principal technologies, fundamentals and CO₂ mitigation potential of the low-emission iron and steel making are presented in the tables **Table 10, Table 11, Table 12, Table 13 and Table 14.**

Additionally the potential of the re-introduction of biomass in iron and steel making has been carefully studied in the Australian program (see **Table 11**), and some of the assessment results very valuable for the further substitution of fossil fuels in the process. The following section builds on the state of the art of biomass in steel production and the future prospects of its usage.

^{xii} ULCOS stands for Ultra-Low Carbon Dioxide (CO₂) Steelmaking. It is a consortium of 48 European companies and organizations from 15 European countries that have launched a cooperative research and development initiative to enable drastic reduction in CO₂ emissions from steel production. The aim of the ULCOS program is to reduce the CO₂ emissions of today's best routes by at least 50 %.

^{xiii} Initiative launched by the Japanese Iron and Steel association since 2008.

^{xiv} Collaborative program between BlueScope Steel, OneSteel, CSIRO and CSRP launched since 2006.

^{xv} Research and development initiative from the American Iron and Steel Institute.

^{xvi} Largest steel producer in South Korea and 6th largest in the world.

Table 10. Principal areas of investigation under the Framework of ULCOS

Source: [5,6,71,72,73,74,75]

Principal areas of investigation	Fundamentals	CO ₂ mitigation potential	References
ULCORED direct reduction	It is proposed to use 100 % oxygen and partial oxidation of the iron ores to replace the use of reformers. This process can use a flexible input of fuels, such as natural gas, syngas, biomass and coal.	It is claimed that ULCORED can reduce the fuel consumption compared to other existing DRI processes.	Knop et al. 2008 Bergman and Larsson 2009
Hlsarna smelting reduction	This proposal merges two existing technologies: the Hismelt and the cyclone converter furnace, in order to generate a fuel efficient smelting reduction process.	This technology can utilize thermal coal instead of coking coal, it also may use low grade iron ores and can reduce the 20 % of CO ₂ emission without CCS.	Meijer et al 2011 Meijer et al. 2009
ULCOWIN electrolysis of iron ore	This is a radical innovation to gain iron from aqueous alkaline electrolysis of iron ore. The generated by-product is pure oxygen, which can be exploited in other areas of the metallurgical process.	Allegedly, with this process 100 % of CO ₂ emissions can be saved in the production of iron, however it requires massive inputs of electrical energy	Moya and Pardo 2013 Pardo and Moya 2013
ULCOS-BF Top gas recycling blast furnace	The injection of recycled gas into the BF hearth via tuyeres (in some version of ULCOS-BF include the use of tuyeres in the shaft). Carbon capture and storage (CCS) is needed to reach the 50 % reduction target in CO ₂ emissions	According to the calculations with integrated steel plant system boundaries, ULCOS-BF showed a maximum of 15 % CO ₂ emission reduction potential per tonne of hot rolled coil. When CCS is applied, a 60 % decrease in the direct emissions of an integrated steel plant can be achieved.	Danloy et al. 2009 Zuo et al. 2009 Meijer et al. 2009

Table 11. Principal areas of investigation under the CO₂ Breakthrough in Metal Production Program (Australia)

Source: [76,77,78,79,80]

Principal areas of investigation	Fundaments	CO ₂ mitigation potential	References
Use of biomass in iron and steel making	Laboratory analysis and initial industrial test of: charcoal as a recarburiser for liquid steel, blast furnace charcoal injection, survey of biomass supply, charcoal densification, iron ore sintering using charcoal as solid fuel, development of self-reducing composite pellets/briquettes, development of strong bio-coke, novel autogenous pyrolysis technology .	Based on LCA framework, Mathieson et al. (2011) estimate that biomass can save from 42 up to 75 % of the total CO ₂ emission in the iron and steel production.	Norgate et al. 2012 Jahanshahi et al. 2015 Norgate and Jahanshahi 2011
Dry Slag Granulation Process	Development of a novel process heat recovery from molten slags through dry granulation.	Based on LCA, the savings in GHG emissions would be 0.027 - 0.27 t CO ₂ e/t- crude steel compared to wet or slow air cooled granulation. Additionally, the DSG process offers saving in water utilization and sulphurous emissions, while generating a valuable by-product for the green-cement production.	Jahanshahi et al. 2011 Xie et al. 2007

Table 12. Principal areas of investigation under the AISI CO₂ Breakthrough Program (USA and Canada)

Source: [81,82]

Principal areas of investigation	Fundamentals	CO ₂ mitigation potential	References
Molten Oxide Electrolysis (MOE)	This technology uses the principle of molten salt electrolysis (similar to the production of primary aluminium) to generate pure iron, at a processing temperature of 1,600°C.	This technology offers a carbon release 345 kg CO ₂ /tonne liquid steel.	Pinegar et al. 2012
Hydrogen Flash Smelting	This technology is based on flash reduction of iron ore concentrate with a gaseous reagent (similar to the flash smelting of copper), such as hydrogen, syngas and/or natural gas..	This process would reduce energy utilization up to 20% by using iron oxide concentrates that do not require pelletization or sintering.	Sohn 2007

Table 13. Principal areas of investigation under the COURSE 50 Program (Japan)
Source: [83]

Principal areas of investigation	Fundamentals	CO ₂ mitigation potential	References
Hydrogen reduction of iron in the Blast Furnace	Reformed COG with high hydrogen concentration is injected for the reduction of iron ores, leading to the generation of vapour instead of CO ₂ .	The combined target of the technologies under the COURSE50 program is to establishing the technologies by 2030, with the final aim to industrialize and transfer the developed technologies by 2050.	COURSE 50
Technologies to capture - separate and recover - CO ₂	Reformed COG with high hydrogen concentration is injected for the reduction of iron ores, leading to the generation of vapour instead of CO ₂ .		

Table 14. Principal areas of investigation under the POSCO CO₂ Breakthrough Technology Development

Source: [Error! Bookmark not defined.,84,85]

Principal areas of investigation	Fundaments	CO ₂ mitigation potential	References
Technology for Capture of CO ₂ from Steelmaking Byproduct Gas	The first pilot plant with a processing capacity of 50Nm ³ /hr started up in 2008.	According to POSCO, it has attained a CO ₂ capture efficiency of over 90 percent and CO ₂ purity of at least 98 percent.	Kim et al. 2013
Sintered Ore Heat Recovery	Using a sealed heat exchanger that it is expected to increase the heat recovery rate and recovery temperature from sintering importantly.	The goal is to achieve an ultimate recovery rate of 70 % of heat and recovery temperature of 450°C.	POSCO Carbon Report 2011
Power Generation by Recovering Waste Heat from Stacks	This technology proposes the development of a stack heat recovery system, which uses a thermal siphon effect to reclaim heat energy from stacks and generate power	From the pilot plant operation it was found that the CO ₂ recovery was 90% and the purity of product CO ₂ was over 98%	Kim et al. 2013
Hydrogen Steelmaking	This long termed technology aims to use hydrogen as reducing agent (instead of coal or natural gas) in the FINEX process.	In theory using hydrogen as reducing agent would completely avoid the generation of CO ₂ emission, due to the clean burning behavior of hydrogen	POSCO Carbon Report 2011

2.4. Uses of biomass char in ironmaking

The use of biomass char in BFs is not a recent concept. Reductants from renewable sources were commonly used until the XVIII century, when Darby first substituted coke for the wooden char used in the process [9], (see **Table 2**). At the time of substitution, this input led to an important increase in productivity, as the coke's heating value was superior to that from wooden char and had better mechanical strength. Consequently, BFs could operate with much larger shafts. From that point in time, HM production has been increasingly associated with high rates of coke and coal utilization, due basically to its relatively low cost (a statement that has been challenged in recent years; refer to **Figure 9**), widespread availability and metallurgical benefits.

As previously mentioned, coke complies simultaneously with different tasks in the BF process: it provides the energy necessary for processing (acts as fuel), serves as a reducing agent for iron ores (acts as a reductant) and supports the burden (acts as a mechanical stabilizer). To this moment no other fuel presents similar characteristics.

When carbon from fossil sources (coke, coal, natural gas) reacts in any metallurgical process, this carbon is released to the atmosphere after having been held deposited in the earth crust for millions of years (see **Table 3** and **Table 8**). When an equivalent amount of energy is consumed from biomass sources, the same amount of carbon is also released to the atmosphere as with fossil coal or coke. The difference is that this carbon has been stored during biomass growth and will be stored again in a few years (Fallot et al. 2008) [86].

As a sustainable reductant, the biomass presents attractive characteristics to iron makers, due to its *carbon neutrality*. Basically, it is assumed that charcoal is a *carbon-neutral* fuel^{XVII} because the char produced from biomass (e.g., wood or forestry residues) is regarded as renewable due to its carbon cycle via biomass generation, which is comparatively shorter (5-10 years) than that of fossil coal (~100 million years) (Gupta 2003) [87]. To portray the carbon balance of ironmaking, **Figure 14** presents a mass balance calculated by Gonçalves (2012) [15] of carbon released and oxygen used during the production of HM with a coke-BF and a charcoal-BF. As

^{XVII} Despite the optimism behind the apparent carbon neutrality of charcoal-BF, some research point out the negative effect of methane generation during the pyrolysis in rural, artisanal beehive kilns. Most of these rudimentary kilns don't have any system for using off-gases and collecting odors, which lead to a high environmental impact.

indicated with the production of HM in charcoal-BF, 2.42 t CO₂/t HM are sequestered, while with coke-BF, 2.06 t CO₂/t HM are liberated into the atmosphere. Additionally the charcoal-BF shows a positive balance of oxygen generation (1.56 t O₂/t HM), while coke-BF consumes 1.41 t O₂/t HM. These values agree with previous assessments by Ribeiro et al. (2001) [88]

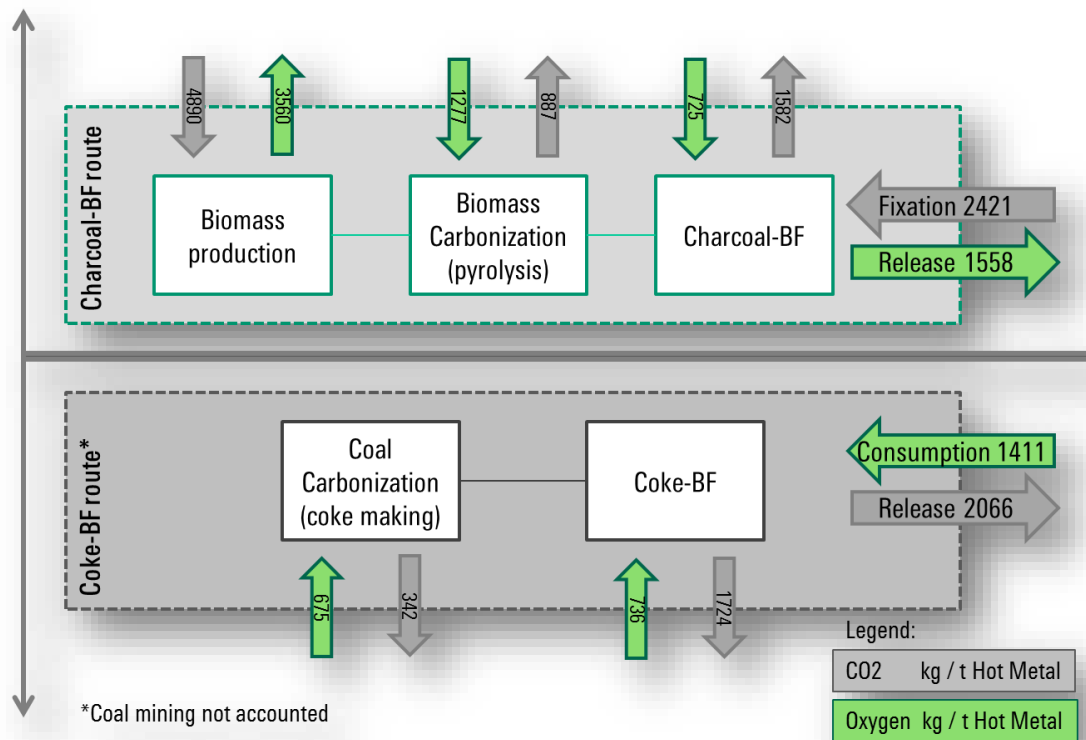


Figure 14. CO₂ and O₂ balance from charcoal- (top) and coke- (bottom) based BF
Source: Gonçalves (2012)

Biomass char can be a sustainable fuel for BF, however according to Norgate et al. (2012) to be completely carbon neutral two important aspects must be provided: sustainable forestry and full utilization of the by-products generated during carbonization [89]. In this sense, Suopajärvi et al. (2013) provides an ind-depth review of the opportunities of replacing fossil fuels in BF's using bio-reducers [90]. The following section builds on the fundamentals of biomass generation, general aspects of carbonization and the current state of the art of charcoal-BF.

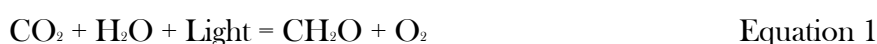
2.4.1. Aspects of biomass generation

Biomass from woods contains different kinds of hydrocarbons, principally cellulose, lignin, resin and waxes. **Table 15** shows the typical composition of the constituents of wood (Kumar and Gupta, 1992) [91]. In addition to the hydrocarbons, biomass is composed of large amounts of water; if its content surpasses 60 % of the biomass weight, the resulting calorific value would be negative. Consequently before utilizing the biomass as fuel an intermediate drying step is usually undertaken.

Table 15. Chemical constituents in biomass (woods)
Source: Kumar and Gupta

Constituent	Quantity in wood	Chemical Compound	Average Ultimate Analysis		
			C	H	O
Cellulose	45–65	(C ₆ H ₁₀ O ₅) _n	44.4	6.2	49.4
Lignin	20–40	C ₃₀ H ₃₃ O ₁₁	63.2	6.1	30.7
Resin	0.5–15	C ₂₀ H ₃₀ O ₂	80	10	10
Waxes	0.2–4	C ₂₉ H ₆₀ O	82	14.2	3.8

The fundamentals of biomass generation are similar to agricultural processes, as the plants grow and develop by absorbing CO₂ (in the atmosphere), water and solar radiation. Their synthesis leads to wood formation (hydrocarbon molecule/CH₂O) and oxygen (Gupta, 2003) [87]. The process is summarized in the **Equation 1**:



The yield of hydrocarbon molecules depends on various elements. An investigation on biomass productivity under Indian conditions (Gurumurti and Raturi, 1982) [92] determined that (**Equation 2**):

$$P = \frac{I \times E}{A \times D / C} \quad \text{Equation 2}$$

Where:

- P: Biomass productivity (ton/ha/yr)
- I: Intensity of solar radiation (kcal/ha/day)
- E: Eco-system efficiency of plant
- A: Area of plantation (ha)
- D: No. of sunshine days in year (days)
- C: Energy stored in dry biomass (kcal/ton)

This means that biomass productivity per area is directly proportional to the solar radiation and the ecoefficiency of the plant (see Equation 2), therefore those areas with higher solar intensity, such as tropical and sub-tropical areas, the biomass generation will be more vastly favorable than in other regions. Additionally, the productivity is highly influenced by the eco-system efficiency of plants. In tropical species this can range between 0.5–2.5 (Gurumurti and Raturi, 1982). The yield and capacity of species to store energy also varies according to the type of species selected. For instance in Brazil, due to the application of state-of-the art technologies, the yield of biomass in eucalyptus plantations has increased from 2.2 up to 19.8 t/ha/yr, and the prospects are to increase to 27 t/ha/yr by the end of 2015 (see **Figure 15**) [93].

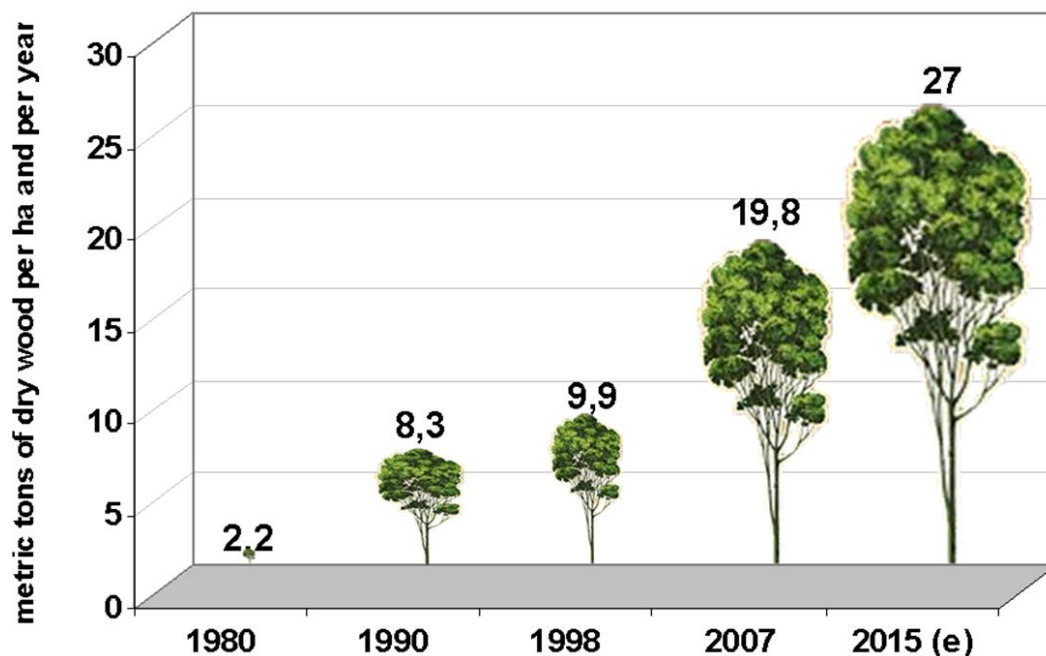


Figure 15. Productivity of dry wood at V&M Florestal

Source: Scherer et al. 2012.

Additionally the eco-efficiency depends greatly on the ecosystem. In this sense estuaries, swamps and tropical rain forests are the most productive environments per unit of area, while deserts and open ocean are the least productive ecosystems (Miller 2008) [94]. Therefore some of the most recent work on 3rd generation biofuels focuses on the possible use of estuaries (for instance algae) instead of other traditional energy crops (Dragone et al. 2010) [95].

2.4.2. Carbonization process

According to the *Handbook of charcoal making* (Enrich, 1985) [96]: “Charcoal is the residue of solid non-agglomerating organic matter, of vegetal or animal origin, that results from carbonization by heat in the absence of air at temperature above 300 degrees Celsius”. This definition differentiates charcoal from other carbon-rich mineral sources. Charcoal is also distinguished from bituminous coals and lignite, because they have not been subject to carbonizing temperatures during metamorphism.

Biomass sources include hard wood, soft wood, wood chips, rice husk ash, manure and biodegradable waste, among other feedstocks. These materials are currently used to supply some of the energy needs for generating electricity, residential heating, fuel for vehicles and energy for industries. The conversion technologies can be subdivided into four different kinds: direct combustion processes, thermochemical processes, biochemical processes and agrochemical processes (Demirbaş, 2000) [97]. Thermochemical processes can be subdivided into pyrolysis, gasification, supercritical fluid extraction and direct liquefaction. In this sense pyrolysis is the process that aims to convert biomass into liquid, biomass char, and non-condensable gases, direct combustion processes are mostly used presently in the production of charcoal for iron production.

As illustrated in Figure 16, charcoal is been manufactured and consumed around the world, and according to National Master (2005) [98] the annual production in 2005 was 44 million tons, based on an estimate of 20 % yield from original biomass (Garcia-Perez et al. 2010) [99]. A total of 220 million tons of feedstock are processed to manufacture charcoal. Brazil is the largest producer with 9.89 million tons/year. This is more than double the second largest manufacturer Thailand (3.9 millions tons/year), while other important producers are (Table 16): Ethiopia, Tanzania, India, Congo, Egypt, Angola, Nigeria and USA.

Table 16. Top producers of charcoal. (2005)

Rank	Country	Tons
1	Brazil	9,893,000
2	Thailand	3,916,000
3	Ethiopia	3,221,000
4	Tanzania	2,506,000
5	India	1,728,000
6	Congo	1,704,243
7	Egypt	1,281,000
8	Angola	982,000
9	Nigeria	976,000
10	USA	940,000

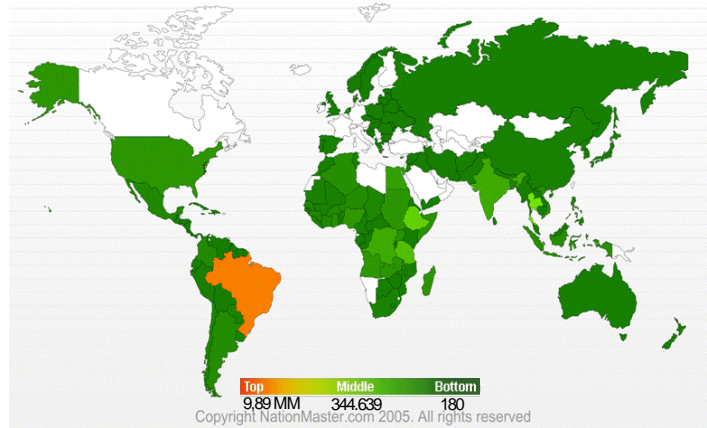
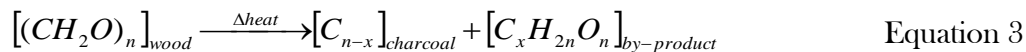


Figure 16. Global production of charcoal
Source: National Master

In order to serve as fuel for ironmaking applications, biomass should be carbonized and its humidity content and C/H concentration need to be adapted. This means the specific heat capacity (heat capacity over a kg of charcoal) is increased. The charcoal is produced from thermal decomposition under highly reductant atmospheres of heterogeneous organic matter; this process is known as pyrolysis or carbonization. Besides generating charcoal (a product of interest to this work), gases and pyrolytic/tars liquids are generated. The carbonization process is represented in Equation 3 (Gupta, 2003):



where:

$(CH_2O)_n$: biomass

C_{n-x} : charcoal generated

$C_x H_{2n} O_n$: carbonization by products (liquids and gaseous)

The heating up of the biomass (Δ_{heat}) liberates the following types of by-products: non-condensable gases (CO , CO_2 , CH_4 and C_2H_6), acetic acid / methanol (pyroacids), tar / heavy oils and water (Garcia-Perez, 2010). It also produces a porous residue constituted mainly of carbon (the charcoal or biochar). Manure, organic waste, biocrops and crops residues can be used as feedstock; in the generation of charcoal valuable by-products are generated (see **Figure 17**, from International Biochar Initiative).

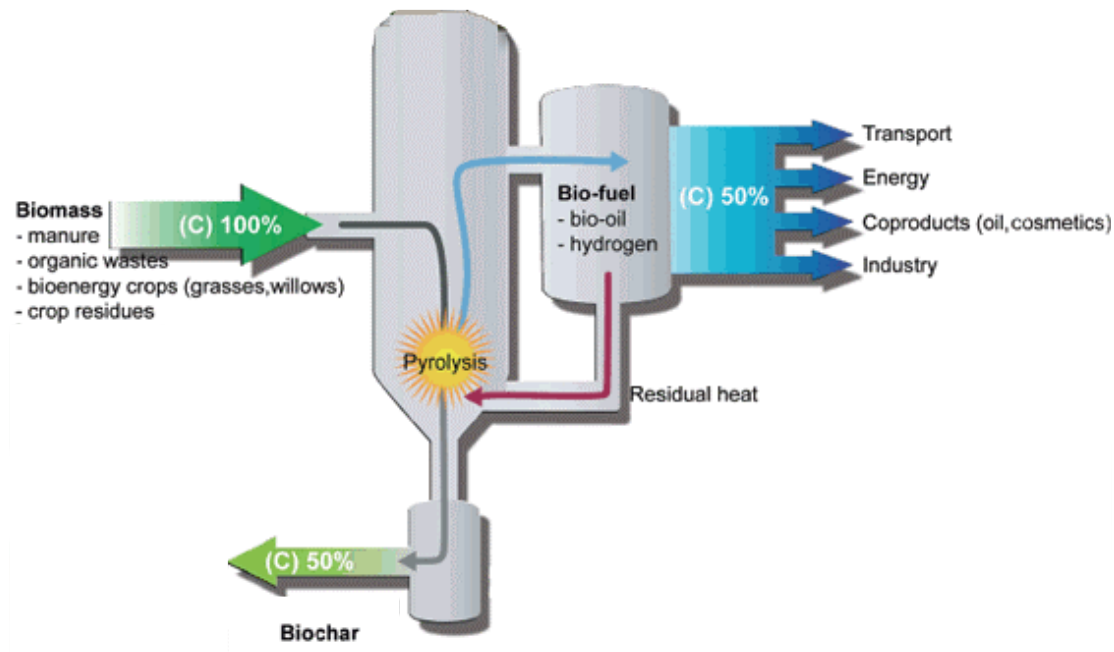


Figure 17. Schematic representation of charcoal/biochar production
Source: International Biochar Initiative [100]

The stages of the carbonization process carbonization process are summarized in the **Table 17** (Lucio, 2012) [101].

Results in Figure 18 show that char yield decreases gradually from 47.1 % to 31.8 % for hazelnut kernel husk samples, while chars from corncob decrease from 31.9 % to 19 %. According to the results, best charcoal yields are obtained at carbonization temperatures below 850 K (577°C), where more than 25 % of the weight of the biomass becomes transformed; beyond 577°C the yield of gas and liquids increases.

Table 17. Stages of carbonization process

Source: Lucio (2012)

Stage	Temp	Energy	Observations
I – Drying	20–110° C	Endothermic	Wood has to be heated in order to vaporize the moisture. Temperature does not increase until the complete drying of wood. When cut, the wood moisture is in the range 50 to 70 %, depending on the species. This moisture should be vaporized before the wood temperature
II- Drying	110 – 175°C	Endothermic	The residual moisture is vaporized, few significant reactions, such as dehydration reactions.
III – Pre-carbonization	175 – 270°C	Endothermic	Wood scorching. Reaction rate increases, starting the emission of volatiles and of gases. Decomposition of the wood starts, liberating CO ₂ , CO ₂ , acetic acid and methanol. Wood becomes scorched (char), dark color.
IV – Transition	270 – 290°C	Exothermic	Decomposition reactions continue, starting the exothermic stage.
V – Carbonization	290 – 380°C	Exothermic	Exothermic reactions, self sustainable. The temperature raises, the thermal decomposition process speeds, liberating more heat, keeping
VI – Carbonization	380 – 500°C	Exothermic	The temperature elevated. Important stage of decomposition reactions and of gases emissions. The chemical composition of gases changes to less oxygenated gases, with the emission of combustible gases containing CO, H ₂ , CH ₄ with CO ₂ and condensable gases. The emission of vapors of acetic acid, methanol, acetone and other substances reaches a maximum. The decomposition rate increases to a maximum showed by a peak in the DTG curve. The final residue of this stage is charcoal. When the temperature goes over 380°C, wood transformation go to almost complete, gases emissions are reduced. The final charcoal fixed carbon content is a function of the temperature. It is desired a final carbon content in the range 70 – 75 % for the hot metal blast furnace.
VII – Gasification	>520°C	Exothermic	Heating over 500°C charcoal gasification and degradation is started.

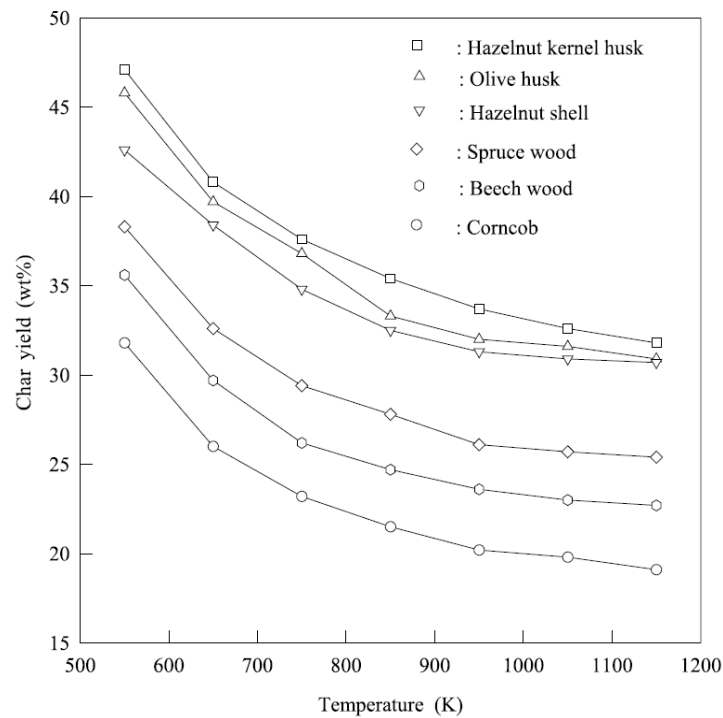


Figure 18. Effect of carbonization temperature on char yield
Source: Demirbaş (2001)

In order to be economically attractive, charcoal production for metallurgical applications should minimize the yield of gas and liquids. Nonetheless, it is important to attain in the char as high a heat capacity as possible. In this sense, studies demonstrate that heat capacity is directly proportional to carbon content and shows inverse proportionality to oxygen content (Demirbaş 2001; Ueda et al. 2009), see figures 19 and 20. Additionally, studies have demonstrated that a high index of crystalline cellulose (for instance in the species *Eucalyptus camaldulensis*) favors the gravimetric yield in charcoal (Pereira et al. 2013) [102], because of this reason Eucalyptus is the most widely utilized species for wood char production in Brazil.

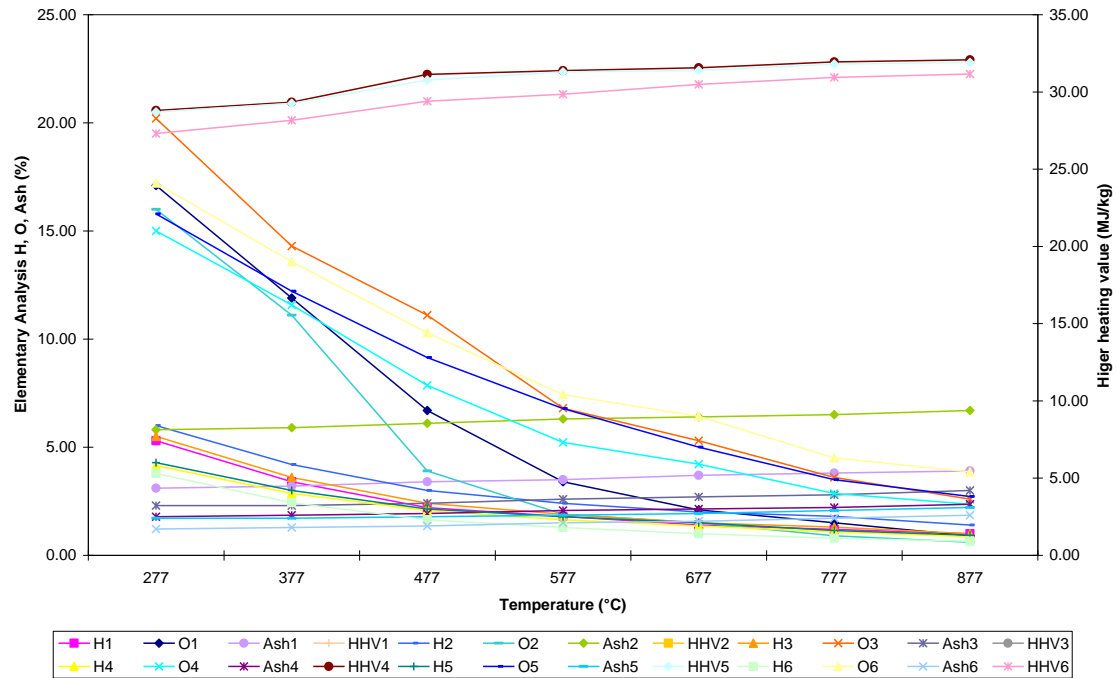


Figure 19. Elementary analysis and higher heating values of charcoal at different pyrolysis temperatures
Source: Demirbaş (2001)

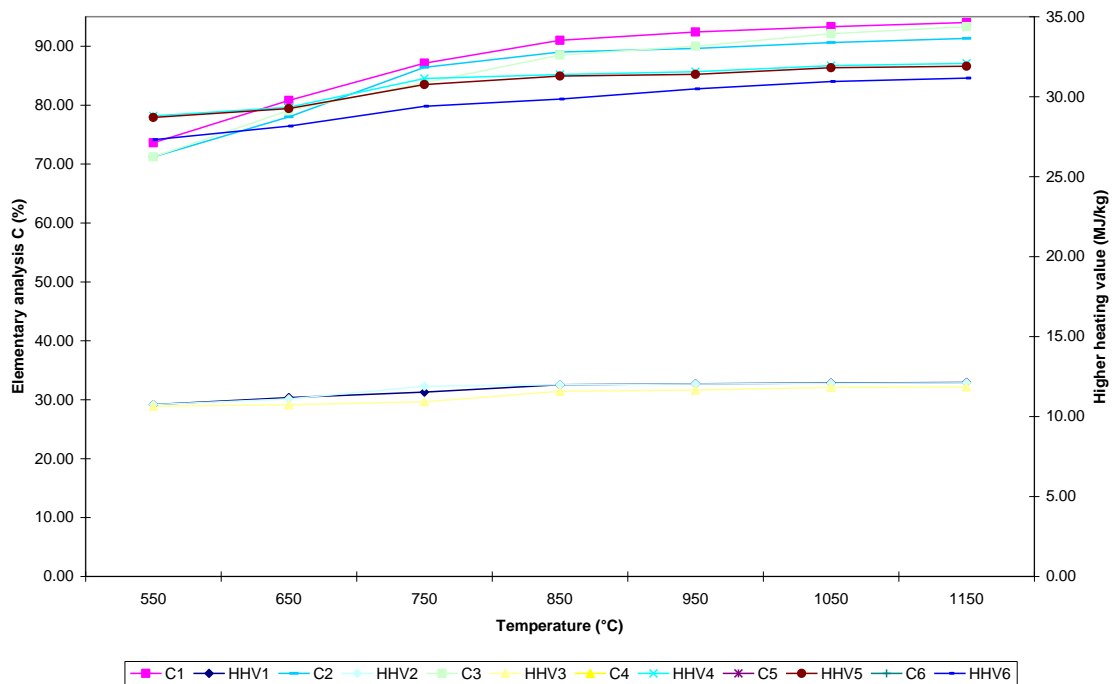


Figure 20. Carbon content and higher heating values of charcoal at different pyrolysis temperatures
Source: Demirbaş (2001)

As previously mentioned, during the char production process, several by-products such as pyrolygneous liquids, vegetal tar, methane and gases are generated through pyrolysis. As a

general rule, a high yield of char is linked with lower emissions, especially of methane, which is a rather negative GHG. As can be observed in **Table 18**, when the charcoal yield increases from 26 to 35 %, the quantity of methane gas emitted is reduced by a half, therefore new carbonization process have been designed to increase yield and lower the potential release of negative GHGs (CGEE 2014) [103].

Table 18. Mass distribution of carbonization production (basis 1 ton of dry wood)
Source: CGEE (2014)

Char yield	Pyroligneous liquid	Vegetal tar	Gases CO ₂ , CO, H ₂ C ₂ H ₄	CH ₄ Methane
	kg	kg	kg	kg
26 %	340	150	230	20
35 %	300	130	210	10

2.4.2.1. Charcoal or biochar? A needed definition

In the literature related to metallurgy, the biomass char is commonly known as *charcoal*. This is the widely accepted term for the carbonaceous residue of a biomass after a carbonization process. Other accepted terms found in the literature are woodchar or simply char (Kumar and Gupta 1998, Ueda et al. 2009) [104,18].

Similarly, *biochar* is also defined as a type of charcoal obtained from the pyrolysis of biomass. The term at present is mostly used to describe the biomass char added to soils to reduce emissions that would otherwise naturally lead to GHG emissions. It is argued that biochar also has significant carbon sequestration value [100].

For the purpose of the present investigation, I define *biochar* as the biomass char gained from sustainable biomass sources, and carbonized using highly efficient kilns with high char yields (higher than 33 %). In spite of its apparent carbon neutrality, unsustainable charcoal production may be detrimental to native forests, if feedstocks are not managed on a sustainable basis. This can occur when trees are harvested and no new trees are planted to regenerate the forest. Additionally, there are severe concerns about GHG balances of artisanal and semi-industrial charcoal production, due the extensive release of methane gases. These are the principal concerns that guide my recommendations in this thesis.

2.4.2.2. Industrial processes for carbonization

In charcoal production the biomass is charged into the kilns to be carbonized. In traditional pit kilns, the wood loaded is burned to dry the biomass and increase the temperature of the complete charge, so thermal transformation commences and is completed autonomously. The wood burned in this way is lost (FAO 1983).

In continuous retort, the heat from pyrolysis off-gases (normally wasted on other processes) is used to pre-heat the fed biomass. With this technological improvement carbonization is carried out without any additional wood being burned. In this sense, the efficiency of the thermal transformation can be boosted by the input of dry biomass, since the removal of water required large amounts of energy. Unit processes of charcoal-making are depicted in **Figure 21**.



Figure 21. Unit processes of charcoal-making (left), beehive kiln (right top) and retort (right bottom)

Source: Valladares and Scherer (2012) [11].

In Brazil, it is estimated that, in 2012, 4.87 million hectares were dedicated to the cultivation of *Eucalyptus spp.* for charcoal making (Melo, 2012) [105]. In this respect, Ferreira (2000) [106] presents an example of sustainable wood farming in Minas Gerais (Brazil), in which eucalyptus are logged after 7, 14, and 21 years without any need of reforestation. Consequently, there is a permanent stock of standing biomass to sustain HM production. As shown in **Figure 22**, once

the trees are logged, the roots, smaller branches and leaves are left in place and constitute an additional carbon stock. Figure 23 depicts the carbon mass contained in the wood as the trees grow. An investigation by Carneiro et al. (2014) also confirmed that the highest yield of carbón and máximo density is attained at 7 years for clones of *Eucalyptus*, leading to high calorific power [107].

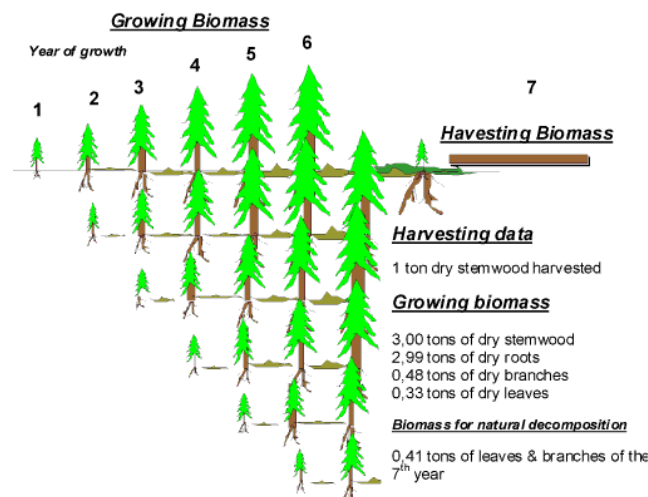


Figure 22. Wood harvesting in Minas Gerais to produce charcoal for metallurgical uses
Source: Ferreira (2000)

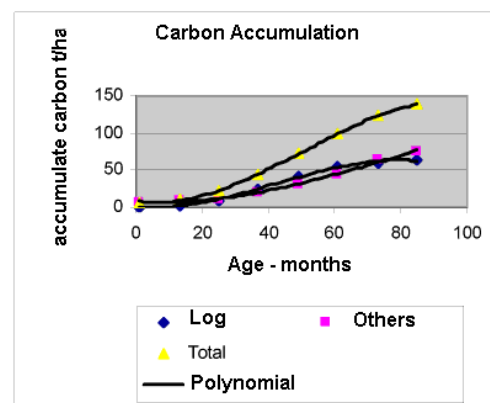


Figure 23. Carbon mass contained in the wood
Source: Ferreira (2000)

Previous assessments in Brazil have focused on the determination of the properties of wood from different clones of *Eucalyptus spp.* to select the species with highest contents of lignin and low content of extractives to attain high char yield and adequate quality (Pereira et al. 2012; Castro et al. 2013) [108,109]. For instance in the plantations of Gerdaul S.A. in *Tres Marias (Minas Gerais)*, it is possible to find two species of eucalyptus clones: *Eucalyptus camaldulensis* and *Eucalyptus urophylla* hybrid. Other plantations in Brazil also cultivate several different clones of *Eucalyptus*, for instance: Plantar S.A., Suzano, V & M Florestal.

The thermal transformations are normally carried out in pyrolysis plants. Garcia-Perez (2010) argues that these plants should be designed with a clear business model in mind, taking into consideration selective, controlled, multi-product, flexible and integrated processes. In this sense the report ‘Hannover Principles of Sustainable Design’ provides the following guiding ideas for designing a pyrolysis reactor:

1. “Pyrolysis units should be net exporters of energy and only operate on renewable energy without reliance on fossil fuels or any sort of remote energy.

2. The heating process must be efficiently incorporated into the design and be generated from renewable resources.
3. The entire design process must use water carefully and conservatively.
4. Beneficial considerations of rainwater and surface water runoff shall be incorporated into the design.
5. Short- and long-term environmental impacts must be considered during the design process.
6. Designs must be flexible enough to accommodate several different production needs.
7. The evaluation of the design shall consider the necessary air, land, water and solids to eliminate pollutant releases.”

Emrich (1985) recommend the following classification between different carbonization reactors [110]:

- **Kiln:** kilns are normally utilized for traditional wood calcination and generate only charcoal.
- **Retorts and Converters:** the industrial reactors are able to produce biomass char and may also recover condensate liquid and syngases. In this sense, Retort refers to reactors that can carbonize pile-wood or logs over 30 cm long and over 18 cm in diameter. Converters produce char by the pyrolysis of small particles, for instance chipped wood.
- **Slow Pyrolysis:** refers to a process in which particles are heated slowly under reducing atmospheres to generate biomass char.
- **Fast Pyrolysis:** refers to reactors designed to maximize the yields of bio-oil, through the use of high temperature.

Table 19. Estimated charcoal yield by process in Brazil.

Source: CGEE (2014)

Beehive kilns	Wagon retorts	Continuous retorts
24 %	32 %	Up to 36 %

A comparison of different carbonization processes in Brazil issued by the CGEE (2014) (see table 19), revealed that the best yield could be attained with the use of a continuous carbonization technology (*Tecnologia de carbonizacao continua* in Portuguese). This technology presents high charcoal yield and with high production output 8.9–13.4 kg/m³/h. Additionally, it allows the exploitation of by-products which can significantly contribute to reduce the cost of biomass char. However, the installation of a kiln with continuous carbonization calls for high capital expenditure, in comparison to other converting technologies

(e.g. beehive kilns). Still to this day most of the charcoal in Brazil is produced in the traditional beehive kiln with low charcoal yield and generation of toxic fumes (Oliveira et al. 2013) [111]. Garcia-Perez et al. (2010) [99] presented in **Table 20** the principal characteristics of the pyrolysis reactors currently used in the manufacture of charcoal

Table 20. Characteristics of pyrolysis reactors.

Source: Garcia-Perez et al. 2010

Cinder Block			Retorts			Wagon Retort
Earth kiln			Large Kilns With Recovery of Pyrolytic Vapors	Small retorts	Retorts with By-product recovery	
Final Product	biochar	Biochar	Biochar, bio-oil and gases	Biochar	Biochar, bio-oil and gases	Biochar, bio-oil
Heat transfer rate	slow pyrolysis	slow pyrolysis	slow pyrolysis	slow pyrolysis	slow pyrolysis	slow pyrolysis
Mode of operation	batch	batch	semi-batch	semi-batch	semi-batch	Continuous
Heating method	auto-thermal	partial auto-thermal	partial combustion, contact with gases	indirect heat	indirect heating through the walls	indirect heat
Construction material	earth	cinder, bricks, concrete and steel	bricks and steel	bricks and steel	bricks and steel	Steel
Portability	built in place	stationary	stationary	portable	stationary	stationary
Reactor Position	horizontal/vertical	horizontal	horizontal	horizontal	horizontal	horizontal
Raw Material	cordwood	cordwood	cordwood	sawmill chips	cordwood, softwood,	cordwood
Loading and discharge	manual	manual, mechanical	manual, mechanical	manual	manual	use of wagon
Size of kiln	small/medium	small/medium	Large	small	small	small to large
Ignition method	small kindled	small kindle wood, burning oil	small kindle wood, burning oil	external combustion with leaves and bark	external combustion chamber	heating with external combustion
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
Pressure	atmospheric	atmospheric	atmospheric	atmospheric	atmospheric	atmospheric
Pretreatment	seasoned wood	none	seasoned wood	none	none	drying

Table 20. Characteristics of pyrolysis reactors (continued)

Source: Garcia-Perez et al. 2010

	Wood logs Converters		Wood chips Converters					
	Reichert converter	SIFIC process	Herreshoff multiple-hearth furnace	Rotary Drums	Auger reactor	Moving agitated bed	Shelf reactors	Paddle pyrolysis kiln
Final Product	Biochar	Biochar	Biochar	Biochar, heat	Biochar, bio-oil and gases	Biochar, bio-oil	Biochar, bio-oil	Biochar
Heat transfer rate	slow pyrolysis	slow pyrolysis	slow pyrolysis	slow pyrolysis, fast pyrolysis	slow pyrolysis, fast pyrolysis	slow pyrolysis, fast pyrolysis	slow pyrolysis, fast pyrolysis	slow pyrolysis
Mode of operation	semi-batch	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous
Heating method	Direct contact with hot gases	Direct contact with hot gases	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	steel	steel
Portability	stationary	stationary	stationary	stationary	stationary	stationary	stationary	stationary
Reactor Position	vertical	vertical	vertical	Horizontal	Horizontal	Horizontal/vertical	Horizontal/vertical	horizontal
Raw Material	cordwood	cordwood	chips, fine particles	chips, fine particles	chips, fine particles	chips, fine particles	chips, fine particles	chips, fine particles
Loading and discharge	mechanical	mechanical	mechanical	mechanical	mechanical	mechanical	mechanical	mechanical
Size of kiln	large	large	large	small	small	medium, large	small	small
Ignition method		hot gases in an external oven	external combustion chamber to produce hot gases		external combustion chamber	external oven		external heater
Process control	direct measurement	direct measurement of temperature	direct measurement of temperature	direct measurement of temperature	direct measurement of temperature	direct measurement of temperature	direct measurement of temperature	direct measurement of temperature
Pressure	atmospheric	atmospheric	atmospheric	atmospheric	atmospheric	atmospheric	atmospheric	atmospheric
Pretreatment needed	none	pre-drying	Ground in chips, fine particles	Ground in chips, fine particles	none	pre-drying	pre-drying	none

2.4.2.3. Influence of biomass on characteristics of the carbonization

Practical experience has shown that the biomass type, humidity content and size are significant elements that influence the pyrolysis process. The charcoal yield of a particular feedstock is influenced by its lignin, holocellulose and extractives contents (Antal and Grønli 2003) [112] (see **Table 15**. Chemical constituents in biomass (woods)). Thus, biomass with elevated lignin provides higher yields of charcoal. Diverse types of biomass can be used to generate charcoal, **Figure 24** depicts some of the most import feedstock utilized for charcoal-making: hard wood (a), soft wood (b), wood chips (c), rice husk ash (d), manure (e) and biodegradable waste (f). Normally in charcoal making for metallurgical application, hard woods are preferred (Gupta 2003; Kumar and Gupta 2001) [87,91], for instance eucalyptus (Ferreira 2000; Adbullah and Wu 2009)[113,114], since these species tend to generate a dense char with good crushing resistance, which is particularly important when the charcoal is fed from the top of the BF.

In a report of charcoal for direct feeding from the top of the BF published by FAO (1987), it is stated that charcoal with optimum properties is produced with log pieces of the size of approximately 25–80 mm diameter, because this granulometry allow a good permeability of gases.

Traditionally it is considered that charcoal produced from softwood (**Figure 24** b) has inferior mechanical strength and a higher tendency to breakdown. However, it is important to note that the charcoal yield is independent of the wood density (Antal and Grønli 2003). From an economic perspective soft woods have normally lower cost. However, it is not significantly important to use hardwood or softwood for charcoal making, when the final utilization is the biomass char injection in BF through the PCI rigs, since the biochar would not need to support the burden in this case.

In recent years, there has been a notable increase in the utilization of biomass to generate fuels, mainly driven for the prospective CO₂ neutrality of its production. However there have been also concerns about the negative consequences of biofuels, such as food price increases, conversion of natural areas to agriculture with consequent losses in biodiversity and mis-utilization of water, leading to a significant debate on the actual benefits of biofuels (these issues are explored in the next chapter). However, this criticism about land utilization and food prices

has also motivated a new line of research on the possible uses of agricultural and forestry residues in the production of biofuels (Greg and Smith 2010).



Figure 24. Types of biomass used for charcoal-making

Sources for residue biomass include agricultural residues (stalks, corn stover, chaff, etc.), forestry residues (tree tops, branches, slash) and mill residues (sawdust, scraps, pulping liquors, etc.), as shown in **Figure 24d**. The final chemical composition of the charcoal can vary according to the type of biomass used, in this respect **Table 21** shows some elemental analysis of charcoal from different feedstocks found in the literature [87,112,115].

Table 21. Ultimate Analysis and Ash Content of Charcoals from Different Sources.

Source: Antal and Gronli (2003), Demirbaş (2000) and Gupta (2003)

	Feed stock	Reference	Average Ultimate Analysis					Ash
			C	H	O	N	S	
1	Coconut shell	Antal and Gronli 2003	92.28	1.09	3.08	0.47	0.04	2.78
2	Corn cob	Antal and Gronli 2003	86.38	1.2	5.34	0.56	0.05	4.31
3	Kukui nut shell	Antal and Gronli 2003	90.31	1.03	4.31	0.42	0.02	3.27
4	Leucaena wood	Antal and Gronli 2003	85.41	1.27	6.37	0.53	0.04	4.62
5	Macadamia nut shell	Antal and Gronli 2003	94.58	0.97	2.93	0.47	0.03	1.04
6	Oak board	Antal and Gronli 2003	91.5	1.22	3.55	0.18	0.01	1.04
7	Oak slabs	Antal and Gronli 2003	92.84	1.09	3.49	0.24	0.04	1.46
8	Pine wood	Antal and Gronli 2003	94.58	1.06	3.09	0.11	0.04	0.69
9	Rice hulls	Antal and Gronli 2003	52.61	0.82	3.87	0.57	0.06	41.34
10	Hazelnut husk	Demirbaş 2000	94.0	1.00	0.9	0.2		3.9
11	Olive husk	Demirbaş 2000	91.3	1.40	0.6	0.2		6.7
12	Hazelnut shell	Demirbaş 2000	93.3	1.00	2.6	0.1		3
13	Spruce wood	Demirbaş 2000	92.1	1.20	3.3	0.1		3.3
14	Beech wood	Demirbaş 2000	91.7	1.30	3.8	0.1		3.1
15	Acacia (<i>Acacia aemula</i>)	Gupta 2003	90		5.48		0.07	4.5
16	Eucalyptus (<i>Eucalyptus Camaldulensis</i>)	Gupta 2003	91.5		4.1			4.4

According to Gregg and Smith (2010), the use of biomass residues allows the same land and production practices to produce multiple products, minimizing the resource inputs and the demand for land associated with producing dedicated energy crops [116]. In this respect, Gregg and Smith (2010) considering the actual residue ratio and energy content generated by some of the most sown crops in the world (for instance wheat, rice, corn, oil crops, sugar crops, etc) (see **Table 22**), assessed that up to 48.71 EJ of energy could have been generated if all the residual biomass from the crops of 2005 would have been collected and transformed into energy.

Table 22. Amount of residue and energy content of the residue generated by selected crops
Source: Gregg and Smith (2010)

Residue Source	Residue ratio dry residue mass/ wet crop mass	Residue retention Mg/ha	Residue energy content MJ/kg	Midprice 2005 USD/kg
Wheat	1.49	2.81	16.22	2.08
Rice	0.99	0.94	13.55	2.08
Corn	0.74	2.20	16.86	2.08
Other grain	1.02	1.09	15.20	2.08
Oil crops	1.28	1.26	13.26	2.08
Sugar crops	0.28	1.24	15.21	2.08
Misc. crops	0.38	0.38	8.17	2.08
Timber	0.33	20.00	18.93	2.48
Mill	0.30	0.00	20.00	1.46

The final products of carbonization may vary significantly according to the volatile matter content and processing temperature. The Carbonization temperature has a significant influence on the charcoal yield, results by Demirbaş (2001) [97], the best charcoal yields are obtained at carbonization temperatures below 850 K (577°C).

2.4.2.4. Humidity content

The humidity content of the biomass is an important parameter as it influences the efficiency of charcoal-making. Moisture content in naturally dried wood is 44–50 % of weight, thus if the carbonization equipment does not possess any preheating system, as in earth pits or small retorts (see Garcia-Perez et al. (2010) [99] presented in **Table 20**), part of the biomass fed is used to evaporate the water inside the wood. In more technologically advanced processes, the

off-gases are utilized to dry or pre-dry the biomass, for instance in wagon retort or moving agitated bed (Garcia-Perez et al. 2010) [99]. Another way of reducing the moisture content is by letting the wood dry in the air. This method does not present any additional heating cost, but there might be economical losses due to fungal decay and insect attack. Also the climate and season may play an important role in the drying time (FAO; 1987).

2.4.2.5. Granulometry

The velocity of charcoal formation is directly dependent of the granulometry of the biomass feed, for instance CGEE (2014) estimated that the carbonization of a small piece of wood at 350 °C can take 3.5 hours, while the pyrolysis of dense pieces of logs can take up to 16.3 hours [117]. This means that the larger the pieces of biomass charged to the reactor, the longer will be the time required to complete carbonization. In this sense, wood chip converters such as the Auger Reactor, Moving Agitated Bed and Self Reactor, provide very rapid and continuous carbonization, also known as fast pyrolysis. However, traditionally, charcoal of relative small size is of low market value. Reactors for log converting, for instance Retort Wagon, Rechert and SIFIC, may generate biochar only through slow pyrolysis (see **Table 20**) (Garcia-Perez et al. 2010) [99].

2.4.3. Constraints of biomass char production

Whereas charcoal can make a significant contribution to metallurgists, by helping to provide part of their energy requirements with low CO₂ emissions, concerns exist about the sustainability of charcoal production. Three important issues concerning charcoal production are atmospheric pollution, forest degradation and social aspects.

2.4.3.1. Atmospheric pollution

The smoke and emissions produced during burning and briquetting are the main sources of atmospheric pollution (Garcia-Perez 2010). Pyrolysis liberates toxic substances and high GHG emissions, such as carbon monoxide and tar smokes, which are poisonous (especially the CO) and have long lasting effects on the respiratory systems. According to a report by CGEE (2014)

[103], it was estimated that the charcoal production in Brazil generates 0.54 MMt of methane which corresponds to a contribution of 11.3 MMt CO₂ equivalent to GHG.

Additionally, some precautions should be taken to minimize the inherent risks presented by the toxicity of gases liberated (FAO 1983). In this sense proper ventilation should be provided and batteries of kilns should be located in remote areas. In Brazil most of the carbonization kilns are located in the vicinity of Eucalyptus plantations, which are away from residential zones.

The use of protective clothing for workers is also recommended as tars and pyroligneous acid can irritate the skin. Additionally these liquids may pollute water supplies for humans and animals. To avoid this source of contamination, liquid effluents should be trapped in settling ponds. Kilns and pits, as distinct from retorts and other sophisticated reactors, do not normally generate liquid effluent; their by-products are mostly dispersed into the air as vapours. Precautions against airborne contamination of the environment are of greater importance in this case (FAO 1983).

2.4.3.2. Forest degradation

Despite its alleged carbon neutrality, charcoal production may be detrimental to the forest if feedstocks are not managed on a sustainable basis. This can occur when trees are cut down and no new trees are planted to regenerate the forest.

Most of the charcoal produced worldwide (Table 16. Top producers of charcoal) comes from kilns with poor efficiency and high dependence on human labor. In addition to the previous argument, Demirbaş (2000) mentions some examples of deforestation and local fuel scarcity in Nepal, parts of India and sub-Saharan Africa.

In 2005 in Brazil 5.5 million tons of charcoal were produced from non-sustainable native forests (52,8 %) and sustainable forestry plantation (47.2 %); nevertheless it is important to note that charcoal from non-sustainable primary sources was reduced by 82 % between 1989 and 1997. Illegal logging in Brazil for charcoal production is considered responsible for the deforestation of approximately 200,000 hectares per year (Nogueira et al. 2009) [118].

Nevertheless, strict legislations have been reinforced in Brazil to prevent the deforestation. The Brazilian law n°. 18,365 established in 2009 sets limits that reduce gradually the consumption of the products or sub-products originated from native forrest, according to this law by 2013, manufacturers may use no more than 15 % of wood from native forests, while from 2014 to 2017 can use up to 10 % and from 2018 on the consumption of forest products from native forests should not be higher than 5 %.

According to Ferreira (2000) [106], due to the increasing limitations of producing charcoal from non-sustainable sources, many companies have implemented reforestation initiatives using several eucalyptus species (e.g. *Camaldulensis*, *Cloesiana*, *Urophylla* and *Pellita*), for instance V&M Florestal, Gerdau S.A., Plantar S.A. (Pereira et al 2012) [102]. These species have adapted well to the Brazilian conditions and present high growing rates (see **Figure 25**).

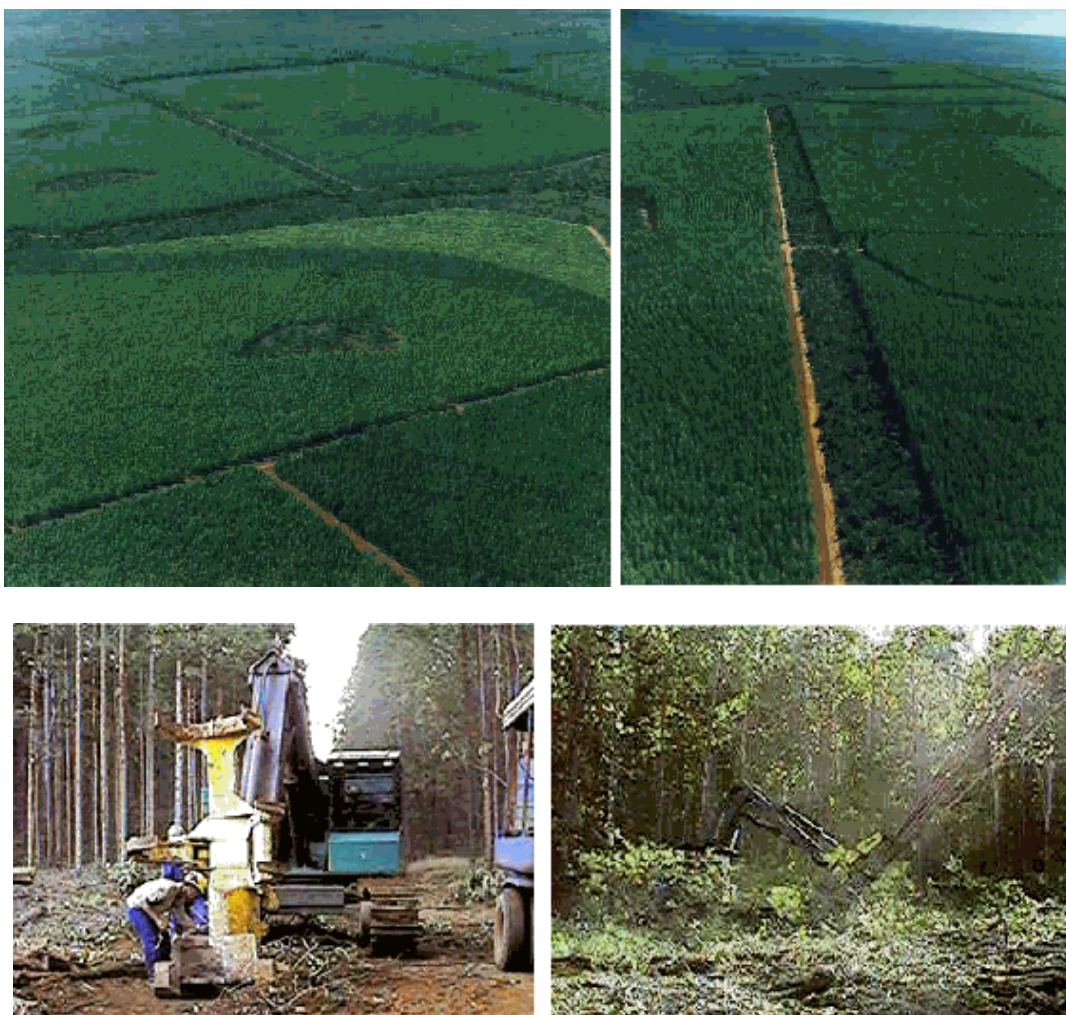


Figure 25. Eucalyptus farming in Minas Gerais for charcoal production
Source: Ferreira (2000)

Nonetheless, there are problems created due to exploitation of vast areas of eucalyptus, such as:

- *Desertification:* According to Cardoso and Pires (2009) [119], the eucalyptus plantations require large quantities of water. It is estimated that each eucalyptus tree needs 30 litres of water per day to grow. Consequently, the eucalyptus plantation can lead to a water deficit in the cultivation areas. Thus many plantations are located in near rivers. There are documented examples where eucalyptus plantation have dried out the soil in the northern region of Espirito Santo (Brazil).
- *Soil erosion:* Some eucalyptus plantations do not receive any soil treatment, therefore after some years of operation the soil is depleted in important minerals, which leads to high erosion. To restore the soil after it is depleted in minerals, high investments are required.
- *Reduction of biodiversity:* In plantations where one species is cultivated, there is little vegetable and animal biodiversity. According to Cardoso and Pires (2009) the only animal species that manage to survive in eucalyptus plantations are ants and birds.
- *Modification of the landscape:* In some areas, eucalyptus plantations severely affect the regional ecosystem, with a consequent transformation of the native landscape.

Currently there are several initiatives in Brazil to counterfight the criticisms against the Eucalyptus plantations (Winter, 2012) [17], for instance to increase the size of the reserve areas to reduce the negative side effect. It has also been prioritized the use of areas to neighbouring watersheds. Additionally corridors have been established between reserves and between water collections. According to Winter (2012), Brazil dedicates only 0.76 % of its extension to monocultives, while other countries such as Japan, India, Thailand and Ukraine dedicate between 5-30 % of their area.

2.5. State of the art of biomass char in ironmaking

Birat et al. (2003) [120] assessed their actual performance in terms of GHG emissions and energy needs. The results are shown in **Figure 26**. In this analysis, Birat et al. (2003) estimate the complete substitution of coke by biomass as the most promising initiative to reduce CO₂

and net energy, with lower emission values as a result of molten bath electrolysis or BF top gas recycling.

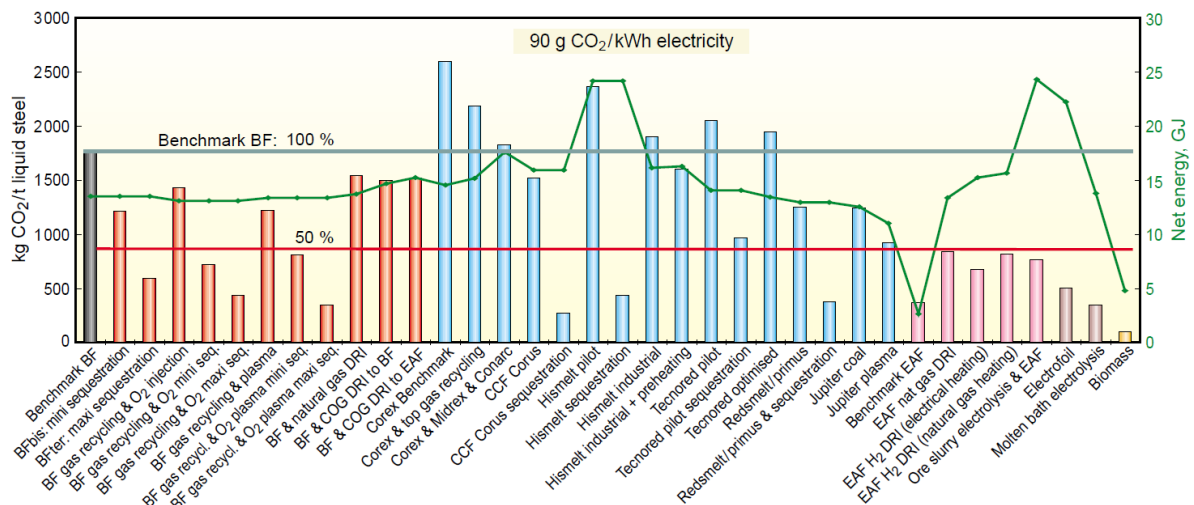


Figure 26. Present and radically new steel production processes in terms of CO₂ emissions and energy consumption

Source: Birat et al.(2003)

In spite of the positive benefits of biomass utilization in ironmaking, Brazil remains as the last niche of charcoal-BF in the world. Thus, it is fundamental to analyze the current state of *ferro gusa* production (hot metal in Portuguese) in this country. According to Schrerer and Braga (2012) [14], Brazil generated a total of 33.1 MMt of HM, from which charcoal-based HM represented an output of 23 %. Charcoal-BF in Brazil produced in 2011 2,1 MMt HM from integrated plants (BOF) and 5.5 MMt HM from independent *ferro gusa* producers^{xviii}. The remaining 25.5 MMt HM were generated in large coke-based BF. Because of this diversity in fuel utilization, the Brazilian *ferro gusa* industry presents unique characteristics. **Figure 27** presents a historical development of production of HM using coke-BF (bars in gray color) and charcoal-BF (bars in green and light green) in Brazil (from 1994–2010) (Carneiro, 2012) [121]. It can be seen that HM from charcoal-BFs have declined its market participation and this trend is likely to continue in the future

As shown in **Table 23** and **Figure 28**, most of the HM production is generated in the states of Minas Gerais, Para, Rio de Janeiro. According to Nascimento et al. (2010) currently there exist only 172 charcoal-BFs operating in Brazil, they remain as the last charcoal-BF operating in the world [125].

^{xviii} without any steel-making plant attached to the production facility

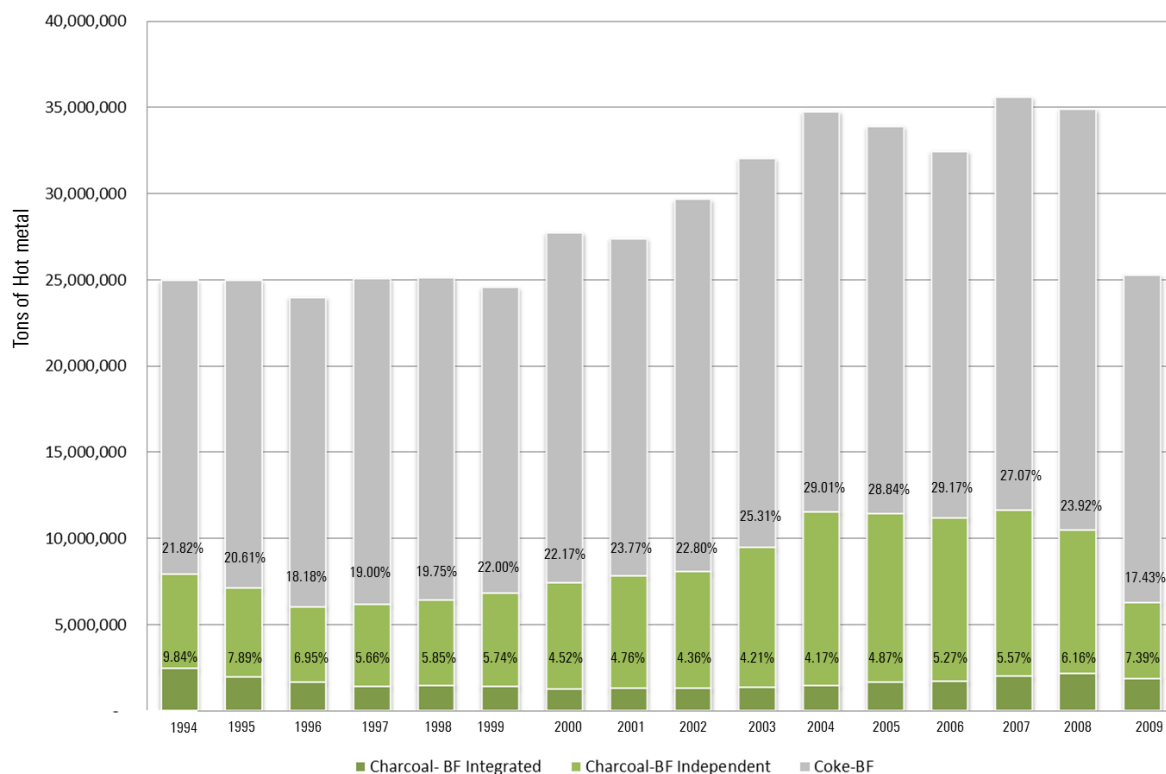


Figure 27. Historical output of charcoal and coke-based BF in Brazil (1994-2009)
Source: Winter et al. (2012)



Figure 28. Principal states of charcoal-ironmaking in Brazil

Table 23. Installed capacity and number of charcoal-BF in the different states of Brazil.

State	Installed Capacity MMt/yr	Charcoal-BF No.
MARANHÃO	1.87	19
PARÁ	2.72	24
MINAS GERAIS	7.52	106
ESPIRITO SANTO	0.45	5
MATO GROSSO DO SUL	0.80	6
BF IN INTEGRATED STEEL PLANT	2.50	12
GENERAL TOTAL	15.86	172

The HM output gained in charcoal-BF represents less than 0.01 % of the total global HM production (see **Figure 29** and **Figure 30**). While the output of charcoal-BF is of little significance to the global trade of pig iron (the common name used by merchants of iron or HM), its CO₂ mitigation potential attracts the attention of many researchers worldwide, as a feasible source for reducing the GHG emissions in the process.

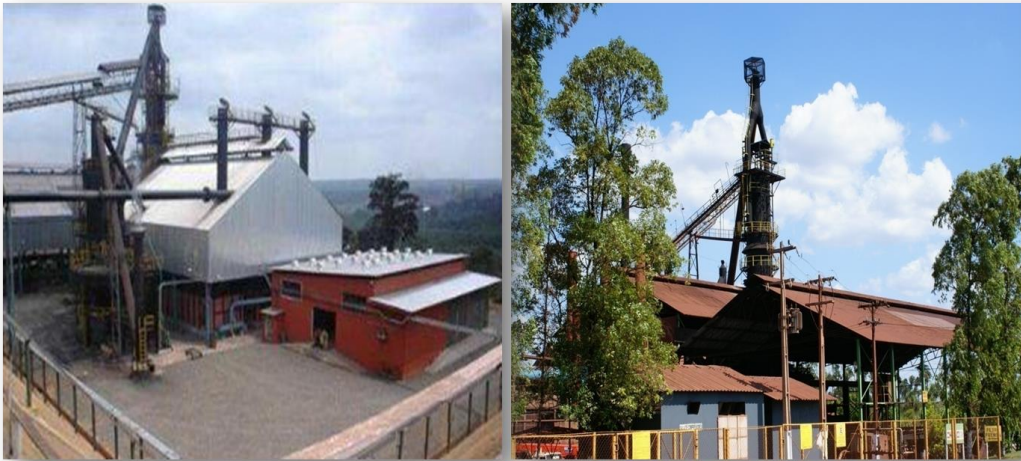


Figure 29. Charcoal-BF: Siderúrgica Viena (left) and Queiroz Galvão Siderurgia (right), Açailândia, Brazil
Source: Valladares and Scherer (2012).



Figure 30. Charcoal- hot metal: ingot casting (left), *ferro gusa* or pig iron (right)
Source: Valladares and Scherer (2012).

In Brazil, many iron producers such as Vallourec & Mannesmann, APERAM, ArcelorMittal, Gerdau, Plantar, Queiroz Galvão, Viena, among others, have their own plantation and production of charcoal to feed their BF's.

The following section describes the difference between coke-BF and charcoal-BF.

2.6. Fundamentals of processes: coke-BF and charcoal-BF

In addition to the alleged carbon neutrality of charcoal-BF, there are significant differences between the operation of a coke-BF and a charcoal-BF. The first and principal difference is the quality of the iron, based largely on the differences in sulfur content. **Table 4** shows some of the principal qualities of HM in Brazil. Charcoal-HM is a product with low sulfur content, 0.006–0.008 % in comparison to 0.02–0.045 % of HM gained in a coke-BF. Therefore, HM smelted in a charcoal-BF is beneficial for steel plants and foundries. In the case of steel, the low sulfur content reduces the refining in stages of secondary metallurgy, for instance in seamless pipe production (Miranda 2012) [122]. In foundries, it is preferable to work with low sulfur hot metal to produce nodular casting with magnesia^{xix}. Thus the charcoal-HM has a market for the production of high value products in Brazil, for instance foundries and seamless pipes.

The operation of the charcoal- and coke BF also present several differences. **Figure 31** schematically contrasts the normal production parameters of these processes (after Pfeifer et al. 2012) [39]. First, the working volumes and production capacities are significantly different in the case of coke- and charcoal-BF. With the charcoal-BF, the volume varies between 30–550 m³, with consequent production rates of 20–450 TMt/year. In an investigation by Assis et al. (1995), it is reported that the utilization of iron ore pellets, instead of lump ore, may increase the productivity in charcoal-BFs [123]. However, modern coke-BF exceeds 450 m³. New coke-BF can be greater than 5.000 m³ with production capacities higher than 1.000 TMt/year (see **Figure 31**), thus the production of 1 single large coke-BF significantly outreaches the production of the largest charcoal-BF.

As depicted in **Figure 31**, because the charcoal-BFs work with a higher volume of reductant (gray stripes in **Figure 31**) and lower volume of ore (white stripes in **Figure 31**), such a burden of distribution leads simultaneously to positive and negative effects. On the negative side, the fast reaction of charcoal may produce a rapid decrease in particle size; this diminishes the permeability of gases in the shaft. Additionally charcoal-BF presents a lower productivity rate. In APERAM, BF 2 changed from coke to charcoal. This change led to a reduction in the HM output of between 1.500 tpd (coke-based) and 1.300 tpd (charcoal-based) (Gonçalves et al. 2012).

^{xix} Sulfur in cast iron foments the cementite formation (metastable crystallization), which leads to contraction problems during solidification and segregation of graphite.

On the negative side, the iron sources (like lump ore, sinter or pellets) has a lower residence time in the Charcoal HM BF, due to the lower density of the fuel used. Additionally due to the high reactivity of the carbon (in the charcoal), then it is expected that the iron ore residence time in the preparation zone will be much more less (compared to HM Coke BF), giving then a higher consumption of carbon in the lower zone of the BF.

The high velocity of reactions of charcoal is linked to its larger specific surface in comparison to coal. In measurements carried out by Ng et al. (2012) [124], it was revealed that charcoal has a specific area of 155 m²/g, while coal has 89 m²/g. The specific area of charcoal originates from the cellular structure of the woody biomass during the carbonization process and leads to a rapid combustion in comparison to coke.

Description	Unit	Charcoal (154 BF) Typical values
Working volume	m3	30 to 550
Production	Kt/a	20 to 500
Cfix	%	75
Volatile matter	%	24
Ashes	%	1
Compression resistance	Kg/cm2	10 to 50
Reductant consumption	Kg/t HM	570 to 700
Pulverized coal injection	Kg/t HM	100 to 200
Blast temperature	°C	600 to 1100
HM temperature	°C	1300 to 1400
Sulfur in HM	%	0,06 to 0,08

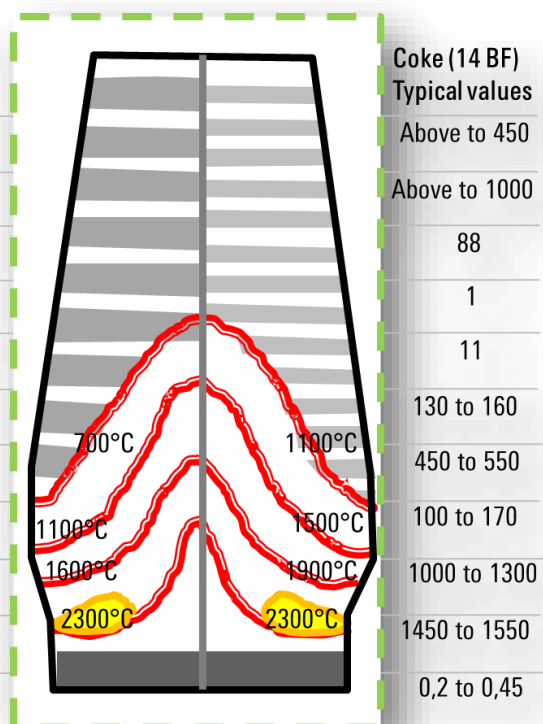


Figure 31. Principal differences between charcoal-based and coke-based BFs
Source: Pfeifer et al. (2012)

The BFs at APERAM^{xx} can clearly illustrate the operational differences between charcoal-BF and coke-BF (Gonçalves et al. 2012); see table 24. In 2012, BF 1 operated with charcoal and BF 2 operated with coke. From its operation parameters, there are important differences in

^{xx} For more information about APERAM, it is recommend to visit the web page: <http://www.aperam.com/>

terms of slag generation and sulfur content. Coke-based operation generates up to 250 kg slag/t HM, while charcoal-based BF produces only 160 kg slag/t HM (see **Table 24**).

Table 24. Processing parameters of BF1 (charcoal-BF) and BF2 (coke-BF) at APERAM
Source: Gonçalves et al. (2012)

BF	Reductant	Working Volume	Top Charge	Bio-PCI	Total Reductant use	Total Carbon use	HM Temp	HM Si	HM S	Slag Volume	SiO ₂	CaO	MgO	Al ₂ O ₃
No.		m ³	kg/t HM	kg/t HM	kg/t HM	kg/t HM	°C	%	%	kg/t HM	%	%	%	%
1	Charcoal	317	416	197	623	414*	1400	0.65	0.004	160	42.0	33.0	8.5	12.0
2	Coke	568	366	204	578	446*	1480	0.45	0.080	250	36.0	43.0	7.0	12.0

*Estimated under the assumption of charcoal composition of C: 70 %, coke C: 88 % and Bio-PCI C: 66 %

Additionally, charcoal-BF operation works with a temperature of 100–150°C lower than coke-BF, due to the lower heat losses and less refractory wear (Gonçalves et al. 2012). Furthermore, charcoal-based BF operates with up to 50% less slag volume, which reduces the energy consumption for the slag melting.

According to Nascimento et al. (2007) [125], there are in Brazil (2007) a total of 172 charcoal-BF with a production capacity of 100 to 500 t HM /day. To fuel these aggregates, in 2005 the Brazilian industrial sector consumed 8.7 Mt of charcoal, representing 90.5 % of total demand of charcoal in Brazil (Nogueira et al. 2007), the figure 32 shows the historical relationship between charcoal and charcoal-hot metal production [118].

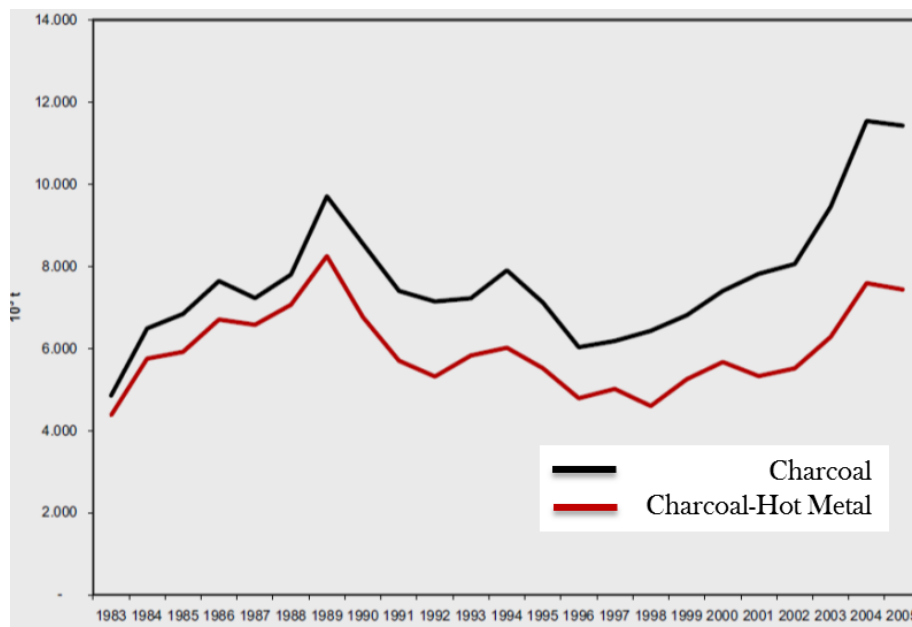


Figure 32. Charcoal Hot Metal production and charcoal consumption in Brazil (1983–2005).
Source Nogueira et al. (2007)

Previous industrial experiences in Australia, Paraguay and the former U.S.S.R. have proven the technical feasibility of charcoal utilization; however, biomass char use has been limited principally due the lack of mechanical resistance to support the burden and the cost of biomass and charcoal.

In summary, the charcoal-BFs present significant technical advantages (compared to a coke-BF), for instance low sulfur content in the HM and lesser slag generation. However, the low production capacity of charcoal-BF represents a major disadvantage to the further proliferation of biomass char in ironmaking. Additionally in the further sections, the critical aspects of the handling and the economic challenges of charcoal-ironmaking will be addressed.

2.6.1. Technical aspects of biomass char use in blast furnaces

The literature reports some technical limitations associated with the utilization of biomass char in BF. The most critical issues are mainly the poor mechanical resistance, low bulk density and transportation issues. In the following sections, these problems will be addressed.

2.6.1.1. Mechanical resistance

As mentioned, the development of the cokemaking process by Darby resulted in an increase in the dimensions of the BF shaft, basically due to the better mechanical resistance of coke. This consequently increased the production output. During the cokemaking, the product considerably increases its crushing resistance, which is fundamental to the mechanical support of the burden. Additionally as coke is hard and dense, its combustion is relatively slow without losing crushing resistance, which helps to support the burden and maintain an optimal permeability of gas flows.

Table 25. Properties of coke and charcoal
Source: Gupta (2003)

Properties	Fixed carbon	Volatile matter	Ash	Moisture	Sulfur	Phosphor	Calorific value	Bulk density (dry)	Size	Crushing strength
Unit	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	kcal/kg	kg/m ³	mm	N/mm ²
Charcoal	> 70	20-25	3	10	Nil	0.08	6800-7200	230-260	10-50	30-40
Coke	85-88	1-3	> 10	2-4	0.7-1.2	0.01-0.03	6500-7200	400-500	50-80	100-150

As shown in **Figure 31** (Pfeiffer et al. 2012), the compression resistance (CR) of charcoal is 1–5 N/mm², while coke exhibits CR values of 10–15 N/mm². While the results reported by Gupta (2003) and Pfeiffer et al. (2012) considerably differ, they both show a marked difference between the mechanical resistance of coke and charcoal. At the time of writing, the largest charcoal-BF at APERAM has a working volume of 568 m³, while the largest coke-BF is BF 1 at POSCO (Korea) with 6.000 m³ [43]. This is a significant difference in working volume is determined by the mechanical resistances of charcoal and coke. The figure 33 shows the different sizes of charcoal used in BF in Brazil.



Figure 33. Sizes of charcoal used in Brazil

2.6.1.2. Density

Charcoal has a relatively low density in comparison to coke. The bulk densities found by Gupta (2003) for charcoal are 230–260 kg/m³, while coke is 400–500 kg/m³ [87], this is generated by the microstructure of each material (see figure **Figure 34**). In consequence, a charcoal-BF has less available working volume in its operation than a coke-based BF, as depicted in **Figure 31**. Nevertheless this element is complemented by the relatively higher reaction capacity of a charcoal-BF in comparison to a coke-based BF.

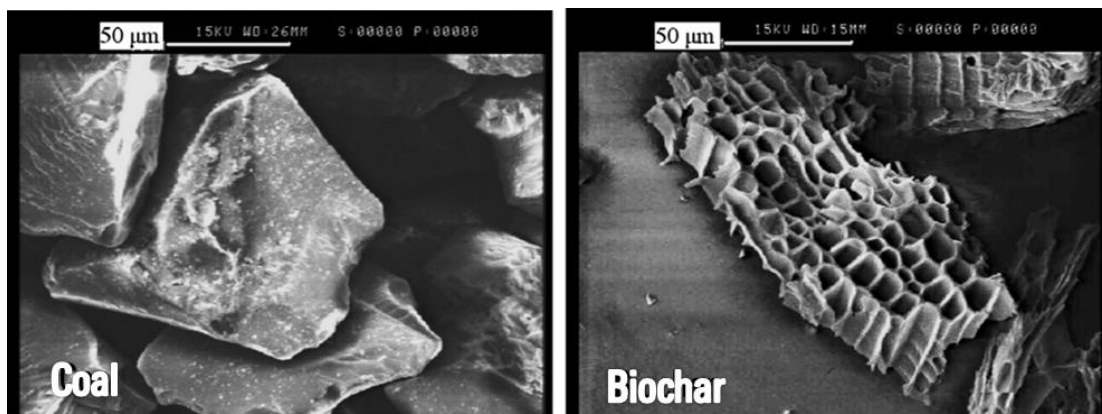


Figure 34. Microstructure of coal (right) and biochar (left).
Source: Babich et al. (2010)

2.6.1.3. Transport issues

The problems related to transport are highly interlinked with the low mechanical resistance and density of charcoal. In contrast to coke, when charcoal degrades, it generates high amounts of fines and dust. Moreover, it is highly hygroscopic, and their pieces have a tendency to absorb humidity. The low density of charcoal is not only a technical problem but also reduces its commercial attractiveness for international trade because the freight costs are relatively high due to the lower bulk density. Additionally, in APERAM (Brazil), it has been reported some issue during the transport of charcoal, because of its high reactivity and spontaneous combustion in the transport and storage bins (Gonçalves et al. 2012) [15].

In the case of using charcoal for tuyere injection in BF's, a study in the Australian company BlueScope Steel shows that its relatively low density makes it difficult to pneumatically convey the small particles of charcoal through the PCI rigs (Mathieson et al. 2012) [126].

2.7. Future prospects of biomass char injection in blast furnaces and other uses

The potential to mitigate the CO₂ footprint in the whole steelmaking process has motivated the investigation of biomass and biochar in diverse uses. As illustrated in the **Figure 35**, there are several potential applications for biomass char in iron and steel production [127], for instance as steel recarburiser (Mathieson 2010; Somerville et al. 2011; Somerville et al. 2010) [128,129,130], as cokemaking blend component (McPhee et al. 2009)[21], as BF pre-reduced composite (Ueda et al. 2009, Matsui et al. 2009, Lucena et al. 2008, Ohno et al. 2012) [18,19,

20,131], as bio-syngas or bio-SNG as fuel in BF or in reheating furnaces^{XXI} (Assis et al. 2011; Johansson 2014) [132,133], as coke replacement (Assis et al. 2007; Lucena et al. 2008) [20,134], as fuel for sintering and as BF tuyere injectant (also known as Bio-PCI) (Suopajarvi and Fabritius 2012; Babich et al. 2010; Mathieson 2010; Ueda et al. 2009; Ueda and Ariyama 2008; Machado et al. 2009)[27,35,135,136,137,138,139].

In 2006 the Australian steel industry and CSIRO initiated an ambitious research agenda to reduce the industry's net greenhouse gas emission by at least 50 % (Jahanshahi et al. 2014) [140], this is shown in Figure 35; to achieve this worthy goal biomass utilization is a key focus of this program. As part of the research agenda, **Figure 36** presents an estimate made by Mathieson et al. (2011) [141] concerning the potential CO₂ mitigation of different charcoal applications in steelmaking.

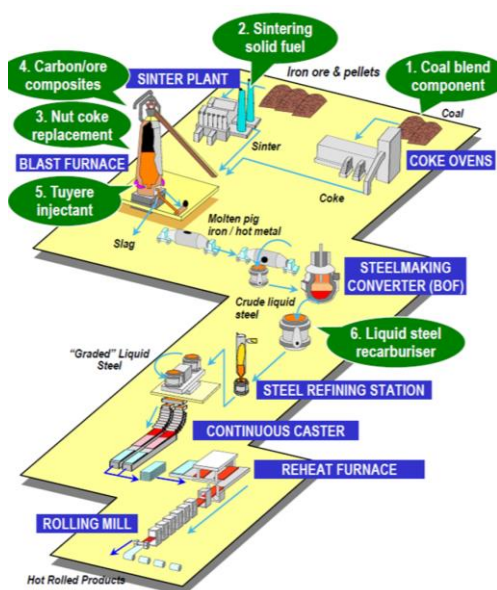


Figure 35. Potential areas of applications for biomass char in the iron and steel production.
Source: Jahanshahi et al. (2013)

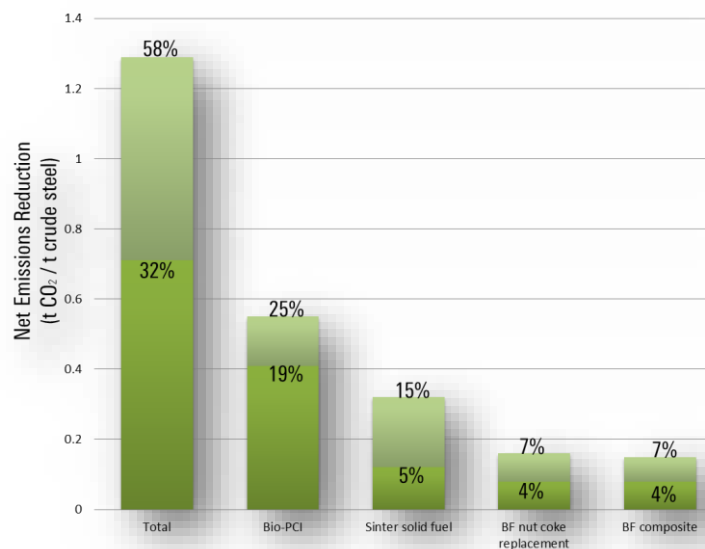


Figure 36. Net emissions reduction by diverse proposed applications for charcoal.
After: Mathieson et al. (2011)

The Bio-PCI route is quite similar to the well-established PCI technology outlined in the previous chapter. This work defines Bio-PCI as the injection of pulverized biomass char

^{XXI} According to Johansson, this option requires some modifications at the steel plant, e.g. burners designed for low-calorific gases, gas distribution systems with larger dimensions and exhaust gas cleaning systems dimensioned for larger gas flows.

through the PCI rigs of sustainable origin in place of fossil coal, which is commonly used in coke-BF, the author uses the term Bio-PCI, to emphasize the biological and renewable nature of the carbon to be injected using the PCI rigs in BF. The basic and key difference is the utilization of a renewable and sustainable carbon source instead of traditional fossil fuels: coal, coke fines, oil or natural gas. The fundamental aim of biomass injection or Bio-PCI is to mitigate the CO₂ emissions of the ironmaking process in BFs (Assis 2008) [54]. In this respect, there is a consensus in the literature about the potential CO₂ saving of biomass utilization in steelmaking, for instance Norgate and Langberg (2009)[25] using a Life Cycle Analysis assessed the potential of CO₂ mitigation in integrated steel processing in 4.5 kg CO₂/kg steel based on a complete fossil fuel substitution by renewable charcoal. While, Mathieson (2010) estimated the net emissions saved with the implementation of Bio-PCI at between 0.4-0.6 t-CO₂/t crude steel (19–25%). In another study by Suopajarvi and Fabritius (2012) [27], it was estimated using gate-to-gate life cycle inventories, the effect of biomass use in a plant site scale with energy balances and CO₂ reduction potential. The findings showed that 15.4 to 26.4 % reduction in fossil CO₂ emissions could be achieved by the use of biomass as auxiliary fuel. Additionally, Hanrot et al. (2009) [142] calculated the mitigation potential in 28 % with a 200 kg Bio-PCI /t HM, while Wang et al. 2015 also estimated that a reduction potential of 28.1 % reduction in on-site emissions is possible by injecting charcoal as auxiliary fuel [143].Gielen and Moriguchi (2002) in an analysis of the CO₂ reduction potential in the Japanese Steel industry argue that it is possible to substitute BF coal injection by charcoal injection [144]. However, at the time of writing of this work, little peer-reviewed information could be found about the CO₂ mitigation potential as a function of the Bio-PCI utilization rate. The author also considers it important to assess the CO₂ reduction potential of Bio-PCI in coke-BFs.

In the literature, several investigations argue that the injection of pulverized charcoal particles into the blast furnace may be a feasible and sustainable initiative to improve sustainability of iron- and steelmaking. For instance in a review of the prospects of woodchar in steelmaking, Gupta (2003) discusses that relatively low mechanical properties of biomass char become redundant when charcoal is used for tuyere injection in large BFs. Also, Norgate and Langberg (2009), in a complete assessment of the CO₂ reduction potential of charcoal in steelmaking, mention that the injection of charcoal as a feasible option in BFs^{xxii}. Additionally, Ueda et al.

^{xxii} Norgate and Langberg additionally mention that charcoal can be used in electric steel mills as recarburizer in the steel and contribute to slag foaming to reduce fuel consumption (in EAFs).

(2009) in an analysis of the reactivity of biomass chars carbonized at various temperatures also demonstrated the potential use of charcoal auxiliary fuel for BF injection. While, Hanrot et al. (2009), in a research to assess the efficiency of biomass and plastic waste in cokemaking and BF process, determined that from the analyzed criteria the optimum CO₂ reduction would be obtained with the injection of biomass chars [87].

The idea of Bio-PCI is consistent with the traditional PCI, as biochar particles have to be ground to a size of approximately 75 µm, dried and pneumatically conveyed into the shaft using the PCI rigs. The Bio-PCI is in theory not only plausible, but also would bring the following benefits to the process:

- *Lower impurity content:* Sulfur is among the most critical impurities in iron and steel. Its presence should be minimized as this element brittles the crystallographic structure leading to problems during solid state forming. In charcoal (compared to coke) the content of this harmful element is substantially lesser, resulting in a better quality of HM [120]. Former operations in Wundowie (Australia) reported sulfur contents of 0.015 % (FAO 1983) [145], whereas in ACEPAR (Paraguay) HM present a composition of 0.03 % of sulfur respectively. The literature review of the present work could not find any estimate of the effect of Bio-PCI over the sulfur content or the impact over the HM chemical composition in a coke-BF.
- *Ash and volatile content:* In modern retort kilns the content of volatiles and ash can be controlled to match the needs of metallurgists. As shown in **Table 26**, the ash content in biochar can be lower than in coke; moreover In Brazil charcoal-BFs generates less than a half slag of coke-BF (Nogami et al. 2004) [146], in consequence it is estimated that the injection of charcoal may also result in lesser slag generation. Nonetheless, at the time of writing this dissertation, this aspect has not been assessed or reported in the literature. As illustrated in **Table 21**, the ash content depends greatly on the feedstock species. For instance in rice hulls ash content can be 41.34 %, while in pine woods the ash is only 0.69 % (Antal and Gronli, 2003). As a general rule, charcoal for metallurgical applications should possess as low ash content as possible. A report of FAO (1983) on charcoal utilization on BF indicates that the optimum range of ash content should be 0.24-1.5 %. This provides more available heat and less slag in the process (<120 kg/thm) (Gupta 2003) [87].

Table 26. Chemical composition of the ashes in charcoal and metallurgical coke
Source: Gupta (2003)

Properties	Unit	Biochar	Coke
Ash composition			
SiO ₂	Wt. %	15-25	40-50
CaO	Wt. %	25-35	2-10
Al ₂ O ₃	Wt. %	2-4	30-35
Fe ₂ O ₃	Wt. %	3-5	8-13
MgO	Wt. %	6-7	1-2
Alkalis K ₂ O	Wt. %	10-15	0.6
Na ₂ O	Wt. %	1-2	0.4
CaO/SiO ₂	Wt. %	1.3-1.5	0-0.25

- *High reactivity:* Biomass chars normally present high porosity. This increases the specific area of the reductant enabling the combustion. In a series of investigations Ueda and Ariyama (2008) [136] and Ueda et al. (2008; 2009)^l investigated the velocity of combustion of samples of coke, pulverized coal (PC) and biomass char carbonized at 300°C and 500°C. The results are shown in Figure 37, indicating that charcoal and PC react at the same velocity, 250 msec. Thus it was inferred that their combustion behavior in the raceway should be similar. These results are in agreement with those of Machado et al. (2010) [147] and Mathieson et al. (2011) [26], in which the combustion performance of the softwood charcoal appears to be significantly greater than those of the hardwood charcoals. Moreover, the high kinetics in the reaction has been also demonstrated by Babich et al. (2010) [35].

In contrast to biochar, coke took much longer to react. Narita et al. (2011) [148] on a study of the kinetics of charcoal from eucalyptus, could not detect any significant difference in the velocity of reduction between samples carbonized at different temperatures, this proves that the injection of biomass char can react in a similar velocity (or even faster) than the commonly used coal as auxiliary fuel.

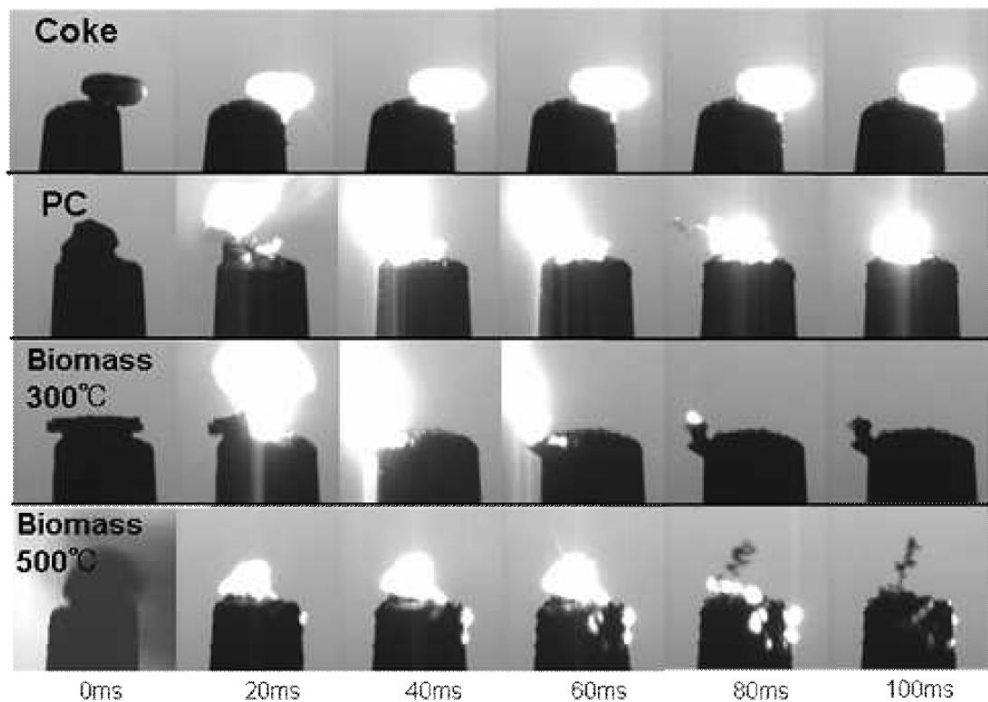


Figure 37. High-speed photograph of pulverized coal and biomass char derived biomass under combustion by Laser heating
Source: Ueda et al. 2009

- *Use of residual biomass for carbonization:* Chen et al. (2012) [28,29] analyzed the torrefaction and burning characteristics of bamboo, palm oil, rice husk, bagasse, and Madagascar almond. At the torrefaction^{xxiii} temperature of 300°C (Topell Energy 2015) [149], it is feasible to transform biomass into an alternative fuel consumed in BFs. In another study, Assis et al. (2014) simulated the feasibility of using residual biomass, such as rice husk, sugar cane bagasse, elephant grass, coffee husk, and eucalyptus bark, as Bio-PCI. Using physical modelling Assis et al. concluded that using biomass char from agricultural waste, it can reduce the specific carbon consumption in the BF burden [150]. Another study by Oliveira et al. (2015) has shown the potential of secondary biomass in EAFs [151].
- *Economic perspectives of Bio-PCI:* While numerous researches build on the technical aspects of biochar production and its further injection in BF, few peer-reviewed articles focus on the economic prospects of Bio-PCI and its impact over the HM production

^{xxiii} According to Topell Energy (2015), Torrefaction is a thermal process that involves heating the biomass to temperatures between 250 and 300 C in an inert atmosphere. At such temperatures, the water evaporates and various low-calorific components contained in the biomass are volatilized. During torrefaction the hemi-cellulose in the biomass decomposes into a product with improved fuel characteristics.

cost (which is the object of this thesis). An initial economic assessment based on an industrial-scale trial has been presented by Mathieson et al. (2007; 2011; 2012) [26,126,137]. This work carried out in Blue Scope (Australia) was based on a Value-In-Use (VIU) methodology and compared diverse fuel elements in the BF. In his assessment Mathieson concluded 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]. This then would lead us to assess the economic impact of Bio-PCI in different coke-BFs.

2.7.1.1. Industrial experiences with Bio-PCI

As mentioned before, the idea of a Bio-PCI is a practical initiative to offset CO₂ emission in the ironmaking process. There is an extensive literature concerning the technical feature of charcoal production and possible utilization, which is summarized in the preceding sections. Up to the present, 46 charcoal-BFs are reported to be actually injecting biomass char. However, there is little scholarly information available on the industrial experiences of Bio-PCI.

According to Luchese (2010)^{XXIV} the first charcoal injection in BF began in Brazil more than 20 years ago [16]. In charcoal-BFs with production ranging from 300–1000 t HM/day, the main objective in these cases was to reduce the use of expensive lump charcoal. As shown in **Table 27**, in small independent producers, the injection rate is limited to 60–100 kg/t HM, due to the lack of availability of O₂ for hot blast enrichment. In large iron plants (normally attached to steel plants) the injection rate can reach 160 kg/t HM, because of the oxygen enrichment in hot blast.

Additionally, Nascimento et al. (2010) [125] presented a paper on the first 18 months of operation of a charcoal fine injection system in the blast furnaces at **Gusa Nordeste**. Working capacities are BF 1 155 m³, BF2 and BF3 163 m³ with an average productivity 2.0 t/d/m³. **Figure 38** shows the installations of the Bio-PCI at Gusa Nodeste: process silo, pneumatic injector and control room. In the plant fines of charcoal of less than 6 mm from the screening process,

^{XXIV} Ricardo Luchese is a independent ironmaking advisor in Brazil

commonly known as *moinha*^{XXV} in Portuguese, are injected. Traditionally the *moinhas* are products of low market value and were sold to cement producers. Thus this was an efficient use for the otherwise unutilized particles.

Table 27. List of companies using charcoal injection in Brazil

Company name	State Brazil	Number of BF	Minimum injection rate kg/t HM	Maximum injection rate kg/t HM	O ₂ enrichment in hot blast
Vallourec Mannesmann	MG	2	130	160	yes
ArceloMital - Juiz de Fora	MG	2	90	120	yes
Gerdau - Barao Cocais	MG	2	90	110	yes
Gerdau - Divinopolis	MG	3	90	110	yes
Gerdau - Sete Lagoas	MG	2	50	70	no
Aperan ArcelorMital	MG	2	130	160	yes
Viena	MA	4	50	70	no
Pindare	MA	3	80	100	yes
Guarany	MA	1	80	100	yes
Gusa Nordeste	MA	2	50	70	no
Sidepar	PA	3	50	70	no
Cosipar	PA	4	50	70	no
Margusa	MA	2	70	90	no
Cisam	MG	1	50	70	no
Alterosa	MG	2	80	100	yes
Sidersa	MG	1	50	70	no
Plantar	MG	2	80	100	yes
Vetorial - RRP	MS	2	50	70	no
Vetorial - Corumba	MS	2	50	70	no
Sidersul	MS	1	50	70	no
CBF - Joao Neiva	ES	2	80	100	yes
Santa Barbara	ES	1	50	70	no
Saint Gobain *	RJ	1			no
VDL *	MG	1			no

Total No BF

48

State: MG= Minas Gerais, ES= Espiritu Santo, MG= Mato Grosso, RJ= Rio de Janeiro, PA= Para, MA= Maranhão

* under construction

According to Melo (2012), in Brazil the high injection rate of biomass char in charcoal-BFs lead to reduce the consumption of lump pieces of charcoal. Therefore, the use charcoal fines (a by product of charcoal grinding) ultimately contributes to lesser eucalyptus plantations areas [105].

^{XXV} The term is used to refer charcoal fines in Brazil



Figure 38. View of the Bio-PCI installation at Gusa Nordeste
Source Nascimento et al. (2007)

From the production viewpoint, at Gusa Nordeste consistent results have been observed during the first months of operation and injection rates reached values of 40–75 kg/t HM, without hot blast oxygen enrichment (see Figure 39). As in other charcoal-BF, results in Gusa Nordeste demonstrate that the replacement rate^{xxvi} achieved is 1 kg charcoal fines injection in tuyere region by 1 kg charcoal granulated by top.

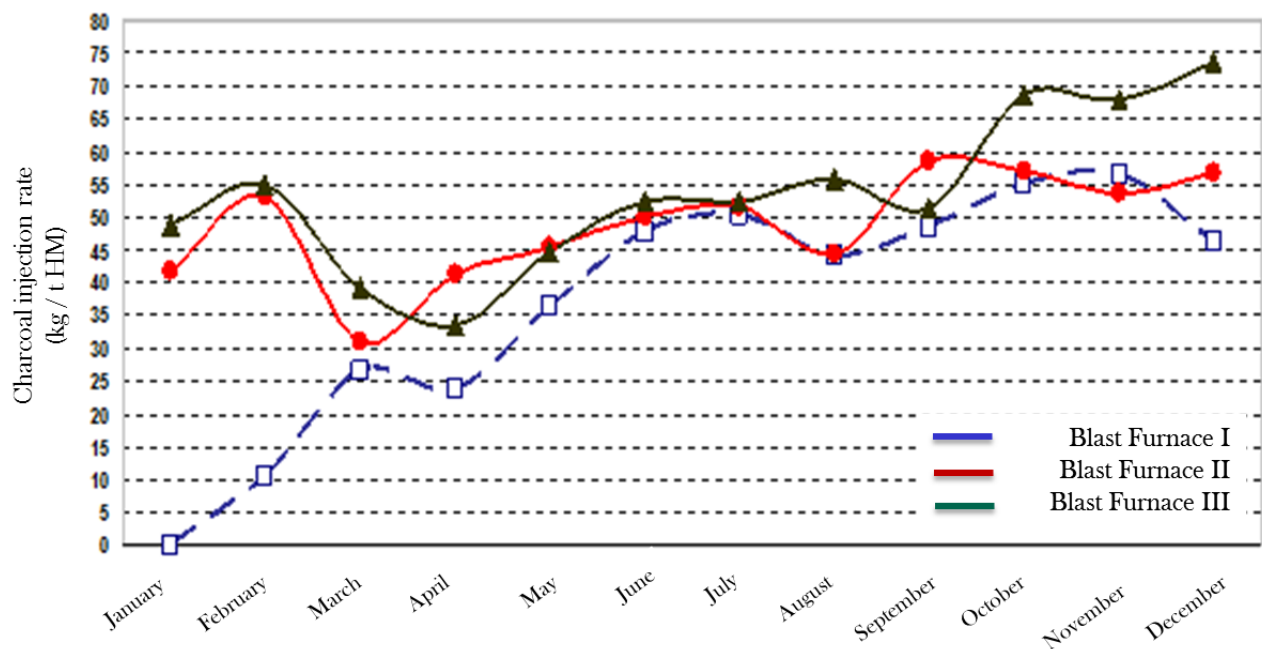


Figure 39. Charcoal injection rate at Gusa Nordeste in 2007
Source Nascimento et al. (2007)

^{xxvi} Replacement rate: substitute of coke or charcoal charged from top

From an industrial perspective, it is important to mention other conclusions obtained from the Gusa Nordeste experience (Nascimento et al. 2007):

- Bio-PCI unit proved to be simple to operate, and expected charcoal fines injection were attained in one month of operation without any loss of productivity.
- Bio-PCI helped to improve the thermal stability of the furnaces.
- There was return of the investment within first year of operation.

To the best of the author's knowledge, BF 2 at APERAM is a unique example where a charcoal-BF was converted into a coke-BF, in 2007 (Gonçalves, 2012). The BF 2 changed from using 171 kg coal /t HM (average), to using 160 kg charcoal /t HM. The Figure 40 shows the different Bio-PCI and PCI injection rates at Aperam.

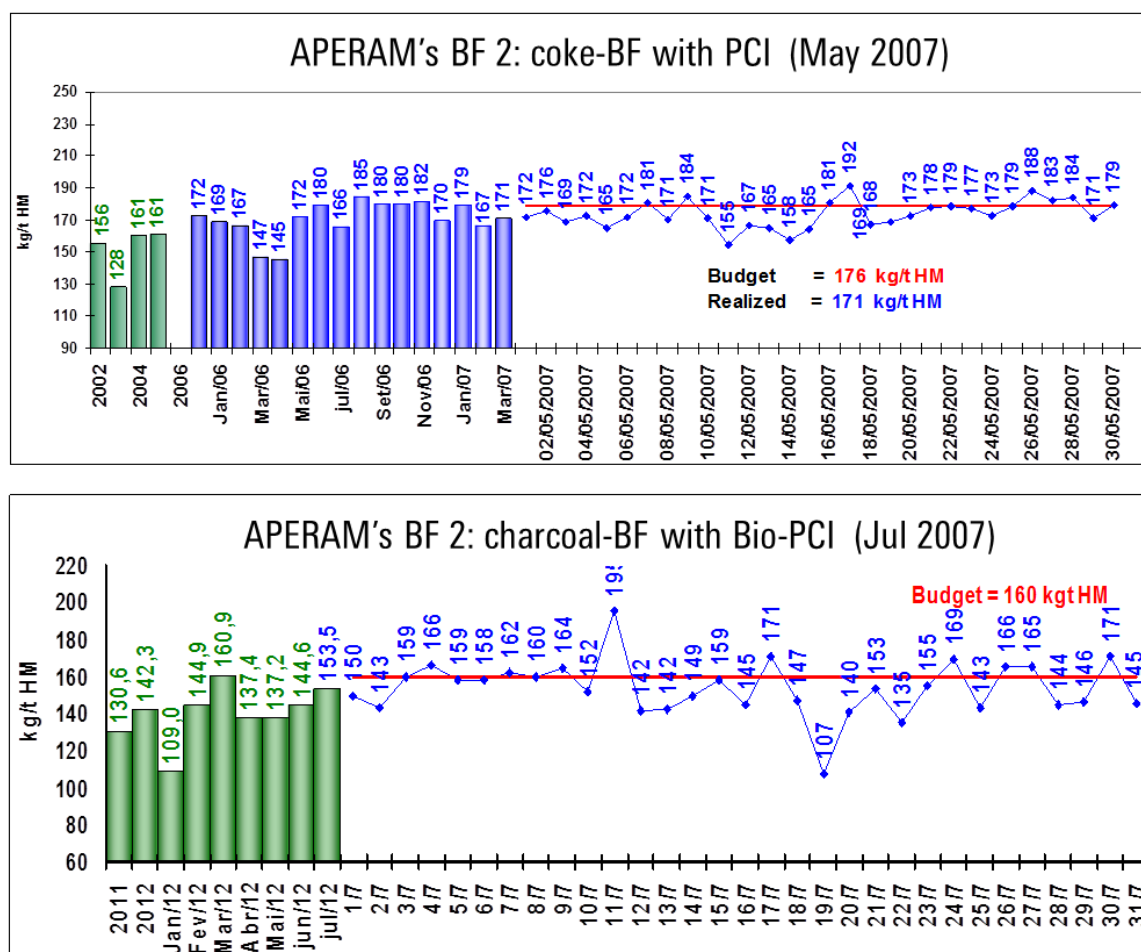


Figure 40. Bio-PCI and PCI injection rate at Aperam
Source Gonçalves (2012)

In another interesting experience at Voestalpine, Bürgler et al. (2011) reported an industrial trial carried out in the coke-BF A, in which biomass pellets were injected as auxiliary fuel at a rate of 20-30 kg/tHM. No significant problem was reported in the trial [152]. These industrial applications demonstrate that Bio-PCI is an industrially viable option. To summarize the main technical advantages the biomass char injection can significantly reduce the CO₂ emissions in the BF process, assist to reduce the amount of sulfur in the HM and decrease the slag generation. The next section discusses the limitations reported in the literature.

2.7.1.2. Limitations to Bio-PCI

Along with the technical advantages, there are some practical limitations to biochar injection. Firstly it possesses lesser heating value than normal coal, due to the relatively higher amount of oxygen compared to coal; however this could be partially adjusted with an increase in temperature or pressure during the carbonization (Ueda et al. 2009) [18]. Secondly, as it was shown before, one of the main tasks of coke in the BF is to support the burden and permit the counter flow of reductant gases through the shaft. In this sense the low crushing strength of charcoal does not allow a complete substitution (see **Table 25**). Therefore the maximum injectable value of Bio-PCI in the BF is similar to normal PCI from fossil sources, 100–220 kg_{PCI}/t_{Hot_Metal} (Peter and Lünen 2009) [153]. Similarly to traditional PCI, when biomass char is injected it is recommended to enrich the oxygen content of the hot blast to improve efficiency (Hanrot et al. 2009) [142].

2.7.2. Biomass char in sintering

Another interesting use of the charcoal fines, generated during the screening process, is in the sintering process of iron ores, which is currently the second most energy-intensive process in the manufacture of steel. The process of sintering can be defined as “the agglomeration of fine mineral particles into a porous mass by incipient fusion caused by heat produced by combustion within the mass itself” (Bashforth, 1964) [154].

In Brazil the *moinhas* may be used as fuel in the sinter plant, and according to Mr Pfeifer, Managing Director of MINITEC^{XXVII}, [155] the sintering is also becoming more popular, as good quality lump ore is scarce in Brazil.

Normally the reaction of coke during the sintering process leads to the generation of SO_x and NO_x emissions. Biomass char appears to be an attractive carbon source. According to Lovel et al. (2004) [156] charcoal can outperform coke in many aspects of iron ore sintering with reduced SO_x and NO_x emissions, while other studies in the literature support the environmental benefits of charcoal utilization in iron ore sintering (Zandi et al. 2010, Gan et al. 2012, Dell'Amico et al. 2004) [157,158,159]. Mathieson et al. estimated the potential CO₂ mitigation of biomass char use in sintering as 5–15 % (2013).

From an industrial perspective, according to Luchese (2015) currently in Brazil, charcoal fines are already being used as fuel in the process of iron ore sintering at the iron mills of Viena, Sidepar and Cosipar. According to this information, biomass char fines are presently in active use in Brazil [16].

^{XXVII} MINITEC is an engineering company from Brazil, which works with most of charcoal-BFs, for more information about the company visit the web page: www.minitec.eng.br

2.8. Economic aspects of biomass char utilization in ironmaking

According to the statistics of Steelonthenet (2013) in Integrated Steel Plants in USA, the principal cost involved in steel production are iron ore (42.8 %), coking coal (23.6 %) and steel scrap (11.24 %) [160]. The total cost distribution is shown in Figure 41. This cost includes the materials utilized in the whole plant, from BF, cokemaking and rolling mill. According to this assessment, fuel (represented by coking coal) is the second major cost in the steel production in integrated mills.

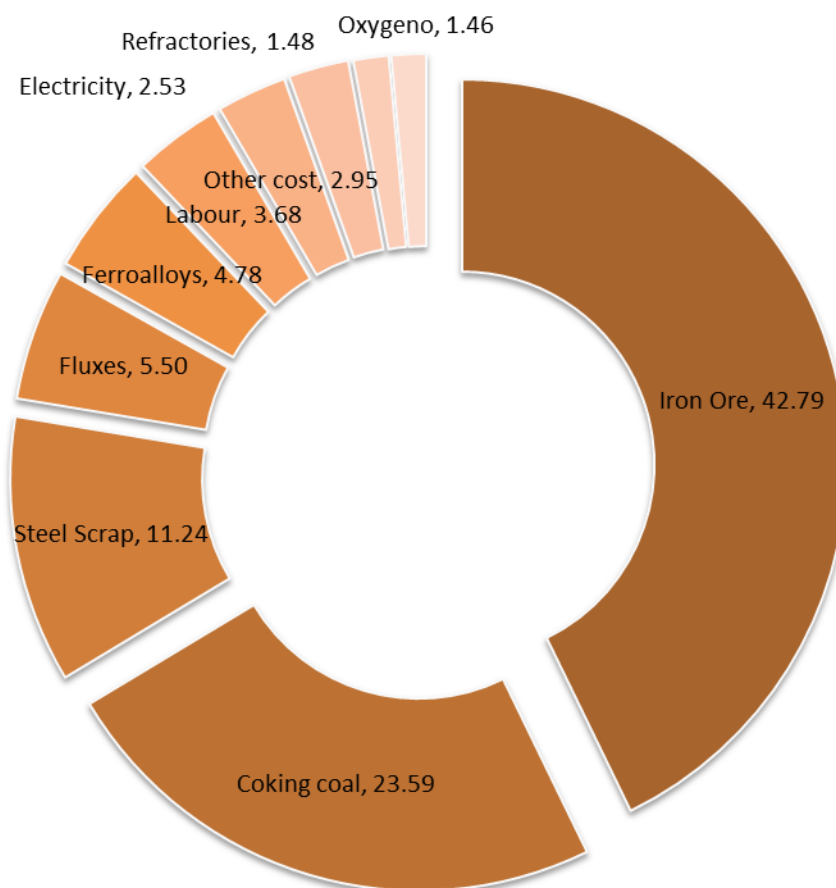


Figure 41. Integrated steelmaking – crude steel cost model 2011
Source: Steel on the net

Figure 41 portrays the main production cost in the USA. Arguably some costs such as labour and electricity may have a larger or lower influence according to the country of production, but worldwide the highest cost for integrated steelmakers are iron ore and coking coal. Therefore,

any increase in the price of fuel has significant implications over the production cost of steel. The cost of fuels has driven the necessity to increase energy efficiency.

Previously it was argued that the utilization of biochar and Bio-PCI in blast furnaces may bring technical benefits and would improve the sustainability of the whole ironmaking process. However, in the opinion of the author, the deployment and establishment of this technology is being hindered by economic factors, principally the difference in costs between biochar and coke. Traditionally the price of biochar has been more expensive than fossil based fuels – because the fossil fuels do not carry their external costs in their price^{xxviii}. In the next sections, the economic aspects of biomass in BFs will be addressed.

2.8.1. Production cost of biomass char

With respect to the cost structure of charcoal production, the unit cost can be separated by using the cost centers of various systems (FAO, 1987):

- The cost of biomass placed at the side of the pyrolysis aggregate (i.e. kiln, pit or retort) including financial costs.
- Carbonization labor costs, including loading and unloading.
- Cost of transport of charcoal to major markets or distribution points.
- Cost of working capital.
- Fixed investment costs of the pits, kilns or retorts.

In an example where traditional clay brick kilns and a savannah forest yielding about 40 m³/ha/yr are used, the FAO reports the unit costs shown in Table 28 apply (expressed as a percentage of the cost of delivered charcoal).

Table 28. Reported cost structure at traditional clay brick at savannah forest (% of total production cost).

Source: FAO 1987

Cost	Wood at kiln	Kiln labor	Working capital	Fixed investment	Transport
%	60	9	3.5	1.5	26

^{xxviii} Traditionally no price has been imposed to carbon emissions to fossil fuels.

As presented in Table 28, in the cost structure 60 % of the cost is represented by the biomass and 14 % by the carbonization process (including investment costs), whereas transport correspond to 26 %. These values are congruent with those reported by Norgate and Langberg (2009) under Australian conditions with continuous retort. They indicate that the cost of production of biochar from wood farms is approximately 386 USD/t, of which 195–330 USD correspond to the biomass (wood), 113 USD/t charcoal production (carbonization) and 13 USD/t transport [25]. In another study Suopajarvi and Fabritius (2013), based on the analysis of the supply chain in Finland, it was estimated the total charcoal production costs of 268 to 478 €/t (343 to 611.84 USD/t) charcoal from logging residues [161]. In a review of technologies for the production of Charcoal, Kammen and Lew (2005) [162] report the case of the Viphyra plantation in Malawi, where in 1989 transport costs make up 60–70 % of total market price for the plantation charcoal (market price was 265–290 USD/t). In contrast to the price of charcoal, traditionally the prices of metallurgical coal were 40–50 USD/t between 1996–2003. These industrial experiences show that the price of wood is the principal production cost in charcoal making.

As shown in Table 29, a key factor in the production cost is the price of the biomass to carbonize. Hardwood from primary sources can represent a cost of 35–67 % of charcoal, while charcoal from corn stover (forestry residue) is only 30.5 %. Therefore the type and source of biomass used may determine the final cost of charcoal.

Table 29. Charcoal costs reported in literature [25,86,163,164,165]

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

Another important factor relates to the biomass output and cost of wood for carbonization. A report by CGEE (2014) [166] compared the productivity and raw material cost of biomass in different countries in the world. As shown in **Figure 42**, Brazil shows the high biomass output and lowest cost for wood in the comparison countries (Chile, Canada, USA and Finland). This is one of the main reasons for the relatively low cost of charcoal in Brazil, in comparison to other countries.

In eastern Australia, a collaborative project between BlueScope Steel, OneSteel, CSIRO and CSRP identified, evaluated and proved the low-price availability of sufficient forest residues and waste disposal to generate up to 1,440,5 t of biomass char per year for metallurgical applications (Haque et al. 2008) [167].

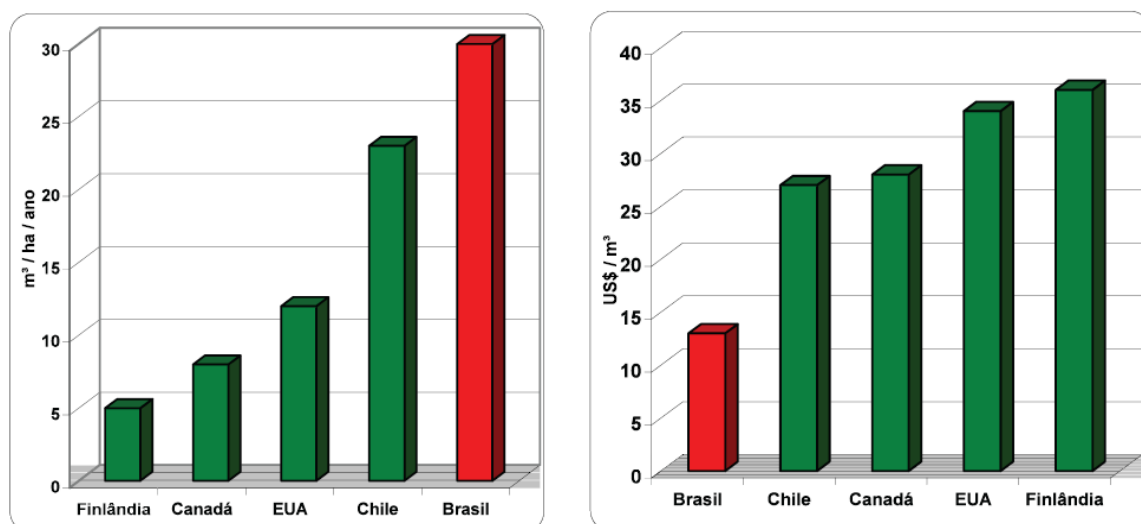


Figure 42. Biomass productivity (left) and cost of wood (right) in selected countries

Source: CGEE (2014)

Currently, the production costs for charcoal exceed those of fossil coal. However, the utilization of state-of-the art carbonization processes can significantly decrease the production cost, due the better yield and credits gained due to collection of valuable by-products: tar, acetic acid and methanol. In this sense, in CSIRO (Australia) there has been developed a process and a pilot plant based on the fundamentals of autogenous pyrolysis of biomass, to prove the autogenous capacity of the slow pyrolysis with the exploitation of various by-products from biomass.

From the economic perspective, Jahanshahi et al. (2015) argue that under a set of assumptions (see original article), the total operating cost with CSIRO's pyrolysis process is 446 AUD/t charcoal (356.82 USD/t)^{XXIX}. The figure 43 presents a flow diagram of the pyrolysis and a photo of the pilot plant at CSIRO. However, the VIU of the revenue generated by the collection of bio-oil can reduce in total 203 AUD/t (162.41 USD/t), leading to an operating charcoal net cost of 243 AUD/t (194.41 USD/t) [78]. This estimation evidences the potential to reduce the biomass char cost by the utilization of low-grade biomass/wood and by the exploitation of the by-products.

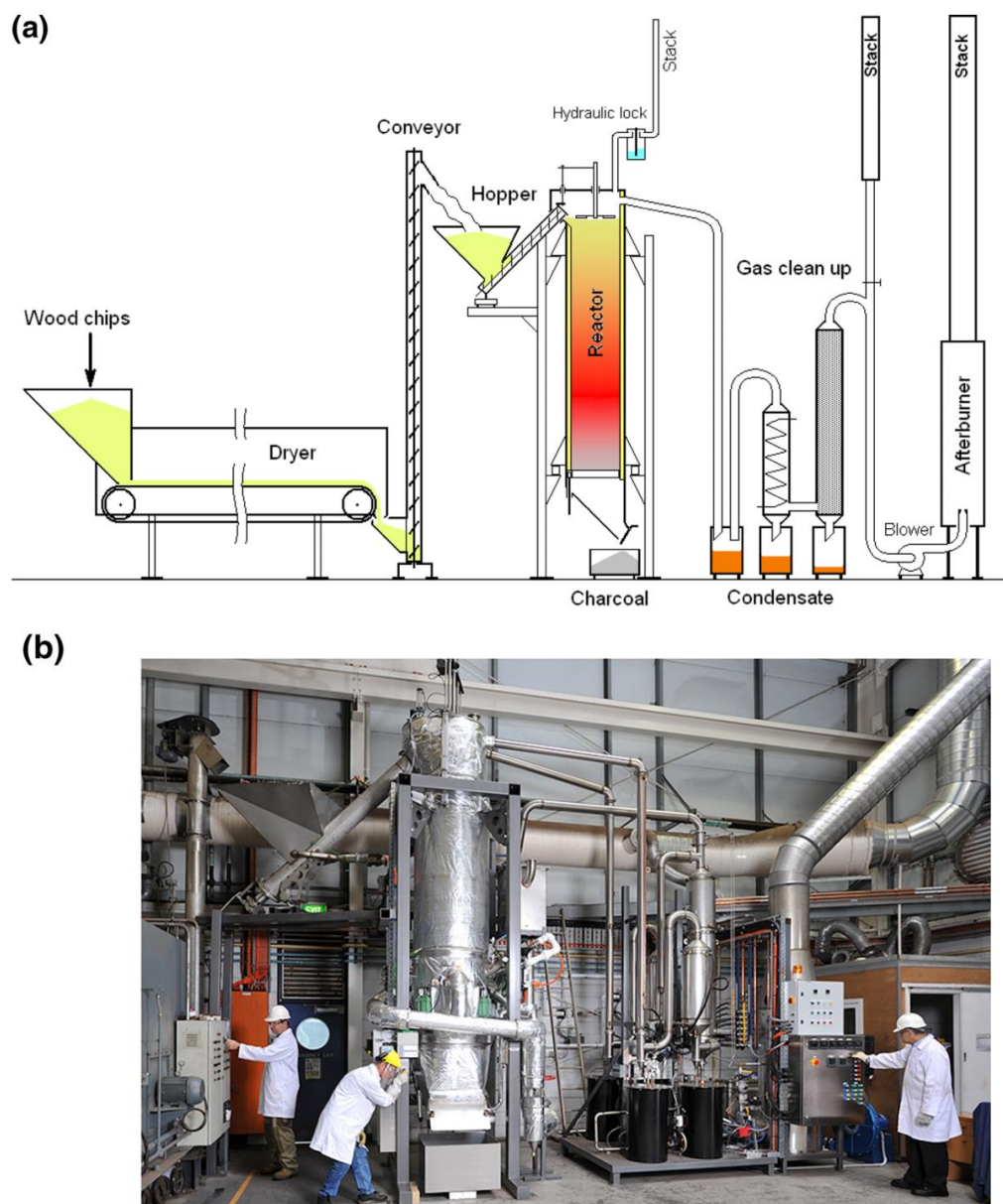


Figure 43. (a) Process flow diagram and Pyrolysis and (b) pilot plant developed at CSIRO

Source: Jahanshahi et al. (2015)

^{XXIX} Exchange rate: 1.25 AUD/USD

Additionally there are industrial experiences that demonstrate the economic advantages of the exploitation of by-products. In a report issued by the CGEE (2014), a comparison is made between the production costs of different industrial charcoalmaking processes in Brazil. The report determines that the improved continuous carbonization process that collects bio-tar can reduce the production costs by up to 48 % (CGEE, 2014) [117]. According to the results, at the plant of APERAM charcoal was produced in 2014 at a cost of 271 Rs/t (135.5 USD/t)^{xxx}, with 125 Rs/t (62.5 USD/t) credits due to the sale of bio-tar (see **Table 30**).

Table 30. Cost structure of charcoal production in selected plant in Brazil
Source: CGEE (2014)

Process (type of kiln)	Biomass cost	Hand Labour cost	CAPEX	By- Product credits	Price	Benchmark
	Rs/t	Rs/t	Rs/t	Rs/t	Rs/t	%
QGS - circular kiln	303.3	132	82.5	0	517.9	100
QGS - RAC 700 without heat exchange	241.7	46.2	139.3	0	427.3	83
QGS - RAC 700 with heat exchange	241.7	48.6	140.8	0	430.8	83
ArcelorMittal - RAC 700	225.4	22.1	101.7	0	349.2	67
ArcelorMittal - AM 32	257.8	26.2	101	0	385	74
Bricarbras	270.8	60.4	187.3	0	518.5	100
Tecnologia DPC	164.5	44.4	130.9	0	339.9	66
Tecnologia DPC improved	217.8	32.3	120.4	-125	245.4	47
Continue Carbonization	194.2	21.5	236.2	-125	326.9	63
Improved Continue Carbonization	217.8	10.8	167.6	-125	271.1	52

The cases of the *improved continuous carbonization process* (Brazil) and the CSIRO pyrolysis process (Australia) show the clear economic benefit presented by the collection and exploitation of bio-tar and bio-oil (which is approximately 6 % of the original biomass). In this sense, Jahanshahi et al. (2015) mention that bio-oil has an energy market value of approximate 438 AUD/t (approximately 350 USD/t)^{xxxi} and the energy content of bio-oil is 50 % of crude oil. Therefore, the exploitation of valuable by-products may significantly provide credits to reduce the production cost of biomass char.

^{xxx} Exchange rate: 2 Rs/USD

^{xxxi} Exchange rate: 1.25 AUD/USD

2.8.2. Influence of biomass char price on hot metal production

With respect to the market price, Figure 44 shows the historic development of HM price from charcoal-BF and coke-BF in Brazil (Winter, 2012). As can be seen in **Figure 44**, the price of charcoal-HM is 32-45 % higher than coke-HM, basically due to the cost difference between coke and charcoal.

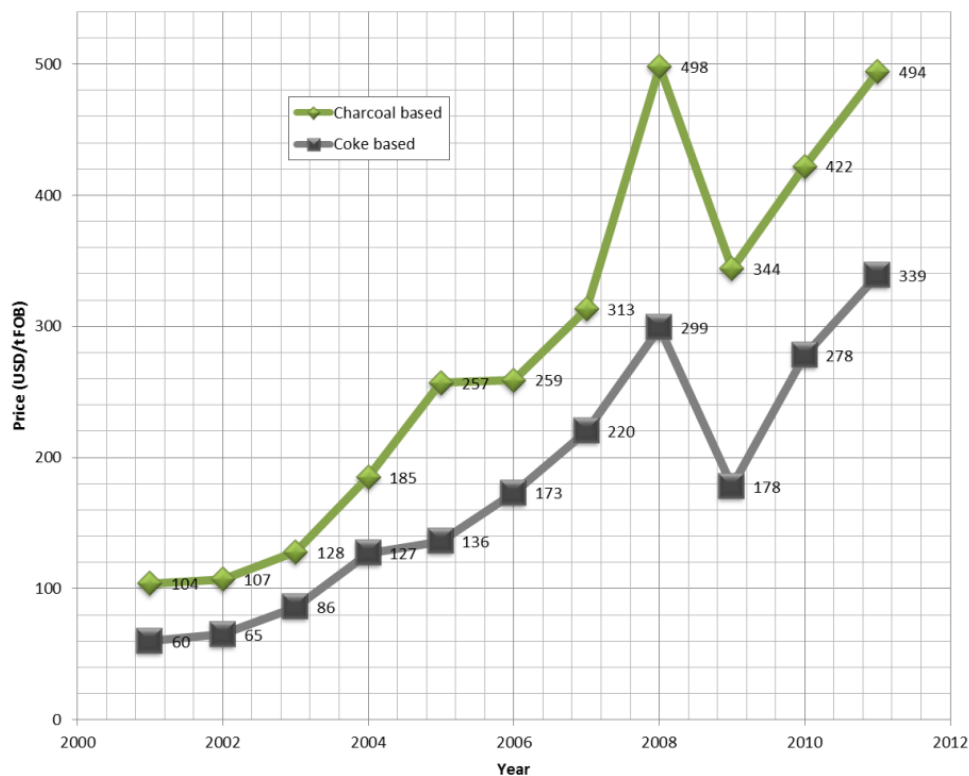


Figure 44. Historical development of price per tonne charcoal-based HM and coke-based HM in Brazil
Source: Winter (2012)

As observed, HM from charcoal-BF is significantly higher in price; however, it is still attractive to steel plants and foundries due to its specific features (Winter, 2012) [17]:

1. Charcoal-HM presents a low sulfur content, which reduces the need for refining in a secondary metallurgy stage in steelmaking plants.
2. Charcoal-HM has high iron content, especially in comparison to scrap and direct reduced iron, the main competing charging material of electric arc furnaces (EAF). Also the charcoal-HM can be charged as molten metal with a significant reduction of energy consumption.

3. Charcoal-HM shows a high carbon content, which reduces the electrical consumption in EAFs.
4. For foundries, HM-charcoal prevents the need for desulfurization, which is possible with CaC_2 or other desulfurizer agent but is costly and requires more processing. Thus, a better product can be achieved.
5. Charcoal-HM increases the load density during the charge of EAFs.

HM from charcoal-BFs is industrially used in the charge of BOF converters in *V&M do BRASIL* (Gonçalves, 2012) and in the charge of EAF in ArcelorMittal Cariacica (2012) [88,168], with a positive increase in the productivity of the metallurgical vessel. Additionally, in the market of HM from charcoal is highly desired for the metallic charge of foundries, EAF and even BOF (mainly in Brazil).

With respect to the characteristics of charcoal-HM, an investigation set out to determine the VIU of some metallic materials utilized in the charging of EAF. It concluded (based on a series of bonuses and penalties) that HM from charcoal-BF had the highest VIU compared to scrap, direct reduced iron (DRI) and coke-BF hot metal (CGEE 2014) (see **Table 31**). This was principally due to the high iron and carbon content and low sulfur content.

Table 31. Value-In-Use of different metallic charges for electric arc furnace
Source: CGEE 2014

Material	Fe (%)			Chem. Comp. (%)		B&P ⁽¹⁾ (US\$)	W ⁽²⁾ (t)	VIU Index
	Tot	Met	Ox,	C	Si			
Coke-HM	98.5	96.5	2.0	4.10	0.20	(7.05)	1.000	100
Shredder (scrap)	97.3	93.7	3.6	0.10	0.20	6.55	0.988	113
Bundles #1	98.5	97.5	1.0	0.10	0.20	10.08	1.000	118
DRI High C Cold	93.4	86.9	6.5	2.00	-	6.52	0.948	109
DRI High C 500°C	93.4	86.9	6.5	2.00	-	12.33	0.948	115
Charcoal-HM	95.5	95.3	-	4.20	0.50	41.88	0.968	149

(1) Bonus and penalties (2) W is the weight corresponding to 1 t of CokeHM, regarding Fe content.

To the best of the author's knowledge, BF 2 at APERAM is a rare documented example where a charcoal-BF was converted into a coke-BF, from 1986-91, and was then later 're-converted' to use charcoal as its fuel in 2007. Basically, Gonçalves et al. (2012) argue that the following elements justified the transition back to charcoal:

1. To substitute coke, from international markets (mainly Japan and China).
2. To use a renewable fuel to reduce the GHG effect and global warming.
3. To profit from the utilization of silviculture, harvesting and charcoal production of Aperam Bioenergia (APERAM's sister company).
4. To promote the social and economic development of Vale do Jequitinhonha (a relatively economically depressed region in Minas Gerais state).

While this is a unique case, it nevertheless provides very important industrial operating data of relevance to this thesis. Firstly, many iron producing countries may replace the use of imported coal by carbonizing indigeneous biomass, this could be the case of Germany, South Korea and Japan. Secondly, the creation of a carbonization industry of biomass may generate new works and social development, for instance in India or China. Thirdly, the use of biomass char can significantly contribute to the reduction of CO₂ in the ironmaking process.

Additional advantages from charcoal-BFs are their robustness and flexibility to adapt to variable burdening materials. This facilitates the change in feeding patterns according to the market price of pellets and lump ores, for instance the case of APERAM. To a large extent, the charcoal-BFs are rudimentary vessels that permitted the production of a remarkable product, in terms of their low content of impurities, with a rather low capital expenditure.

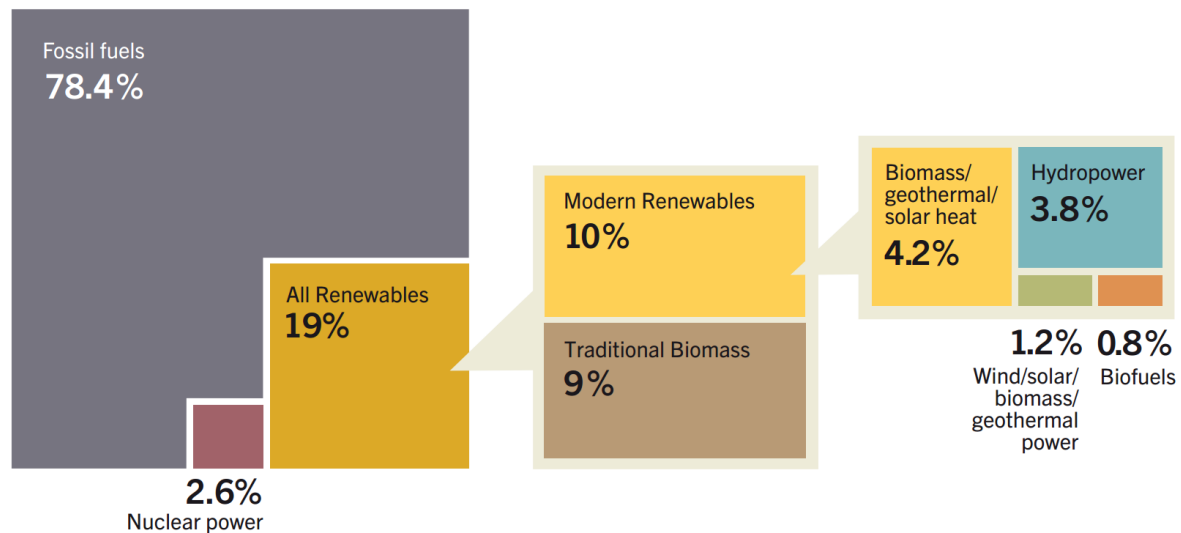
Despite the benefits of HM from charcoal-BF, significant barriers to the widespread use of charcoal ironmaking exist, as few countries present adequate conditions for sustainable biomass and charcoal production. The following section presents a summary of the principal challenges of charcoal ironmaking.

2.8.3. Discussion of economics of biofuels

According to Renewables 21 Global Status Report 2014^{xxxii} [169], in 2012 approximately 78.4 % of the global supply of energy was comprised of fossil fuels (oil, coal, and natural gas) while renewable energy contributed in 19 % (see **Figure 45**). From this total renewable energy,

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

the vast majority of supply was regenerated from biomass, for instance wood and agricultural wastes. Renewable sources, such as hydro, wind, solar, tidal, and geothermal, contributed with approximately 5 % of the energy usage (see **Figure 45**). At the present moment, biomass based energy is principally consumed in developing countries (Rajagopal and Zilberman 2007) [170].



Traditional biomass refers to solid biomass that is combusted in inefficient, and usually polluting, open fires, stoves, or furnaces to provide heat energy for cooking, comfort, and small-scale agricultural and industrial processing, typically in rural areas of developing countries. It may or may not be harvested in a sustainable manner. Traditional biomass currently plays a critical role in meeting rural energy demand in much of the developing world. Modern biomass energy is defined in this report as energy derived efficiently from solid, liquid, and gaseous biomass fuels for modern applications.

Figure 45. Estimated renewable energy share of global final energy consumption, 2012
Source: REN 21 (2014).

In this respect, biomass generated for the purpose of carbonization can be also considered as a solid biofuel. The substitution of fossil fuels with renewable fuels presents the opportunity to mitigate GHG emissions, and additionally supporters argue that this can reduce the depletion of fossil endowments and minimize the importation of oil and coal from foreign countries [171]. Detractors point out that the production of biomass for biofuel requires potentially a vast area of plantations, water-use and fertilizers. Other disadvantages mentioned are that changes in land utilization can increase GHG emission and even increase the price of food. In addition, and more controversially, it is alleged that according to the biomass, processing and time span of the assessment, some biofuels can generate even more GHGs than fossil fuels (Searchinger et al. 2008) [172,173]. However, it is argued that some underlying assumptions in the assessment by Searchinger et al. are perceived to be too diffuse and arbitrary to be meaningful for rule-making, for instance assumptions about indirect land use change effects (Mathews and Tao 2009)[174].

While the present work focuses on the prospects of biomass char in ironmaking, it is important to understand the history of liquid fuels. Looking at biofuels, the first generation was produced from sugarcane, corn, soybean, canola and animal fat^{xxxiii}. In contrast, the second generation of biofuels can be manufactured from cellulose, which can be obtained from non-food crops and residual biomass such as corn stover, corncobs, straw, wood, and wood by-products. The second generation biofuels are also known as *cellulosic biofuels* (Naik et al. 2010) [175], since they can use cellulosic biomass or residual biomass as feedstock. This aims to avoid any impact over food prices and incorrect land utilization. As an additional benefit, the yeast produced in biofuel with single-cell protein (SCP) could be utilized as a high-protein animal feed supplement (Mathews et al. 2011) [176]. Presently, there is a third generation of biofuels which utilize algae as the main raw material (Dragone et al. 2010) [95].

From a commercial perspective, up to now, ethanol is the most widely used biofuel, as cellulosic biofuel only commenced production in 2013. During the writing of this dissertation, third generation biofuels (using algae) are not yet produced commercially [171].

Supporters of biofuel mention the following potential economic benefits:

- The generation of biomass in theory can be sustained indefinitely, since it is based on renewable feedstocks (not on exhaustible resources). Additionally, biofuels can decrease GHG emissions in comparison to fossil fuels (Hertel et al. 2010, Huang et al. 2013) [177,178].
- As shown by the Brazilian experience, and replicated in many developing countries, biofuels present an opportunity for economic development – especially in tropical countries, which have an abundance of land, water and sunshine that provides them a competitive advantage in the production of biofuels (Mathews 2007) [179].
- Second and third generation biofuels can be generated using marginal land (no arable land). Additionally, in the case of residual biomass, no agricultural production is needed.
- Biofuels (especially second and third generation) can be manufactured in most countries; this would lead to lower dependency on foreign fossil resources (Huang et al. 2013).

^{xxxiii} The yeast SCP can partially substitute for grass in the feed of cattle grazing on pasture

- Some beneficial practices in biofuels harvesting could be propagated to the agricultural industry. For instance: shifting from wasteful annual crops to perennials, sequestering carbon in soil (organically and as biochar); improving conservative water management practices; and recycling resources (Mathews 2009) [180].

Similarly, detractors of biofuels mention the following potential economic negative consequences:

- Some biofuel feedstock include crops that could be used for human consumption, or as animal feed. This may lead to reduced land area devoted to agriculture, and higher food prices.
- Second generation biofuels (cellulosic type) may compete for resources (land, water, fertilizer, etc.) that could be dedicated to food production. This may also lead to changes in land use patterns^{xxxiv} (Searchinger et al. 2008) [172].
- Feedstocks grown on land cleared from tropical forests, for instance soybeans in the Amazon and oil palm in Southeast Asia, can release high GHG emissions (Fargione et al. 2008).
- Biofuel production can also generate GHGs. Fertilizer application releases nitrous oxide, a GHG. Also some investigations indicate that GHG emissions from biofuel production and use may be higher than those generated by fossil fuels (Melillo et al. 2009) [181].
- Economic models suggest that biofuel use increases crop prices. For instance, a study by Zhang et al. (2013) [182] found projections for the effect of biofuels on corn prices ranging from a 5–53 % increase.

In the views of the author, the injection of biomass char into BFs would present similar benefits exhibited by biofuels worldwide, such as decrease CO₂ emissions, improving the economic opportunities of rural areas, biomass char can be produced in marginal land and would also reduce the dependency of foreign fuel source. In addition, in the implementation of Bio-PCI, there are some mechanisms to overcome the major pitfalls of biofuels. For instance, if biomass char is generated from residual biomass (instead of primary wood), then theoretically it would not compete for resources (water, land, fertilizers, etc.) with the food production. Also, if the

^{xxxiv} This may increase GHG emissions by releasing terrestrial carbon stocks to the atmosphere

pyrolysis is carried out in efficient state-of-the-art kilns, the release of methane and other GHG is significantly minimized.

2.8.4. Options to improve the economic perspectives of renewable fuels

From an economic viewpoint, the implementation of renewable fuels (biomass, wind, geothermal, etc.) generally requires some market interventions to be economically attractive against fossil fuels (Mathews and Tan 2009) [174]. The following will describe some of the most common policies to improve the economic attractiveness of biofuels.

2.8.4.1. Carbon taxes

Some countries have implemented taxes on CO₂ emissions, in order to increase the competitiveness of biofuels. The *carbon taxes center*^{xxxv} presents a list of the countries with carbon taxes and their values by 2014 (see **Table 32**) [183]. From these countries, Sweden and Finland were the first to introduce a penalty in the use of fossil fuels in 1990 and 1991 respectively (Rajagopal and Zilberman 2007) [170]. From an economic viewpoint, several authors regard carbon taxes as more effective in CO₂ reduction than providing subsidies for renewable fuel generation (Jaffee et al. 1999; Popp 2006) [184,185], since carbon taxes penalize polluters (*polluter-pay principle*).

Table 32. Estimated carbon tax price to improve the attractiveness of Bio-PCI
Source: Carbon tax center (2014)

Country	Canada [^]		Australia	Chile	Sweden	Finland	New Zealand	USA
Area/state	British Columbia	Quebec						Bourder
Tax value [*] USD/t CO ₂	25	1.16	19.60	5	150	24.39	10.67	7

^{*}USD equivalent, [^] In Canada, the carbon taxes are approved by the local regional authorities.

Additionally, it is argued that carbon tax may have a positive effect in motivating technology changes and increasing fuel effectiveness. Nevertheless, there are also significant disadvantages to carbon taxes. Firstly, applying a carbon taxes in a specific country can potentially lead the migration of the pollutant industries to other countries with lesser environmental restrictions

^{xxxv} The Carbon Tax Center ("CTC") is an American initiative lunched in 2007, to support the taxing emissions of carbon dioxide.

(Bruvoll and Faehn 2006) [186], with a consequent lost for the economy of the country with no GHG abatement. Secondly, carbon taxes (like taxes in general) are politically unpopular and are commonly replaced by subsidies.

2.8.4.2. Carbon credits

Carbon credits are an important part of the global effort for the abatement of GHGs. In principle, one carbon credit is a permit to an organization or person to emit one ton of CO₂ (or any other GHGs). The fundamental idea behind carbon credits (also known as carbon offsets) is that polluters are not required to reduce their generation of GHGs (at least not immediately). They can instead pay for a permit from other company to reduce emissions and achieve the same desired environmental effect (Conte and Kotchen 2010) [187]. Normally, carbon credits are generated through investments in renewable energy, improvements in energy efficiency or reforestation, to mention the most common initiatives. According to Conte and Kotchen (2010), the Kyoto Protocol provides two mechanisms for the reduction of GHGs: the Joint Implementation (JI) and Clean Development Mechanism (CDM). With the JI mechanisms, industrialized nations can purchase carbon credits from emission-reducing projects located in other industrialized nations or nations with transition economies. Under the CDM, industrialized countries can purchase offsets in much the same way, although CDM credits are acquired through the financing of projects in developing nations.

Conte and Kotchen (2010) argue about the actual benefits of carbon credits. They argue that the emitter should reduce their carbon footprint, instead of paying others to minimize their CO₂ emissions. A more practical criticism focuses on the credibility and permanence on carbon credits. Other concerns relate to carbon reduction or sequestration in forestry-based offsets, which present some uncertainties in terms of land utilization, health of trees and risk of fire.

2.8.4.3. Benefits and limitations of carbon pricing

Carbon pricing presents benefits and limitations. This section describes the main criticisms of carbon taxes and carbon credits.

Supporters of carbon credits, argue the following (Hepburn 2007) [188]:

- With carbon credits, CO₂ and GHGs equivalent emissions are managed as commodities; thus they can be traded and their price may fluctuate according to the dynamic of the market.
- The flexible mechanisms of the Kyoto Protocol are targeted to guarantee that the investment is utilized in sustainable carbon reduction schemes.
- Supporters argue that setting a limit level of GHGs emission (cap) can be (somehow) attained eventually, whereas with carbon taxes the present emission level may remain over a period of time.
- Carbon credits rewards sequestration or CO₂ reduction schemes, such as forestry plantation or improvement in renewable energy use.

On the other hand the benefits of carbon taxes may be the following:

- Simple to implement and straight forward to assess.
- It is easier to verify GHGs emissions.
- Permits a centralized management of generated tax incomes
- The price of carbon tax is determined by the government; thus it is partially more stable than a market based scheme, with a possible high price fluctuation.

From the viewpoint of the author, the pricing on carbon (both by the implementation of carbon taxes and/or carbon credits) would certainly increase the economic attractiveness of biomass in ironmaking and reduce the price difference between renewable and fossil carbon in BFs. However, these incentives may have also a negative impact over the production cost on the countries that implement them, which can ultimately reduce the competitiveness of iron and steel production. In this sense, it is the opinion of the author that through the incorporation of efficient pyrolysis technologies and the use of alternative biomass sources, the production price can be reduced to proportionally compete against fossil fuel, especially in those countries without indigenous reserves of coal.

3. Methodology and data

This chapter builds on the methodology and data used for the diverse research presented in the dissertation.

3.1. Methods for economic assessment of innovations in ironmaking

While there are numerous investigations of the injection of charcoal in BF, few peer reviewed works focus on the economic prospects of Bio-PCI deployment. Chronologically, the first attempt found in the literature was presented by Mathieson (2007; 2011) [26,126,137], in research carried out in Blue Scope, Australia. In his contribution, Mathieson proposed an assessment based on a VIU methodology. The schematic outline of the model is shown in **Figure 46**. For the purpose of the study, VIU was defined as the rational purchasing price of a raw material, as compared with a referential coal for PCI.

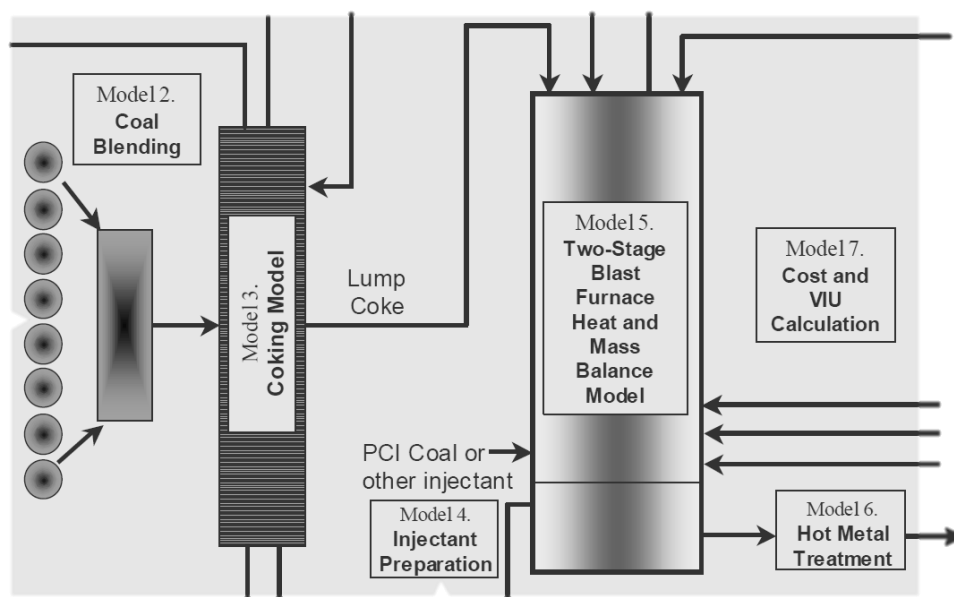


Figure 46. Schematic outline of the VIU model
Source: Mathieson (2007)

Under the VIU framework, a qualitative value 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, 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

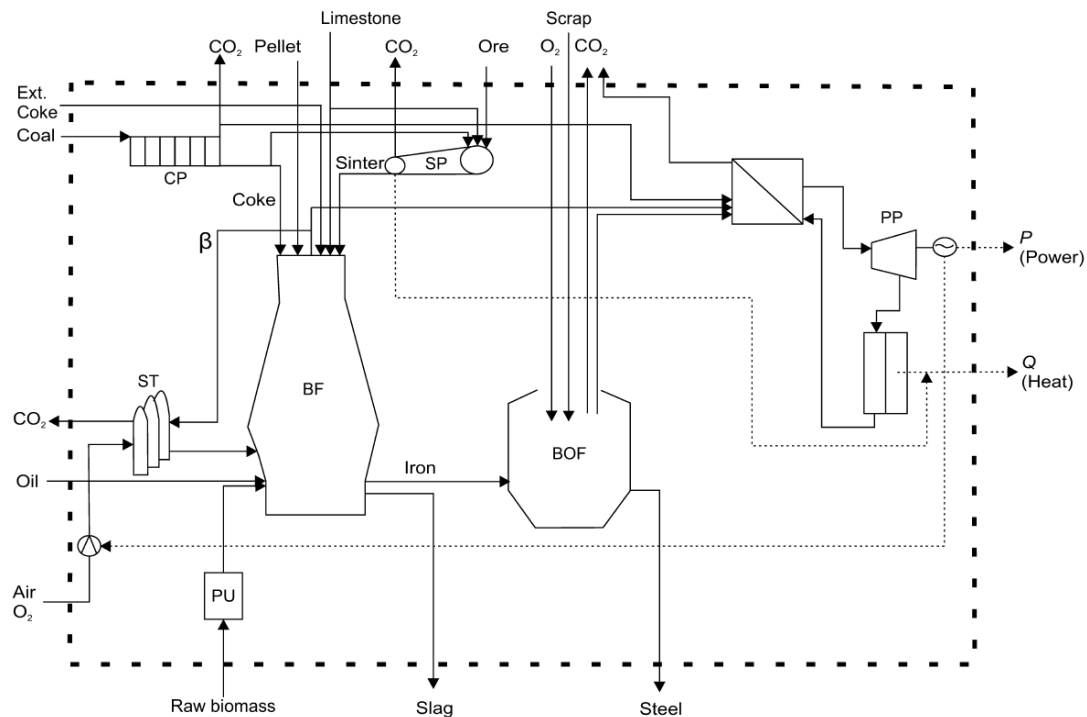
and penalties). In his findings, Mathieson argued that the VIU of charcoal injection has comparatively *high comparative value*, this is a fundamental study on which this thesis builds [137]. This is a fundamental study on which this thesis builds.

In another widely celebrated article, Norgate and Langberg (2009) [25] used a life cycle assessment (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 for. Additionally CO₂ credits were provided during the growth of wood, based on the life cycle inventory (LCI) proposed by Wu et al. (2005) [114] for the growth of eucalyptus. Furthermore, LCA has been used in previous works to assess the environmental impact of metal production processes and remark on the influence of deteriorating ore on the energy and GHG for the production of copper and nickel (Norgate et al. 2007; Norgate and Jahanshahi 2006) [189,190].

Both VIU and LCA frameworks offer tools for analyzing the economic attractiveness of competing injection fuels. Nevertheless, both methodologies present disadvantages. For instance, a key limiting factor for the LCA method is the accuracy and availability of data, since incorrect data can also lead to inaccuracy of results. In this regard, data from generic processes may be based on averages, unrepresentative sampling, or outdated results (Nadav, 2005) [191]. In a comparison of the different BF operations, the LCA method shows rigid system boundaries that complicate the accounting for individual process parameters. Whereas the VIU method is based on 25 factors (see original article) [137], these facilitate an analysis of diverse fuels to be utilized in a specific operation. However, comparison of the economic benefits of the different BFs under diverse economic conditions makes the assessment difficult.

A third type of framework has been used by Saxen et al. (2009) [192], Helle et al. (2009)[193], and Wiklund et al. (2012; 2013) [194,195] for 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 and Saxen, 2006) [196]. At the time of writing, similar frameworks has been applied in several works, for instance, in the estimate of the potential of GHG emissions mitigation in steel production (Riesbeck and Larsson 2012) [197], Effects of Biomass Use in Integrated Steel Plant (Suopajarvi and Fabritius 2012) [27], Top Gas Recycling in BF (Helle et

al. 2010; Helle et al. 2010; Mitra et al. 2011) [30,31,195], Steelmaking with a Polygeneration Plant (Ghanbari et al. 2012) [32], Optimization of Ironmaking in the BF (Pettersson et al. 2009) [33], BF Operation Combined with Methanol Production (Ghanbari et al. 2011) [34].



CP: coke oven, SP: sinter plant, ST: hot stoves, PU: biomass pyrolysis unit, BF: blast furnace, BOF: basic oxygen furnace, and PP: power plant.

Figure 47. Schematic of the system studied by Helle et al. (2009).

In the above-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 (lump ores, pellets, and sinter), fuels/reductants (coal, coke, charcoal, and electricity), oxygen, and carbon taxes. However, other key financial elements are not taken into consideration. The following paragraph builds on this topic.

The findings of the different works mentioned previously appear to be more flexible for the comparison of different BF processes (than other results based on LCA or VIU), as they take into consideration the actual variable production parameters of the BF operation, which results in comparable results. The simulation using F , in principle, could 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 innovations in the ironmaking process.

The method is not exempt of criticism. Firstly, key financial elements of steelmaking are ignored in the model. These elements can represent up to 37.8 % of the total steel production cost, according to the crude steel cost model of Steelonthenet [160]. The costs absent in the model are capital charges, hand labor, ferroalloys, refractories, and raw material transportation to the plant. Secondly, in previous works by Saxen et al. (2009), Helle et al. (2009), and Wikulund et al. (2013), biomass pyrolysis is performed in the steelwork, while in practice, charcoal manufacturing is a separate entity of. Finally, the findings of previous authors appear to be based on arbitrarily selected raw materials prices, with no relation to actual raw materials costs.

The contribution aims to respond to the following original strategic questions:

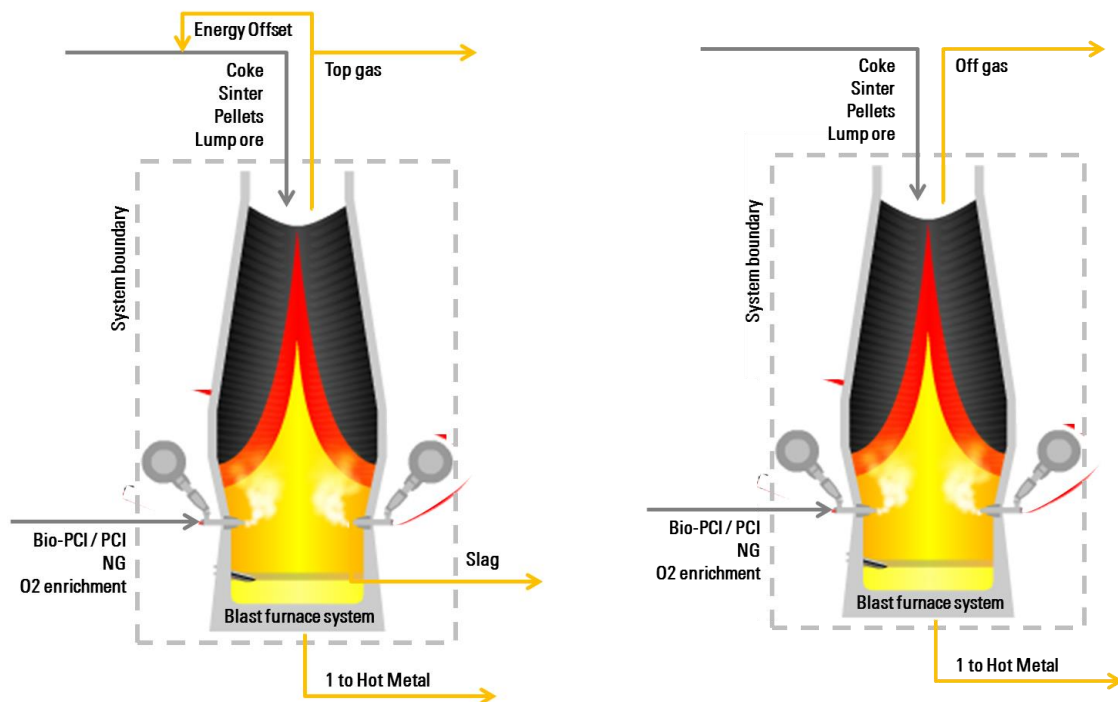
- *What is the effect of Bio-PCI introduction on the economy of a coke-BF?*
- *How can charcoal prices influence the economics of HM production in a coke-BF with Bio-PCI?*
- *How can carbon taxes influence the economics of HM production in a coke-BF with Bio-PCI?*
- *Which countries present the best prospects for Bio-PCI deployment in BF's?*
- *How does co-injection affect the economy of a coke-BF operation?*
- *How can carbon taxes influence the economics of HM production in a coke-BF with Bio-PCI and coal co-injection?*

In this respect, the present study clearly differentiates itself from previous works, as the focus is given to the ironmaking in BF (not on the entire steel process). It identifies Bio-PCI as the most feasible way to replace fossil-based coals and coke. It aims to measure the economic impact of biomass char injection based on actual processing parameters and ironmaking costs.

3.2. System boundaries

Selection of the proper limits of the system, also called system boundaries, is essential in order to adequately assess the impact of different reductants in the BF. According to Churchman

(1968) [198], variables inside the system are those that can be affected and those that might be affected by the system—burden materials, oxygen, and fuels in the present case. Outside the system are those variables that influence the system, but conversely are not influenced by the system, for instance carbon taxes, raw material prices, and energy prices. As the purpose of the present work is to evaluate the economic impact of Bio-PCI in BF, the system boundaries are defined as schematically depicted in **Figure 48**. 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., HM, top gas, slag). In contrast to previous works by Saxen et al., Helle et al., and Wikulund et al. [192,193,194,195], the present contribution only considers input and output elements to the BF, while all other aggregates in steel plants are excluded (coke ovens, BF stoves, steel shop, rolling mill, etc.). It is important to note that in papers IV and V, the system considered a re-utilization of the heat capacity in the top gas. However, it did not show any major economic contribution. Thus, the system boundary in paper III does not consider the re-utilization of top gas.



a) System boundaries in papers IV and V

b) System boundaries in paper III

Figure 48. Schematic outline of system boundaries for this study

Some other assumptions underlying the present contribution are that coke and charcoal used in the BF are provided entirely from external sources^{xxxvi}, while coal and charcoal are only used for injection through tuyeres (PCI/Bio-PCI). Additionally in the calculations, credits are provided by electricity generation due to top gas calorific power, in papers IV and V. With respect to slag, the authors acknowledge that it can be sold as raw material for other applications, for instance, cement, motorway pavements, and as a pH modifier in agriculture (Feliciano 2005) [199]; however in the present investigation, no credits are given for the commercialization of slag.

3.3. Blast Furnace process simulation

To the knowledge of the author, currently 46 plants in Brazil inject charcoal in the BFs. Moreover, it is known that a vast majority of large size coke-BFs inject coal as auxiliary fuel through PCI rigs. In this respect, it was necessary to simulate the effects of biomass char injection (Bio-PCI) on the coke-BF process. The present work used the interactive simulation of Steel University to assess the technical influence of charcoal substitution. This simulation tool has been designed as an educational and training tool for both students of ferrous metallurgy and for steel industry employees [200].

The basic aim of the simulation was to verify the variations in operational parameters in a coke-BF when charcoal replaced coal as an auxiliary injecting fuel. Table 33 shows the chemical compositions of coke, coal, and charcoal used in the simulation (after Babich et al. 2010) [35].

Table 33. Chemical composition of coke, coal and charcoal used in the BF simulation
Source: Babich et al. (2010)

	Fixed carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	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

In order to simulate the scenarios of replacement, it is necessary to adapt the interphases of the BF simulation (see **Figure 49**): chemical composition of raw materials, production settings, charging rates, and production environmental parameters. Once all interphases were

^{xxxvi} It is acknowledged that most steel plants have coke batteries, while some few BF import coke from overseas. However, the present analysis focus exclusively on the BF process, therefore all elements introduced in the process are considered external elements.

successfully reviewed and adjusted, the system delivered results based on the given parameters and conditions.

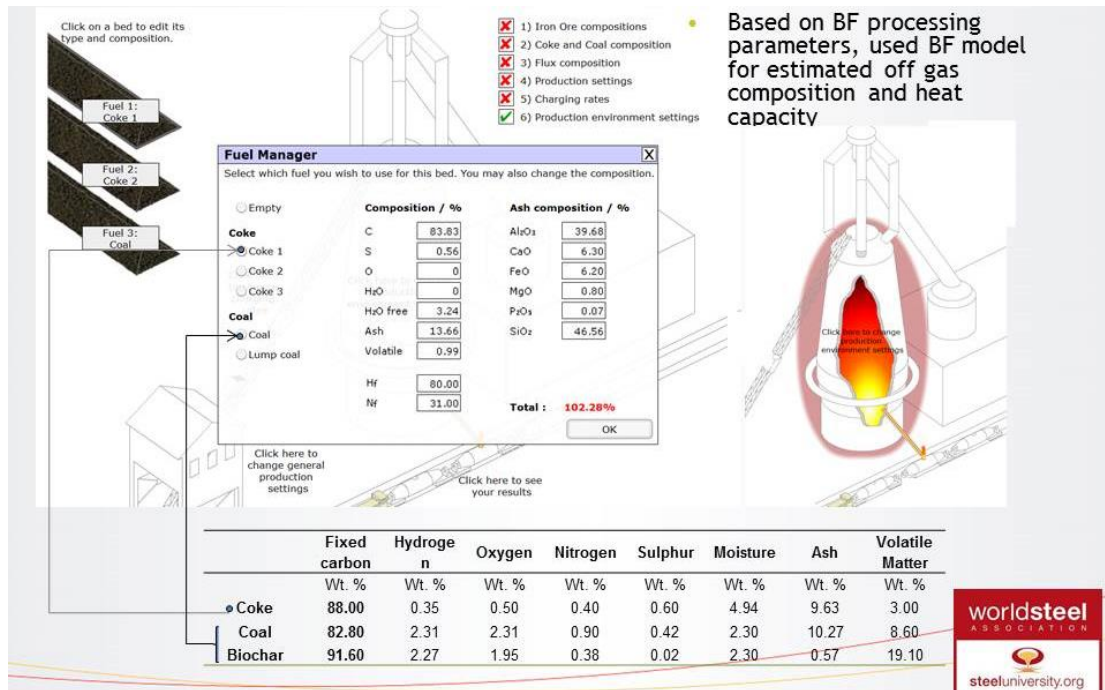


Figure 49. Process simulation by Steel University

With respect to the selection of raw materials, the specific rate of charge was adjusted to the actual patterns of charge of the BFs selected for the study (see table 38). However, the chemical composition of sinter, pellets, and lump ores was used according to the default values present in the simulation.

Table 34. Chemical composition of sinter, pellets and lump ore used in the BF process simulation. Source: Steel University (2012)

	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

Similar to the charge of the iron bearing elements (sinter, pellets, and lump 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) with charcoal.

The mass balance is calculated comparing the quantity of input and output materials, according to the following formula:

$$\sum_{i=1}^n \sum_{j=1}^k M_i X_{ij} = \sum_{i=1}^m \sum_{j=1}^l M_j Y_{jt} \quad \text{Equation 4}$$

Where masses of the balance are the following (**Table 35**):

Table 35. Mass balance assessment (per metric ton hot metal)	
Mass in	Mass out
Mixed iron ore weight	1,000 kg hot metal
Coke weight	Slag weight
PCI or Bio-PCI weight	Top gas weight
Flux weight	Moisture in top gas weight
Hot blast weight *	Dust weight
Free water	
Total incoming M_{in}	Total outgoing mass M_{out}

* Hot blast volume is calculated based on O₂ content in blast and the weight of carbon burnt in the combustion area, and then with density of blast, the blast weight is obtained.

Similar to the mass balance, the heat balance is estimated according to the following formula:

$$\sum_{i=1}^n \sum_{j=1}^k W_{ij} H_{ij} = \sum_{i=1}^m \sum_{j=1}^l W_{ij} H_{ij} + Q_{loss} \quad \text{Equation 5}$$

Where masses of the balance are the following (**Table 36**):

Table 36. Heat balance assessment	
Heat in	Heat out
Carbon oxidation	Oxide decomposition
Hot Blast	Carbonate decomposition
Hydrogen oxidation	Free water evaporation
Slag formation	Coal decomposition
Heat provided by the materials	Molten iron
	Top gas

Heat Loss

Slag

Total incoming H_{in}	Total outgoing mass H_{out}
-------------------------	-------------------------------

With respect to the process parameters used in the BF simulation, processing data from representative BFs available in the 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), and AM Eisenhüttenstadt (Germany) [201,202,203,204,205,206,207,208]. The actual top gas composition and its heat capacity were calculated for each case using Equation 8 and the coefficients in table 37 [200]. It is important to note that BF top gas generates valuable power that can be used in other areas of the steel mills. This is schematically illustrated in Figure 48 (System boundaries). The parameters used in the estimates are presented in **Table 37**.

$$C_p = 4.18 \times (a + bT + eT^2) J. mol^{-1}. K^{-1} \quad \text{Equation 6}$$

Table 37. Coefficients for calculation of gas heat capacity

Material	a	b x 10 ⁻³	c x 10 ⁻⁵
O ₂	7.16	1	-0.04
N ₂	6.66	1.02	
H ₂	6.52	0.78	0.12
CO	6.79	0.98	-0.11
CO ₂	10.55	2.16	-2.04
CH ₄	5.65	11.44	-0.46
H ₂ O _(g)	7.17	2.56	0.08

It is also important to mention some of the underlying assumptions of the simulation. Firstly, because of the similar carbon content of the biochar and coal used in the assessment, it is assumed that 1 kg of biochar replaces 1 kg of coal as the auxiliary fuel, because of the chemical composition of biochar and coal used for the assessment. Another assumption considered in the calculation is the substitution ratio, the model estimates that a part of the material is lost during charging due to mechanical degradation and powder formation—values vary from 0.01–0.03 %. Thirdly, the model assumes that all materials charged are dried (water free).

Table 38. Parameters used in the process simulation.

		AM Eisenhüttenstadt	Baosteel BF3	Nippon Steel Oita	NLMK	POSCO BF 5	Tata Steel Jamshedpur BF H	Gerdau Acominas BF 9	Alchevsk Iron & Steel BF1
	Unit	Symbol							
Productivity	t/m ³ d		2.31	2.19	2.22	2.99	2.55	2.37	2.04
Coke rate	kg/tlm	M _{coke}	414.5	290	356.3	421	302	380	365
PCI rate	kg/tlm	M _{pci}	176.9	208	98.4	0	180	160	140
NG rate	kg/tlm	M _{ng}	0	0	0	98.7	0	0	20
Sinter	%	M _{sinter}	79.6	68.89	78.5	80e	75	70	86.9
Pellets	%	M _{pellets}	12.8	13.97	7	20e	10	0	0
Lump ore	%	M _{ore}	7.5	17.14	14.5	0	15	30	13.1
O ₂ 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
Working volume	m ³			4,350	5,245		4,350	3,230	1,750
Top gas composition ^a	Unit								
CO ₂	%		17.29	20.73	23.89	24.94	21.84	20.83	20.62
CO	%		27.12	23.02	20.42	25.54	22.3	26.17	23.12
H ₂	%		3.35	4.05	2.89	2.97	3.82	3.47	3.21
N ₂	%		51.76	51.71	52.31	45.99	51.54	49.02	52.57
CH ₄	%		0.49	0.49	0.5	0.56	0.49	0.52	0.49
Top gas heating value	kJ/t HMI		191	165.1	149	137.1	158	173.4	165.5
CO ₂ emissions	tCO ₂ /tHM		1.749	1.463	1.351	1.546	1.42	1.598	1.496
									1.747

3.3.1. Cost Objective Function

As mentioned before, at the Heat Engineering Laboratory in the *Åbo Akademi*, a numerical model was developed for the assessment of the techno-economic impact of innovations in the BF ironmaking process. The economic part of this model, also known as the 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 utilization rates, products, and by-products. F provides an indication of the production cost of HM when fossil-based coal for PCI is replaced 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 economy of HM production.

F is aimed at showing how principal raw materials prices used in HM production (coke, coal, charcoal, sinter, lump iron ore, pellets, and limestone) can affect 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 for in the model—for instance, capital charges, hand labor, 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:

In paper IV:

$$F = 1.58[(C_{ore} \cdot M_{ore}) + (C_{pellet} \cdot M_{pellet}) + (C_{sinter} \cdot M_{sinter})] + 1.27[C_{coal} \cdot M_{coal/coke}] + [C_{charcoal} \cdot M_{PCI}] + [C_{CO_2Tax} \cdot M_{CO_2fossil}] - [P_{offgas} \cdot C_{el}] \quad \text{Equation 7}$$

In papers III and VI:

$$F = 1.58[(C_{ore} \cdot M_{ore}) + (C_{pellet} \cdot M_{pellet}) + (C_{sinter} \cdot M_{sinter})] + 1.27[C_{coal} \cdot M_{coal/coke}] + [C_{charcoal} \cdot M_{PCI}] + [C_{CO_2Tax} \cdot M_{CO_2fossil}] \quad \text{Equation 8}$$

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 economic assessment, a survey was carried out to identify representative raw material prices. The next section builds on the data collection of prices used in the cost objective function.

3.3.1.1. Economic data used in the cost objective function

Little peer-reviewed data is available on the costs of charcoal and biomass. **Table 29** 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 and Angerman (2011) report charcoal prices of 780 USD/t in Finland, while Fallot et al. (2008) report prices of 162 USD/t in Brazil.

In order to create rational economic scenarios, it is important to utilize the most accurate economic data possible. For this reason, the author consulted the biomass prices of 37 producers and traders in over 19 countries to assess the market price of primary biomass. The survey took place from April–September 2012. A summary of the results is shown in **Appendix 1**.

Additionally, histograms of consulted prices of primary biomass (minimum and maximum prices) have been issued using the statistical tool MINITAB®14 (see **Figure 50**). The results show that the mean minimum price is 310 USD/t (with a standard deviation of 121 USD/t), while the mean maximum price is 400 USD/t (with a standard deviation of 201 USD/t).

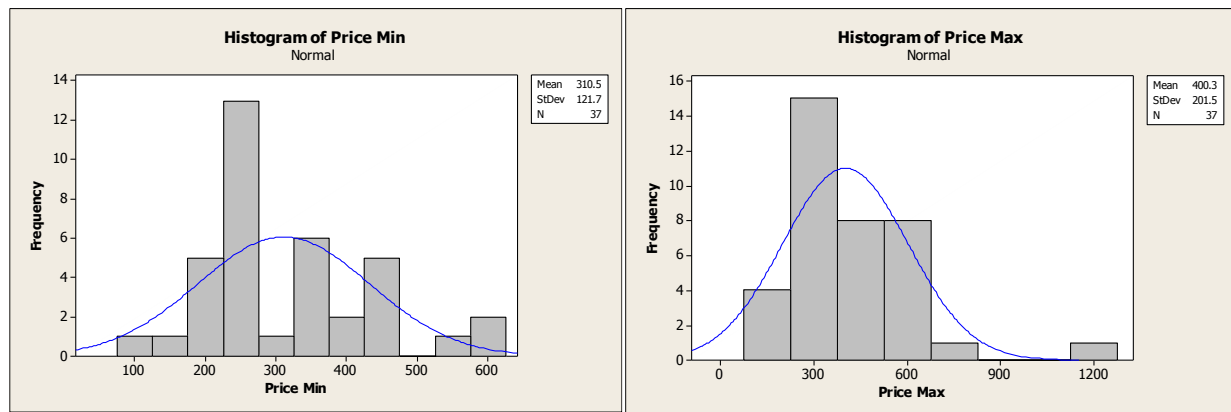


Figure 50. Histogram of minimum (left) and maximum (right) prices for primary biomass

Residual biomass, such as biomass briquettes, palm kernel, coconut shell, wood chip, wheat straw hay, corn straw pellets, and rice husk pellets, are forestry and agricultural wastes that can be used for the purposes of charcoal making with significant cost abatement. Similar to the cases of primary biomass and charcoal, the author consulted the biomass prices of 48 producers and traders in over 19 countries. The survey took place from April–September 2012. A summary of the results is shown in Appendix 2.

As in the case of primary biomass (**Figure 50**), histograms of the consulted prices of residual biomass (minimum and maximum prices) have been issued using the statistical tool MINITAB®14 (see **Figure 51**). The results show that the mean minimum price is 107 USD/t (with a standard deviation of 39 USD/t); while in the case of the 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.

Similarly, 29 producers and traders in eight countries were consulted on the prices of charcoal. The survey took place in April 2012, and a summary of the results is presented in **Appendix 3**. It is important to mention that no information was available concerning the sustainability of the biomass and charcoal; thus, it cannot be distinguished if the biomass or charcoal shown in **Appendix 3** comes from well-managed sustainable plantations.

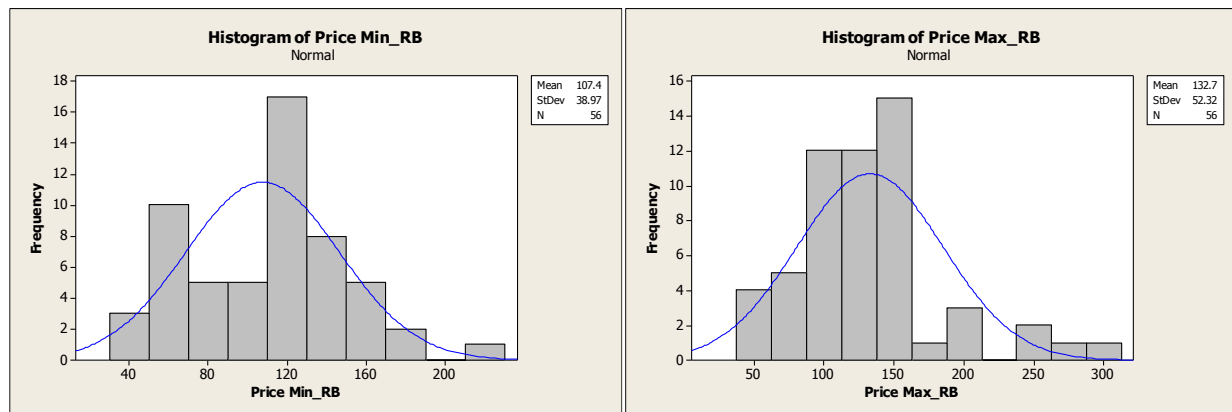


Figure 51. Histogram of minimum (left) and maximum (right) price for residual biomass

To recreate scenarios of raw material cost for the BFs selected, the most relevant charcoal prices were used, and these prices are shown in **Appendix 3**. Some of the other costs listed in **Appendix 3** come from the following sources (see table 40 and 41):

Table 39. Source of references used in **Table 40**

Cost	Source	Reference
Coal	International Coal Report by Platts, Issue 1030 (July 11, 2011)	[209]
Iron Ore	Daily China import iron ore fines average 2010 – 2012 March (63.5 % Fe) \$ per dry metric tonne cfr main port (Metal Bulletin)	[210]
Pellets	China import iron ore pellet 2010–2012 March (65-66 % Fe) \$ per dry metric tonne cfr main port (Metal Bulletin)	[211]
Limestone	Mineral Commodity Summaries: Lime, by US Geological Survey (September 2011)	[212]
Electricity	2011 Key World Energy Statistics by International Energy Agency (2012)	[213]
Carbon	<ul style="list-style-type: none"> <i>Analyse van de CO₂-markt, Emissierechten</i> 	[214,215,216]
Tax	<ul style="list-style-type: none"> 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. 	

Table 40. Costs used in the economic objective function

Table 37, Cost used in economic objective function

Country	Symbol	China	Japan	Russia	South Korea	India	Brazil	USA	Ukraine	Germany
Coal	C_{coal}	134	135	121	134	120	117	124	121	125
Charcoal	$C_{charcoal}$	330	510	570	375	320	270	360	370	480
Iron ore	C_{ore}	163	163	163	163	163	163	163	163	163
Pellets	C_{pellet}	178	178	178	178	178	178	178	178	178
Sinter*	C_{sinter}	175	175	174	175	174	174	174	174	157
Limestone	$C_{limestone}$	125	125	125	125	125	125	125	125	125
Electricity	C_e	24	232	96	84	123	113	116	40	324
Carbon tax	C_{CO_2}	0	20.85	0	33.25	1.07	0	5	1	18.62

* Cost of sinter material was calculated as follows: $C_{sinter} = 0.93[C_{ore}] + 0.14[C_{limestone}] + 0.042[C_{coal}]$

With respect to the values of iron ore and pellets used in the cost objective function, the present work calculated average values of the following:

- Iron ore fines from 2010–2012 March (63.5 % Fe) \$ per dry metric ton incoterm cfr main port (Metal Bulletin).
- Pellets China import iron ore pellets 2010–2012 March (65–66 % Fe) \$ per dry metric ton cfr main port (Metal Bulletin) (see **Figure 52**).

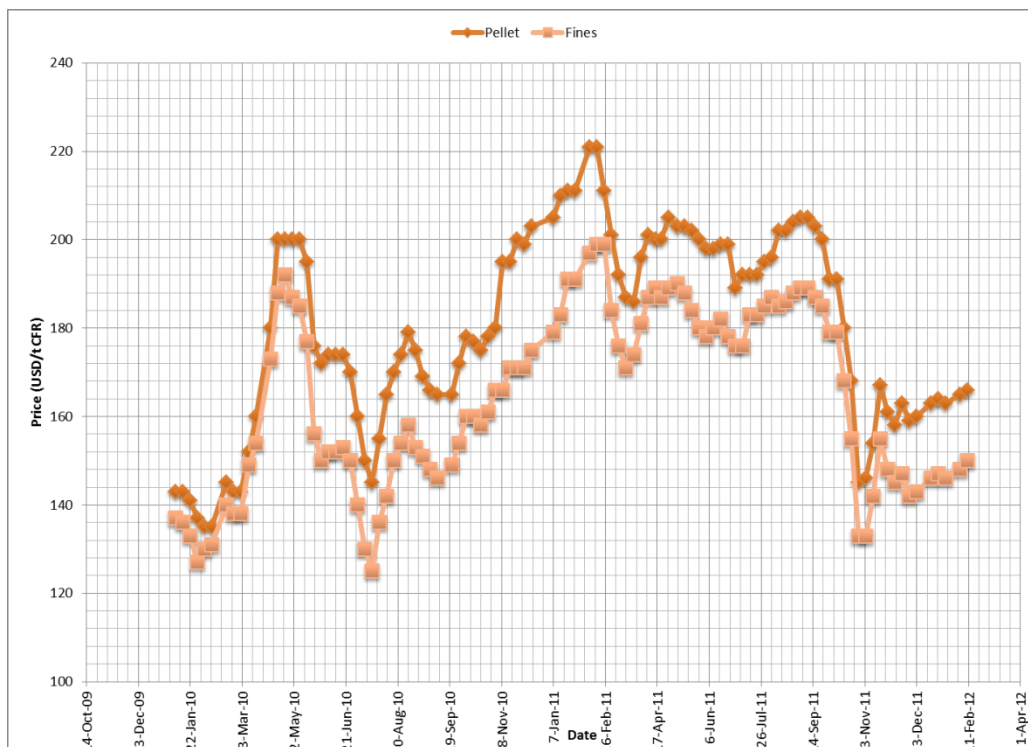


Figure 52. Price development of iron ore fine and pellets (China) January 2010–February 2012
Data source: Metal Bulletin

3.4. Assessment of CO₂ mitigation potential, biomass use, and plantation areas to sustain charcoal-ironmaking

Papers I and II aim to elucidate the benefits and consequences of using charcoal instead of fossil fuel (coal, coke, and natural gas) for ironmaking. A methodology has been designed to assess the CO₂ mitigation potential, the charcoal consumption, the required amount of biomass, and the required plantation areas.

Based on the assumption of a generation of 2.06 t CO₂ / t HM (Winter 2012) [17], the CO₂ emissions of the ironmaking process in coke based BF has been calculated as follows (eq. 9):

$$t_{CO_2} = 2.06 * t_{HM} \quad \text{Equation 9}$$

where:

$$t_{CO_2} : \text{ton CO}_2 \quad t_{HM} : \text{ton hot metal}$$

According to Schmöle et al. (2009), 416 kg reductant/t HM is necessary for the production of one ton of HM, thus the following equation was used for the estimate of charcoal utilization (equation 10):

$$t_{charcoal} = 0.416 \frac{t_{charcoal}}{t_{HM}} * t_{HM} \quad \text{Equation 10}$$

where:

$$t_{charcoal} : \text{ton charcoal} \quad t_{HM} : \text{ton hot metal}$$

Biomass is required for the production of charcoal. Norgate and Langberg (2009) [25] argue that for the production of a ton of charcoal, 8.6 t of biomass is necessary^{xxxvii}. Therefore, the tonnage of biomass was estimated using the following equation (11):

$$t_{biomass} = 8.6 * t_{charcoal} \quad \text{Equation 11}$$

where:

$$t_{biomass} : \text{ton biomass} \quad t_{charcoal} : \text{ton charcoal}$$

The biomass yield depends largely on the tree species and the geographical position of the plantation. However, to produce charcoal for ironmaking, eucalyptus seems to be the most widely used tree species in Brazil. The yield of eucalyptus can also significantly vary from 1 t/ha/yr to more than 50 t/ha/yr [217]. Thus, for the purposes of the present study, a rate of 30 t biomass/ha/yr has been used. The formulation for the assessment of the plantation areas is shown below (eq. 12):

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

$$\frac{A}{y} = 30 * t_{biomass} \quad \text{Equation 12}$$

where:

$$\frac{A}{y} : \text{Plantation area per year} \quad t_{biomass} : \text{ton biomass}$$

(ha/yr)

To illustrate the case of charcoal ironmaking, the CO₂ mitigation potential, tonnage of charcoal, tonnage of biomass, and plantation areas were calculated for the total iron production in the world and the top nine producing countries in the world^{xxxviii}.

^{xxxviii} Top nine iron producers in the world: China, Japan, Russia, India, South Korea, USA, Ukraine, Germany, and Brazil. Combined, these countries produce 89 % of all hot metal in the world.

4. Summary of contribution

This section shows the main contributions of the appended papers that constitute the present dissertation. Papers II, IV, and VII have been published in international journals, while papers I, III, V, and VI have been presented at international conferences and have been published in the respective conference proceedings. All of the articles have been accepted after a process of peer reviewing.

The following summary of contributions is not based on the chronological order of publication of the diverse articles; instead, the contributions are sorted according to the level of relevance of the overall argument.

4.1. Paper I

TECHNICAL AND ECONOMIC LESSONS FROM THE LAST CHARCOAL-BLAST FURNACES

In proceedings of the Symposium of Sustainability in Ironmaking/Steelmaking, Toronto 2015

This article aims to inform the reader of the present status of charcoal-BF and to emphasize the main limitations behind charcoal-ironmaking. The objective of the paper is to provide a comprehensive overview of the state of the art and to present a strategic analysis of the economic perspectives of iron production with charcoal, based on the experiences of the *ferro gusa*^{xxxix} industry in Brazil, the last country with charcoal-based BF still in operation. The paper builds on two principal research questions:

- *What are the main limiting factors for the expansion of charcoal-based ironmaking?*
- *What are the future prospects of charcoal utilization in ironmaking?*

In recent years, researchers worldwide have ‘re-discovered’ the use of charcoal in ironmaking, mainly driven by the potential of CO₂ reduction in the process. However, currently there are few prospects for wider dissemination of charcoal-BFs, due to the many challenges to be

^{xxxix} Hot Metal in Portuguese.

overcome from technical, environmental, and economic perspectives. The following sections summarize the benefits and key limiting factors of charcoal-BF.

4.1.1. Main benefits of charcoal ironmaking

To begin with the benefits, the analyses of the industrial practice show the principal advantages of charcoal-ironmaking:

1. The production of a tonne charcoal-HM liberates 1.558 t O₂/t HM and simultaneously sequesters 2.421 t CO₂/t HM.
2. Charcoal-HM presents low sulfur content.
3. Charcoal-BFs generate less slag than coke-BFs (see also assessment in paper IV).

The charcoal-HM or *ferro gusa* is a high value product, 32–45 % more expensive than coke-HM, which is mainly used in foundries.

4.1.2. Limiting factors of charcoal ironmaking

Several factors hinder the prospects of a wider proliferation of biomass char in ironmaking. This work aims to emphasize the technical, environmental, and economic limiting factors associated with charcoal-BFs in Brazil.

4.1.3. Technical limiting factor of charcoal in blast furnaces

From a technical viewpoint, industrial experiences show that biomass chars lack sufficient mechanical resistance to support the weight of the burden in large BFs. Consequently, in the ironmaking industry, BFs fueled with 100 % biomass char have a limited working capacity. For instance, the largest charcoal-BF presents a working volume of 658 m³ (APERAM, Brazil), while the largest coke-BF has 6.000 m³ (POSCO, South Korea) [218,43]. Therefore, it is technically not possible to convert any coke-BF larger than 660 m³ to operate 100 % with charcoal.

In addition, due to the low crushing strength of charcoal, the industrial experience has shown that charcoal tends to generate fines and dust during transportation and storage. The charcoal

finer (or *moinhas* in Portuguese) are considered undesirable for feeding from the top in BFs, because they can block the gas permeability, which leads to operational problems.

Another limiting factor is the porosity of biomass chars, as charcoal presents 50 % of the bulk density of coke. Consequently, charcoal-BFs operate with less available working volume (in comparison to a normal coke-BF). Additionally, the high porosity also increases the tendency to absorb humidity, which reduces the thermal efficiency in the operation.

In summary, the lack of mechanical resistance and density are problems that limit the technical attractiveness of charcoal utilization in BFs. Previous contributions by Babich et al. (2012) and Winter (2012) also emphasized these negative aspects [17,219].

From the perspective of sustainability, today a vast proportion of the biomass char is still produced from trees from native forests, and only a small part of production is gained from sustainable plantations—for instance eucalyptus and pine plantations in Brazil (Melo 2012) (Nogueira 2009) (Melo 2012)(Nogueira 2009) [105,118]. This leads to the inference that a further growth in charcoal ironmaking based on primary biomass would lead to higher deforestation unless more areas are dedicated to the development of sustainable plantations.

4.1.4. Environmental concerns of charcoal making

One element that hinders the sustainability of charcoal making is the thermal efficiency of the kilns used for pyrolysis. Presently, most of the furnaces used for charcoal making are rudimentary beehive kilns with low char yields. Normally such aggregates present a relatively low yield of char (20–25 % charcoal/dry wood). Moreover, beehive kilns are labor intensive and have a rather high environmental impact (e.g., odors, pollution). Finally, the lack of proper drying of biomass reduces the yield of charcoal, since large amounts of energy are used in the system to evaporate the water in the wood.

A very critical issue is the plantation area required to generate the biomass for pyrolysis. As estimated in paper II, the plantation area required to substitute 100 % of coke by charcoal is ~132,660,000 ha. This result agrees with previous estimates made by Piketty et al. (2007). According to their calculations 143.5 MM ha would be required to sustain global HM production [220]. To dedicate such vast increases in arable area, nutrients, and water to grow a

fuel is economically, politically, and ethically challenging. This leads the author to infer that alternative sources of biomass, for instance agricultural and forestry residues (also called residual biomass), could be used for the generation of charcoal.

Finally, paper I argues that there is a significant price difference between mineral coal and renewable charcoal. In Brazil, historical data (Winter 2012) shows a price difference of 32–45 % between coke- and charcoal-HM [17]. In spite of the benefits of charcoal-HM (less sulfur, lower slag production), the price difference with coke-HM significantly hinders further proliferation of charcoal-BFs. In the absence of any carbon price, it is still currently more economical for metallurgists in Brazil to produce coke-HM.

In light of the main challenges of charcoal ironmaking, the prospects of wider dissemination of an ironmaking industry that is 100 % fueled with biomass chars appear to be limited. However, it is also acknowledged that some interesting and promising research is currently underway in Australia (Jahanshahi et al. 2015) and Finland (Suopajarvi et al. 2014) [23,78]. The injection of small charcoal pieces^{xi} via PCI rigs (here called Bio-PCI) is identified as a technically, environmentally, and economically feasible initiative to reduce CO₂ emissions from the BF process. Other authors also mention that biomass char injection appears to be a technically feasible alternative for charcoal ironmaking in the future (Hallot et al. 2009; Mathieson et al. 2011; Gupta 2003). From an environmental viewpoint, 19–40 % of the CO₂ emission can be reduced by incorporating Bio-PCI. From a technical perspective, the injection of charcoal can take place in normal BF injection rigs (PCI rigs). Strategically, with the use of residual biomass (e.g., agricultural wastes), two main problems of charcoal ironmaking can be offset—low plantation areas with reasonable biomass cost. The environmental, technical, and economic feasibility of Bio-PCI is examined in detail in papers III, V, and VI.

^{xi} Smaller than 2 mm.

4.2. Paper II

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

In journal: Journal Tecnologia em Metalurgia, Materiais e Mineracao, 2015

Originally presented as:

IS CHARCOAL-BASED IRONMAKING SUSTAINABLE? ECOLOGICAL AND ECONOMIC ASPECTS OF BIOMASS USE IN BF

In proceedings of 6th Steel Industry Conference and Exposition, CONAC 2014, Monterrey, Mexico 2014

Following the lines of analysis of paper I, the objective of paper II is to assess the future prospects of charcoal-based ironmaking on its environmental benefits and principal limitations. Therefore, a strategic question is presented: Is charcoal-based ironmaking sustainable? Additionally, other research questions are investigated:

- *What is the potential CO₂ reduction in the BF process with charcoal utilization?*
- *What are the amounts of biomass, plantation areas and fertilizer required for the expansion of charcoal-based ironmaking?*

4.2.1. CO₂ mitigation potential of biomass ironmaking

Charcoal ironmaking is considered carbon neutral since the trees fix carbon during their growing process. According to Goncalvez (2012), 1 t of HM produced with coke and coal generates 2.06 t of CO₂ [15]. Based on this estimate, the replacement of fossil fuels by charcoal can help to reduce CO₂ emissions. In this sense, different scenarios of utilization were assessed among the top nine iron producing countries in the world^{xii}.

According to the estimates in paper I, in 2012, 1.11 MMt HM together with 2.29 MMt of CO₂ were generated (see Goncalves et al. 2012). Logically, the use of charcoal instead of coke could significantly reduce the CO₂ emissions in BFs, up to a theoretical 100 %. Currently, due to the

^{xii} According to the hot metal output in 2014 from Worldsteel, the top nine iron producing countries in the world generate ~88 % of the total hot metal output.

low crushing resistance of biomass char, the complete substitution of coke is, in practice, not feasible, especially in large BF's. However, it seems technically possible to reduce CO₂ emissions between 10–25 % (1,718.66–2,062.39 TMT CO₂), if part of the coke were replaced by charcoal. **Table 41** presents the details of CO₂ reduction potential among the top nine HM producers.

Table 41. Potential reduction in CO₂ emissions (MMt CO₂) as function of charcoal replacement rate (2012)

Country	Charcoal replacement rate (MMt CO ₂)		
	100 %	25 %	10 %
China	1,355.07	338.77	135.51
Japan	167.68	41.92	16.75
Russia	104.03	26.01	10.4
India	98.88	24.72	9.89
Korea	85.9	21.48	8.59
USA	66.13	16.53	6.61
Ukraine	58.71	14.68	5.87
Germany	55.62	13.91	5.56
Brazil	55.41	13.85	5.54
Total World Potential MMt CO₂ reduction	2,291.54	572.89	229.15

4.2.2. Assessment of charcoal, biomass, plantation areas and fertilizer

In order to provide answers to the research questions, a methodology was established to estimate in figures the actual amount of charcoal, biomass, plantation areas, and fertilizer required to support charcoal-based ironmaking (see Section 3.4).

As indicated in **Table 42**, 462.76 MMt of charcoal is required to sustain the current production rate of HM. The total charcoal output in 2005 was only 9.89 MMt charcoal [98]. Therefore, in that year, the entire charcoal production would only suffice to sustain 2.14 % of the global HM

production in 2012 (~23.77 MMt HM). This naturally presents a challenge for the further growth of charcoal-based ironmaking.

Similarly, to sustain the current trend of iron production completely, the present work estimates that 3,979 MMt of biomass are required. Consequently, a total of 132.66 MMha^{xlii} of plantation areas should be deployed to generate biomass from primary sources (e.g., eucalyptus, pine). Under a different set of assumptions of charcoal yield, Piketty et al. (2007) [220], estimated that 1 MMt HM requires ~129,000 ha (1,290 km²) of plantation area. Under the assumptions of Piketty et al., 143.5 MMha would be required to sustain the global iron industry. While both calculations may differ slightly (by above 8 %), both analyses show the exorbitant dimensions of plantation areas required if charcoal ironmaking were to become widespread. Additionally, 21.89 MMt of fertilizer would be used for the production of biomass necessary for charcoal making. **Table 42** summarizes the estimated amounts of charcoal, biomass, plantation areas, and fertilizer required as a function of the coal/coke replacement rate.

Table 42. Estimated amounts of charcoal, biomass, plantation areas and fertilizer Required to sustain a charcoal replacement in ironmaking (2012)

	Charcoal replacement rate			
	Unit	100 %	25 %	10 %
Charcoal ⁱ	MMt	462.76	115.69	46.28
Biomass ⁱ	MMt	3,979.72	994.93	397.97
Plantation areas ⁱⁱ	MMha	132.66	33.16	13.27
Fertilizer consumption ⁱⁱⁱ	MMt	21.89	5.47	2.19

Amounts calculated based on the following assumptions:

$$^i t_{\text{charcoal}} = 0.416 t_{\text{HM}}$$

$$^i t_{\text{biomass}} = 8.6 t_{\text{charcoal}}$$

$$^{ii} A/y = 30 t_{\text{biomass}}$$

$$^{iii} t_{\text{fertilizer}} = (t_{\text{fertilizer}} / 0.165) * (A/y)$$

Based on the results in **Table 42**, a complete or even a partial replacement of coke by biomass char would consequently lead to dedicated large areas of plantation areas. Despite the possible CO₂ mitigation offered by the re-introduction of charcoal in ironmaking, the author considers the further proliferation of BFs fueled 100 % with charcoal to be very challenging. On one hand, some countries with significant HM production (e.g., Japan, South Korea, and China) lack sufficient arable land to generate the necessary biomass to partially substitute coal.

^{xlii} MMha = Millions of hectares

Additionally, in countries such as China, Russia, India, or USA, it is unlikely that vast areas of arable land will be used to grow trees for charcoal making. Even today, Brazil dedicates only 4.78 MMha to the cultivation of eucalyptus for charcoal making (Melo, 2012) [105].

The estimates from the present work and previous analysis of the literature reveal that the main limiting factors for further deployment of charcoal in ironmaking are availability of large plantation areas, biomass availability, and economic factors. All of these limitations could be partially offset by substituting agricultural and forestry residues (residual biomass) for primary wood (e.g., logs). Sources of residual biomass may include agricultural residues, forestry residues, and mill residues. Arguably, the residual biomass allows for multiple products with a reduced demand for land (Gregg and Smith, 2010) [116]. From an economic perspective, the residual biomasses are significantly less expensive than primary biomass.

4.3. Paper III

TECHNOLOGICAL, ECOLOGICAL AND ECONOMIC ASSESSMENT OF THE COKE BASED BLAST FURNACE OPERATION WITH CHARCOAL INJECTION

In the proceedings of METAL 2014, Brno, Czech Republic 2014.

The proposed biomass char injection (Bio-PCI) is aimed at replacing coal as the auxiliary fuel in coke-BFs. Therefore, paper III intends to assess, by simulation, the effect of Bio-PCI on the principal production parameters of a traditional coke-BF. Thus, this work presents three fundamental research questions:

- *What is the effect of Bio-PCI introduction on the chemical composition of hot metal, slag, and top gas in a coke-BF?*
- *What is the CO₂ reduction of a coke-BF operating with Bio-PCI?*
- *What is the effect of Bio-PCI introduction on the economy of a coke-BF?*

In order to answer these questions, the operation of the POSCO BF 5 (a highly fuel efficient BF) was reproduced using Steel University's *Blast furnace simulation tool* [200]. The simulation substituted the auxiliary coal injected through the PCI rigs with charcoal (Bio-PCI), which presented different chemical compositions and prices (see **Table 33**). For the purposes

of the assessment in both cases, the injection ratio was maintained at 180 kg/t HM. **Figure 48** (b) presents the schematic outline of system boundary used in the study.

4.3.1. Effect of Bio-PCI over coke-BF's products and by-products

The results of the simulations are depicted in **Figure 53**. These findings show that, with the chemical composition used, BF's operating with charcoal (Bio-PCI) would generate less slag—167.76 kg/t HM compared with 182.84 kg/t HM in the case of traditional coal injection. These findings are consistent with industrial experiences in Brazil, in which charcoal-based BF's operate with less slag (Nascimento et al. 2007) [125]. This could be explained by the lower ash content of charcoal than coal (0.50 % compared to 9.73 %). However, top gas generation in both cases are quite similar—1,888.9 kg/t HM in the case of PCI and 1,888.7 kg/t HM in the case of Bio-PCI (see **Figure 53**).

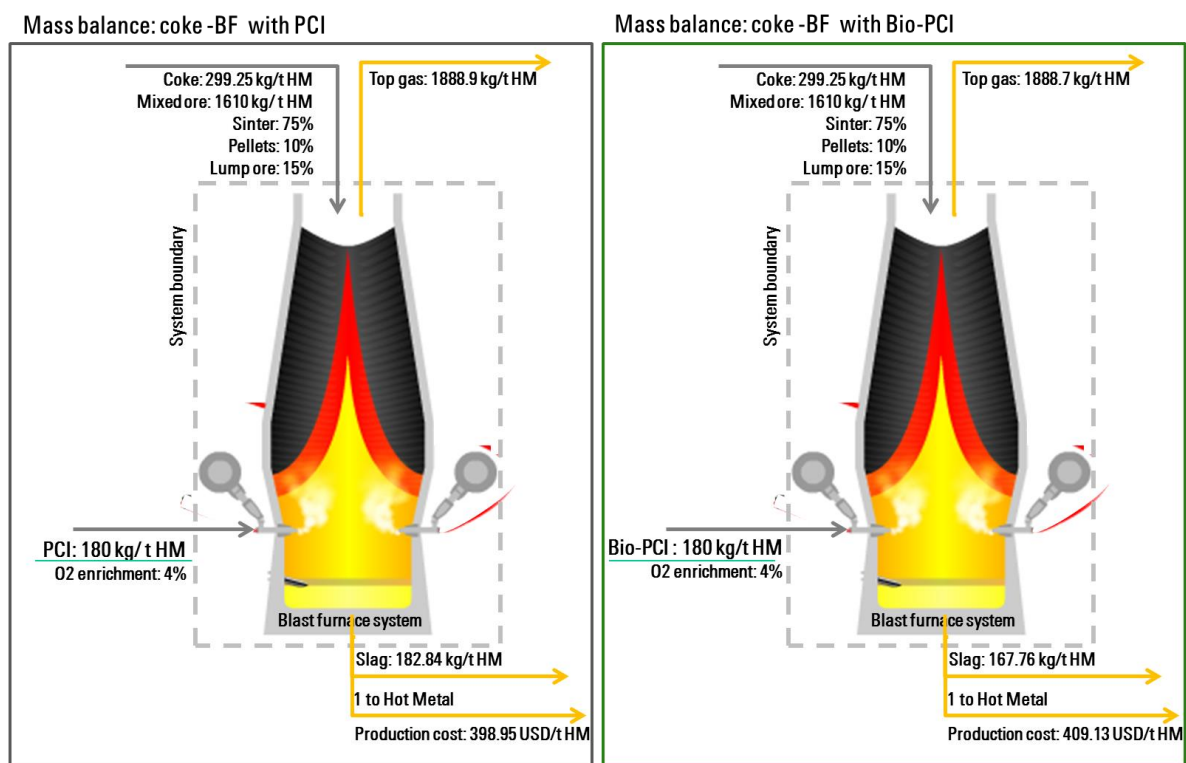


Figure 53. Mass balance of BF system with coal (left) and charcoal (right) as auxiliary fuel

With respect to the case of HM, slag, and top gas chemistry, the results of simulation are shown in in **Table 43**. The chemical analysis of HM, slag, and top gas present similar values in all cases. These findings show that in spite of the different chemical compositions of coal and

charcoal (see **Table 43**), the injection of charcoal does not negatively influence operation of the coke-BF.

Table 43. Chemical composition of hot metal, slag composition and top gas with coal and charcoal injection

Hot metal	PCI	Bio-PCI	Slag	PCI	Bio-PCI	Top gas	PCI	Bio-PCI
	Wt. %	Wt. %		Wt. %	Wt. %		Wt. %	Wt. %
C	3.5	3.5	FeO	2	2.18	CO	29.5	29.48
Si	1.1	1.1	CaO	37.44	40.58	CO ₂	21.28	21.58
Mn	0.28	0.28	SiO ₂	36.89	33.8	N ₂	49.09	48.79
Ti	0.01	0.01	Al ₂ O ₃	15.31	14.59	CH ₄	0.56	0.57
S	0.02	0.02	MgO	9.36	10.02			
P	0.08	0.08	MnO	1.99	1.99			

Before performing the simulation, the author was expecting to see some reduction in the sulfur content, as the sulfur content of coal is 0.39 % and charcoal is 0.02 %. However, in both cases the HM sulfur content was 0.02 %. It can be inferred that in both cases, coke was the main source of most of the sulfur dissolved into the HM (sulfur content 0.65 %).

4.3.2. CO₂ mitigation potential

For the study, the potential CO₂ reduction was estimated. The injection of charcoal for the processing conditions of POSCO BF 5 would lead to a reduction of 34.72 % of CO₂ emissions in comparison to traditional BF operation with coal injection. Such results are congruent with the findings of papers IV and V and previous assessments of Hanrot et al. (2009) and Mathieson et al. (2011), which emphasize the CO₂ mitigation potential of Bio-PCI [26,142].

4.3.3. Economic impact of Bio-PCI

This final section assesses the economic impact of charcoal substitution. According to the results, the production of one ton of HM with coal injection would cost 398.95 USD/t HM, while the production of a ton of HM with charcoal injection would have led to a HM production cost of 409.13 USD/t HM. This infers that the implementation of Bio-PCI would increase the production cost of HM.

The reason for the increase in production cost expressed in paper III can be found in the significant price difference between fossil coal and renewable charcoal, which for the present investigation was 134.00 and 181.34 USD/t, respectively. These coal and charcoal prices were the default prices available in the simulation tool.^{XLIII}. However, the price of charcoal can vary significantly according to the country (refer to paper VI). For instance, in Brazil, charcoal can have a price of 270 USD/t, while in Japan the price can be 570 USD/t. Therefore, if the charcoal prices used had been more realistic, the increase in production cost would have been significantly higher.

^{XLIII} The Steeluniversity simulation does not accept changes in the prices of raw material.

4.4. Paper IV

BIO-PCI A RENEWABLE REDUCTANT FOR BF_s: CO₂ MITIGATION POTENTIAL AND ECONOMICAL ASSESSMENT

In journal: Journal of Material Research and Technology, 2014

Originally in proceedings of the 6th International Congress on the Science and Technology of Ironmaking, Rio de Janeiro, Brazil 2012

The objectives of paper IV are to assess the effect of Bio-PCI over the CO₂ mitigation potential and its impact over the economy of common coke-BFs. In this respect, paper IV presents several research questions:

- *What is the potential CO₂ reduction in the coke-BF process with Bio-PCI?*
- *How can charcoal prices influence the economics of HM production in a coke-BF with Bio-PCI?*
- *How can carbon taxes influence the economics of HM production in a coke-BF with Bio-PCI?*
- *Which countries present the best prospects for Bio-PCI deployment in BF_s?*

4.4.1. CO₂ reduction potential

Firstly, to quantify the environmental benefit of Bio-PCI, the CO₂ abatement potential for the selected BF_s was estimated based on the fact that 1 kg Bio-PCI offsets 1 kg PCI.

In the cases studied, the potential CO₂ reduction accounts for 0.28 to 0.59 t CO₂/t HM (18.0–40.2 %) when Bio-PCI is used instead of fossil fuels (see **Figure 54**). Consequently, BF operating with high PCI rates would profit from a larger reduction of CO₂, which is the case of Baosteel, Posco, and AM Eisenhüttenstadt, where current PCI injection rates are 208, 180, and 176.9 kg PCI/t HM respectively.

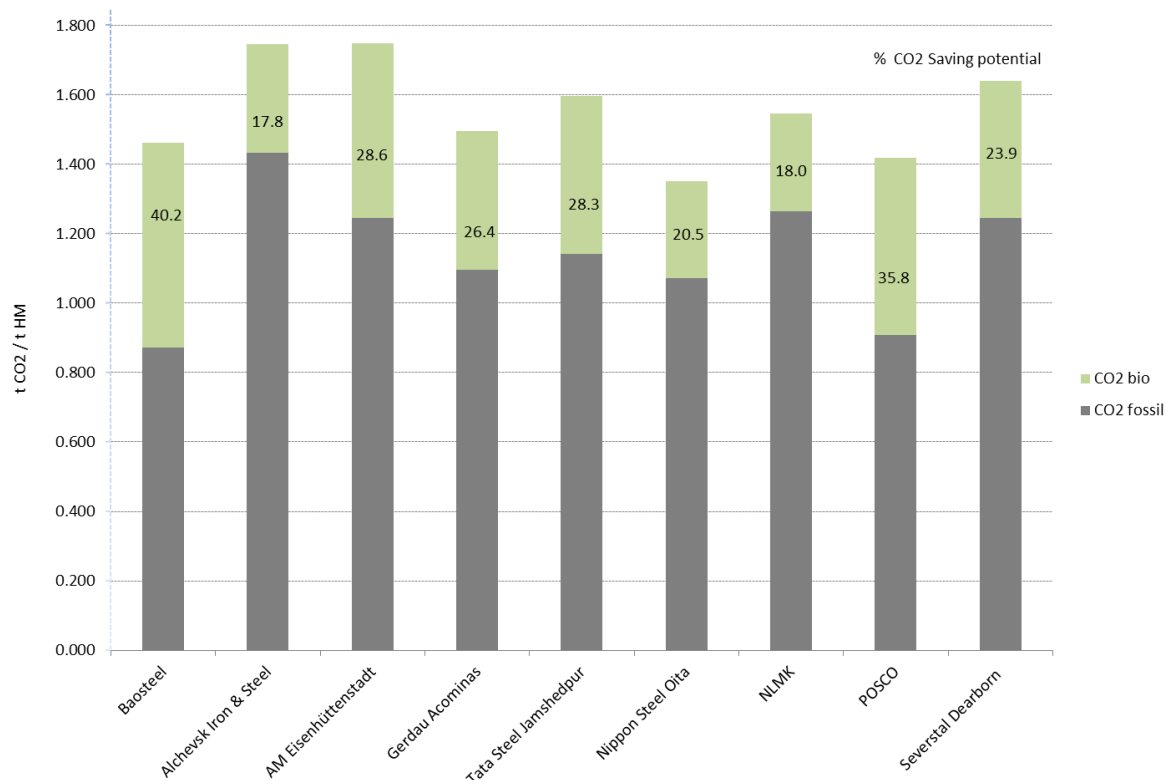


Figure 54. CO₂ saving potential using Bio-PCI

The results presented here are congruent with previous mitigation prospects of biomass char injection calculated by Hanrot et al. (2009) [142], Mathieson et al. (2011) [141], and paper IV, which estimates the potential CO₂ emission savings as 19–40 % CO₂. These findings clearly indicate that Bio-PCI may significantly reduce CO₂ emissions in coke-BFs.

4.4.2. Economic prospects of Bio-PCI

To analyze the economic scenario of Bio-PCI utilization, the present work utilizes a cost objective function (F). In this case, F allows the measurement and comparison of the economics of ironmaking in BF in terms of the specific costs of raw materials with compensation for the heating value of top gas. **Figure 48** (b) presents the actual system boundaries considered in the simulation, it is important to note that the model assumes that biomass pyrolysis occurs outside of the iron plant.

Model F is aimed at showing how principal HM input prices can influence production costs through a cost benchmarking type of approach. The model proposed has been largely used in

the literature for the assessment of the economic prospects of technological innovations in iron- and steel-making [192,193,194,195,196,197]. F is summarized in the Equation 7.

With respect to the data used for estimates, actual BF operational parameters from representative data available in the literature were utilized. The processing data comes from the literature about the operation of the following BFs: *Baosteel (China)*, *Nippon Steel (Japan)*, *NLMK (Russia)*, *Posco (South Korea)*, *Tata Steel Jamshedpur (India)*, *Gerdau Acominas (Brazil)*, *Severstal Dearborn (USA)*, *Alchevsk Iron and Steel (Ukraine)* and *AM Eisenhüttenstadt (Germany)* [201,202,203,204,205,206,207,208]. The top gas composition and its heating value were calculated for each case using the BF simulation from *Steel University* [200], as top gas generates valuable power that can be used in other areas of the steel mills. The parameters used in the calculation of F are shown in **Table 34**.

For the economic assessment, a total of 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 the calculations. Therefore, a price reported for charcoal-ironmaking (270 USD/t) was used for the calculations (Steel Business Bulletin). The iron ore and pellet prices are average prices from 2010–2012 (March) (Metal Bulletin), while the sinter prices were estimated. Industrial electricity costs were obtained from data from the International Agency of Energy. The complete list of costs used in F is shown in **Table 40**.

With regards to the carbon taxes shown in **Table 40**, they come from current regulations. This is the case of India, Germany, and the USA^{XLIV}; while other values reported in the media are likely to be imposed in South Korea and Japan. The literature review of this work could not find any determined value of carbon taxes in China, Russia, Brazil, or Ukraine

Results for Bio-PCI incorporation show that its deployment would have a significant impact on the final cost of HM. When biochar completely substitutes coal as the auxiliary injection fuel, F increases from 5.20 % to 16.61 %, as shown in **Table 44**. The F value shows a higher dependency on charcoal cost than on the existing carbon tax. Gerdau Açominas presents a

^{XLIV} No nationwide CT; taxes have been introduced in Colorado, California, and Maryland. The value in the state of Maryland has been used in this paper (5 USD/t CO₂).

production cost difference of 5.20 % due to a relatively low charcoal price in Brazil. In the case of POSCO, F increases by 6.48 % due to the carbon tax to be implemented (33.25 USD/t CO₂). In contrast, NLMK and Baosteel show a large increase in production cost due to the absence of any carbon tax, the relative expense of charcoal, and the low cost of industrial electricity.

Table 44. Objective function cost (F) using PCI and Bio-PCI

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

The charcoal prices ascertained in the survey carried out for the development of this work, fully agree with biomass char prices found in the literature (see **Table 29**). Charcoal prices are 270–570 USD/t in the cases studied, with Brazil showing the lowest cost for charcoal. With respect to charcoal production, Brazil is the top charcoal producer, followed by India, USA, and China [98]. Countries with small or no charcoal production, such as Germany, Japan, and Russia, present the largest price difference between coal and charcoal.

According to the estimates, to be economically competitive, biochar prices should be 130–236.4 USD/t under the actual and prospective carbon taxes schemes (**Table 45**).

One reason for the significant price difference between renewable charcoal and fossil coal might be the source of biomass. For the present calculations, all charcoals included were produced from hardwood (e.g., oak, eucalyptus), which is significantly more expensive than residual biomass. Residual biomass (e.g., agricultural and forestry residues) presents lower prices than hardwood and can produce charcoal of reasonable quality in term of heating value.

Table 45. Estimated biochar prices necessary to be competitive with coal

Case	Estimated biochar prices USD/t
Baosteel BF3	134.6
Nippon Steel Oita	207.8
NLMK	151.7
POSCO	236.4
Tata Steel Jamshedpur BF H	133.5
Gerdau Acominas BF 2	147.9
Severstal Dearborn BF C	130.1
Alchevsk Iron & Steel BF 1	140.2
AM Eisenhüttenstadt	189.3

4.4.3. Effect of carbon taxes

Another feasible alternative to reduce the price difference between renewable and fossil PCI is the implementation of a carbon price by means of carbon credits and/or carbon tax. With major simplification, *carbon credits* can be defined as allowances generated from carbon sequestration that occurs during biomass growth. These allowances can later be traded. On the other hand, carbon taxes are penalties paid by CO₂ emitters.

The price of carbon taxation that could make Bio-PCI economically competitive was estimated and the results are presented in **Figure 55**. According to the findings, carbon taxes in the range of 47.1–198.7 USD/t CO₂ are necessary, in order to be economically feasible. The cost of taxation significantly varies among the countries studied. While Brazil, China, the USA, and India present relatively low carbon tax values (47.1, 69.7, 69.7, and 70.8 USD/t CO₂, respectively), the taxes necessary for Russia, Japan, and Germany are considerably higher (198.7, 132.9, and 125.4 USD/t CO₂, respectively).

The cost implication on HM production with a carbon tax of 43 USD/t CO₂ in all studied processes was calculated (Swedish carbon tax) [221]. This scenario is illustrated in **Figure 55** (dark bars). In this case, when Bio-PCI substitutes fossil PCI, a change in F in the range of 0.42–11.58 % occurs. Countries such as China, Japan, South Korea, India, Brazil, the USA, and Ukraine present a difference smaller than 7 % in the value of F.

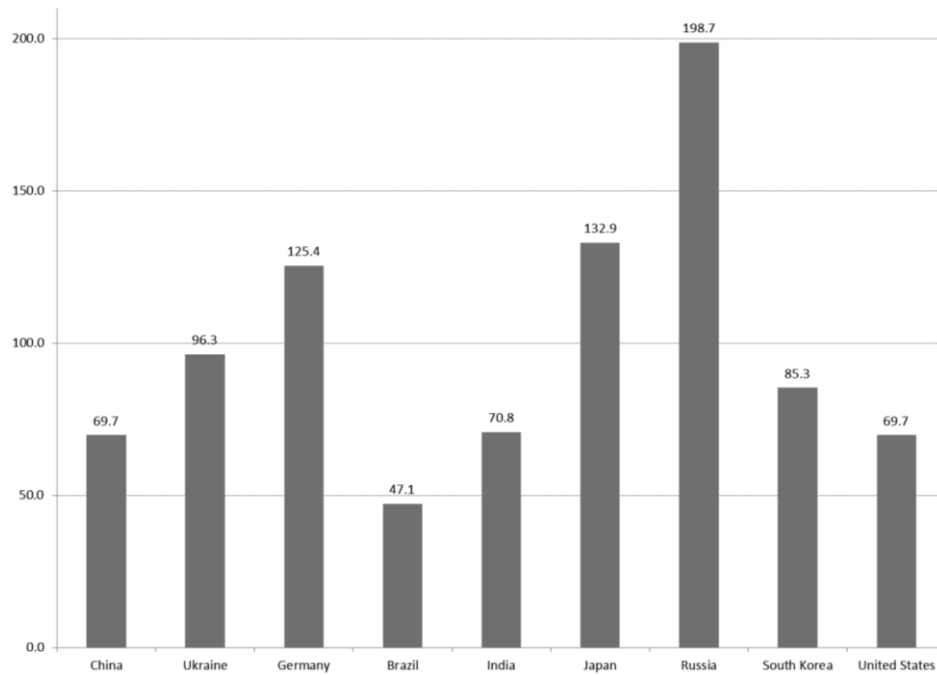


Figure 55. Carbon tax level necessary for Bio-PCI to be economically competitive

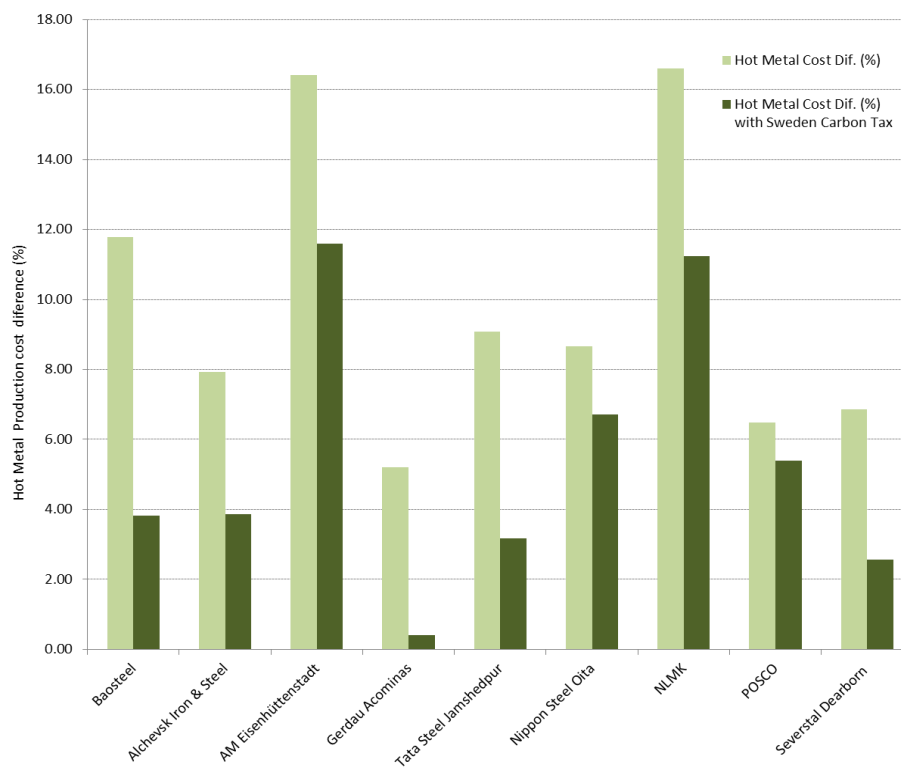


Figure 56. Cost difference of Bio-PCI implementation:
Current carbon taxes (pale green), Swedish carbon tax (dark green)

The present results are in agreement with previous calculations made by Norgate and Langberg [25]. In their assessment, based on a life cycle analysis, it was determined that a carbon tax of 95-115 USD/t CO₂ is required to be economically competitive for complete charcoal substitution.

The results described in previous sections infer that Bio-PCI is a feasible initiative to reduce one-quarter of the CO₂ emissions in BF (see **Figure 54**). Nevertheless, under present conditions, 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 emissions and give credits to carbon sequestration; arguably, the cost of carbon may be the driving force for the emergence of renewable fuels in coke-BF.

4.4.4. Which countries present the best prospect for Bio-PCI deployment

Finally, some words about the countries with best options to incorporate Bio-PCI. The analysis of the economic effects of biomass char shows that Brazil presents the best prospects for its deployment for the following reasons:

1. Brazil has a large and consolidated charcoal industry; the metallurgical industry already consumes ~90 % of local charcoal production. Additionally, the charcoal fines (considered a low value sub-product) can be used for the purpose of Bio-PCI (in coke- and charcoal-based BF). Moreover, the only 46 known industrial references on Bio-PCI actually come from Brazil.
2. The country is the only producer of charcoal-based HM; 23 % of Brazil's production in 2011 was generated in charcoal-based BF.
3. Vast areas of land are used to generate biomass for charcoal making. According to Melo (2012), 4.87 million hectares are dedicated to the cultivation of eucalyptus for charcoal making [105].
4. There are no indigenous sources of coking coal (essential for coke making); thus, most of the metallurgical industry in Brazil depends on coal and coke imported from overseas.

Nonetheless, a challenge to overcome for the charcoal industry in Brazil is the sustainability of carbonization. In 2005, 52.8 % of the country's charcoal was produced from deforestation, and only 47 % was produced from sustainable forestry plantations [118]. The implementation of a carbon tax of 47.1 USD/t CO₂ may help to improve the prospects of biomass char in coke-BF.

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

- *Relatively low cost of charcoal:* India, China, and the USA also have a consolidated charcoal industry with relatively low costs (320, 330, and 360 USD/t, respectively). Thus, the impact of Bio-PCI on 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 the significant consumption of steel, mainly manufactured in integrated mills.

The carbon tax necessary to make Bio-PCI competitive is below 70 USD/t CO₂, which is low in comparison to Russia, Japan and Germany.

Our assessment indicates that Japan, Germany, and Ukraine have significantly fewer prospects to deploy Bio-PCI due to the elevated cost of charcoal (510, 480, and 370 USD/t, respectively), which is caused by limited local charcoal production. According to our calculations, rather expensive carbon taxes of 132.9, 125.4, and 96.3 USD/t CO₂ are necessary for Bio-PCI to become economically attractive in Japan, Germany, and Ukraine, respectively.

With respect to Russia and South Korea, it is necessary to gather more data regarding charcoal prices to draw a conclusion.

4.5. Paper V

CHARCOAL INJECTION IN BLAST FURNACES (BIO-PCI): ENVIRONMENTAL, TECHNICAL AND ECONOMICAL ANALYSIS

In proceedings of Sustainable Development Seminar, 19th IAS Steel Conference, Rosario, Argentina 2013

Paper V aims to reproduce the simultaneous injection of coal and charcoal (known as co-injection) and their main impacts on CO₂ emissions and economy in the BF process. In this respect, paper V focuses on responding to the following research questions:

- *What is the potential CO₂ reduction of co-injection of charcoal and coal?*
- *How does co-injection affect the economy of a coke-BF operation?*
- *How can carbon taxes influence the economics of HM production in a coke-BF with Bio-PCI and coal co-injection?*

To provide an answer to the above questions, the operation of the BF 3 at BAOSTEEL (a highly fuel efficient BF) was reproduced using the Steel University's Blast Furnace simulation tool. The simulations substituted the auxiliary coal injected through the tuyeres (PCI) with charcoal (Bio-PCI), which presented different chemical compositions. For the purposes of the assessment, the maximum injection rate of charcoal was 208 kg/t HM. **Figure 48** presents the schematic outline of the system boundaries used in the study. It is important to note that the system appears quite similar to that used in paper IV, but the case of **Figure 48** does not consider any energy offset by transformation of top gas into electrical energy for the steel work.

In the present case, the aim was to measure the effect of Bio-PCI incorporation in the process. For this purpose, a cost objective function (F) was used. F takes into consideration the primary costs of BF operation, pellets, lumps and sinter, coke, coal, charcoal, and even carbon taxes, which are based on utilization rates, products, and by-products. F provides an indication of the production cost of HM when fossil-based coal for PCI is substituted by charcoal (Bio-PCI) (see Equation 7).

4.5.1. Bio-PCI: CO₂ reduction potential and economic impact

The results show that the maximum injection rate of 208 kg charcoal/t HM can lead to a mitigation potential of 0.592 t CO₂/t HM, which represent a reduction of 40.8 % of emissions of the BF process in comparison to traditional coal injection.

In spite of the environmental benefits, as CO₂ emissions reduce with the increase of charcoal injection, there is consequently an increase in the HM production cost (represented by the increase in F) (see **Figure 57**). The Bio-PCI implementation may increase the F of HM production by 11.75 % in the absence of any carbon tax or carbon-trading scheme. This leads

us to conclude that while Bio-PCI is beneficial in environmental terms; its deployment also negatively affects HM production costs.

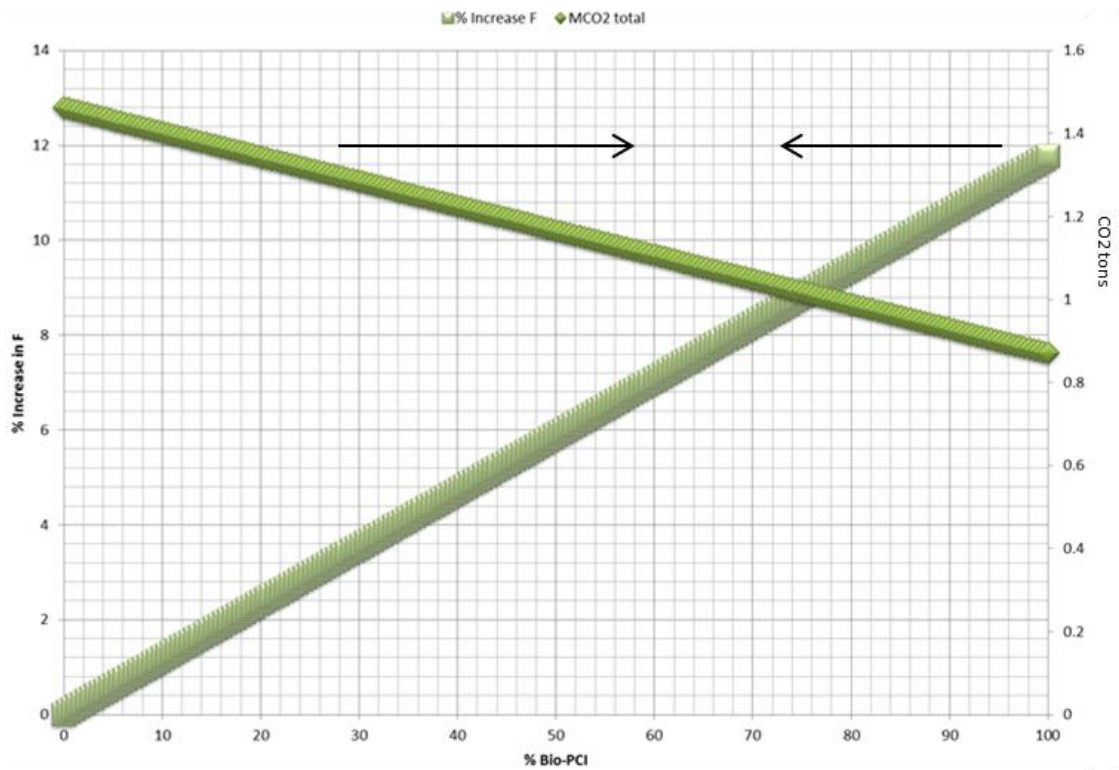


Figure 57. CO₂ mitigation potential and economic impact as function of Bio-PCI utilization

4.5.2. Assessment of carbon taxes

Based on the previous calculations, different carbon tax levels necessary to introduce the Bio-PCI were estimated. According to the findings, the carbon tax required to make the introduction of Bio-PCI economically competitive is 173.6 USD/t CO₂. These results agree with the findings in paper V and previous investigations by Norgate and Lambert (2009) [25].

4.6. Paper VI

BIO-PCI, CHARCOAL INJECTION IN BLAST FURNACES: STATE OF THE ART AND ECONOMIC PERSPECTIVES

In journal: Revista de Metalurgia, 2013

Originally in proceedings of: 5th Steel Industry Conference and Exposition, CONAC 2012, Monterrey, Mexico 2012

Previous analysis in the literature and works by the author (see papers III, IV, and V) debate the necessity of reducing the cost of biochar. They mentioned the possible use of residual biomass for charcoal making. In this sense, paper VI builds on the topic of charcoal production from forestry and agricultural residues (residual biomass) for the purpose of Bio-PCI and focuses on the following strategic questions:

- *What is the effect of biomass cost on the biomass char production cost?*
- *How does the use of residual biomass affect the economics of biomass char production?*
- *How does the use of residual biomass affect the technical features of biomass char?*

4.6.1. Charcoal production cost

In order to analyze the relative value of biomass in charcoal production, the production costs of charcoal from different sources are compared in **Table 46**. As shown, between 10.9–67.6 % of the total charcoal production cost is represented by biomass. The biomaterials used in brick kilns and continuous retorts come from primary (wood) or secondary (agricultural and forestry residues) sources. Although the charcoal cost structures indicated in references A, B, F, and G date from 1985 and prices cannot be directly compared with other more recent references (C, D, and E), it is important to note the actual relative biomass cost in charcoal production. In this sense, lower relative biomass costs arise from charcoal manufactured out of secondary/residual sources (forestry and agricultural residues). This means a relative biomass cost ranging between 10.9–32.9 % (references F, G, and H in **Table 46**). Whereas, when charcoal was produced from primary wood sources, the relative cost of biomass is significantly higher (27.6–67.4 % (references A, B, C, D, and E). This indicates that biomass from secondary sources may help to reduce the price difference between fossil coal and charcoal.

4.6.2. Cost of primary and residual biomass

The author 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 charcoal making. The survey was carried out between February and April 2012. **Table 47** presents the prices reported. The bands vary from the minimum to maximum offered prices, with an average price of primary wood (eucalyptus, hardwood, etc.) and biomass residue (biomass briquettes, palm kernel, sawdust, etc.).

Table 46. Charcoal production cost analysis
Source: [142,163,222]

Reference (year)	Carbonization unit		Biomass source	Biomass cost	Biomass Relative cost	Total charcoal cost
				USD/t	(%)	USD/t
A	(1985)	Brick Kiln	Primary Wood	65	47.7	136.14
B	(1985)	Continuous retort	Primary Wood	43.4	27.6	157.1
C	(2011)		Primary Wood	390	50	780.0
D	(2011)		Primary Wood	91.6	36	254.6
E	(2009)	Continuous retort	Primary Wood	260	67.4	386
F	(1985)	Continuous retort	Forest residues	13.4	10.9	122.56
G	(1985)	Brick Kiln	Forest residues	30	32.9	91.14
H	(2011)		Agriculture residues	83	30.5	272.0
Cells in gray: Primary wood			Cells in white: biomass residues			

As shown in **Table 47**, primary wood prices rank between 303–395 USD/t, while biomass residue prices are between 72–155 USD/t. Thus, residual biomass costs are ~50 % more economical than are those of primary woods. Additionally with the use of biomass residues instead of primary wood, no vast areas of agricultural land are required to sustain the charcoal production.

Table 47. Survey of biomass costs

Type of biomass	No. consulted	Minimum price	Maximum price	Average price
		USD/t	USD/t	USD/t
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		

4.6.3. Technical specifications of residual biomass

With regards to the technical specifications of primary and residual biomass, **Table 48** compares some key parameters for charcoal making—for instance density, ash content, calorific value, volatile matter, and moisture content. The residual biomass analyzed is less dense, 900–1,300 kg/m³, than the primary biomass. In addition, the caloric value in the residual biomass is lower than in the primary biomass, but remains sufficiently attractive for the objective of charcoal production.

Table 48. Properties of primary and residual biomass
(Survey on biomass)

Biomass residue	Density (kg/m ³)	Ash (wt%)	Caloric value (kcal/kg)	Volatile matter (wt%)	Moisture content (wt%)
Eucalyptus	1,510	1.2	4,850	82.4	5.2
Acacia	1,440	1.00%	4,585	84	5.9
Peanut shell pellets	900-1,100	< 7 %	4,200-4,500		11
Saw dust pellets		1.00 %	4,500	83.46	45
Biomass briquettes		6.78 %	4,200	62-68	7.2-8.0
Rice husk briquettes		12.50 %	4,000	4.3	
Wood pellets	1,100	0.50 %	4,600	8	4.5
Corn straw pellets	1,100-1,300	8.00 %	3,800-4,200		9
Cells in gray: primary wood			Cells in white: biomass residues		

4.7. Paper VII

BIO-PCI A RENEWABLE REDUCTANT FOR IRON PRODUCTION: WHERE CAN IT FLOURISH?

In proceedings of the 4th Baosteel Biennial Academic Conference, Shanghai, China 2010

This paper provides a technological and metallurgical summary of the potential benefits of Bio-PCI in the iron and steel industry, and asks a strategic question:

- *Where is Bio-PCI innovation likely to be taken up soonest?*

In the opinion of the author, the actual deployment of Bio-PCI may have been limited by the traditional and relatively economically available fossil-based reductants, most prominently coke and coking coal, as well as the lack of international awareness of CO₂ emissions and legislation regulating its emissions.

The present analysis estimated that Bio-PCI has better prospects for development in emerging countries than in industrialized ones. In particular, Brazil, India, and certain areas of Southern China are identified as prime candidates to incorporate Bio-PCI.

These countries simultaneously comply with some minimum conditions: important land availability located in tropical and subtropical areas suitable for energy farming, relatively economical labor costs, and more importantly the prospects of a growing HM production based on BF.

Although these are fundamental conditions, they do not necessarily guarantee the development of a bio-fuel industry and its integration into the value chain of iron production. Moreover, other countries that do not satisfy those conditions may actually implement bio-reductant in their production—for instance Australia, Japan, Finland, Germany, or USA. Nonetheless, in our consideration, Brazil, followed by India and China, may be in a more favorable economic position than those previously mentioned.

5. Discussion of results

This chapter evaluates and assesses the results reported in the papers included in this thesis. The chapter is structured around the four major areas of contribution: environmental perspective, technical perspective, economic perspective, and strategic analysis.

5.1. Technical perspective

5.1.1. Limits of charcoal-ironmaking

Charcoal has been used in metallurgy since the beginning of ironmaking around 5,000 years ago. Indeed, for centuries, biomass chars were the only fuels/reductants available for iron production until Abraham Darby succeeded in producing iron, utilizing coke from coal rather than charcoal at Coalbrookdale (England) [9]. Since then, the technical feasibility and limitations of charcoal ironmaking have been amply researched and industrially proven. Coke has been substituted for charcoal almost globally, and in the 21st century, it is only possible to find charcoal-BFs in Brazil. The quality of output is known to be remarkable from the operation of the last 172 charcoal-BFs, according to the figures of Schrerer and Braga (2012) they produced in 2011, 7.6 MMt HM [14]; technical analysis reveals that the quality of HM is superior due to the low sulfur content. Additionally, charcoal-BFs generate less slag and operate with lower temperatures. Because of these advantageous features, charcoal-HM has higher market values (35 % more expensive than coke-HM). Additionally, charcoal-ironmaking is considered carbon neutral, as long as the biomass char is gained from industrial kilns and biomass is gained in a sustainable manner.

However, charcoal went from being the sole fuel used worldwide for metallurgy 300 years ago, to being only partially used in Brazil ^{XLV}. This reduction in use is due to the main limiting factors to support charcoal-based iron production: vast areas of arable land and the cost of biomass char. From a technical perspective, other elements that limit the proliferation of charcoal-BF include poor mechanical properties and low density.

^{XLV}During the writing of this dissertation, Paraguay's charcoal-BF ceased to produce.

The lack of sufficient crushing resistance makes it difficult (when not impossible) to completely substitute coke with charcoal in BFs larger than 600 m³, in this sense the **Figure 58** shows the working volume of some of the largest charcoal-BFs in Brazil. Because biomass char cannot support the weight of the burden, the crushing of charcoal can lead to undesired blockages in the permeability of BF. In addition, industrial experiences at Aperam report charcoal generates unwanted amounts of fines during transportation and storage, which leads to poor fuel efficiency and economic losses (Gonçalves et al. 2012) [15]. Furthermore, the porosity of charcoal results in high absorption of humidity, while its low density reduces the working volume of iron ore (pellets, sinter, or lumps) in the burden.

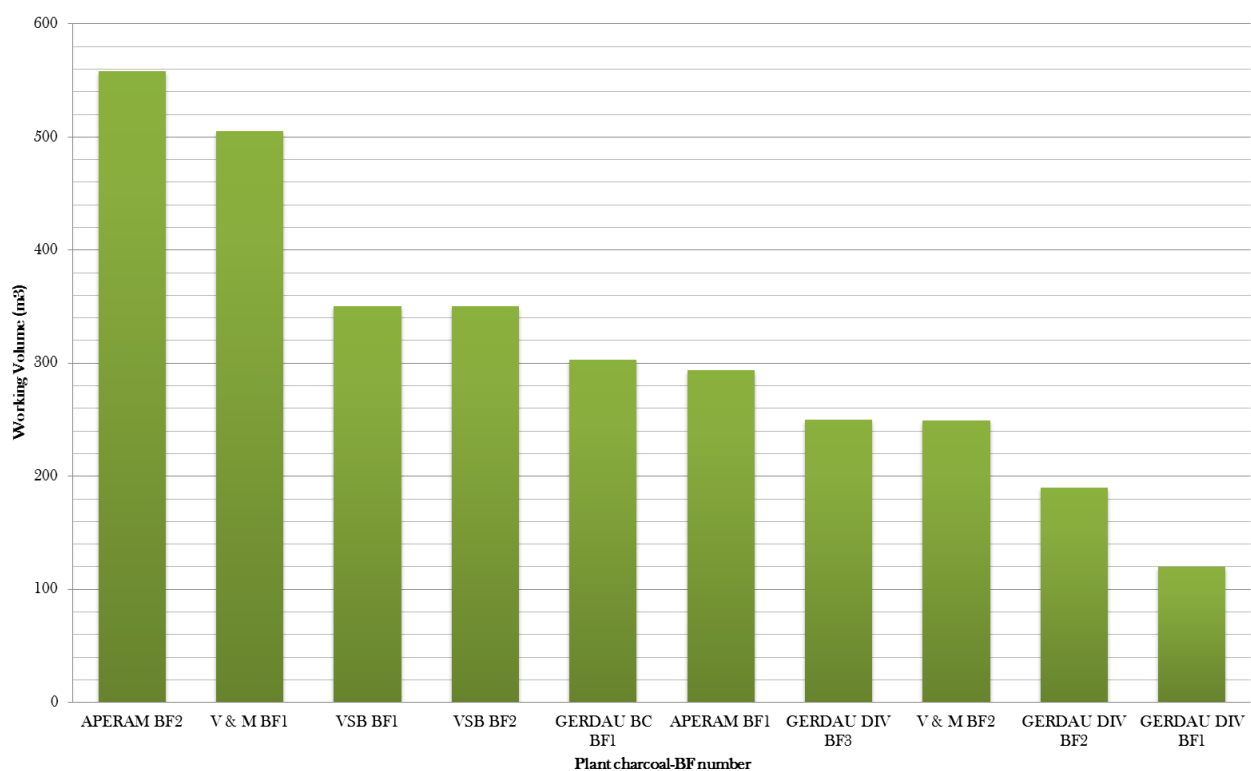


Figure 58. Working volume of some of the largest charcoal-BF in Brazil.

Source: Scherer and Braga (2012)

Based on these technical disadvantages, the author considers the further proliferation of an ironmaking industry based 100 % on biomass char to be very challenging. However, the injection of small biomass char particles (Bio-PCI) presents a feasible alternative. The next section discusses the technical features of this option.

5.1.2. Technical feasibility of Bio-PCI

Currently in Brazil, 46 BF_s inject charcoal fines to reduce the use of lump charcoal, as shown in the **Table 23** (installed capacity and number of charcoal-BF in the different states of Brazil), the current injection rates of charcoal fines (or *moinhas de carvão vegetal* in Portuguese) vary from 50 to 160 kg/t HM. In this sense, the highest injection rates reported in the literature are the BF₂ at Aperam and the BF₂ at Vallourec Mannesmann with 160 kg/t HM, While the BF at ArcelorMittal - Juiz de Fora injects 120 kg/t HM. As demonstrated through industrial practices, the Bio-PCI procedure is well known and technically proven (Assis, 1991) [223].

Technically, the injection of small biomass char pieces into a BF (Bio-PCI) has positive outcomes in coke-BF for the following reasons:

1. Biomass char does not need to sustain the burden; therefore, the lack of mechanical resistance does not matter.
2. The high porosity leads to a high reaction rate, which improves combustion.
3. Biomass char can be injected into a coke-BF. Thus, it is not necessary to completely replace coke or reduce the BF capacities.
4. Charcoal can be injected through the normal PCI rigs into the BF with minor adaptations/re-engineering of existing facilities.
5. Alternative biomass sources can be used, for instance forestry and agricultural residues (residual biomass). This avoids the use of vast areas of arable land and contributes to reducing the cost.

5.1.3. Bio-PCI in coke-BFs

The results of the simulations in Paper III show that the introduction of Bio-PCI in a coke-BF would not have any particular influence on the chemical composition of HM, slag, and top gas. Therefore, the findings in the simulation lead us to infer that Bio-PCI would not negatively affect the HM composition. Based on the results, it is concluded that the substitution of PCI (fossil coal) for Bio-PCI (biomass char) would not affect the operation of a normal coke-BF. Such findings agree with the industrial experience of BF₂ at Aperam, which operates with coke and biomass char are injected at a rate of 160 kg/t HM (Gonçalves et al. 2012) [15], also trial

experience at Voestalpine (Austria), in which biomass pellets were injected in the coke-BF A^{XLVI} at Voestalpine (Austria) reported by Bürgler et al. (2011) [152].

Additional results show that the coke-BF operating with Bio-PCI generated less slag—~ 8 % less slag than in the case of traditional PCI. These results are consistent with industrial experiences in Brazil, in which charcoal-BFs operate with less slag [125]. This is achieved because of the lower content of ash present in the biomass char.

Originally, a reduction in sulfur content was expected with the introduction of Bio-PCI. However, no noticeable reduction in the HM sulfur was observed. In both cases, most of the sulfur came from coke, which may explain this result.

According to the literature, charcoal BFs generate a higher calorific power in the top gas than coke BFs. Consequently, it was expected that the utilization of Bio-PCI in coke-BF would lead to a higher calorific power top gas. However, results of the simulation of nine coke-BFs do not show a significant variation in the top gas heat capacity when PCI or Bio-PCI is used (see **Table 43**). Apparently the replacement of coal by biomass char did not have a major effect on the top gas composition and consequently in its calorific power (as shown in **Table 49**).

^{XLVI}Trial carried out in the Linz Hochofen A at Voestalpine.

Table 49. Estimated top Gas composition

Case	Top gas Composition : Bio-PCI cases						Top gas Composition : PCI case					
	CO ₂ %	CO %	H ₂ %	N ₂ %	CH ₄ %	Heating value kJ/tHM	CO ₂ %	CO %	H ₂ %	N ₂ %	CH ₄ %	Heating value kJ/tHM
AM Eisenhüttenstadt	17.29	27.12	3.35	51.76	0.49	191.00	17.38	27.08	3.36	51.70	0.49	191.70
Baosteel BF3	20.73	23.02	4.05	51.71	0.49	165.10	21.40	23.50	4.15	50.46	0.50	164.90
Nippon Steel Oita	23.89	20.42	2.89	52.31	0.50	149.00	23.99	20.39	2.89	52.23	0.50	148.50
NLMK	24.94	25.54	2.97	45.99	0.56	137.10	25.03	25.51	2.97	45.92	0.56	136.70
Posco	21.84	22.30	3.82	51.54	0.49	158.00	22.01	22.26	3.83	51.41	0.49	157.10
Tata Steel Jamshedpur BF H	20.83	26.17	3.47	49.02	0.52	173.40	20.95	26.14	3.48	48.92	0.52	172.70
Gerdau Aconinas BF 2	20.62	23.12	3.21	52.57	0.49	165.50	20.74	23.08	3.22	52.48	0.49	164.80
Severstal Dearborn BF C	18.20	24.73	3.00	53.60	0.47	184.70	18.27	24.69	3.01	53.55	0.47	184.10
Alchevsk Iron & Steel BF 1	18.40	27.73	2.75	50.62	0.50	184.10	17.82	26.79	2.69	52.21	0.49	183.60
	Cells in white: Bio-PCI cases						Cells in gray: PCI cases					

^a estimate

5.2. Environmental perspective

5.2.1. CO₂ mitigation potential of biomass char

From an environmental viewpoint, the substitution of coal by biomass char in BFs can theoretically lead to a 100 % reduction in the CO₂ emissions associated with HM production. According to the estimates of Winter (2012), each ton of HM from a charcoal-BF liberates 1.5 t of O₂ and sequesters 2.4 t of CO₂ [17]. This fact has driven the interest of researchers worldwide to assess the chances of re-introduction of biomass in BFs, for instance Suopajarvi et al. (2014), Mathieson et al. (2011), Ueda (2009), and Gupta (2003) [27,87,126,163]. **Table 41** presents different scenarios of mitigation according to the charcoal substitution rate. For instance, the substitution of 25 % coke and coal for biomass char could save up to 572 MMt CO₂ per year. Based on this CO₂ reduction potential of biomass, the Australian steel industry and CSIRO launched in 2006 comprehensive research initiatives to reduce the industry's net GHG emission by at least 50 % (Jahanshahi et al. 2014) [140].

However, industrial practice reveals that charcoal-BFs are small in capacity, mainly because of the poor mechanical properties of biomass char to sustain the burden. Consequently, at this moment the largest BF has a working volume of only 658 m³ in APERAM (Brazil) [218].

Additionally, large plantation areas are required to generate the necessary biomass for charcoal making. In Brazil, the charcoal HM industry, also known as *carvão vegetal ferro gusa* industry, clearly illustrates the problems associated with charcoal-BF. In the country, 48,700 km² are dedicated to the production of eucalyptus, the main biomass used to generate charcoal in Brazil (Melo 2012) [105]. All of this charcoal fuels the last remaining 172 charcoal-BFs in operation, but these generated only 7.6 MM t HM in 2011. Therefore, Brazil utilizes large plantations to generate merely 23 % of the total HM production of the country, while the remaining 77 % of iron is produced in coke-BFs, with coal from overseas as the principal auxiliary fuel. Hardly any other country can dedicate similar plantation areas to the development of a biochar ironmaking industry. Moreover, there are additional criticisms that 'sustainable plantations' in Brazil generate so called 'green deserts' because of the damage to the native forestry and animals (Cardoso and Pires, 2013) [119].

Considering the facts, the introduction of biomass char injection through the PCI rigs in BF, called Bio-PCI, appears to be the most feasible future alternative for charcoal-ironmaking. It is a practicable way to mitigate part of the emissions from the current industrial practice, which principally fuels the BF process with coke, non-coking coal, natural gas, and tar. Most of the currently used fuels come from fossil endowments that ultimately contribute to GHG and global warming. In this sense, the estimates in the present work show that the introduction of Bio-PCI into coke-BFs can lead to a reduction of up to 40 % of the CO₂ emissions in the process. Previous assessments found in the literature also indicate similar CO₂ potential saving values (see **Table 50**) [26,27,142,143].

Table 50. Saving potential of Bio-PCI in coke-BF in different studies

Reference	Injection rate kg/t HM	CO ₂ potential reduction %
Paper III	180	34.72
Paper VI	208	40.2
Mathieson et al. (2011)	150-200	19-25
Suopajärvi and Fabritius (2012) [£]	98-142.5	15.4-26.4
Wang et al. (2015)	155	28.1
Hanrot et al. (2009)	200	28

[£] In this case, the injection of heavy oil was replaced with charcoal at a rate of 1/1.15. The authors also suggest that the injection of charcoal may increase the BF productivity.

Based on the findings of paper IV, the CO₂ potential savings were plotted against the biomass char injection/Bio-PCI (see **Figure 59**). As can be seen, there is a direct correlation between the rate of Bio-PCI and the total CO₂ mitigation. The results lead us to conclude that the achievable CO₂ reduction with Bio-PCI depends directly on the rate of Bio-PCI injection.

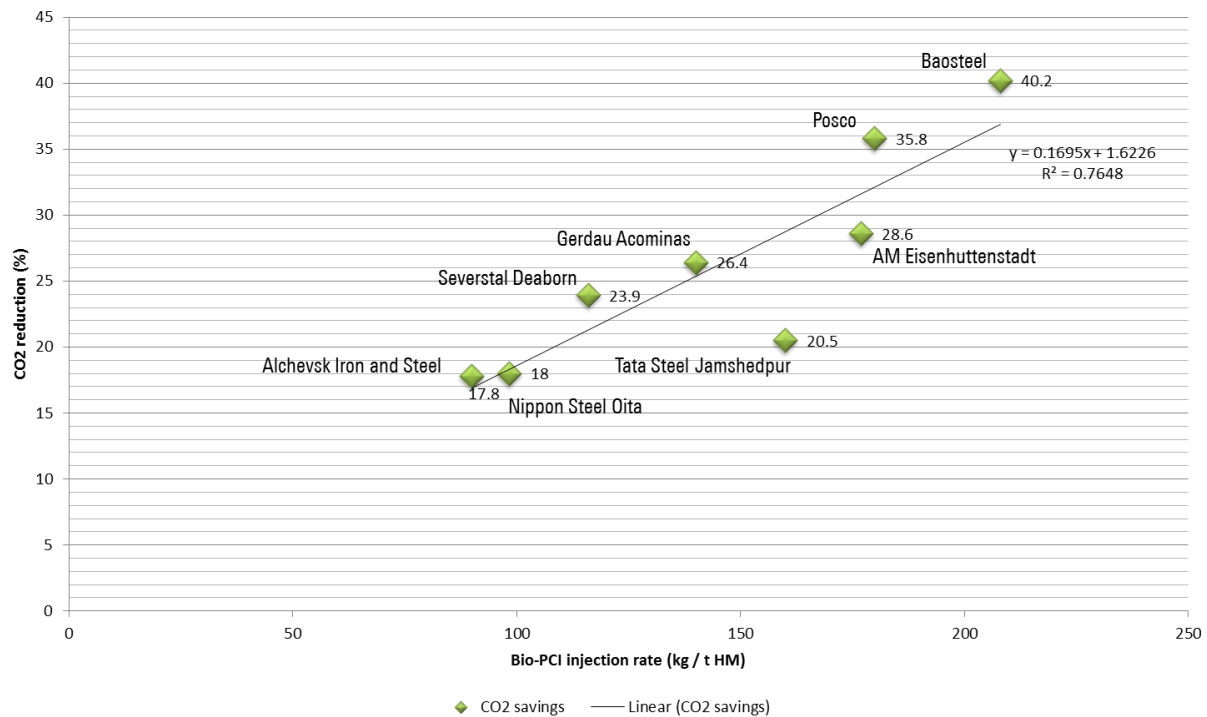


Figure 59. CO₂ reduction according to charcoal injection rate

5.2.2. Negative aspects of the re-surge of charcoal-ironmaking

Together with the positive mitigation prospects of charcoal-ironmaking, there are concerns about the negative aspects of the re-surge of charcoal-BF. Initially, there is a certain risk that any increase in the utilization of charcoal in iron- and steel-making will also lead to further deforestation, as a large portion of charcoal is currently generated from native forests (Nogueira et al. 2008) [118]. Paradoxically, the replacement of charcoal by coke was positive for the environment in the XVIII century because the technical innovation introduced by Abraham Darby (use of coke in BF) helped to prevent the deforestation of large parts of England and Germany. Until 1735, wood was the only fuel available for iron ore smelting. In this respect, **Table 51** summarizes the estimated amount of charcoal, fertilizer, and plantation areas required to sustain an increase of biomass char participation in ironmaking.

According to the present estimate, 1.32 MM km² (132.66 MMha) are required to sustain current rates of iron production globally. Under the assumptions of Piketty et al. (2007) [220] 1.43 MM km² (143.5 MMha) would be required to sustain the global iron industry. While both calculations may differ marginally (by >8 %), they both show the large dimension of plantation areas required if charcoal ironmaking is to prosper. As illustrated in **Table 51**, to replace just

10 % of the coke by charcoal, a plantation area of 132.70 MM km² ^{XLVII} (13,270 MMha) would be required. While, to replace just 25 % of the coal would require a plantation area of 330.000 km², in perspective, this represents 1/3 the total arable land of the European Union or the 56 % of the cultivation land in Brazil (according to the figures of the FAO) [224]. To dedicate such a vast arable area, nutrients, and water just to grow a fuel is economically, logistically, and ethically challenging. In the viewpoint of the author, it would be more profitable and ethical to dedicate such vast arable areas, water, and fertilizer to the production of food, pulp, paper, or other agricultural products.

Table 51. Plantation areas required to sustain hot metal production, 2012

Annual production (2012)		Charcoal substitution rate			
		100 %	50 %	25 %	10 %
Hot metal (2012)	TMt	1,112.40	556.2	278,100	111,240
Charcoal consumption [§] (estimated)	TMt	462,760	231,380	115,690	46,280
Plantation area ^{§§} (estimated)	MMkm ²	1.32	0.66	0.33	0.13
Fertilizer consumption ^{§§§} (estimated)	TMt	803.98	401.99	201	80.4

§ Charcoal utilization calculation based on injection rates of 416 kg/ton HM

§§ Plantation areas calculated under the following constrains: 8.6 t Biomass/t Biochar, biomass yield of 30 t_{biomass}/ha/y.

§§§ Fertilizer consumption calculated under following constrains: 165 kg Fertilizer/ha/y

In addition, there are concerns about the negative impact of artisanal and semi-industrial charcoal production on GHG balances (Garcia-Perez, et al. 2010) [99]. For instance, it was estimated that the charcoal production in Brazil generates 0.54 MMt of methane, which corresponds to a contribution of 11.3 MMt CO₂ equivalent to GHG (CGEE 2014) [103]. The significant methane release from outdated carbonization units hinders the optimism portrait of the palliative effects of good plantation management on deforestation impacts. Therefore, the present work strongly supports the idea that any increase in biomass char utilization to replace fossil fuels in metallurgy should be accompanied by the generation of biomass in a sustainable manner and the introduction of processes with high carbonization efficiency. For instance, state-of-the art pyrolysis allow usage of the exhausted heat to dry out the biomass, permit the

^{XLVII} MM Km² = Millions of square kilometers

collection of by-products generated during pyrolysis, and present a high yield of char (up to 36 %). It is not possible to produce such results with traditional beehive kilns that show a low charcoal yield of <25 %.

5.2.3. Role of residual biomass

Paper VI discusses the possible usage of residual biomass, from agricultural or forestry industries, to produce biomass char. The utilization of residual biomass instead of primary biomass can significantly reduce the production costs, but additionally can help to decrease the plantation areas required to generate charcoal. Greg and Smith (2010) argue that residual biomass can be used for the production of energy without any additional plantation area; some examples are mentioned in **Table 22** [116]. In academia, the possibility of carbonization of residual biomass such as bamboo, palm oil, rice husk, bagasse, sugar cane bagasse, elephant grass, coffee husk, and eucalyptus bark has been demonstrated (Chen et al. 2012; Assis et al. 2014) [28,29,150].

Additionally, there is already one documented experience of the utilization of Bio-PCI from residual biomass: USIPAR (Brazil), where biomass char from asahi seeds (*Euterpe oleracea*) are used. This residual biomass (asahi seeds) is an abundant agricultural by-product in the *Para* region, with no other industrial use [225]. Moreover, there have been several investigations into the torrefaction and injection of bamboo, banyan, willow, and rice husk [28,29,226,227] in BFs, with promising results for metallurgists. Additionally, new process of carbonization are primarily intended to process residual biomass (for instance, forest residues and wood wastes), this is the case of the CSIRO pyrolysis process, where the biomass in the reactor is heated spontaneously by exothermic pyrolysis reactions (other than combustion) without supply of any external heat or air to the reactor (Deev et al. 2015) [228].

The author also acknowledges that the present work focuses on biomass char ironmaking and Bio-PCI. Nevertheless, there are other plausible alternatives to reduce the CO₂ emissions in the iron and steel making processes with the use of biomass char. For instance, there are some interesting industrial experiences in the use of biochar as fuel for sinter production at Viena, Sidepar, and Cosipar (Brazil) [16]. Additionally, previous studies have also demonstrated the technical feasibility of using biomass char in other industrial applications, for instance, as a replacement for BF nut coke, as an iron ore composite, as a coke making blend component,

and as a steel recarburizer. With all the above-mentioned alternatives combined, Mathieson et al. estimate that up to 58 % of the CO₂ emissions from the steelmaking process can be reduced [141]. It is important to mention that the assessment of Mathieson et al. also presents Bio-PCI as the single largest possible contributor to CO₂ mitigation.

Finally, it is worthwhile considering opinions about the future prospects of biomass carbonization for ironmaking. In fact, the use of biomass offers a realistic opportunity to significantly reduce the CO₂ emission in BFs. However, certain elements should be considered for the future deployment. Firstly, the present work considers it fundamental that any further participation of biomass in iron- and steel-making should be done on a sustainable basis using wood or residual biomass gained from well-managed plantations. Secondly, it is mandatory that the biochar is carbonized under highly efficient processes (e.g., retorts kilns), with a system for collecting valuable by-products and preheating wood. Otherwise, the use of charcoal in BFs can reduce the CO₂ footprint of iron production, but increase the overall balance of GHG due to the release of methane during the artisanal charcoal production in beehive kilns. Thirdly, the use of agricultural/forestry residues is a potential source of abundant and economical biomass that can be pyrolyzed to generate a fine char for the purpose of Bio-PCI.

5.3. Economic perspective

While some authors have investigated the technical feasibility and CO₂ reduction potential of biomass char utilization in BF, the economic prospects of charcoal-ironmaking have been studied less so far. Firstly, it is the author's opinion that the use of biomass char in metallurgy has been hindered by the significant price difference between fossil coal and renewable charcoal. Thus, one of the key aspects of the present dissertation has been to find feasible ways to make biochar economically attractive for ironmakers. The following sections build on this challenge.

5.3.1. Current economic attractive of charcoal-ironmaking

It is known that charcoal-HM has a high market value—higher than coke-HM, mainly because of the lack of sulfur. However, coke-BFs remain more economically attractive than charcoal-BFs worldwide. To this day, the vast majority of BFs operate with coke as the principal fuel and

coal or natural gas as auxiliary fuels. Presently, coking coal is largely available in most countries by sea freight at a relatively low cost (~ 50 % more economical than charcoal).

Firstly, the utilization of a highly efficient carbonization process, for instance DPC Tecnologia, can help to reduce the biochar cost by up to 125 Rs/t (~ 56 USD/t), according to a report issued by CGEE (2014), in which several pyrolysis processes in Brazil are compared [117]. Such benefits can be achieved with a high carbonization yield, pre-heating of wood, and the commercial exploitation of by-products (recuperation of condensable gases, for instance). However, there are elevated capital costs associated with the construction of such highly efficient carbonization processes. Therefore, it is expected that the replacement of low efficiency carbonization kilns by others with higher char output will take time and financing mechanisms in order to be achieved.

Brazil remains the last niche for charcoal-ironmaking. In spite of the large charcoal production in the country (9 MMt per year), in 2013 Brazil still generated 77 % of the total HM output in coke-BFs, mostly using coal as auxiliary fuel. From an economic perspective, some valuable lessons can be extracted from the experience of the *carvão vegetal ferro gusa* industry in Brazil:

- Charcoal-BFs are limited in their working volume; thus, they present low HM output compared to coke-BF.
- Charcoal-HM is more expensive than coke-HM; therefore, charcoal-HM is mostly used for the production of special steel, cast iron or even ferroalloys.
- Vast areas of arable land, water, and fertilizers are required to sustain the production of charcoal-BFs.

Unfortunately, few other countries present the same favorable conditions as Brazil, with its land availability, abundant quality iron ore, and lack of indigenous sources of coking coal. Moreover, to the best of the knowledge of the author, outside Brazil there are no plans for constructing any 100 % charcoal-BFs. Based on these points, evidently the economic prospects of further increasing to 100 % charcoal-ironmaking appear to be limited. In this respect, a feasible option for biomass char utilization is the injection of biomass char in BFs through PCI rigs.

5.3.2. Economic prospects of Bio-PCI in coke-BF

Based on the calculations of papers III, IV, V, and VI, the results demonstrate that the injection of Bio-PCI into a coke-BF would increase HM production costs. For instance, when biochar completely substitutes coal as an auxiliary fuel, the cost objective function (F) of HM production increases proportionally, between 5.20–16.61 % (see **Table 44**. Objective function cost (F) using PCI and Bio-PCI).

In addition to the previous estimates for the Bio-PCI to be economically competitive, biomass char prices should be 130–236.4 USD/t under the actual and prospective carbon taxes schemes (see **Table 45**. Estimated biochar prices necessary to be competitive with coal). This estimated biomass char price is significantly below the current market price. Consequently, for the time being and the assumptions considered, it is concluded that charcoal cannot compete against fossil carbon solely based on price.

In this regard, two options are explored to make the introduction of biomass chars potentially more economically competitive: through the implementation of carbon taxes and/or with the use of residual biomass instead of primary biomass. These options are discussed in the following sections.

5.3.2.1. The effect of carbon taxes

Papers IV, V, and VI explore the value of carbon taxes necessary to make Bio-PCI economically competitive in coke-BFs. For Bio-PCI to be implemented, the overall production costs of injecting biomass char must be approximately similar to the case of coke-BF operating with coal as the auxiliary fuel. To achieve economic equilibrium, the carbon taxes from HM production must be at least equal to the corresponding increase in HM production costs.

For the studied coke-BFs, the necessary carbon tax was estimated to be between 47.1–198.7 USD/t CO₂ (**Table 52**). Naturally, the countries where biomass char presents the lowest cost would consequently require lower carbon taxes. This would be the case for Brazil, India, China, and USA, where analysis shows that carbon taxes lower than 70 USD/t CO₂ would be necessary. Other countries with high charcoal prices would require higher carbon taxes, as in the case of Russia, Japan, and Germany.

Table 52. Estimated carbon tax price to improve the attractiveness of Bio-PCI

Case	Country	Carbon tax USD/t
Baosteel BF3	China	69.7
Nippon Steel Oita	Japan	132.9
NLMK	Russia	198.7
POSCO	South Korea	85.3
Tata Steel Jamshedpur BF H	India	70.8
Gerdau Acominas BF 2	Brazil	47.1
Severstal Dearborn BF C	USA	69.7
Alchevsk Iron & Steel BF 1	Ukraine	96.3
AM Eisenhüttenstadt	Germany	125.4

The estimated values for carbon taxes in the present work agree with those previously calculated by Norgate and Lambert (2009), despite the different methodology used for the estimate. These authors argue that a carbon tax on the order of 95–115 USD/t CO₂ would be required for the integrated and direct smelting routes (including BOF) ^{XLVIII} [25]. Their calculations were made using a LCA methodology and a charcoal price of 386 USD/t. Also, Suopajarvi et al. (2014) estimated that for the Finnish conditions that the CO₂ allowance price should be 42.24–88.32 USD/t CO₂ (33–69 €/t CO₂) without by-product credits or 33.28–69.12 USD/t CO₂ with byproduct credits (26–54 €/t CO₂) ^{XLIX} to reach the break-even point [23].

Concerning carbon taxes and carbon pricing, experts regularly discuss the real benefits of such initiatives. On one hand, establishing a price on carbon may “drive the emergence of renewable energies” (Mathews 2008) [229]. The most common form of carbon prices are: carbon taxes and carbon credits (Victor and House 2004) [230]. Carbon credits present a significant environmental benefit; they provide certainty about the GHGs emission abatement. On the other hand, carbon taxes are easier to put into effect [231]. In this respect, the present dissertation does not aim to build on the discussion of the benefits or limitations of carbon pricing or carbon taxes, but strongly proposes that the incorporation of a global carbon tax on HM production would significantly affect the overall economical attractiveness of iron production, which could be detrimental to the steel industry. Thus, in the opinion of this author, the price on carbon is not the solution (at least not the complete solution), it is fundamental to find economical ways to reduce the production cost of biomass char and

^{XLVIII} This carbon tax is calculated without carbon credits.

^{XLIX} Exchange rate: 1/1.28 USD/ €.

increase the economical attractiveness of biomass char. Therefore, this work has examined an alternative path to improve the cost processing option of biomass char usage: the utilization of residual biomass.

5.3.2.2. The use of residual biomass to reduce the cost of biomass char

Traditionally, most of the charcoal production worldwide uses trees as the principal raw material. Technically, it can be argued that the remaining charcoal-BF industry in Brazil completely depends on a continuous supply of logs from plantations—for instance eucalyptus plantations as in the cases of APERAM or V&M (Brazil) [15]. The charcoal gained from eucalyptus and other primary biomass sources generates large pieces of char (also known as lump charcoal) that show the best mechanical resistance attainable with biomass char (however, it is still much lower than coke). Thus, these charcoal lump pieces are used for direct feeding of small charcoal-BF from the top. Therefore, biomass char for 100 % charcoal-BF must come from wood, preferably from hardwood—for instance from eucalyptus or pines.

However, for the purpose of injection as auxiliary fuel in coke-BF (Bio-PCI), there is no requirement in terms of mechanical properties from the biomass chars. On the contrary, small size particles are preferred for injection and combustion. In this sense, alternative biomass sources, for instance palm kernel, saw dust, wood chip, or rice husk, can be pyrolyzed to generate biomass char of reduced size for the purpose of Bio-PCI. Several investigations have demonstrated the technical feasibility of generating charcoal from biomass residues (e.g., Demirbaş 2001; Assis et al. 2014) [97,134], and assessed the availability of residual biomass, for instance the wood and forrest chip availability in Finland by Suopajarvi and Fabritius (2013) [161]. Additionally, many industrially established carbonization processes exist that use biomass residues for the production of char—for instance small retorts, Herreshoff multiple-hearth furnace, rotary drums, Auger reactor, moving agitated bed, shelf reactors, paddle pyrolysis kiln, to mention some of the available technologies (Garcia-Perez, et al. 2010) [105]. Chen et al. (2012) [28] examined the torrefaction and burning characteristics of bamboo, oil palm, rice husk, bagasse, and Madagascar almond. These results show that it is possible to produce biochar fines from residual biomass for the purpose of Bio-PCI.

In the view of the author, the development of an efficient biomass carbonization technology is a fundamental step forward for the establishment and use of renewable carbon. Currently, some interesting technological options are presented by the development of the Continuous Direct Feeding (improved) process in Brazil (CGEE, 2014) [117]. Moreover, another promising pyrolysis process is currently under development in CSIRO (Australia), which can use wood chips or pellets as feedstock and is able to capture the valuable by-products generated in the slow pyrolysis process: bio-oil and bio-gas (Deev et al. 2015, Jahanshah et al. 2015) [228,78]. Despite the fact that both processes are in the early stages of development and industrial utilization, they both present comparable economic benefits because of the use of residual biomass and the exploitation of important by-products. As the learning curve of these and other pyrolysis processes progresses, there will probably be a production cost reduction along the shared value^L chain of biomass char (Porter and Kramer 2011) [232].

Economically, the analysis of market prices for primary and residual biomass leads us to infer that the utilization of residual biomass may assist in significantly reducing the production cost of biomass chars by about 120–180 USD/t with respect to the charcoal produced from primary wood. This result also supports the assessment issued by Kumar and Sarkar (2009) [233] about the potential reduction in the cost of charcoal by using forestry residues. Such reduction in biomass cost would certainly help to alleviate the price difference between coal and charcoal.

Biomass char produced from residual biomass in a highly efficient pyrolyzation kiln, combined with the recovery of from charcoal making by-products (pyrolysis condensates and gas) with a carbon price for CO₂ emissions in ironmaking, and an electricity co-product credit during charcoal making may improve the economic attractiveness of Bio-PCI and drive the emergence of Bio-PCI.

5.4. Strategic analysis of biomass char use in blast furnaces

The present dissertation aims to indicate the directions for future research in the deployment of Bio-PCI. The author strongly believes that it is important to generate prudent strategic decisions to shift the structure of fuel utilization in ironmaking. In the vision of the author, the

^L Porter and Kramer defined share value as: “as policies and operating practices that enhance the competitiveness of a company while simultaneously advancing the economic and social conditions in the communities in which it operates. Shared value creation focuses on identifying and expanding the connections between societal and economic progress.”

replacement of fossil fuel in ironmaking is not only a moral problem, but also a geo-economic challenge to overcome.

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 for an initial implementation of the Bio-PCI, also significant efforts are evidenced in Australia and Finland. The amount of residual biomass likely to be used logically depends on the costs associated with collection and carbonization of the residues and the consequent establishment of synergies between biomass producers and iron makers. In this sense, it must be acknowledged that proper, well-managed structures need to be developed to create a biomass char industry to support iron production. In the views of the author, principally developing countries may profit from the generation of a biomass char industry for the following reasons:

- Biomass char can be a business opportunity to generate a new industry that creates jobs, revenues, and benefits to the national economies of iron producing countries.
- The utilization of indigenous biomass may reduce the dependence on external sources of fossil coal (see **Table 53**) [234].
- The link between the output of the agricultural and forestry industries and the input in the iron and steel industry would improve the recirculation of resources in the national economies (see the work of Yuan et al. (2006) on circular economy in China) [235].

Table 53. Top coal importers in 2013^e
Source: World Coal Association.

China	Japan	India	South Korea	Chinese Taipei	Germany
MMt	MMt	MMt	MMt	MMt	MMt
327	196	180	126	68	51

^e estimated

In addition to the countries examined in this dissertation¹¹, some other countries present interesting initiatives to incorporate biomass utilization in iron and steel production, for instance the CO₂ Breakthrough Program in Australia. This is a collaborative project between BlueScope Steel, OneSteel, CSIRO, and CSRP, operating since 2006 with excellent results in

¹¹ Which represent 88% of total iron output.

incorporating biomass char as auxiliary fuel and reducing agent ^{LII} (Jahanshahi et al. 2011, Jahanshahi et al. 2015).

Another element to be considered is the financing of new, efficient converting technologies. In the view of the author, this should be done through the creation of a green credit system, for instance, through the creation of green bonds or climate bonds. Finally, the establishment of environmental incentives (i.e., carbon taxes) may also improve the opportunities of biomass char use in ironmaking.

5.4.1. Is Bio-PCI economically attractive?

The results suggest that Bio-PCI is *currently* not economically attractive, as its incorporation would increase the production cost of HM. Does this imply that it will never be economically attractive? In the opinion of the author, the development of efficient carbonization technologies that capture and exploit valuable by-products, together with the utilization of residual biomass may offer a chance for biomass in ironmaking to be competitive. In this respect, it is important to analyze the case of two related industries: aluminum production and biofuels.

Today aluminum is among the most used materials in the world, because of its unique characteristics: lightweight, lustrous, and corrosion resistant. However, this metal was a semiprecious metal before Charles Martin Hall discovered an economical method to release aluminum from its ores using a molten cryolite bath in a carbon-lined pot. To this day, this valuable metal is sourced using the Hall-Heroult process [236]. The introduction of this technology permitted commercial-scale production of aluminum worldwide. Because of the introduction of the Hall-Heroult process, the price of aluminum ingots significantly decreased from 4.86 USD per pound in 1888 to 0.78 USD in 1893 [237]. Certainly, the introduction of this process allowed a proliferation of the metal as a construction material.

The second example is from the biofuels industry. Initial developments focused on the generation of bio-alcohols by distillation (first generation biofuels), using sugar crops and corn

^{LII} The CO₂ Breakthrough Program also proposes a novel process for Dry slag granulation (DSG) developed at CSIRO. Jahanshahi et al. (2015) indicates that the DSG process reduces water consumption and decreases sulphurous emissions, and it can also recover a large amount of heat in molten slag, which ultimately reduces GHGs emission.

as feedstock (primary biomass). However, there were criticisms due to the unintended effects of land utilization and the increase of food prices (Naik et al. 2010) [238]. Limitations of the first generation biofuels led to the development of biofuels using residual biomass and algae as feedstock (second and third generation biofuels) instead of primary biomass (Dragone et al. 2010) [239]. Consequently, in the field of biofuels, development has been aiming to reduce the plantation areas and re-utilize a food production by-product. Unfortunately, to this day in most of the world, survival of the biofuel industry depends on subsidies, grants, and other economic incentives.

Both examples illustrate two possible paths to improve the economic perspectives of Bio-PCI in coke-BFs. On one hand, highly effective pyrolysis processes such as the continuous direct feeding (improved) show remarkable low production costs (270 Rs/t–135 USD/t) in its operation in APERAM (Brazil) (CGEE, 2014) [117], other promising alternative is presented by the CSIRO pyrolysis process in Australia. Also another alternative could include the upgrading of the pyrolysis vapors (Shabangu et al. 2014; Larsson et al. 2013) [240,241]. These processes show that a relatively low production cost can be attained through a combination of beneficial technical aspects: high charcoal yield, autogenous energy, and continuous feeding. More importantly, the processes collect vegetal tar, lignitic liquids, etc., which are valuable products, and their commercialization provides credits for the production of biomass char. The implementation and scale-up of these and other highly efficient processes may significantly reduce the operating costs and drive the emergence of higher biomass char utilization in ironmaking.

As in the case of first generation biofuels, wood for charcoal making currently comes mostly from ‘sustainable plantation’ or deforestation; both cases have significant criticisms, as outlined in Section 2.3. In this respect, it is fair to say that currently primary biomass is a relatively expensive feedstock that requires large plantation areas, water, and fertilizer (similar to first generation biofuels). In the opinion of the author, residual biomasses, such as stalks, corn stoves, chaff, and wood chips, are feedstocks that are more economical and do not require vast areas of arable land. In this regard, as with the case of biofuels, the second and third generation of biomass char will most probably be produced using residual biomass as feedstock.

6. Conclusions

In summary, the main objective of this work has been the strategical analysis of the present and future prospects of sustainable biomass char or biochar in blast furnaces (BFs). From this perspective, biomass char presents an attractive potential source of CO₂ abatement in ironmaking, and currently the production of charcoal-BFs in Brazil is regarded as being carbon neutral since trees sequester CO₂ during their development. According to the present estimations the replacement of 25 % of coal by biochar in blast furnaces worldwide would contribute to prevent the release of 572.89 MMt CO₂. Naturally, as long as biomass is generated in a sustainable manner and the char is produced in highly efficient kilns with the recovery of valuable by-products.

Despite the potential CO₂ reduction, at the present moment biomass char is only used in the last 172 Charcoal-BFs in Brazil, which represents less than the 1 % of the total global hot metal production. These BFs produce a valuable hot metal quality with low sulfur content. Nonetheless, the analysis of their operation revealed the numerous technical and economical obstacles that hinder the proliferation of biomass char in ironmaking worldwide:

1. Charcoal-BF present limited production capacity, due to relative low crushing resistance of charcoal (compared to coke). Consequently, it is not possible to re-engineer a large coke-BF to operate solely with charcoal.
2. The industrial experience shows that vast plantation areas are required to support the operation of charcoal-BFs.
3. The carbonization of wood in rural beehive kilns contributes to the release of high amounts of methane and other negative greenhouse gases.
4. The price of charcoal is historically more expensive than fossil coal, consequently charcoal-hot metal in Brazil is 32-45 % more expensive than iron from a traditional coke-BF.

According to the estimations of the present work, if 25 % of the fossil coal would be replaced by biomass char, then it would be required to generate 994.93 MMt of biomass and dedicate 330.000 km² of plantations. In perspective, this represents 1/3 the total arable land of the European Union or the 56 % of the cultivation land in Brazil. In the views of the author, to dedicate such large extensions of arable land, fertilizer and water to grow a fuel, is economically, politically and ethically challenging.

Because of these technic-economic limitations, the role of charcoal in BFs has significantly decreased, from being the only fuel available for iron production to be only used in Brazil, moreover it appears that ironmaking fueled exclusively with biomass char is likely to progressively disappear in the future. Instead, the evidence shows that a partial substitution of fossil fuels seems to be more technically and economically feasible (e.g. biofuels mixes with gasoline). From the different options examined in the literature, the injection of biomass char pieces through the blast furnaces tuyeres or Bio-PCI has been demonstrated to be a favorable, technically feasible and economically viable way to mitigate part of the CO₂ emissions in coke-BFs. The current estimates showed that Bio-PCI may reduce between 19-40 % of the total CO₂ emission in a coke-BF.

Moreover, according to the estimations made in this work, the injection of biomass char in a coke-BF would not negatively affect the chemical composition of hot metal and slag which provides further confirmation of its suitability as an auxiliary fuel in the process, this is consistent with previous industrial experiences in Brazil. Furthermore, the amount of slag generated using Bio-PCI would decrease by 8 % according to present calculations.

Nonetheless, in the current scenario with the relative absence of carbon pricing, the calculations show that the introduction of Bio-PCI would incur a significantly higher production cost over that of hot metal. This is mainly because of the higher price of charcoal compared to fossil coal. In this respect, two options were analyzed to improve the economic competitiveness of Bio-PCI: the establishment of a carbon tax or the utilization of residual biomass in charcoal making.

On one hand, according to the present calculations, a carbon tax of 47.1 to 198.7 USD/t CO₂ would be required to increase the economic attractiveness of Bio-PCI and mitigate the effect of biomass char used in the process.

On the other hand, industrial experience shows that biomass is the single highest cost in the carbonization process. Biomass from agricultural and forestry residues (residual biomass) is significantly lower in cost than primary biomass. Therefore, the present work identifies residual biomass as a potential source to decrease the production cost of biomass char significantly. According to present estimates, the production cost of biochar could be reduced by 120–180 USD/t with the use of agricultural and forestry residues. Furthermore, the use of residual biomass can generate small pieces of char suitable for pneumatic injection in BFs. Additionally, the use of residual biomass would alleviate one of the major disadvantages of charcoal-ironmaking: the dedication of vast land areas, since residual biomass allows the generation of diverse products with limited resources inputs using the same land.

Based on the assessment of cases studied in iron producers in the world, it is strongly indicated that Brazil presents the best conditions for the further deployment and establishment of Bio-PCI. Firstly, in the country already 46 blast furnaces were prepared to inject biomass chars as auxiliary fuels in 2015. Secondly, the country already possesses a large and consolidated charcoal industry with over 48.700 km² dedicated to the plantations of eucalyptus and pines. Thirdly, the charcoal prices are relatively economical, compared to the rest of countries examined. Arguably, three other countries also present favorable conditions to incorporate Bio-PCI into their BF processes: India, China, and the USA, due principally to the relatively low cost of charcoal.

The present findings have significant implications for metallurgists, scholars and decision makers in the iron industry worldwide, since they remark the advantageous role of biomass char in Blast Furnaces and the potential of Bio-PCI to reduce significantly the CO₂ emissions in coke-BFs. The Bio-PCI is technically feasible; however, currently the introduction of Bio-PCI is challenged from the economic perspective, due to the high price of biomass char and the absence of carbon taxes. Until the introduction of coke, biomass char was for centuries the only fuel available for blast furnaces, today due the techno-economic barriers reported in this work, its current role in ironmaking is set to progressively decline. However, this works argues that while biomass char was a major fuel in the past of ironmaking, its CO₂ potential can certainly drive its future utilization. *How to make this possible?* In the views of the author, the development and commissioning of highly efficient pyrolysis process combined with the use of sustainable residual biomass, together with the introduction of carbon taxes can create the

economic conditions to produce small pieces of carbonaceous residues at a competitive price. These conditions can drive the re-emergence of biomass char utilization in Blast furnaces.

7. Recommendations for future work

The present dissertation has focused on analysis of the limitations of biomass char utilization in ironmaking and the future options of using biochar in coke-BFs to reduce the CO₂ footprint of the process and to assess the options for making Bio-PCI economically feasible. In this sense, the studies have been fundamentally theoretical, based on actual processing parameters and raw material costs used in the principal ironmaking countries of the world. Therefore, the logical consequence of the present work is to carry out industrial trials of the injection of biochar into a coke-BF and verify the effect of Bio-PCI over the process parameters. To this moment, in the literature it was found few documented experiences of coke-BF using biomass char as auxiliary fuel, for instance at Voest Alpine (Austria) and Aperam (Brazil). Therefore, it becomes fundamental to progress in the understanding of the effect of biochar combustion in the operation of a coke-BF, for instance *what is the effect of biochar injection over the raceway adiabatic flame temperature, dissemination of gases/heat in the raceway?* Also an industrial trial would provide more clarity of the required conditions for the pneumatic injection in PCI rigs and storage in dosing silos, since biomass char present lesser bulk density and higher combustion potential.

This work identifies the agricultural and forestry residues as potential source of manufacturing cost reduction in the generation of biochar. One compelling approach could be the investigation of the establishment of possible synergies between the ironmaking industry and the agricultural/forestry industry, to link outputs of one process to inputs in another in order to effectively increase the material re-utilization, commercial trade under the frame work of *Circular Economy*. Such analysis would be particular interesting in countries such as Brazil, China, USA and India with high agricultural production and large carbon footprint generated in blast furnaces.

Additionally, it would be interesting to perform a techno-economic analysis of the effect of different carbonization processes, the carbon footprint and the economic effect that the exploitation of valuable by-products may have in the reduction of the biomass char processing cost. In particularly the assessment of the pyrolysis process to generate small biochar pieces for Bio-PCI purposes is considered by the author valuable.

It would also be valuable to examine the economic prospects of biomass char utilization in other related applications, for instance in iron ore sintering, the production of bio-composites, or steel recarburizers. Additionally, the techno-economic advantages of biomass use in other industrial applications can be explored, for instance in the ferroalloy industry and in the production of silicon for use in crystalline silicon solar cells.

The sustainability of biomass sources is a fundamental topic of the present work, this dissertation advocates for the larger utilization of biochar in metallurgy, nonetheless any attempt to re-introduce biomass char in ironmaking should be linked with a thoughtful analysis of the impact over the environmental consequences of biomass generation, carbonization and the transportation to the iron plant. There are many investigations about these impacts, however, in the light of the present results; it would be interesting to identify: *what are the potential environmental consequences of biomass generation, carbonization and transportation of biochar for ironmaking purposes?*

The present thesis argues that Brazil shows advantageous conditions for the deployment of Bio-PCI, Further analysis can focus on the particular conditions of different regions of the country, with an in-depth analysis of the federal laws of each state to look for favorable aspect that may further encourage the use of biomass in ironmaking. Additionally, it would be important to study the regulatory measurements required to improve the policy making for renewable fuel utilization in iron and steel production, in Brazil and other countries. This can be achieved throughout interviews among experts, scholars, and practitioners in the field.

Another significant element to consider is a comparative analysis of the social aspects of biomass char production using different pyrolysis processes. In addition, the social impact of carbonization in countries with a large iron production capacity should be considered.

Appendix

Appendix 1. Prices consulted for primary biomass

Producer	Biomass	Country	Price	Minimum Price	Maximum Price
			USD/m ³	USD/t	USD/t
Guangzhou Jingsenhuang Import And Export Trading Co., Ltd.	Natural Wood Veneer	China	500-1000	588	1176
Ocean East Co. Ltd.	Eucalytus	Thailand	198 - 470	233	553
WATA CI Sarl	Hardwood	Cote D'Ivory	200 - 450	235	529
Perspekta	Siberian pine	Rusia	160	188	188
Khafaga tropical Woods	Bubinga Logs	Cameroon	180 - 200	212	235
World Wood Export	Greenheart	Guayana	200	235	235
World Wood Export	Darina	Guayana	200	253	253
World Wood Export	Tatabu	Guayana	215	253	253
World Wood Export	Purpleheart	Guayana	280	329	329
World Wood Export	Jatoba	Ecuador	290	341	341
World Wood Export	Mascarey	Ecuador	290	341	341
World Wood Export	Saligna	Angola	320	376	376
World Wood Export	Ipe	Ecuador	480	565	565
Shandong Huaxin Jiasheng Wood Co., Ltd.	Eucalytus	China	200 - 500	235	588
Veritas International	Eucalytus	Zambia	385 - 400	453	471
KM Korea	Acacia Timber	Vietnam	190-235	233	276
Kwa Zulu timbers	Teak	South Africa	375-500	441	588
TKL Sawmill Sdn. Bhd.	Keruing	Myanmar	380-450	233	529
Khafaga tropical Woods	Padauk logs	Cameroon	180-200	212	235
Ace Link Pte Limited	Azobe	Liberia	190	224	224
Nis Limitada	Hardwood	Mozambique	250-300	294	353
Nicewood Company Ltd	Balau	Vietnam	400-480	471	565
Evergreen Hardwoods, Inc.	Pine	Vietnam	200-220	235	259
D & W Agencies	Turpine logs	South Africa	200-220	235	235
Hoang Hai SX & XNK Co. LTD	Keruing	Vietnam	320-380	376	447
Pro Forestry	Eucalytus	South Africa	150	176	176
Kwanita Import & Export Co.	Hickory	USA	350-400	235	471
Fidelity Group Ltd	Kayno	Gambia	200-220	235	259
ionel baluta	Hardwood				
thetaj	whitewood	Romania	200	235	235
	Kwila	Australia	300-400	453	471
	hardwood				
Veritas International	Eucalytus	India	385-400	453	471
IEL International LTD	Lumber	Papua New Guinea	185-220	353	259
Charles Thom	Wamara	Guyana	300-350	353	412
Ultrawoods Ent.		Guyana	100-350	118	412
Green Farms LLC	Timber	USA	300-450	353	529
Alpha Farmers LTD	Timber	Cameroon	500-700	588	824
Abdullahoglu Orman Urunleri	Oak	Bulgaria	125	147	147
Mobilya Insaat Ithalat Ihracat					
Sanaya Ve Ticaret Limited Sirketi					

Appendix 2. Prices consulted for residual biomass

Producer	Country	Biomass	Price	Density	Fixed carbon	Ash	Caloric value	Volatile matter	Moisture content	Size
MAH & Co.	Pakistan	Wheat straw hay	USD/t	Kg/cm ³	(%)	(%)	Mj/kg	(%)	(%)	(mm)
MAH & Co.	Pakistan	Sugar cane Bagasse	115-120							
Zigma International	India	Coconut shell	85-90							
Galavin Trading	Philippines	Coconut shell	150-300							
Live-Fix Resources	Kenya	Coconut shell	120-130							
Zakza Utama Enterprise	Malaysia	Coconut shell	130							
Truong Kim Trading and Investment JS Co	Vietnam	Coconut shell	120							
Speedway Marketing	Malaysia	Cashewnut shell	220-240							
IBIG Ghana Limited	Malaysia	Palm kernel shell	95-100							
Evergreen Multi Resources	Ghana	Coconut shell	150-200							
CV. Prina Desain Widya Adicipta	Malaysia	Palm kernel shell	65-85							
Taio Energy SDN BHD	Indonesia	Palm kernel shell	70-75							
JPG Continental Link Ltd	Malaysia	Palm kernel shell	45-60							
Dalian Minglu International Trade Co., Ltd.	Nigeria	Palm kernel shell	50-55							
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		
Dalian Minglu International Trade Co., Ltd.	China	Peanut Shell Pellets	140-190							
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		
Nong Trai Xanh Co. LTD.	Vietnam	Pine Wood Shavings	130							
Vietwoodee Joint stock Co.	Vietnam	sawdust	55-90							
Vietwoodee Joint stock Co.	Vietnam	Wood chip	120-135							
Binh Uhoc Export Import Joint Stock Co.	Vietnam	Acacia Sawdust	40-100							
Bioenergy Machinery SDN. BHD.	Malaysia	Saw dust pellets	100-140		1	4500 kcal/kg	4.50%	6 x 30		
Qingdao Aibang International Trading Co., Ltd.	China	Wood Sawdust	110-160			4501 kcal/kg	6-8%	6 mm		

Appendix 2. Prices consulted for residual biomass (continuation)

Producer	Country	Biomass	Price	Density	Fixed carbon	Ash	Caloric value	Volatile matter	Moisture content	Size
Qingdao Chengyang Xingwang Charcoal Mechanism Factory	China	Biomass briquette	150-250			5%	4500		10%	50*500
Matsuri International CO. LTD.	Thailand	Biomass briquette	120		16.19		2000 kJ/kg		6.83	50*400
Dalian Minglu International Trade Co., Ltd.	China	Biomass briquette	120-150							
Xinxiang Yitong Machine Co., Ltd.	China	Biomass briquette	180-280			6%	1340000		12%	18*60
Jinan Jutao Bioenergy Technology Co., Ltd.	China	Biomass briquette	68-120							
RAM EXPORTS	India	Biomass briquette	100-105	1		7%	4200 J		10%	90 mm
Gordie Global	Ireland	Biomass briquette	125-180				17.76 MJ/kg		10-12%	
Natural Environment Company	Vietnam	Biomass briquette	85-100		16.91	8.96%	4491		6.43%	85*350
AADITYA IMPEX	India	Biomass briquette	110-150			7.00%	4000		8.00%	90
FiberTay	Malaysia	Biomass briquette	50-100				3500 kJ/kg		<10%	
Sri Balaji Bio Fuels	India	Biomass briquette	95	0.8-1.2			> 4200			90
SC Adelphin Boys Impex SRL	Romania	Biomass briquette	110-156							
eClouds	India	Biomass briquette	125-130							
JSC Agrostiphus	Ukraine	Biomass briquette	65-104							
Nguyen Brothers Company	Vietnam	Rice Husk briquette	90-100			8.96%	4491		6.43%	85*350
Brazil Biomass and Renewable Energy-Exports Wood Chips	Brazil	Wood briquette	156	1.4		1.50%			<10%	60*150
Century Biomass	Malaysia	Rice Husk briquette	60-70			14.50%	3900-4300		9.48%	95*270
EMSI	India	Biomass briquette	77-88							
PELLETFARM SDN.BHD.	Malaysia	Biomass briquette	130-133			2.00%	19		6.00%	8*50
Fuel India Agrinergy Syndicate	India	Biomass briquette	125-150		47.1	6.78%	4200		7.2-8%	
MADEIRAS GOEDE LTDA - EPP	Brazil	Biomass briquette	147							
Agro-Foresty Waste Management	Bangladesh	Biomass briquette	110			6.00%	4200			
Ralm Inc.	Vietnam	Rice Husk briquette	75-78			12.50%	4000	4%		3000*90

Appendix 2. Prices consulted for residual biomass (continuation)

Producer	Country	Biomass	Price	Density	Fixed carbon	Ash	Caloric value	Volatile matter	Moisture content	Size
Americanstone Contractors	USA	mesquite fuel chip	54			10			15.00%	
Archana Enterprises	India	Bio-fuel	175-200	0.8-1.2	40-55	3-7%	4200-4600		<5	
Jinan Jutao Bioenergy Technology Co., Ltd.	China	Biomass briquette	68-120				3500-5000			
MUSAAB MOOSA ENTERPRISES	Pakistan	Wheat straw hay	120-130							
ASK Enterprises	India	Wheat straw hay	125-160							
Dalian Minglu International Trade Co., Ltd.	China	Corn Straw pellet	150-160	0.9-1.1		7.00%	4200			8*15
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

Appendix 3. Prices and characteristics of charcoal from different traders and producers

Producer	Country	Charcoal's raw material	Price	Fix	Ash	Caloric	Volatile matter	Moisture Content
Gongyi Xiaoyi Hongji Machinery Factory	Japan	Oakwood charcoal	1 USD/ton 380-450	%	%	MI/kwh	%	%
Nanchang Twin Win Import & Export Trade	Japan	Saw dust briquette	500-800	85-90	10-Max	7800-8900	3	5-10.
Ganzhou Eastern Dragon Household Articles	Japan	Bamboo lump charcoal	499-749		5 max	8500		
Gongyi Xiaoyi Hongji Machinery Factory	Japan	hardwood charcoal	430-530	77.6	1-2-	7440		4.8
Olympian protect product manufacture	S.Korea	Coconut shell lump	350-380					
Pt Indo Java Terigu	Germany	hardwood charcoal	428	72-84	2-5	6500-7200	7-17.	4.8.
Cocofire Kokoskohle	Germany	Coconut shell lump	980-990	75	4	7650		7
Climsy Agro International company	Germany	hardwood charcoal, coconut	450-500					
Sindicarv	Brazil	Charcoal for BF	251-288					
SMI International Inc	USA	Hardwood charcoal	250-300					
Consto traders, LLP	USA	From Iroko, Oak, Mahogany	207-255	78-80	3	7400	12-13.	1
Aldana's Corp	USA		300					
Carlos Augustin	USA		300-400	75-85	1.3			6.5
Oconee Energy inc	USA	Hardwood charcoal	550-600	76-89				
Baikal Herbs trade	Russia		505-638					
Publiaromas	Bolivia	Hardwood charcoal	350	85	5			5.0-7
Ganzhou Yaxin Trading Co., Ltd.	China	Bamboo lump	450	75-85	4-8	7000-7500	15-20	8.0-13
Nanchang Twin Win Import & Export Trade	China	Bamboo	300-700		2	8500		
Gongyi Xiaoyi Hongji Machinery Factory	China	Lumps from hardwood	270-340		3	8200		
Ying Lan Sawdust Charcoal Manufacture	China	Lumps from hardwood	400-600		3	7500-8000	2.5	4
Yongkang Harvest Industry & Trade Co., Ltd.	China		350-500	85-90	4	8000	2	5
Iianxi Taisheng Charcoal Industry Co., Ltd.	China	Bamboo lump charcoal	200-250		8	7000		
Yongkang Harvest Industry & Trade Co., Ltd.	China	Coconut shell lump	350-500	85-90	4	8000	2	4
Gongyi Xiaoyi Hongji Machinery Factory	China	Hardwood charcoal	290-320		0.3	7800		
Jianyang Eagle Bamboo And Wood Products	China	Lump from bamboo	20-50					
	China	Briquettes from coconut	650-750	87	5	7500		6

. Appendix 4 Prices and characteristics of charcoal from different traders and producers (continuation)

Producer	Country	Charcoal's raw material	Price	Fix	Ash	Caloric	Volatle matter	Moisture Content
Ukrainian charcoal holding El-fut	Ukraine	hard wood charcoal	USD/ton 332-400	% 82-86	% < 3	MT/kg 7500 -8120	% < 6	
EUROWOOD Ltd	Ukraine	hard wood charcoal	360-380					
VKN Groups	Ukraine	hard wood charcoal	380-400					
M/S Kilanga enterprises	India	Babul hardwood charcoal	250-280	65-75	< 1	> 6500		5-10.
Maruthi Prasad	India	hard wood charcoal	225					
Sikumar Trading and Service Co.	India	hard wood charcoal	400-500					
Sairam Charcoal Export and Consultants	India	hard wood charcoal	300-400					
Universal Enterprises	India	Lump charcoal	600-650	70-75				10
Jier leh ting industrial co., ltd.	Taiwan	tyre pyrolysis black charcoal Mangrove charcoal	330 430-460					

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