Energy for Sustainable Development 27 (2015) 93–104

Contents lists available at ScienceDirect

Energy for Sustainable Development

Carbon neutral merchant pig iron in Brazil: Alternatives that allow decoupling from deforestation

Thiago Fonseca Morello

Centro de Engenharia, Modelagem e Ciências Sociais Aplicadas, Universidade Federal do ABC (UFABC), Rua Arcturus, 3, Jardim Antares, 09606-070 São Bernardo do Campo, SP, Brazil

ARTICLE INFO

Article history:
Received 2 February 2012
Revised 25 April 2015
Accepted 25 April 2015
Available online 21 May 2015

Keywords:
Merchant pig iron
Carbon pricing
Deforestation
Climate change

ABSTRACT

Brazilian merchant pig iron (MPI) mills, even those relying exclusively on charcoal, are at least as harmful to the global climate as the coal-based competitors they confront in international trade. However, when timber from deforestation is replaced by sustainably managed forest plantations, a carbon neutral process emerges. Yet the cost of growing trees can be large enough to discourage mills from pursuing such a climate change mitigation route. The paper shows that the impasse can be overcome by the improvement of pyrolysis kilns coupled with a multilateral agreement in which (1) Brazil supplies attested carbon-neutral MPI and (2) importers of Brazilian MPI take environmental concerns to the field of MPI trade, paying a premium of 19% of MPI price or of US$3 per ton of avoided emissions.

Introduction

The economic contribution of an industry to human well-being, through the provision of useful commodities, jobs and tax revenue, is considerably overestimated when the long-term environmental impacts of its activities are not accounted for (Daly and Farley, 2004; Ayres and Ayres, 2010; World Bank, 2011). This conclusion should apply to metallurgy, a throughput-intensive industry (Yellishetty et al., 2010, 2011), given its dependence on coal (Piketty et al., 2009 p.180). But even without coal and with charcoal, metallurgy can be a matter of environmental concern, as the reality of Brazilian Merchant[1] Pig Iron (MPI) suggests.

Relying on the extraction of considerable amounts of timber from biomes of high ecological significance, such as the Brazilian *Cerrado* and the Atlantic and Amazon forests, the conversion of iron ore into MPI is generally conducted by small- to medium-sized firms (Monteiro, 2006; Carvalho et al., 2008; Vital and Pinto, 2009; Sathaye et al., 1999).[2] The majority of production is exported to leading economies such as the USA and China (MME, 2009, p.60).

The linkage with deforestation, whose magnitude is estimated in The size of the problem section of this paper, brings the industry a more negative environmental image than would be the case if it were based on coal. Charcoal derived from forest plantations provides an appealing and environmentally acceptable alternative to the status quo (Cowie et al., 2007; Boyd et al., 2007). However, decoupling the industry from its dependence on native forests is not without cost, as detailed in Primary economic and ecological aspects section of the paper.

Fortunately, market-based solutions are available, as detailed in Raising the gravimetric yield and Pricing carbon neutrality sections. The former focuses on pyrolysis-efficiency improvements (as a cost-abatement tool) and the latter on pricing carbon neutrality. The structure of the international market for Brazilian MPI and Agreement costs subsections evaluate the possibility of Brazilian MPI exporters and foreign importers reaching an agreement about the market value of carbon neutral MPI. A brief conclusion then follows.

The deforestation charcoal issue

The size of the problem

The amount of deforestation charcoal consumed by Brazilian MPI mills has not been the object of any comprehensive survey.[3] There is no alternative option aside from relying on estimations from the available data on charcoal consumption and timber supply from forest plantation (FP). The difference between the estimates of charcoal consumption of MPI mills and the renewable, FP-based, charcoal supply, hereafter referred to as the "renewable gap", is a measure for the consumption of deforestation charcoal. This section presents

E-mail address: fonseca.morello@ufabc.edu.br.

[1] The word "merchant" denotes solid ingots of pig iron traded in markets, which have to be distinguished from the hot metal (liquid) pig iron that flows, within steel mills, from blast furnaces to the subsequent stage of steelmaking.

[2] The industry is also accused of buying charcoal from suppliers who keep their workers under illegal and poor work conditions, including slave labor (Greenpeace, 2013).

[3] The charcoal supply/demand balance prepared by the Minas Gerais State Silviculture Association (AMS), referred to here as Calais (2009), is no exception, because it reports (in its pages 8 and 9) only the national consumption of deforestation charcoal, which includes other industries (such as ferroalloys) and households.

http://dx.doi.org/10.1016/j.esd.2015.04.008
0973-0826/

the primary assumptions behind two alternative procedures for estimating the renewable gap: bottom-up and top down.[4]

The "bottom-up" approach consists of two steps. First, full capacity MPI production data at the firm level (data source: Quaresma, 2010), together with additional data on the charcoal rate (the amount of charcoal consumed in average by each ton of MPI produced). CEMIG (2010) and AMS (2009) are used to estimate full-capacity-charcoal demand at the state level. Second, the supply of renewable charcoal is estimated from the eucalyptus forest plantation area,[5] owned by MPI mills, in each of the Brazilian states considered.[6] It is assumed that all plantation areas operate at full productivity, which corresponds to a production of 120 cubic meters of charcoal per hectare per year (Calais, 2009, p.13). This datum, which is aggregated at the state level, comes from a renewable charcoal supply/demand study prepared by the Minas Gerais Silviculture Association (a trade union that represents the MPI industry). The study is referred to hereafter as Calais (2009). For the states of Carajás pole (Pará and Maranhão), firm-level data on the plantations, collected from fieldwork (SINDIFERPA, 2010), are used. For Minas Gerais, the number adopted is the supply of renewable charcoal estimated by Calais (2009), net of the self-supply of charcoal-based steel mills.[7]

The "top-down" approach also estimates supply and consumption, but from data at the national level. This approach requires fewer assumptions than the bottom-up approach because data at the national level are directly available. The joint charcoal consumption of steel and MPI mills is annually reported in the national energy balance (EPE, 2010). The amount of planted forest timber devoted to charcoal production (eucalyptus, exclusively) is provided by the annual report of the Brazilian Association of Forest Plantation Producers (ABRAF), which is hereafter referred to as ABRAF (2010). The self-supply of renewable charcoal by steel mills and also their charcoal consumption must be discounted to obtain the renewable gap of the MPI industry. This gap is obtained by referring to a report issued by the Brazilian Steel Institute (IABr, 2010), which contains the precise data needed, including the renewable gap of charcoal-based steel mills.

Sections S1 and S2 of Supplementary Information (SI) present the parameters adopted and the calculation details behind the bottom-up and top-down approaches, respectively.

The results of the two procedures are presented in Tables 1 and 2.

The consumption and supply estimates are higher under the bottom-up approach because MPI production and renewable charcoal production from plantations are both assumed to operate at full capacity. The top-down procedure takes into account the production levels effectively attained in 2008 for MPI and for renewable charcoal. This is the main methodological difference between the two approaches.

A second relevant difference pertains to the assumption regarding the amount needed for the renewable self-supply of steel mills, a magnitude that is discounted from the renewable supply estimated by the two methods to obtain only the fraction that corresponds to MPI mills. The number used in the top-down procedure is 5.389 million cubic meters of charcoal (M m^3Ch), while in the bottom-up procedure, a number equal to 2 M m^3Ch is adopted, which explains half of the discrepancy in the estimates for the renewable charcoal supply (3 million out of 6 million cubic meters of charcoal). The remaining half is caused by the methodological peculiarity clarified in the previous paragraph.

In absolute terms, the renewable gap estimated using the bottom-up approach is significantly higher than that using the top-down procedure. The explanation lies in the fact that charcoal production operates closer to its full-capacity level than MPI mills. The MPI industry develops a considerably lower level of its productive potential compared to the forest plantations devoted to charcoal making.

A limitation common to the two methods is that the supply of renewable charcoal comprises not only the amount employed by MPI mills but also the amount that flows to other industries as ferroalloy and cement (14% of total charcoal consumption, according to the national energy balance, EPE, 2010). In conclusion, for the two procedures, the renewable fraction of charcoal consumed by MPI mills is overestimated, or, equivalently, the renewable gap is underestimated.

The bottom-up approach assumes that charcoal trade among states other than those considered is negligible,[8] because the renewable gap (estimated consumption minus estimated renewable supply) is calculated at the state level, except for the case of the Carajás Pole. Consequently, the possibility of MPI producers buying renewable charcoal produced from plantations located elsewhere is not accounted for, and, consequently, the bottom-up approach underestimates the renewable charcoal supply; this error is avoided with the top-down approach because it employs data at the national level. In light of the results obtained, the underestimation in question proves not to be big enough to compensate for the main methodological difference between the approaches, because the renewable supply proves to be larger when estimated through the bottom-up procedure.

In terms of percentage, however, the renewable gap estimated by the two methods is essentially the same. *It can thus be claimed that 67% to 70% of the charcoal consumed by the Brazilian MPI industry is not renewable.*

Primary economic and ecological aspects[9]

MPI, a solid mix of carbon and iron, is employed as a raw material for steelmaking but also for the iron casting industry (Fig. 1). The Brazilian MPI industry was, in 2008, composed of 62 companies (Quaresma, 2010) located in the southeastern state of Minas Gerais (50.3% of the 2008 national production, AMS, 2009), 16 located in the northern states of Pará and Maranhão (SINDIFERPA, 2010; 41.4% of production, AMS, 2009), and 7 located in the states of Espírito Santo (southeast) and Mato Grosso do Sul (center-west) (AMS, 2009; 8.3% of production).

Over half of the production, 62%, was exported in 2007 (Fig. 1), which placed Brazil as the leader in global MPI exporters, a position that had been previously disputed with Russia since at least 1999 (World Steel, 2010).

While the use of coal-made coke, a fossil fuel, dominates iron ore reduction worldwide, in Brazil, MPI is almost completely made from charcoal. Nevertheless, it would be premature to conclude from the use of charcoal that the industry has lower GHG emissions. As multiple studies have shown, the perceived environmental advantages of biomass-based fuels, such as charcoal, can be illusory, depending on how they are produced (Goldemberg and Coelho, 2004; Rosillo-Calle et al., 2000; Romijn et al., 2010; Buchanan and Levine, 1999).

As The deforestation charcoal issue section indicates, in Brazil, 66–70% of MPI producers' full-capacity charcoal consumption depends

[4] Calculation details are given in sections S1 and S1 of the supplementary information (SI).

[5] As table 3.02 of ABRAF (2010) indicates, in Brazil, renewable charcoal is made only from eucalyptus trees.

[6] It is the actual extension of land areas allocated to forest plantations that are considered and not the potential extension (the latter being relevant only for an analysis of the potential supply of renewable charcoal as it is the object, for instance, of the paper by Piketty et al. (2009)).

[7] There are no steel mills located in the other states considered (Espírito Santo, Mato Grosso do Sul, Pará and Maranhão), as can be inferred from the list of the associates of the Brazilian Steel Institutes (IABr, 2010, p.6). The only exception is the state of Pará, where there is one steel mill that, nevertheless, started producing steel only in May–September 2008 (SINOBRAS, 2009: p.14).

[8] If the considered states trade renewable charcoal among themselves, the gap of the sellers is overestimated at a magnitude equal to the one in which the gap of the buyers is underestimated. The errors, thus, cancel each other out when state's renewable gaps are added up to obtain the national gap.

[9] The data employed in this section refer primarily to the years before the world economic crisis, which severely impacted the activity of the Brazilian MPI industry (2008/2009, according to MME (2010, p.58)). A picture of the industry (and of the supply chain it integrates) that is more coherent with the historical average level of activity is preferred, even though this option requires the use of non-updated data.

Table 1
Renewable charcoal gap of Brazilian MPI industry, bottom-up estimation, 2008.

Region	MG[a]	PA + MA	MS	ES	Brazil
Full-capacity production level (Mt MPI[b]/year)	8	4	1	0.79	14
Full-capacity charcoal consumption (M m^3Ch/year)	22	12	2	2.19	39
Full-capacity renewable charcoal supply (M m^3Ch/year)	10	2	0.34	0.14	13
Renewable gap (M m^3Ch/year)	12	10	1.91	2.05	26
Renewable gap (%)	55%	83%	96%	94%	67%

Source: Bottom-up estimation. Details in section S1 of Supplementary Information (SI).
[a] Brazilian states: MG: the southeastern state of Minas Gerais; PA: Pará;MA: Maranhão; PA + MA represents the Carajás pole in northern Brazil; MS: Mato-Grosso do Sul, center-west of Brazil; ES the southeastern state of Espírito Santo.
[b] "M" denotes million, "t", tonne and m^3Ch, cubic meters of charcoal.

on the processing of unsustainable, or traditional, in the sense of Goldemberg and Coelho (2004) biomass, obtained through deforestation (Sathaye et al., 1999).

This high dependence on the clearance of native vegetation has led to severe impacts on a number of globally important ecosystems. For example, in the state of Minas Gerais, two biodiversity hot spots (Conservation International, 2013) are under pressure from charcoal makers: *Cerrado*, or the Brazilian Savanna, and the Atlantic Forest (Vital and Pinto, 2009).[10] In the northern states of Pará and Maranhão, the Amazonian forests are the primary source of carbon for MPI. In the west of the country, more specifically in the state Mato Grosso do Sul, a report published in 2008 revealed that the area of influence for MPI mills has extended to the transition zone between the *Cerrado* and the Brazilian *Pantanal*, the world's largest freshwater wetland (Carvalho et al., 2008). Fig. 2 highlights the municipalities where MPI mills are located, taking as reference the physical limits of the Brazilian biomes.

It must be highlighted that charcoal making is not the sole motive of the deforestation that threatens Brazilian biomes. Generally, charcoal making, logging and the expansion of agriculture and cattle ranching act synergistically as causes of deforestation and as interdependent sources of income for the agents that drive the process (Rosillo-Calle et al., 2000, section 8.4). There is no available evidence to disentangle the individual contribution of each activity.

Notwithstanding, the linkage of MPI with native forest degradation is of special concern because it is well known that deforestation and the related land use change has promoted Brazil to sixth place in the rank of the world's GHG emitters (Climate Analysis Indicators Tool, CAIT, 2014; Abramovay, 2010). Charcoal represents over 50% of the total MPI production costs, and the lack of economic incentive has been a major factor blocking the growth of the production of renewable biomass from forest plantations (Monteiro, 2006). Research conducted from 2009 to 2010 in the Carajás region has provided data for elaborating the cost estimations in Table 3.

The reliance on deforestation charcoal can only be reverted when MPI mills begin to see sound economic reasons for taking the renewable route. To evaluate the feasibility of this shift, the two of the primary components of the profit differential between renewable-charcoal-based MPI and deforestation-based MPI are separately examined in the next two sections; these two components are (i) the charcoal production cost and (ii) the market value, or price, at which each of the two varieties of MPI can be sold.

Raising the gravimetric yield

Pyrolysis kilns

A recent study contracted by the Brazilian Government states that 80% of the industrial charcoal produced in the country comes from the so-called "hot-tail" or "*rabo-quente*" kiln (Pinheiro et al., 2008; Peláez-Samaniego et al., 2008), which is characterized by a low performance in terms of both gravimetric yield (tons of charcoal produced per ton of timber consumed) and energy efficiency (CGEE, 2010). Hot-tail kilns generally comprise a semi-spherical brick construction with a large side hole through which the timber is inserted and several (21, generally) air outlets in the sides. On average, they have three meters in diameter and one meter in height, as illustrated in Fig. 3.a. The management of hot tail kilns generally depends upon sensory signals, such as smoke color, smell and apparent temperature, which are imprecise indicators of how well pyrolysis is developing. This imprecision, thus, results in significant biomass waste (Pinheiro et al., 2008; CGEE, 2010) as the last column of Table 4 suggests.

In contrast, a "Mineirinho" kiln is an improved version of the hot-tail kiln, in which the multiple air inlets are replaced by only one chimney and a single air inlet. This distinction gives the operator much more control over pyrolysis and, all else being equal, results in a higher gravimetric yield (Table 4, Fig. 3.b).

A third style of kiln, the Missouri kiln, is a large-scale pyrolysis kiln made of masonry that requires mechanized loading and unloading (Massengale, 2006). The model taken into account here is that employed by Arcelor Mittal in Minas Gerais (Table 4, Fig. 3.c).

Finally, a model of kiln here referred simply as "Metallic", to preserve the confidentiality of the company that offers it, employs a combination of multiple pyrolysis reactors contained within rectangular concrete and metal constructions. The system optimizes biomass and energy, being inspired by retorts such as the Lambiotte model (FAO, 2008). Additionally, methane emissions can be controlled and by-products, such as tar, can be recovered (Firm Me, 2010, Fig. 3.d).

Cost of charcoal

As the previous sections suggest, MPI mills have several options for producing charcoal. Eight possibilities are considered in this paper, each, herein referred to as a charcoal production project, is defined as a combination of two sets of characteristics, (i) biomass source, $b = \{TB, PB\}$, where TB stands for deforestation-based "traditional biomass" and PB for eucalyptus forest plantation (EFP) biomass and, (ii) pyrolysis kiln, $k = \{HT, Mi, Mo, Me\}$. The kilns are indicated by "HT" for hot-tail, "Mi" for "Mineirinho", "Mo" for Missouri and "Me" for Metallic.

Projects are structured with the goal to supply the quantity of biomass annually consumed by one kiln and consist in 12 year schedules of operations. They start with kiln purchase, an operation which is repeated whenever kiln lifetime expires. TB is also purchased even on projects designed to operate with PB, since the first harvest of plantations occurs six years after their establishment. After the first harvest, use of TB is suppressed on plantation-based projects. The cost effectiveness index adopted for comparing the eight projects is the present value of

Table 2
Renewable charcoal gap of the Brazilian MPI industry, top-down estimation, 2008.

Charcoal consumption (M m^3Ch/year)	23
Renewable charcoal supply (M m^3Ch/year)	7
Renewable gap (M m^3Ch/year)	16
Renewable gap (%)	70%

Source: top-down estimation. Details in section S2 of SI.

[10] The two biomes are of high ecological relevance (Conservation International, 2013; Werneck, 2011; Klink and Machado, 2005). "Cerrado is the richest tropical savanna in the word" (Klink and Machado:, 2005), gathering 7000 plant species and 2566 animal species. The Atlantic forest is a tropical rainforest ecosystem located in the Atlantic coast of Brazil that gathers 20,000 plant species and 2315 animal species (Conservation International, 2013).

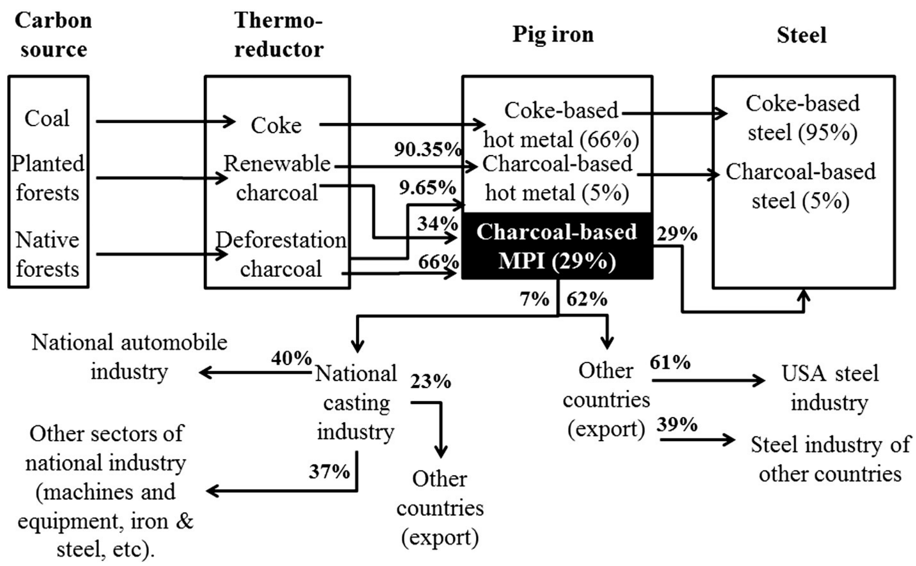

Fig. 1. The scheme for the Brazilian MPI supply chain. Source: (a) Supply of charcoal for charcoal-based hot metal production (steel mills): 2009 data from IABr (2010, p.33 and 34); (b) supply of charcoal for MPI production: 2008 data from Table 2 of this text; (c) distribution of the MPI industry production (national and international markets): 2007 data from MME (2008); (d) distribution of casting industry production, 2006 data from MME (2007); (e) share of coke-based hot-metal pig iron, charcoal-based hot metal and MPI: 2006 data from SINDIFER (2013); (f) share of coke-based steel and charcoal-based steel: 2009 data from IABr (2010, p.33).

investment, PV, normalized by total charcoal production, i.e.:

$$\frac{PV(b,k)}{\sum_{t=0}^{11} Y_k} = \frac{\sum_{t=0}^{11} A_t(b,k)\delta^t}{\sum_{t=0}^{11} Y_k} \tag{1}$$

Where b and k are the biomass-source-kiln that defines the project, Y_k is the annual production of charcoal by the k-th kiln in m^3Ch/kiln, $A_t(b,k)$ is the project's current expenditure on period t. The discount factor is $\delta = (1 + r)^{-1}$ with r being the discount rate, assumed to be of 10.75% per year, the Brazilian economy basic interest rate at 31 December 2010.

Current expenditures (R$/kiln) for the PVs associated with PB and TB are detailed in equations below. On PB and TB projects, kiln purchase vary being non-zero only when kiln's age, l(t), is above kiln's lifetime. On PB projects, expenditures on biomass vary with EFP maturation stage, s(t). The cost of land for EFPs is the only component which varies across Brazilian biomes.

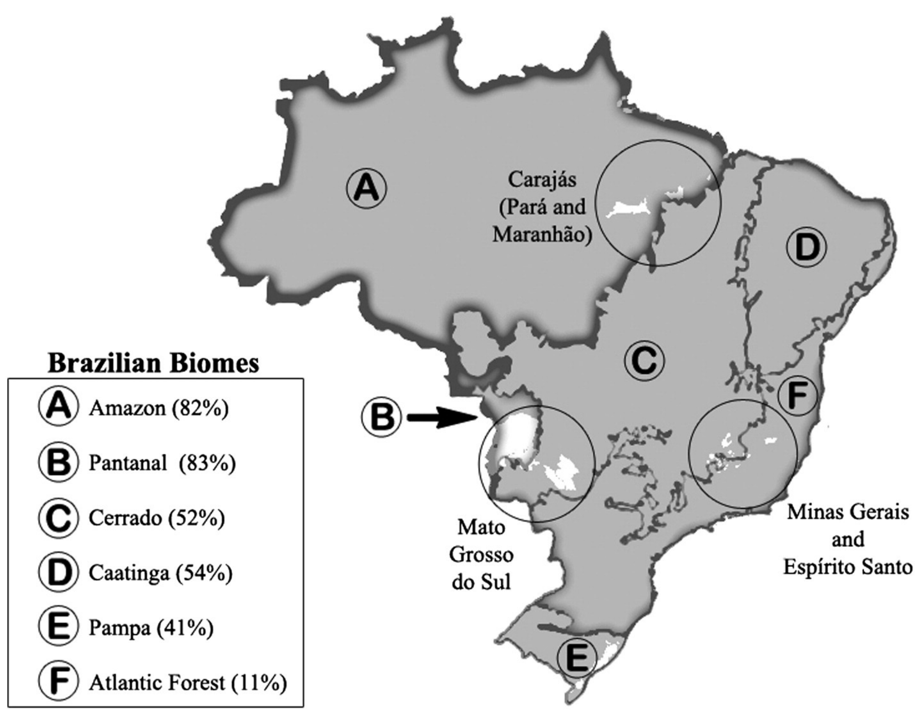

Fig. 2. Municipalities (white areas within the circles) and states where MPI mills are located and the Brazilian biomes. Note: Numbers in parentheses are the percent of the original vegetation that remains for each biome. Source: (i, MPI mills localization) Quaresma (2010); (ii, biomes' limits): IBGE (2011); and (iii, biome's percent of remaining vegetation); (iii.a, Atlantic forest) SOS Mata Atlântica (2010); (iii.b, Cerrado) IBAMA (2009); (iii.c, Amazon) IBGE/INPE (2011) for accumulated deforestation and MMA (2011) for the biome's area; (iii.d, Caatinga) IBAMA (2010a); (iii.e, Pampa) UFRGS (Federal University of Rio Grande do Sul State) (2007); (iii.f, Pantanal) IBAMA (2010b).

Table 3
Cost of biomass, Carajás pole, 2010[a].

Biomass	Severity of impact on native forest ecosystems	Production cost ($R\$/m^3T$[b])
Traditional [a]	High	48 [c]
Eucalyptus	Null	64 [d]

Source: Table 5 below.
[a] "Traditional", in the sense of Goldemberg and Coelho (2004), stands for biomass obtained through deforestation (of Amazon forest, in this case).
[b] m^3T denotes cubic meters of timber.
[c] Details on note "d" to Table 5 below.
[d] Only eucalyptus forest plantation cultivation costs plus harvest and transport costs are considered (see Table 5 below).

$$A_t(PB,k) = T_{s(t)}\gamma_k Y_k + L_{s(t),b}\alpha_k Y_k + B_{s(t)}\alpha_k Y_k + H_{s(t)}\beta_k Y_k + \$K_{k,l(t)} + P_k Y_k$$
$$A_t(TB,k) = T\gamma_k Y_k + \$K_{k,l(t)} + P_k Y_k$$

with

$T_{s(t)}$ and T ≡ price of TB ($R\$/m^3T$)
s(t) ≡ EFP's current maturation stage
γ_k ≡ conversion factor of cubic meters of charcoal into cubic meters of TB (m^3Ch/m^3T)
$L_{s(t),b}$ ≡ cost of land purchase for biome "b" (R$/ha)
α_k ≡ conversion factor of hectares into cubic meters of charcoal (m^3Ch/ha)
$B_{s(t)}$ ≡ cost of EFP cultivation (R$/ha)
β_k ≡ conversion factor of cubic meters of charcoal into cubic meters of PB (m^3Ch/m^3T)
$H_{s(t)}$ ≡ cost of plantation harvest, log transport and cut in R$/ha,
$\$K_{k,l(t)}$ ≡ price of the k-th kiln (R$/kiln)
l(t) ≡ kiln's current age
P_k ≡ cost of pyrolysis (kiln operating expenses) in $R\$/m^3Ch$

Table 5 lists the adopted values for general charcoal cost parameters and Table 6 the values for kiln-specific parameters. Kilns' prices ($K) and lifetimes are taken from Table 4 above.

Tables 7 and 8 report detailed charcoal cost calculations for two selected projects and for Amazon biome. Tables for the remaining projects are found in Section 4 of Supplementary Information. The final costs for all projects are presented in Table 9.

Pricing carbon neutrality

GHG budget of alternative MPI production systems

Table 10 presents the GHG budget of eight MPI production systems. The first row covers the coke-based system. Second to fourth rows account for the possibility of Eucalyptus forest plantations (EFP) being established with deforestation of biomes that concentrate MPI production - a report from the Brazilian Science and Technology Ministry reveals that 138,429 ha of forest were converted into forest plantations (FP) from 1994 to 2002 (MCT:, 2010). EFP-based system 4, the alternative this paper advocates, is deforestation-free. Three traditional biomass-based (TB) systems, i.e., that rely on deforestation timber, complete the table. They also incorporate the carbon heterogeneity of biomes' vegetation. It is assumed that deforestation emissions of EFP systems are valid inferior limits for those of TB-based systems, as justified in Section S3 of SI.

The relative carbon-rank of the three options considered is as follows:

TB 1 to 3 and EFP 1 and 2 > Coke > EFP 3 > EFP 4

Two are the main factors that make five of the seven charcoal-based systems more carbon-intensive than the coal-based system. First, the emissions from deforestation. Second, the methane emitted by pyrolysis, as Table 11 details.

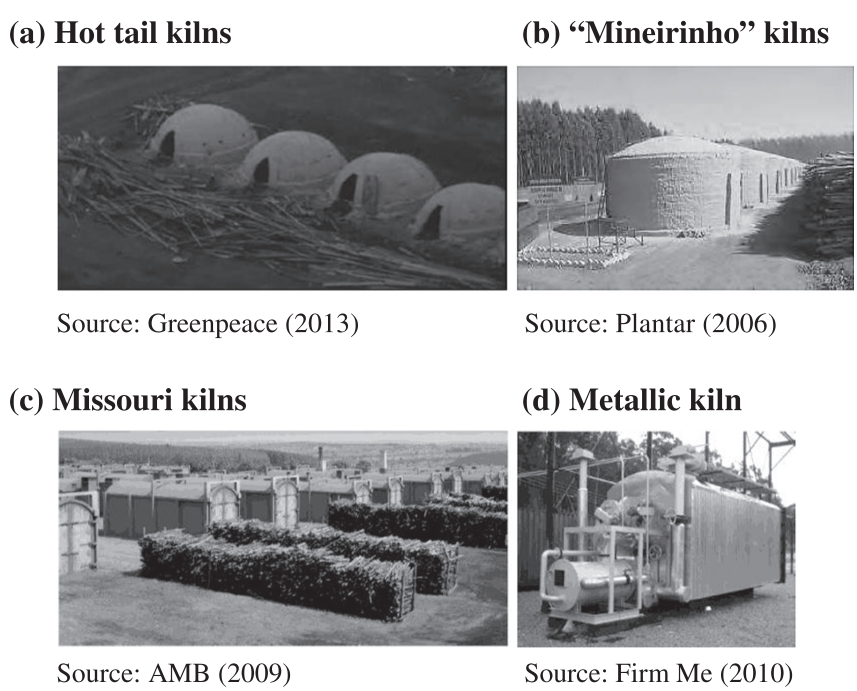

Fig. 3. Pyrolysis kilns.

Table 4
Kiln characteristics.

Kiln	Nominal volume (m^3T)	Average production (m^3Ch/kiln/month)	Price per kiln (R$/kiln)	Lifetime (years)	Operating cycle (days)	Gravimetric yield (tCh/tT)
Hot-tail (ht)	12.6 [a]	25 [e]	2120 [e]	2 [f]	8 [h]	0.2 [i]
"Mineirinho" (mi)	10.5 [b]	30 [b]	5000 [b]	5 [b]	7 [b]	0.25 [b]
Missouri (mo)	230 [c]	480 [c]	240,000 [c]	15 [c]	12 [c]	0.3 [c]
Metallic (me)	110 [d]	400 [d]	247,500 [d]	16 [g]	3 [e]	0.35 [d]

[a] Estimated on the basis of data on (i) monthly timber consumption per kiln informed by firm S (2010) and (ii) average operation cycle of hot-tail kilns according with Pinheiro et al. (2008) and Rosillo-Calle et al (1996). Source: firm S (2010);
[b] Source: Firm E (2010);
[c] Source: firm Mo (2008);
[d] Source: firm Me (2010);
[e] Estimated considering a total of 400 bricks per kiln (firm S, 2010), a price of brick of 0.47 R$/brick (SINDIFERPA, 2010) and labor and clay costs according with on-field personal communication;
[f] Source: firm S (2010);
[g] According to Firm Me (2010), the monthly maintenance cost of the containers corresponds to 0.5%, what amounts to 6% on an annual basis. It can thus be assumed that the equipment physically depreciates at this rate, having, thus, a life cycle of 1/0.06 years;
[h] Source: Rosillo-Calle et al. (1996), table 4.1;
[i] Source: Pinheiro et al. (2008) and firm S (2010).

Table 10 has two major implications. First, when deforestation is relied on, the resulting charcoal, even when made from EFP timber, has a larger global warming impact than coke. Second, the only true carbon neutral MPI production system is the one based on charcoal from EFPs that have not taken the place of forests.[11]

Table 5
Adopted values for general parameters.

Parameter	Cost	Unit
L, Amazon [a]	50,324.75	R$/harvestable ha
L, Cerrado [b]	35,538.46	R$/harvestable ha
L, Atlantic Forest [b]	28,875.00	R$/harvestable ha
B_0 [c]	3749.46	R$/ha
B_1 [c]	769.28	R$/ha
B_2 [c]	313.27	R$/ha
B_3 [c]	374.71	R$/ha
B_4 [c]	276.29	R$/ha
B_5 [c]	276.29	R$/ha
B_6 [c]	286.11	R$/ha
T for K = {HT,Mi} [d]	48.26	R$/$m^3T$
T for K = {Mo,Me} [d]	38.22	R$/$m^3T$
H for K = {HT,Mi} [d]	33.7	R$/$m^3T$
H for K = {Mo,Me} [d]	25.02	R$/$m^3T$

[a] There is no official source of land price data in Brazil. In Amazon, such information is especially difficult to obtain due to the illegality of land transactions. A reasonable value seems to be the opportunity cost of land informed by a certified logging company (Firm W, 2010 of Pará state) which charged local charcoal-makers R$1437.86/ha for the right of collecting logging residuals. This value, even not being, actually, a land price, seems reasonable under the light of two datum, first, the average land price of Pará state on 2008, was of R$1102 according with IFNP (2008), second, Gayoso (2012), informs an average land price of R$908 for Santarém region, Pará state. The mandatory fraction of farm area that has to be kept untouched as forest, the legal reserve, is of 80% in Amazon. To ensure timber supply in a continuous basis, it is necessary to buy a number of land parcels numerically equal to the rotation period of seven years. Each parcel has an extent compatible with annual charcoal production. A "harvestable" hectare corresponds to 7 × 1/(1–0.8) = 35 planted hectares.
[b] Land price for Minas Gerais state was of R$3300/ha in 2010, according to CIF (2015) and the legal reserve is of 0.35 and 0.2, respectively, for Cerrado and Atlantic Forest biomes. It is also necessary to multiply land cost by the rotation duration, 7 years, to ensure biomass production on a continuous basis. In these two cases, the harvestable hectare amounts, respectively, to 10.77 and 8.75 planted hectares.
[c] EFP cultivation cost comprises silvicultural maintenance procedures, applied to plantations, and incorporate fertilization, weeding and protection against pests and fires. As informed by Firm E (2010), which grows eucalyptus for more than 20 years in the state of Pará.
[d] Firm E (2010) informed a harvest cost of R$16.8/$m^3T$ and a plantation-factory transport cost of R$8.22/$m^3T$ (40 km). This cost is also considered for TB, first because TB transport is generally paid by the consumer and, second, by adopting the same distance (and, therefore, transport cost), it is avoided to introduce differences on biomass costs which are unrelated with the respective production processes. There is an additional cost of cutting the logs to fit on HT and Mi kilns, which is of R$8.68 for PB and of R$10.04 for TB (Firm R, 2010). The price of TB, R$30/$m^3T$, corresponds to the 95-percentile of timber price values across the municipalities of Pará (IBGE:, 2009).

Another corollary of Table 10 is that the deforestation free EFP-based MPI production has a dual function: it not only generates a specific input for iron casting or steel mills, but it also neutralizes, with carbon-sequestration, the carbon balance of the MPI supply chain.

The neutralizing service is not currently captured by the market price of MPI, remaining a positive uninternalized externality. To correct this market failure is thus to incentivize MPI producers to opt for the carbon neutral system. One possible solution is to create a new international market niche for carbon neutral MPI. It would gather demanders that value carbon neutrality and thus agree on paying a higher price than the one prevailing on the carbon-intensive niche.

It can only be feasible that Brazil, the only large scale producer of carbon neutral MPI worldwide, leads in the creation of the new market niche if the country has a non-ignorable power of price making in the international market. The following subsection addresses this issue.

The structure of the international market for Brazilian MPI

Evaluating the feasibility of internalizing the emission abatement service through the MPI market requires a more detailed assessment of market characteristics (as recommended by Povellato et al. (2007)). The influence of a market player (country) on the price that closes a transaction, in which it takes part, can be measured by the degree in which the player depends on a transaction. Metrics for dependence are, for exporters, the share of total production sold to a trade partner and, for importers, the share of apparent consumption bought from a partner. The Appendix A at the end of the text formalizes this metrics.

[11] The two results might lead to the interpretation that filling the renewable gap might generate a considerable amount of GHG emissions. Fortunately, a simple calculation shows that in order to achieve such goal it is not necessary to rely on deforestation. Piketty et al. (2009) conducted an assessment of land availability to grow eucalyptus in Brazil where the following criteria has been adopted to identify the total suitable area: (i) only degraded non-forested area, with low agricultural potential were considered; (ii) area allocated to agriculture is not considered, (iii) areas included register a rainfall level of 800–1499 mm/year and a population density of 80 persons/km^2 at most, (iv) conservation areas required by the forest code are excluded. By applying the criteria, it results that there is a total area of 67 to 77 Mha available to grow eucalyptus in Brazil. This extent of land, it must be highlighted, corresponds to land deforested in the remote past, whose soil is degraded and is unsuitable for agriculture. Let it be assumed a charcoal yield of 120 m^3/ha and that to harvest a hectare it is necessary to plant seven hectares (in coherence with The size of the problem section). With these numbers, the area that has to be planted in order to supply the renewable charcoal gap of MPI producers (16–26 Mm^3charcoal, The size of the problem section) is of 933–1517 thousand hectares, 1.4%–2.3% of the total available area in Brazil (67 Mha) estimated by Piketty et al (2009).

Table 6
Adopted values for kiln-specific parameters.

Kiln	Hot-tail	"Mineirinho"	Missouri	Metallic
Y [a] (m^3Ch/kiln/year)	300	360	5760	4800
$\alpha \times 100$ [b] (ha/m^3Ch)	1.25	1	0.83	0.71
β [c] (m^3T/m^3Ch)	2.5	2	1.67	1.43
P (R\$/m^3Ch)	7 [d]	7 [e]	7.98 [f]	4.78 [g]
γ [h] (m^3T/m^3Ch)	2.50	2.00	1.67	1.43

[a]Y = average production × 12 months/year, with average production as registered on Table 4. [b] $\alpha = (\text{ha}/200\text{m}^3\text{T}) \times (1\ \text{m3}/0.5\text{tT}) \times (1/g) \times (0.25\text{tCh}/\text{m}^3\text{Ch}) \times 100$, where g is the gravimetric yield of Table 4. It is assumed a density of 1 m^3/0.5tT for eucalyptus timber and of 0.25tCh/m^3Ch for charcoal. [c] $\beta = (1\ \text{m}^3/0.5\text{tT}) \times (1/g) \times (0.25\text{tCh}/\text{m}^3\text{Ch}) \times 100$, where g is the gravimetric yield of Table 4. [d] The operations of kiln loading, kiln operation and unloading amount, in average, to R\$5.01/ m^3Ch and the cost of provision of food and shelter to workers is estimated to be of R\$1.99/ m^3Ch (Pinheiro et al, 2008 and Firm S, 2010). [e] the same operating cost of hot-tail kiln is assumed, given the similarities of both kilns. [f] [g] Kiln loading, operation and unloading is estimated to amount to R\$7.57/m^3Ch and R\$4.37, respectively, for Missouri and Metallic kilns (Firm Mo, 2008 and Firm Me, 2010). For both kilns, a cost of provision of food and shelter to workers is estimated to amount to R\$0.41/m^3Ch. [h] $\gamma = (1\ \text{m}^3/0.5\text{tT}) \times (1/g) \times (0.25\text{tCh}/\ \text{m}^3\text{Ch}) \times 100$, where g is the gravimetric yield of Table 4. It is assumed a density of 1 m3/0.5tT for traditional biomass timber.

According to the United Nations COMTRADE data for 2000–2008, presented in the Appendix A, eight MPI trade partners of Brazil depend less on the country than it depends on them, with the inverse being true for the remaining partners. Major pig iron importers such as the USA, South Korea, Italy, Taiwan, Japan and China are among the group that appears to have more price-making power than Brazil. These countries were responsible, jointly, for 68% of the world pig iron imports (in tons) in 2008 (World Steel, 2010).

On the contrary, in trade with Spain, a country that ranked tenth in 2008 pig iron imports (World Steel, 2010) – representing, thus, an important share of the global market – it is Brazil that holds price making power. Spain is an important exception to the rule (claimed by Monteiro (2006)) that Brazil has no power to influence the price at which it trades pig iron. Mexico's position illustrates a similar situation, given that it ranks above Spain in terms of average pig iron import share from 2000 to 2008 (World Steel, 2010).

From the evidence that Brazil holds price making power it cannot be concluded that the best way to incentivize carbon neutral MPI production is through a price increase unilaterally promoted by the country.[12] It can only be concluded that there are some countries with non-negligible willingness to join a multilateral agreement for building the carbon neutral MPI market niche. Such willingness is grounded on the dependence on Brazilian MPI exports. With the countries not driven by such motivation it is necessary to appeal for their commitment with biodiversity conservation and climate change mitigation.

Six of the eight Brazilian MPI importers that hold a price making advantage on the trade have ratified the Convention on Biological Diversity (CBD, 2014) and seven have ratified the Kyoto Protocol (UNFCCC, 2014). Japan has not ratified but accepted the CBD. Nevertheless, CBD acceptance has the same legal effect as ratification (CBD, 2014).

USA is the only trade partner that has not ratified both agreements. But considerable progress on binding commitments has been made by the country on the climate change mitigation front, as attested by the Climate Action Report (USA, 2014). The commitments with biodiversity conservation are also clear, as attested by the Tropical Forest Conservation Act of 1998, and other several initiatives (USAID, 2014).

Additionally, it is intuitive that the probability of a country to join the agreement should be a negative function of the cost the agreement imposes on the counterparts. This cost unfolds into (i) the price differential to be paid for carbon neutral MPI and (ii) the transaction cost of identifying carbon neutral MPI.

[12] This is not desirable since a mere price might increase, if demand is inelastic, the profit of all MPI producers, being their MPI carbon neutral or not.

Agreement costs

The price differential of carbon neutral MPI

A Brazilian MPI producer has incentive for relying on deforestation-free EFPs if the profit obtained in return is superior to the profit returned by traditional biomass MPI. This last production system represents, according to The size of the problem section, the business as usual (BAU) option.

Let $P - C_{Ch} - C_R$ be the average profit (US\$/tMPI) yielded by BAU MPI, where P is free-on-board (FOB) price of MPI, C_{Ch} is the cost of charcoal and C_R totalizes remaining production costs. The charcoal cost and FOB price for the carbon neutral MPI alternative will be denoted respectively by P^N and C^N_{ch}, with superscript "N" for "neutral".

Carbon neutral MPI is economically rewarding if and only if $P^N - C^N_{ch} - C_R \geq P - C_{Ch} - C_R$, or, equivalently, $P^N - P \geq C^N_{ch} - C_{Ch}$. The minimum carbon neutral price differential, thus, is given by $C^N_{ch} - C_{Ch}$, being, therefore, equivalent to the charcoal cost differential on a US\$/tMPI basis – this is intuitive since only charcoal is being shifted with MPI production technology remaining untouched. This number is reported, for the four pyrolysis kilns and three Brazilian biomes, in Table 12.

The higher the gravimetric yield of the kiln (tCh/tT), the lower the minimum price differential. In fact, the kiln with the highest yield, the Metallic, offers a negative differential, which means that the cost of growing an EFP is more than compensated by the physical economy of timber the kiln allows for.

Owing to the low gravimetric yield of hot-tail kiln and also to the risks it imposes to workers' health (Greenpeace, 2013), the possibility of employing it with EFP timber is disregarded. Such kiln is the BAU pyrolysis technology.

Table 12 shows that the carbon neutral MPI has to be sold for a price whose absolute magnitude is superior in, at most, US\$80/tMPI than the price of deforestation-based MPI. The average FOB price of MPI, according to annual price data from 2007 to 2013, was of US\$417/MPI (SINDIFER, 2014). Therefore, a maximum price differential of 19% is needed for carbon neutral MPI to pay-off. This is the largest margin demanders have to pay for fostering carbon neutral MPI.

The carbon neutral price differential can also be seen as the cost of sequestering carbon through EFP-based MPI production. Actually, the quotients of the differentials in Table 12 by the CO_2e differentials relative to the BAU system are breakeven carbon offset prices, i.e. they correspond to the price to be paid, on a per tCO_2e basis, for MPI producers in order to incentivize them to opt for carbon neutral MPI. Such carbon offset prices capture two simultaneous changes on the MPI production system, biomass source and kiln.

The BAU biomass defines the amount of emissions to be offset. The higher the carbon content of the BAU biomass, the higher is the offset achieved by shifting from BAU biomass to the deforestation-free alternative. As Table 13 shows, Amazon forest has the highest CO_2 content and the Atlantic forest, the lowest.

The investment needed to shift depends on the kiln employed for converting deforestation-free biomass into charcoal. The higher the kiln's gravimetric yield, the lower the investment in USD per ton of MPI, as seen in Table 12. The metallic kiln has the highest gravimetric yield and, consequently, who opts for it to convert eucalyptus into charcoal faces the lowest investment per ton of MPI.

The final carbon offset prices in Table 14 are a composite of traditional biomass replacement effect and of kiln replacement effect. Results indicate a range for breakeven carbon offset price of −US\$9/tCO_2e to US\$8/tCO_2e. Negative values indicate that the cost of growing EFPs is more than compensated by the physical timber economy yielded by the Metallic kiln. MPI producers which can purchase this kiln with own or borrowed funds should not receive an offset payment, since they already have incentive to opt for the carbon neutral route. For the others, the price of the offset needed to breakeven is not larger than US\$3/tCO_2e for the Missouri kiln and of US\$8/tCO_2e at most for the "Mineirinho" kiln.

Table 7
Cost of charcoal, project TB & HT.

Expenditure class	Unit	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11
Biomass cost, R$	R$	36,195	36,195	36,195	36,195	36,195	36,195	36,195	36,195	36,195	36,195	36,195	36,195
Kiln capital investment	R$	2120		2120		2120		2120		2120		2120	
Kiln operating expenses	R$	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100
Net expenses	R$	40,415	38,295	40,415	38,295	40,415	38,295	40,415	38,295	40,415	38,295	40,415	38,295
Present value of expenses	R$	472,260											
Charcoal production	m^3/year	300	300	300	300	300	300	300	300	300	300	300	300
Unit charcoal cost	R$/$m^3$Ch	131											

Source: section S4 of SI.

Table 8
Cost of charcoal, project PB & Mo, Amazon biome.

Expenditure class	Unit	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11
Traditional biomass cost		463,296	463,296	463,296	463,296	463,296	463,296						
Investment in plantation	R$	2,595,562	216,899	231,936	249,922	263,184	276,446	290,179	290,179	290,179	290,179	290,179	290,179
Plantation operation	R$	–	–	–	–	–	–	240,192	240,192	240,192	240,192	240,192	240,192
Kiln capital investment	R$	240,000											
Kiln operating expenses	R$	45,965	45,965	45,965	45,965	45,965	45,965	45,965	45,965	45,965	45,965	45,965	45,965
Net expenses	R$	3,344,823	726,160	741,197	759,183	772,445	785,707	576,336	576,336	576,336	576,336	576,336	576,336
Present value of expenses	R$	10,587,533											
Charcoal production	m^3/year	5760	5760	5760	5760	5760	5760	5760	5760	5760	5760	5760	5760
Unit charcoal cost	R$/$m^3$Ch	153											

Source: section S4 of SI.

On the European carbon market, the price of European Union Allowances (EUA) was US$8.17 per ton of CO_2 in December 2012 and US$6.3/t$CO_2$ in December 2013. The price of Certified Emission Reduction (CER) offsets in December 2013 was US$0.56/t$CO_2$, this being the offsetting option based on the United Nations Clean Development Mechanism.[13]

Currently, carbon emission permits are exchanged in the Regional Greenhouse Gas Initiative (RGGI), the only active mandatory offset program in the USA (Lee et al., 2013) for a price of US$2/t$CO_2$ (RGGI, 2013).

Conclusively, only with a gravimetric yield of 0.3 tCh/tT, the Missouri kiln level, the shift for EFP-based MPI is compatible with the offset prices that prevail on major carbon markets in recent years. If this shift is implemented by all MPI producers of Minas Gerais states and Carajás pole,[14] the emission of 50 thousand gigagrams (Gg) of CO_2 can be avoided, as calculated in Section S7 of SI. This magnitude is comparable to the emission reduction Brazilian government plans to achieve by 2020 through the increased use of biofuels (MMA et al., 2009).

The cost of identifying carbon neutral MPI

Even if the price differential of carbon neutral MPI is not a barrier, the cost of attesting carbon neutrality might be relevant even with a specific certificate for carbon neutral MPI. Fortunately, initiatives are being developed to reduce this cost.

The Task Force on Sustainable Charcoal (*Grupo de Trabalho Carvão Sustentável*), created in 2012, gathers Brazilian and International third-sector institutions such as Ethos Institute of Business and Social Responsibility, Fundación Avina and IMAFLORA, the last being engaged in promoting sustainable forest management. The International Labor Organization (ITO) is also part of the taskforce, and also WWF-Brazil (Ethos, 2014 and IMAFLORA, 2014).[15]

A modular surveillance tool for the whole MPI supply chain, ProMoVE (acronym in Portuguese) has been designed and released in April 2014. It consists of four modules of progressive adaptation to socioenvironmental standards, which can take, at most, eight and half years to be completed. The adherence is voluntary, but, once opted for, the enterprise must present documents attesting its charcoal supply, including an accounting of how much charcoal from EFPs and native forests are used and also how much charcoal is bought from each supplier. Charcoal suppliers can also adhere to the ProMoVE system and must report their timber sources.

The progressive environmental soundness of adherents aims to the complete replacement of deforestation-based charcoal/timber for EFPs or logging residuals from sustainable forest management. For this, two audits per year are conducted by IMAFLORA, one of them not being planned in advance (surprise audit). Both charcoal and timber supplies and working conditions are checked.

In parallel with ProMoVe, the Brazilian Association of Technical standards (ABNT), is producing a standard of sustainability norms to be followed by MPI producers (IABr, 2013, p.10).

On the state of Maranhão, part both of the Amazon and of the Northeastern region of the country, there is a third sector organization, *Carvão Cidadão* (imperfectly translated as "Civilized Charcoal"), which monitors labor code compliance of charcoal producers that supply Amazonian MPI mills and also their timber sources (ICC, 2014).

The three initiatives mentioned have two main implications. The first is to reduce the cost for producers to prove their MPI is carbon neutral, which attenuates one of the barriers the certification of sustainability faces around the world and which is most stringent for small to medium entrepreneurs (Auer, 2012),[16] the case of a relevant proportion of Brazilian MPI producers. The second is to diffuse the idea that EFP-based MPI is environmentally superior compared with deforestation-based MPI, what might have an ethical effect on enterprises that still rely on the second variety of MPI.

[13] The prices informed correspond to the prices of EUA and CER future contracts on their month of delivery (data source: ICE, 2014). Values in Euros (€) were converted into Dollars with exchange rates of US$1.2848/€ for 2012 and US$1.3281/€ for 2013 (Eurostat:, 2014).

[14] 86% of Brazilian MPI full-capacity production level.

[15] The next two paragraphs build on information obtained by personal communication with Ethos and IMAFLORA representatives (Ethos, 2014 and IMAFLORA, 2014).

[16] "(…) costs for certification tend to be among the most commonly cited drawbacks of third-part certification schemes – whether in rich or poor countries (Auer:, 2012)."

Table 9
Cost of charcoal (R$/$m^3$Ch), all projects and biomes.

Biomass & biome/kiln	HT	Mi	Mo	Me
TB	131.18	106.99	75.15	63.68
PB: Amazon	233.97	189.22	153.18	114.53
PB: Cerrado	218.57	176.9	142.91	105.73
PB: Atlantic forest	211.63	171.35	138.28	101.76

Source: section S4 of SI.

Conclusion

Although there are feasible paths for Brazilian MPI industry to become carbon neutral, none of them has an insignificant cost.

Nevertheless, in accordance with Agreement costs section, the shift of Brazilian MPI mills to a carbon neutral production system can be incentivized through a price differential which is not high. In fact, with a gravimetric yield of pyrolysis of 0.3 tCh/tT or above, the price differential is of 19% of the MPI price or of US$3 per tCO_2 of avoided emissions. Additionally, new initiatives are being developed in Brazil in order to reduce the cost of attesting carbon neutrality.

These results establish the feasibility of an agreement between Brazil and its MPI trade partners in which:

(1) Brazil commits to offer carbon neutral MPI;
(2) Importer countries commit to pay at least the breakeven price for certified carbon neutral MPI and, therefore, a higher price than the one paid for MPI with non-certified carbon intensity.

The Brazilian MPI industry has the opportunity to stop being a threat to biodiversity-rich ecosystems and become a provider of one of the currently most valued environmental services, carbon sequestration.

It is, however, necessary that the Brazilian government gives support to private and third sector initiatives to control timber and charcoal sources and also labor conditions. Besides, it has to promote the multilateral agreement here proposed, establishing effective channels of communication among the Brazilian MPI industry, international importers and stakeholders. Another crucial action is publicizing, with global reach, the information that carbon neutral MPI has a higher production cost than deforestation-based MPI, due to the need of growing carbon-sequestering trees.

The governments of importer countries also have to act, taking biodiversity conservation and climate protection commitments to the field of MPI trade and clearly signalizing their willingness to join the agreement proposed. This positioning is a necessary condition for the rise of the share of carbon neutral MPI in the international and Brazilian markets. It is especially among countries with price making power on MPI trade with Brazil that a pro-biodiversity and pro-climate attitude is needed.

Table 11
GHG emissions of coke and charcoal production (through pyrolysis).

Variable/pyrolysis output	Coke	Charcoal
Pyrolysis CO_2 (tCO_2/t fuel) [a,b]	0.56	0
Pyrolysis CH_4 (tCH_4/t fuel)	10^{-7} [c]	0.0475 [d]
t fuel/tMPI	0.522 [e]	0.69 [f]
Total pyrolysis CO_2e burden (tCO_2e/t MPI) [g]	**0.29**	**0.82**

[a] "tCO_2" stands for ton of carbon dioxide, "tCH_4" for tons of methane, tCO_2e for tons of CO_2 equivalent and "t fuel" stands for tons of coke or tons of charcoal (as defined by the column).
[b] IPCC (2006, v.4.ch4. tables 4.1);
[c] IPCC (2006, v.4.ch4. tables 4.2);
[d] AMB (2009, p.51);
[e] AMB (2009, p.42);
[f] The 1999–2008 charcoal rate of Minas Gerais MPI producers (see section S1 of SI, figure S1.1);
[g] A global warming potential of 25 CO2e is assumed for CH4 (Forster et al, 2007, p.212, table 2.14).

Abbreviations for measurement units

ha	hectares
M	million
tCO_2e	ton of CO_2 equivalent
m^3T	cubic meters of timber
m^3Ch	cubic meters of charcoal
tT	tons of timber
tCh	tons of charcoal
tMPI	tons of merchant pig iron
toe	ton of oil equivalent
R$	Brazilian currency (R$2.04/US$ on December 2012)
US$	North American dollars

Acknowledgments

The author thanks Toby Alan Gardner for gently reviewing the text and Marie Gabrielle Piketty for checking the cost calculations. The Agence Française de Développement (AFD, "Energia e Reflorestamento" project) funded the on-field research from which the data for the cost calculations were collected.

Table 10
Carbon balance of MPI production systems, $kgCO_2$/tMPI [a].

Production system/emission source or sink	Biome deforested	Deforestation (net of sequestration due to 3.5 years of EFP growth)	Further sequestration	Pyrolysis	Logistics	Blast furnace	Balance
Coke-based	Does not apply	Does not apply	Does not apply	Does not apply	134	1589	1883
EFP-based 1	Amazon	4531	−2902	934	144	1508	4214
EFP-based 2	Cerrado	2625	−2902	934	144	1508	2309
EFP-based 3	Atlantic forest	1214	−2902	934	144	1508	898
EFP-based 4	None	0	−5805	934	144	1508	−3219
TB-based 1	Amazon	>4531	0	934	144	1508	>7117
TB-based 2	Cerrado	>2625	0	934	144	1508	>5211
TB-based 3	Atlantic forest	>1214	0	934	144	1508	>3800

Source: section S3 of SI.
[a] "$kgCO_2$" stands for kilogram of CO_2 equivalent and tMPI for ton of MPI.

Table 12
Calculation of the minimum price differential of carbon neutral MPI, US$/tMPI.

BAU biomass source/kiln on the alternative scenario	"Mineirinho"	Missouri	Metallic
Traditional: Amazon	78.41	29.71	−22.5
Traditional: Cerrado	61.76	15.84	−34.39
Traditional: Atlantic forest	54.26	9.59	−39.75

Source: section S5 of SI.

Table 13
Carbon offset, $kgCO_2e$/tMPI.

BAU biomass source	Carbon offset ($kgCO_2$/tMPI)
Traditional: Amazon	10.335
Traditional: Cerrado	8.43
Traditional: Atlantic forest	7.019

Source: Table 10 above.

Appendix A. Structural analysis of international market for Brazilian MPI

It is coherent to employ a structural approach even being MPI a commodity since its trade is based on bilateral contractual transactions that do not necessarily follow a unique price.[17] Contrariwise, there is considerable variation on the price for which transactions are closed. The statistics on table below, which capture transactions where Brazil is the exporter, evidence a relevant volatility of the FOB implicit price (Total value traded/Total quantity traded) across transaction partners (importers). The coefficient of variation, CV, the ratio of the standard deviation and the mean, attains values above 20%, for four of the six years.

Table A.1
Statistics for the variability, among trade partners, of the implicit price of MPI exported by Brazil (FOB, values in US$/tMPI).

Year/statistic	CV	Min	Max	Mean	Median
2008	27.22%	331.51	898.13	524.6	491.44
2009	38.11%	163.62	872.22	382.53	365.08
2010	14.96%	306.94	556.65	469.77	486.68
2011	25.61%	400	1263.73	566.69	550.61
2012	11.79%	338.78	571.2	472.7	473.33
2013	27.22%	331.51	898.13	524.6	491.44

Source: MPI export data from the Brazilian Ministry Development, Industry and Foreign Trade (Aliceweb, 2014).

The range, given by the difference of the maximum and the minimum price is also considerable.

One can measure a transaction's degree of importance from the exporter's standpoint by means of the proportion the transaction represents of the exporter's total production. Focusing on the Brazilian MPI industry,

$$\text{Transaction importance (for the exporter)} = \text{Export quantum (in tons)/Brazilian output (in tons)}$$

[17] The price that perfectly balances market supply and market demand, according to the economic model of perfect competition. This model rests on the assumption that market players are numerous and small enough for their actions to exert no influence on market price. This hypothesis does not apply to some commodity markets, especially the MPI international market, since the size of players, measured in quantities bought or sold, is not negligible as it is clearly the case of USA, China, Brazil and Russia (Barrington, 2010).

Table 14
Carbon offset breakeven prices, US$/$tCO_2e$.

BAU biomass source/kiln on the alternative scenario	"Mineirinho"	Missouri	Metallic
Traditional: Amazon	7.59	2.87	−2.18
Traditional: Cerrado	7.33	1.88	−4.08
Traditional: Atlantic forest	2.89	−2.67	−9.12

Source: section S4 of SI.

If the weighted average from 2000 to 2008 is taken, where the weight is year t's share of the period's total output, we can derive the following transaction importance indicator:

$$\text{Transaction importance (for the exporter)} = \sum_{t=2000}^{2008}\left(\frac{X_t}{Y_t}\right)\left(\frac{Y_t}{\sum_{t=2000}^{2008} Y_t}\right) \tag{1}$$

where X_t ≡ MPI export quantum (tMPI) at year "t" and Y_t ≡ MPI production quantum (tMPI) at year "t".

From the standpoint of the importer, in the case of a non-Brazilian industry that employs Brazilian MPI as raw material,

$$\text{Transaction importance (for the importer)} = \text{Import quantum(in tons)/Importer's apparent consumption (in tons)}$$

Again, taking the weighted average from 2000 to 2008, with weight given by year t's share of the period apparent consumption, the importance indicator is derived as follows:

$$\text{Transaction importance (for the importer)} = \sum_{t=2000}^{2008}\left(\frac{M_t}{A_t}\right)\left(\frac{A_t}{\sum_{t=2000}^{2008} A_t}\right) \tag{2}$$

where M_t ≡ MPI import quantum (tMPI) at year "t" and A_t ≡ MPI apparent consumption quantum (tMPI) at year "t".

Table A.2
Absolute and relative importance of MPI trade transactions for Brazil and trading partners, 2000–2008.

Partner[a]	Importance		Brazil/partner
	Brazil[b]	Partner[c]	
Argentina	0.30%	1.06%	0.29
Australia	0.68%	0.89%	0.76
Belgium	0.15%	0.16%	0.93
Canada	0.20%	0.20%	1.02
Chile	0.16%	1.25%	0.13
China	1.23%	0.03%	35.14
North Korea	0.29%	10.99%	0.03
Germany	0.58%	0.16%	3.61
Italy	0.61%	0.41%	1.48
Japan	0.78%	0.08%	10.02
Mexico	1.73%	3.12%	0.56
Netherlands	0.61%	0.89%	0.69
Paraguay	0.00%	0.02%	0.01
South Korea	0.99%	0.29%	3.47
Spain	2.20%	4.10%	0.54
Taiwan	4.50%	3.73%	1.21
United Kingdom	0.16%	0.13%	1.23
USA	46.05%	8.54%	5.39

[a] Source of data: UN COMTRADE (2010), AMS (2009) and World Steel (2010).
[b] The importance for Brazil was calculated from UN COMTRADE data for the country's exports and from AMS (2009, a Brazilian institution that supports MPI business) data on Brazilian production.
[c] The apparent consumption is production + imports–exports, where production data was taken from World Steel (2010) and import and export data from UN COMTRADE (2010). Import data were not directly taken from the partner country's statistics, because two of the countries have not reported their Brazilian MPI imports to UN COMTRADE: North Korea and Taiwan. The data that UN COMTRADE reports as "Other Asia" is accounted for as Taiwan.

The ratio between Eq. (1) and Eq. (2), calculated for each MPI transaction where Brazil plays the role of exporter, is an indicator of the relative importance from the standpoint of the exporter (Table A.2).

The partners for which pig iron production data were not available (from World Steel, 2010) or that imported Brazilian MPI, according to the available statistics (UN COMTRADE, 2010), for a number of years smaller than half of the period considered (fewer than 5 years) are disregarded. Omissions for the first reason are dictated by data limitations; omissions for the second reason are a choice whose objective is to base the evaluation on durable trade relations.

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.esd.2015.04.008.

References

ABRAF. ABRAF statistical yearbook. Brazilian Association of Forest Plantation Producers; 2010 [Base year: 2009. Available at http://www.abraflor.org.br/estatisticas.asp].

Abramovay R. Decarbonizing the growth model of Brazil: addressing both carbon and energy intensity. J Environ Dev 2010;19:358.

Aliceweb. Merchant pig iron export data (Commodity 7201.10.0100 on NCM nomenclature). Trade database of the Brazilian Ministry Development, Industry and Foreign Trade; 2014 [Available at aliceweb.mdic.gov.br//index/home].

AMB (Arcelor Mittal Brazil). Use of charcoal from renewable biomass plantations as reducing agent in pig iron mill at ArcelorMittal Juiz de Fora, Brazil. Project Development Document Form. Arcelor Mittal Brasil; 2009 [Available at http://cdm.unfccc.int/index.html].

AMS. Minas Gerais Association of Silviculture. Anuário estatístico 2008; 2009 [Available at http://www.silviminas.com.br/].

Auer MR. Group forest certification for smallholders in Vietnam: an early test and future prospects. Hum Ecol 2012:1–10. [January 2012. Available at SSRN: http://ssrn.com/abstract=1995026}.

Ayres R, Ayres E. Crossing the energy divide: moving from fossil fuel dependence to a clean-energy future. USA: Pearson Education, Wharton School Publishing Upper Saddle River, New Jersey; 2010.

Barrington C. Merchant pig iron, overview of global trends. Presentation from the secretariat of the International Pig Iron Association (formerly known as IPIA, currently International Iron Metallics Association); 2010. (Available at http://www.gladiatorresources.com.au/Pig.pdf).

Boyd E, May P, Chang M, Veiga FC. Exploring socioeconomic impacts of forest based mitigation projects: lessons from Brazil and Bolivia. Environ Sci Pol 2007;10(5):419–33. [August 2007].

Buchanan L, Levine SB. Wood-based building materials and atmospheric carbon emissions. Environ Sci Pol 1999;2(6):427–37. [December 1999].

Calais D. Florestas energéticas no Brasil: demanda e disponibilidade. Study issued by the Minas Gerais Silviculture Association (AMS); 2009 [Available at: http://www.silviminas.com.br].

Carvalho AP, Monzoni Neto MP, Hübner DB, Figueiredo JC, Amorim PQR. Impactos socioeconômicos e ambientais do complexo minero-siderúrgico de Mato Grosso do Sul. Revista Política Ambiental, N. 6, Fevereiro de 2008. Conservação International; 2008.

CBD. Website of the Convention on Biological Diversity. List of parties; 2014. Available at http://www.cbd.int/convention/parties/list/.

CEMIG. Balanço Energético do Estado de Minas Gerais 2009. Available at http://www.cemig.com.br/, 2010.

CGEE, 2010. Incremento do carvão vegetal renovável na siderurgia brasileira. Relatório Final. Centro de Gestão e Estudos Estratégicos. Ministério do Desenvolvimento, Indústria e Comércio Exterior (MDIC). Unpublished report.

CIF. Centro de Inteligência em Florestas. Price of Land in Minas Gerais state. Available at: http://www.ciflorestas.com.br/dado.php?id=136, 2015.

Climate Analysis Indicators Tool (CAIT), 2014. World Resources Institute. Available at http://cait2.wri.org/.

Conservation International. Information on Brazilian Atlantic Forest. Available at: http://www.conservation.org/where/priority_areas/hotspots/south_america/Atlantic-Forest/Pages/default.aspx, 2013.

Cowie A, Schneider UA, Montanarella L. Potential synergies between existing multilateral environmental agreements in the implementation of land use, land-use change and forestry activities. Environ Sci Pol 2007;10(4):335–52. [June 2007].

Daly HE, Farley J. Ecological Economics: principles and applications. Washington, U.S.A.: Island Press; 2004

EPE. Balanço Energético Nacional. Empresa de Pesquisa Energética; 2010 [Available at http://ben.epe.gov.br].

Ethos. Personal communication with the public policy projects coordinator of the Brazilian NGO Ethos. Introductory and technical documents on the modular surveillance toolProMoVE have been transmitted through e-mail. May 2014; 2014.

EUROSTAT. Series “Exchange rates versus national currencies, annual average (tec 00033)”. Available at http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&language=en&pcode=tec00033&plugin=1, 2014.

FAO. Industrial charcoal production. Zagreb, Croatia. Available at http://www.drveniugljen.hr/assets/files/pdf/FAO_Industrial%20charcoal%20production.pdf, 2008.

Firm E. Eucalyptus plantation and pyrolysis data collected in field work research; 2010 [Turucuí, Pará].

Firm Me. Metallic kiln folder. Obtained during fieldwork on Carajás pole, January 2009–June 2010; 2010.

Firm Mo. Confidential data transmitted by the firm through personal contacts made in 2008, during participation on Ultra Low CO_2 Steelmaking (ULCOS) project. Belo Horizonte: Minas Gerais; 2008.

Firm R. Data on wood processing and transport costs, collected in field research; 2010.

Firm S. Confidential data transmitted by the firm through personal contacts made in 2010, during participation on “Energia e Reflorestamento na Amazônia” research project. Maranhão; 2010.

Firm W. Confidential data transmitted by the firm through personal contacts made in 2010, during participation on “Energia e Reflorestamento na Amazônia” research project. Paragominas, Pará; 2010.

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, et al. Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. Climate Change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007.

Gayoso S. Territórios e mercado de terras no Baixo Amazonas: expansão da sojicultura e valorização fundiária. VI Encontro Nacional da Anppas; 2012. [18 a 21 de setembro de 2012. Available at: http://www.anppas.org.br/encontro6/anais/ARQUIVOS/GT18-663-342-20120711090149.pdf].

Goldemberg J, Coelho ST. Renewable energy: traditional biomass vs. modern biomass. Energy Policy 2004;32(6):711–4. [April 2004].

Greenpeace. Driving destruction in the Amazon. How steel production is throwing the forest into the furnace; 2013 [Available at http://www.greenpeace.org/international/Global/international/publications/forests/2012/Amazon/423-Driving-Destruction-in-the-Amazon.pdf].

IABr. Relatório de sustentabilidade. Brazilian Steel Institute; 2010 [Base year: 2009, Available at http://www.acobrasil.org.br/site/portugues/sustentabilidade/relatorio.asp].

IABr. Protocolo de Sustentabilidade do Carvão Vegetal (Sustainability protocol for charcoal). Brazilian Steel Institute; 2013 [Available at http://www.acobrasil.org.br/site/portugues/sustentabilidade/downloads/resultados-protocolo.pdf].

IBAMA. Relatório técnico de monitoramento do desmatamento no bioma Cerrado. Período de 2002 a 2008. Brazilian Institute of Environment and Renewable Natural Resources; 2009 [Available at http://siscom.ibama.gov.br/monitorabiomas/cerrado/Relatorio%20tecnico_Monitoramento%20Desmate_Bioma%20Cerrado_CSR_REV.pdf].

IBAMA. Relatório técnico de monitoramento do desmatamento no bioma Caatinga. Período de 2002 a 2008. Available at http://siscom.ibama.gov.br/monitorabiomas/caatinga/relatrio_tcnico_caatinga_72.pdf, 2010.

IBAMA. Relatório técnico de monitoramento do desmatamento no bioma Pantanal. Período de 2002 a 2008. Available at http://siscom.ibama.gov.br/monitorabiomas/pantanal/RELATORIO_PANTANAL_2008_PMDBBS.pdf, 2010.

IBGE. Silviculture and extraction survey (Pesquisa da Extração Vegetal e Silvicultura). Sistema de recuperação automática de dados (SIDRA). Edição de 2009. Instituto Brasileiro de Geografia e Estatística; 2009. Available at http://www.sidra.ibge.gov.br/.

IBGE. Mapa de Biomas e de Vegetação. Instituto Brasileiro de Geografia e Estatística. Sistema de recuperação automática de dados (SIDRA). 2011. Available at http://www.ibge.gov.br/home/presidencia/noticias/21052004biomashtml.shtm.

IBGE/INPE. Accumulated deforestation in Brazilian Amazon, as measured by the National Institute for Space Research (INPE). Obtained from IBGE's Sustainable Development Indicators; 2011 [Available at http://www.sidra.ibge.gov.br/bda/pesquisas/ids/default.asp].

ICC. Instituto Carvão Cidadão (Civilized charcoal institute website). Available at http://www.carvaocidadao.org.br/, 2014.

ICE. Intercontinental exchange website. Available at http://www.theice.com, 2014.

IFNP. Análise do Mercado de Terras, relatório bimestral. Instituto FNP; 2008.

IMAFLORA. Personal communication through e-mail with the forest certification coordinator of the Brazilian NGO IMAFLORA. May 2014; 2014.

IPCC. IPCC Guidelines for national greenhouse gas inventories. Industrial processes and product use, vol. 3. ; 2006. [Chapter 4].

Klink CA, Machado RB. Conservation of the Brazilian Cerrado. Conserv Biol 2005;19(3):707–13. [June 2005].

Lee CM, Lazarus M, Smith GR, Todd K, Weitz M. A ton is not always a ton: a road-test of landfill, manure, and afforestation/reforestation offset protocols in the U.S. carbon market. Environ Sci Policy 2013;33(2013):53–62.

Massengale R. Black Gold: a history of charcoal in Missouri. USA: Author House; 2006.

MCT. Emissões de dióxido de carbono no setor uso da terra, mudança do uso da terra e florestas (report on emissions from land use change and forests). Second Brazilian greenhouse gases (GHG) inventory. Brazilian Science and Technology Ministry; 2010 [Available at http://www.cetesb.sp.gov.br/userfiles/file/mudancasclimaticas/geesp/file/docs/publicacao/nacional/2_comunicacao_nacional/rr/uso_terra/brasil_mcti_uso_terra.pdf].

MMA. Web Page on the Amazon biome. Available at http://www.mma.gov.br/sitio/index.php?ido=conteudo.monta&idEstrutura=72&idConteudo=10601&idMenu=10989, 2011.

MMA, MAPA, MME, MF, MDIC, MCT, et al. Cenários para Oferta Brasileira de Mitigação de Emissões, São Paulo, 13 de novembro. Available at http://www.forumclima.pr.gov.br/arquivos/File/CenariosparaOfertaBrasileiradeMitiga.pdf, 2009.

MME. Statistical Yearbook. Base year: 2006. Brazilian Ministry of Mines and Energy. Secretariat of Geology, Mining and Mineral Transformation - SGM; 2007 [Available at: http://www.mme.gov.br/sgm/menu/publicacoes.html].
MME. Statistical Yearbook. Base year, 2007. Brazilian Ministry of Mines and Energy. Secretariat of Geology, Mining and Mineral Transformation - SGM; 2008 (Available at: http://www.mme.gov.br/sgm/menu/publicacoes.html).
MME. Statistical Yearbook. Base year: 2007. Brazilian Ministry of Mines and Energy. Secretariat of Geology, Mining and Mineral Transformation - SGM; 2008 (Available at: http://www.mme.gov.br/sgm/menu/publicacoes.html).
MME. Statistical Yearbook. Base year: 2009. Brazilian Ministry of Mines and Energy. Secretariat of Geology, Mining and Mineral Transformation - SGM; 2010 (Available at: http://www.mme.gov.br/sgm/menu/publicacoes.html).
Monteiro MA. Em busca de carvão vegetal barato: o deslocamento de siderúrgicas para a Amazônia. Novos Cadernos NAEA1516-6481, 9, n. 2. ; 2006. p. 55–97. [dez. 2006].
Peláez-Samaniego MR, Garcia-Perez M, Cortez LB, Rosillo-Calle F, Mesa J. Improvements of Brazilian carbonization industry as part of the creation of a global biomass economy Review Article. Renew Sust Energ Rev 2008;12(4):1063–86. [May 2008].
Piketty M-G, Wichert M, Fallot A, Aimola L. Assessing land availability to produce biomass for energy: the case of Brazilian charcoal for steel making. Biomass Bioenergy 2009; 33(2):180–90. [February 2009].
Pinheiro PC Da C, Sampaio RS, Rezende MEA, Viana E. A Produção de carvão vegetal: teoria e prática. 2a Edição Revista e Ampliada. Belo Horizonte; 2008.
Plantar. Mitigation of methane emissions in the charcoal production of Plantar, Brazil. Clean Development Mechanism Project Design Form (CDM-PDD); 2006 [Available at http://cdm.unfccc.int/Projects/DB/DNV-CUK1175235824.92].
Povellato A, Bosello F, Giuponni C. Cost-effectiveness of greenhouse gases mitigation measures in the European agro-forestry sector: a literature survey. Environ Sci Pol 2007; 10(5):474–90. [August 2007].
Quaresma LF. Perfil do ferro-gusa. Relatório técnico 59. Projeto de assistência técnica ao setor de energia. Ministério de Minas e Energia (MME). Secretaria de geologia, mineração e transformação mineral (SGM); 2010 [Available at http://www.mme.gov.br/sgm/galerias/arquivos/plano_duo_decenal/a_transformacao_mineral_no_brasil/P33_RT59_Perfil_do_Ferro-Gusa.pdf. Last consult in 09/11/2010].
RGGI. Annual report on the market of RGGI CO_2 allowances: 2012. Potomac Economics; 2013 [April 2013. Available at www.rggi.org].
Romijn H, Raven R, Visser I. Biomass energy experiments in rural India: insights from learning-based development approaches and lessons for strategic niche management. Environ Sci Pol 2010;13(4):326–38. [June 2010].
Rosillo-Calle Frank, et al. The charcoal dilemma: finding sustainable solutions for Brazilian industry. Intermediate Technology Publications Ltd (ITP); 1996 [1996].
Rosillo-Calle F, Bajay SV, Rothman H. Industrial uses of biomass energy: the example of Brazil. King's College London, University of London; 2000.
Sathaye JA, Andraskob K, Makundia W, La Rovere EL, Ravindranath NH, Melli A, et al. Concerns about climate change mitigation projects: summary of findings from case studies in Brazil, India, Mexico and South Africa. Environ Sci Pol 1999;2(2):187–98. [May 1999].
SINDIFER. Indicadores, Gráficos e tabelas. Trade union that represents Brazilian MPI industry; 2013 [Available at http://www.sindifer.com.br/Anuario_2007.html].
SINDIFER. SINDIFER statistical yearbook. Trade union of the Merchant Pig Iron industry of Minas Gerais State; 2014 [Available at http://www.sindifer.com.br/institucional/anuario/anuario_2013.pdf].
SINDIFERPA. Data on production and productive capacity of Carajás pole merchant pig iron mills. Excel spreadsheet collected on field work; 2010 [Belém, Pará].
SINOBRAS. Relatório de sustentabilidade. Siderúrgica Norte Brasil; 2009 [Available at http://www.sinobras.com.br/arquivos/].
SOS Mata Atlântica. Atlas dos remanescentes florestais da Mata Atlântica. Período 2008–2010; 2010 [Available at http://mapas.sosma.org.br/site_media/download/atlas_2008-10_relatorio%20final_versao2_julho2011.pdf].
UFRGS (Federal University of Rio Grande do Sul State). Cobertura vegetal do bioma Pampa. Relatório Técnico; 2007 [Available at http://www.ecologia.ufrgs.br/labgeo/arquivos/downloads/dados/Mapeamento_bioma_pampa/Relatorio_bioma_Pampa.pdf].
UN COMTRADE. UN COMTRADE database. Available at: http://comtrade.un.org/, 2010.
UNFCCC. Kyoto protocol website. List of parties. Available at http://unfccc.int/parties_and_observers/items/2704.php, 2014.
USA. United States climate action report 2014. Available at http://www.state.gov/documents/organization/219038.pdf, 2014.
USAID. USAID website. International forest and biodiversity conservation actions conducted by the United States of America. Available at http://www.usaid.gov/biodiversity/policy, 2014.
Vital MHF, Pinto MAC. Condições para a sustentabilidade da produção de carvão vegetal para fabricação de ferro-gusa no Brasil. BNDES Setorial, 30. p. 237–97. [Avaiable at http://www.bndes.gov.br/SiteBNDES/bndes/bndes_pt/Institucional/Publicacoes/Consulta_Expressa/Setor/Mineracao_e_Siderurgia/200909_06.html. Last consult on 09/11/2010].
Werneck FP. The diversification of eastern South American open vegetation biomes: historical biogeography and perspectives. Quat Sci Rev 2011;30(13–14):1630–48. [June 2011].
World Bank. The changing wealth of nations: measuring sustainable development in the new millennium. Available at http://siteresources.worldbank.org/ENVIRONMENT/Resources/ChangingWealthNations.pdf.
World Steel. World Steel Association Statistical Yearbook 2009. Available at http://www.worldsteel.org/.
Yellishetty M, Ranjith PG, Tharumarajah A. Iron ore and steel production trends and material flows in the world: is this really sustainable? Resour Conserv Recycl 2010; 54(12):1084–94. [October 2010].
Yellishetty M, Mudd GM, Ranjith PG, Tharumarajah A. Environmental life-cycle comparisons of steel production and recycling: sustainability issues, problems and prospects. Environ Sci Pol 2011;14(6):650–63. [October 2011].