THE GREENHOUSE GAS FOOTPRINT OF CHARCOAL PRODUCTION AND OF SOME APPLICATIONS IN STEELMAKING

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ABSTRACT

Fossil fuel-based carbon is widely used in iron and steelmaking in a number of forms and applications including:

- coke as a reductant (for reducing metallic oxides to metal) and as a fuel;
- coal and natural gas as fuels;
- carbonaceous materials for special purposes, eg. recarburiser carbon for increasing the carbon content of liquid steel.

Charcoal produced from biomass is considered renewable because the carbon cycle via wood (biomass) is very short (5-10 years) compared to fossil coal (approximately 100 million years). By using charcoal derived from biomass in place of fossil fuel-based carbon in the above steelmaking applications, the non-renewable greenhouse gas footprint of steelmaking can be reduced. Life cycle assessment methodology has been used to estimate the greenhouse gas footprint of charcoal production from biomass, as well as potential reductions in greenhouse gas emissions from the use of charcoal from biomass in steelmaking. Steel production processes examined in the study included the integrated blast furnace route, direct smelting and mini-mill routes, with charcoal substitution rates ranging from 20% up to 100%.

Keywords: charcoal, steelmaking, life cycle assessment, greenhouse gases

1. INTRODUCTION

Primary metal production contributes about 5% to total world greenhouse gas emissions, and of this, iron and steel production accounts for about 70% [1]. It is therefore apparent that the major opportunity for reducing greenhouse gas emissions from primary metal production is in the ironmaking and steelmaking process. While there are a number of short-term approaches to reducing CO_2 emissions from ironmaking and steelmaking [2], the longer-term approach will require gradual substitution of fossil fuel-based carbon materials such as coke and coal by renewable sources of carbon such as biomass carbon. The term biomass is a general descriptor of biologically produced material that readily burns or can be converted into char. Biomass materials include wood and wood wastes, agricultural crops and their waste products. Biomass and char have been used as fuels and as reductants in metallurgical processes since ancient times [3]. The use of biomass wood char in ironmaking has been extensively reviewed by Gupta [2], while Burgess [4] and Dell'Amico et al [5] have also described applications of biomass wood char in ironmaking. Woodchar or biomass char is considered renewable because the carbon cycle via wood (biomass) is very short (5-10 years) compared to fossil coal (approximately 100 million years). However, the challenge is to be able to develop and manage the wood source on a sustainable basis and to develop charcoal production technology that produces charcoal at a significantly lower cost [6] and with lower environmental impacts than current production methods.

The two main steelmaking routes are the integrated (blast furnace) process and the mini-mill (electric arc furnace) process, with about 71% of world's steel production of 1220 million tonnes in 2009 being produced by the integrated route and about 28% by the mini-mill route [7]. However, blast furnaces, in general, suffer from a number of disadvantages (eg. agglomerated or lump feed, coke not coal, coke ovens). A range of “direct smelting” processes using bath smelting technology have been developed in recent years to address these issues. One of these processes is the HIsmelt ironmaking process [8], which is then followed by the conventional basic oxygen furnace (BOF) steelmaking process. The main differences between the processes is the manner in which the molten steel is derived. While the potential use of charcoal in various stages of steel production have been investigated both conceptually [9] and experimentally, eg. sintering [6, 10], iron ore reduction [11], very little has been published on the environmental aspects of charcoal use in steelmaking [12]. A study was therefore undertaken to provide initial estimates in regard to this issue. The study was indicative, rather than detailed, in nature, and was based on a given set of assumptions for each of the three steelmaking routes referred to above, as well as for the charcoal production process. The results will be used to assist in direction setting for future research in the use of biomass charcoal in ironmaking and steelmaking.

2. CHARCOAL PRODUCTION

There are several commercial processes currently available to pyrolise biomass to charcoal. Historically, batch kilns have been used, but they are labour intensive and require a high degree of control to produce good quality, and high yields, of charcoal. Consequently, charcoal produced in batch kilns often lacks uniform quality. Continuous retorts (eg. Lambiotte and Lurgi) are used in Australia [13] and elsewhere to overcome quality and operational issues of kilns, and where large production capacity is required. Although the pyrolysis method affects the yield and properties of charcoal, other critical factors are wood species, moisture content and size. A schematic diagram of charcoal production from biomass is shown in Figure 1. Volatiles from the charcoal production process can be recovered as bio-oils which contain useful chemicals [14] or utilised to generate electricity [15, 16] and/or heat [17]. Thus charcoal production technologies range from batch processes with no by-product recovery at one end, up to continuous processes with by-product bio-oil, electricity and/or heat at the other. A good example of the latter process is the integrated wood processing (IWP) plant developed by Enecon [15,16] based on fluidised bed technology developed by CSIRO.

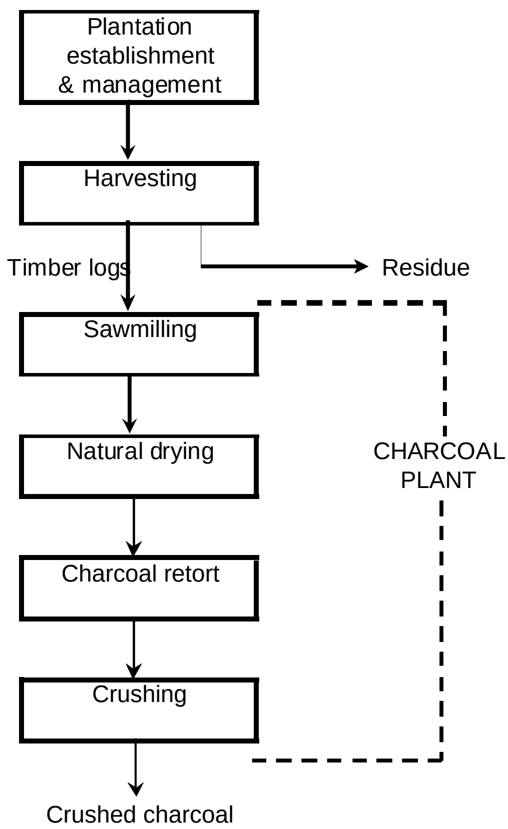

Figure 1. Schematic flowsheet of charcoal production.

Existing plantations, forests and agricultural residues are all sources of biomass. New plantations can also be a source of biomass, and there is considerable interest in the potential for new tree crops such as Mallee eucalypts to be planted in agricultural regions across Australia to reduce the impact of dryland salinity. Wu et al [18] examined Mallee biomass production, while Stucley [15] reported details of a full-scale plant built in Western Australia for integrated processing of Mallee eucalypts (wood, bark, twigs and leaves) to produce charcoal or activated carbon, electrical power and eucalyptus oil. This latter scenario (charcoal production with electricity and eucalypts oil co-products from Mallee eucalypts) was used as the basis for the life cycle assessment (LCA) of charcoal production described below, although the no by-product case was also included for comparative purposes. While the main source of biomass in the study was Mallee eucalypts, forestry or logging residues were also assessed as an alternative source of biomass for charcoal production.

3. LIFE CYCLE ASSESSMENT OF CHARCOAL PRODUCTION

The various LCA inventory inputs derived from the data provided by Wu et al [18] for the plantation establishment and management, harvesting and transportation of Mallee eucalypt biomass to the charcoal plant are given in Table 1, while the electricity and eucalyptus oil co-product credits for the charcoal plant based on data reported by Enecon [16] for Mallee eucalypt biomass are given in Table 2. These credits are based on the assumption that the by-product electricity replaces electricity generated from black coal, while the by-product eucalyptus oil replaces oil produced using diesel fuel. The electricity co-product credit of 6.08 t CO_2e/t charcoal in Table 2 corresponds to 1.02 t CO_2e/t dry biomass[1] (wood, bark, twigs and leaves). Other assumptions made in relation to the charcoal plant were:

- retort biomass feed properties: 20% moisture (after natural drying), 44.4% carbon (dry basis);

Table 1. Inventory data for biomass production.

Plantation establishment	*Energy inputs* 0.17 kg diesel/t green biomass [1] 0.5 kWh/t green biomass [1]
Plantation management	*Energy inputs* 0.63 kg diesel/t green biomass [1] 1.8 kWh/t green biomass [1]
Harvesting	*Energy inputs* 1.57 kg diesel/t green biomass [1] 4.5 kWh/t green biomass [1]
	Yield & composition 19.2 t/ha.y 40% wood (45% H_2O, wet basis (wb)) 25% bark and twigs (45% H_2O, wb) 35% leaves (45% H_2O, wb)
Transportation to charcoal plant	*Energy inputs* 2.2 kg diesel/t green biomass [a, b]

a. Assumes 58% of energy consumption is diesel (cal value 41 MJ/kg), balance is electricity.
b. Transport distance 70 km.

Table 2. Electricity and eucalyptus oil co-product credits.

Electricity [a]	63.2 GJ/t charcoal (GER credit – non-renewable) = 63.2x 0.35/3.6 = 6.1 MWh_e/t charcoal 6.08 t CO_2e/t charcoal (GWP credit – non-renewable)
Eucalyptus oil [b]	1.4 GJ/t charcoal (GER credit – non-renewable) 0.12 t CO_2e/t charcoal (GWP credit – non-renewable)

a. Assumes electricity generated during charcoal production (6.1 MWh/t charcoal, Enecon [16]) replaces electricity generated from black coal at 35% efficiency (987 kg CO_2e/MWh).
b. Assumes energy for avoided eucalyptus oil production is from diesel fuel.

[1] 100 t of naturally dried biomass feed at 20% moisture corresponds to 80 t of dry biomass which produces 13.4 t charcoal, ie. 6.0 t dry biomass/t charcoal.

- charcoal yield in retort is 13.4% (wet basis) for wood, bark, twigs and leaves feed[2] (Enecon [16]);
- charcoal properties: 4.5% moisture, 88.3% carbon, ash 2.3%, sulphur 0.2%, calorific value 31.1 MJ/kg (dry basis).

An LCA spreadsheet model of charcoal production as shown in Figure 1 was set up based on the above assumptions and incorporating the inventory data given in Tables 1 and 2. The LCA model also included inventory data for the production of the various raw material and energy (eg. electricity) inputs into the charcoal process. The main environmental impact category considered was greenhouse gas emissions on an aggregated gas basis (ie. Global Warming Potential [GWP]), with the IPCC (Intergovernmental Panel on Climate Change) characterisation model being used to calculate this impact category. The Gross Energy Requirement (GER), also referred to as embodied energy or cumulative energy demand, which is the cumulative amount of primary energy consumed in all stages of the life cycle was also included in the LCAs. It was assumed that electric power was generated from black coal in all cases, at a generation efficiency of 35%. The study used the international standards framework for conducting life cycle assessments contained in the ISO 14040 series with a functional unit of one tonne of charcoal . The methodology used in carrying out the LCAs in the study (charcoal and steel production) was similar to that used previously by the authors in carrying out cradle-to-gate LCAs of various metal production processes [19-21].

The results from the LCA of charcoal production are given in Table 3 with the GER broken down into both renewable (from biomass) and non-renewable (from fossil fuels) components. It is these non-renewable components that must be reduced if significant reductions in greenhouse gas emissions from fossil fuels are to be achieved. In the case of the GWP, the renewable component of the gross impact was equal to 6.62 t CO_2e/t charcoal[3]. However, these emissions are offset by an equivalent renewable GWP credit due to the CO_2 sequestered during the growth of the biomass as shown in Figure 2. Thus the net renewable GWP component of the gross impact shown in Table 3 is equal to zero. From Table 3, the non-renewable GWP impact for charcoal production is 220 kg CO_2e/t charcoal (or 250 kg CO_2e/t C for 88.3% carbon in the charcoal), which reflects the fossil fuel used in its production. SERDF [12] reported a non-renewable GWP impact of 120 kg CO_2e/t charcoal for charcoal production, but when corrected to the same charcoal yield (dry basis) considered here, the value corresponds to 210 kg CO_2e/t charcoal, very similar to above. The contributions of the various stages to the greenhouse gas footprint of charcoal production is shown in Figure 3. The by-product credits referred to above significantly reduce the non-renewable GER and GWP impacts of charcoal production, resulting in negative values in Table 3, indicating an overall net credit.

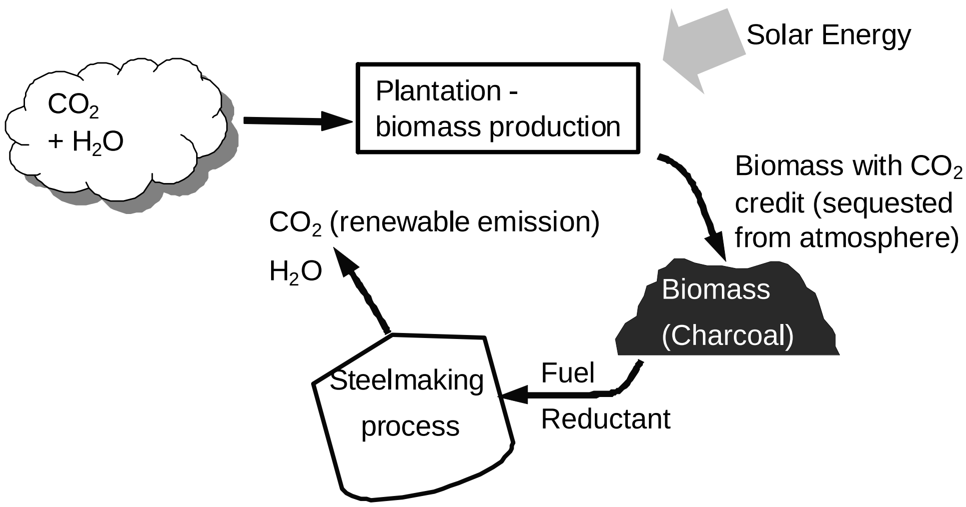

Figure 2. Schematic illustration of biomass carbon cycle.

[2] Compared with 23.2% charcoal yield (wet basis) for wood only.
[3] From listed assumptions = [((0.8 x 0.444) – (0.134 x 0.955 x 0.883))/0.134] x 44.01/12.01 = 6.62 t CO2e/t charcoal.

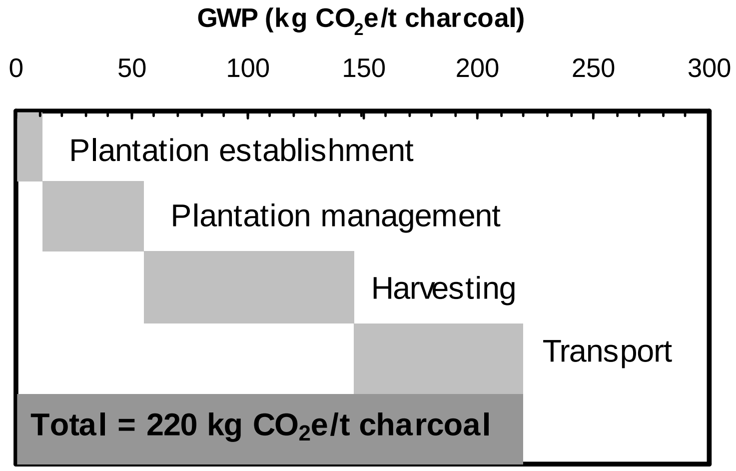

Figure 3. Stage contributions to greenhouse gas footprint of charcoal production.

It is of interest to compare the energy and greenhouse gas footprints for the production of biomass feed material delivered to the charcoal plant from the two alternative sources of biomass considered in the study. The non-renewable energy and greenhouse gas footprints of the Mallee eucalypt biomass in Table 3 are 470 MJ/t dry biomass and 37 kg CO_2e/t dry biomass respectively[4]. The non-renewable greenhouse gas footprint for the forestry residues, covering the same stages of biomass production in Table 1, was estimated to be 40 kg CO_2e/t dry biomass from a separate LCA model. However, this latter material requires additional stages of chipping, screening, washing and drying. Including these stages in the LCA model, together with fertiliser application in the plantation stage, increases the greenhouse gas footprint of biomass from forestry residues to 81 kg CO_2e/t dry biomass. But plantations are established and operated for the production of sawlogs and other main products, and hence harvesting must be carried out whether residues are extracted or not. Very little utilisation is normally made of these residues, so in most instances they are not considered to be valuable co-products. Without the need to allocate the energy and greenhouse gas impacts of plantation and harvesting to these residues, the greenhouse gas footprint drops to 49 kg CO_2e/t dry biomass. This value is only slightly higher than that for Mallee eucalypt biomass, and reflects the additional processing required for this material. As noted earlier, the following assessment of the use of charcoal in steelmaking is based on charcoal produced from Mallee eucalypts.

Table 3. LCA results for charcoal production from Mallee eucalypts.

	Gross impact (no credits)	Electricity & euc. oil credits	Net impact (with credits)
Gross Energy Requirement			
Renewable (GJ/t charcoal)	109.7	0.0	109.7
Non-renewable (GJ/t charcoal)	2.8	64.6	-61.8
TOTAL (GJ/t charcoal)	112.5	64.6	47.9
Greenhouse gases (GWP)			
Renewable (t CO_2e/t charcoal)	0.00[a]	0.00	0.00
Non-renewable (t CO_2e/t charcoal)	0.22	6.20	-5.98
TOTAL (t CO_2e/t charcoal)	0.22	6.20	-5.98

a. Renewable greenhouse gas emissions from charcoal production are 6.62 t CO_2e/t charcoal, but these are offset by an equivalent amount sequestered in the biomass – hence net emissions are zero.

4. STEELMAKING AND OPPORTUNITIES FOR CHARCOAL USE

The integrated steelmaking route begins with iron ore extracted from the earth. After crushing and screening, the iron ore fines are either sintered or pelletised and then fed into the blast furnace along with lump iron ore. Coke, produced from coal in coke ovens, is used as a fuel and reductant

[4] Based on approximately 6.0 t dry biomass/t charcoal in charcoal retort as outlined in earlier footnote.

in the blast furnace together with fluxes to produce pig iron and slag. Natural gas or pulverised coal injection is also commonly used as a supplementary fuel in the blast furnace. The pig iron is transferred to the basic oxygen furnace (BOF) along with steel scrap, where oxygen is used to refine the pig iron into steel by reducing the carbon content and other impurities.. In direct smelting processes, smelting takes place in a single reactor where ore and coal are both charged into the same melt or bath (hence the name “bath smelting”). The processes utilise post combustion of the process offgases, the heat released being transferred back to the bath to compensate for the endothermic smelting reactions. The HIsmelt process produces molten iron from fine iron ores (and other iron-bearing fines) and non-coking coals. The iron oxides are rapidly reduced by the bath whilst carbon from the coal dissolves in the bath. The primary product from the HIsmelt process is hot metal (iron). This iron is tapped continuously through an open forehearth and is slag-free. It can be used as direct feed to steelmaking processes or cast into pig iron.

The main opportunities for the use of biomass in the integrated route for steelmaking would appear to be:

- replacement of coke as a reductant and fuel in the blast furnace;
- replacement of coal and natural gas as a fuel in the blast furnace;
- replacement of coke as a fuel in sintering and pelletising.

However, it has been suggested that it is impossible to operate large blast furnaces with 100% substitution of charcoal for lump coke due to the much lower crushing strength of charcoal compared to coke, with substitution rates up to 20% being considered practical [12]. While supporting this view for large blast furnaces, Gupta [2] reports that this mechanical property of charcoal becomes redundant when charcoal is used as lump in small blast furnaces or as powder for tuyere injection in bigger blast furnaces. For this reason, the use of charcoal to replace both 20% and 100% of coke in the blast furnace was considered in the study. The lower crushing strength of charcoal is not likely to be a significant issue in the direct bath smelting process for ironmaking, with charcoal substitution rates for coal as a reductant and fuel up to 100% being envisaged.

The mini-mill steelmaking route produces steel by melting steel scrap, or some form of scrap substitute, in an electric arc furnace (EAF). The liquid steel is further refined in the ladle metallurgy furnace (or ladle refining station) and is then poured into a casting machine. Where steel scrap is in short supply, scrap substitutes such as pig iron or direct reduced iron (DRI) are often used. Carbonaceous material is added to the mini-mill/EAF process for three purposes in addition to as an energy supplement:

- as charge carbon, the primary purpose of which is to provide a reducing atmosphere during melting which minimises the oxidation of alloys and metallics;
- injectant carbon, also known as slag foaming carbon, where the technique of foaming slag in the EAF is used to increase productivity, lower operating costs and increase the quality of the steel produced:
- recarburiser carbon, for recarburising the liquid steel, and is usually added to the ladle after tapping from the EAF.

All three uses present opportunities for biomass to replace these carbonaceous materials in the mini-mill/EAF process. The issue of charcoal crushing strength is less of a concern in EAFs due to short furnaces and absence of any impinging hot blast [2]. For the purposes of this study, charcoal was assumed to fully replace all three types of carbon additions above. For comparison purposes, two feedstock cases were considered, 100% scrap and 90% scrap/10% pig iron.

5. LIFE CYCLE ASSESSMENT OF STEELMAKING PROCESSES

LCA spreadsheet models of each of the three steelmaking routes were set up, and “cradle-to-gate” LCAs of each of these routes were carried out using the inventory data given in Table 4, which were derived from numerous published sources, eg. IISI [22]. In this case the functional unit was one tonne of steel. It should be noted that for the integrated route, coke production has been assumed to be internalised within the steelworks, and the GER and GWP contributions from the products of this process (coke and coke oven gas) have been accounted for by converting[5] the coke inventory inputs in Table 4 to coal equivalents (as coal is the external input to the steelworks, not coke). Other minor inputs into steelmaking such as ferroalloys, refractories and argon gas are not included in Table 4 as their contributions to the overall result are much less significant than the inputs shown and are similar for either coal or charcoal. The results of these LCAs are given in Table 5. The GWP values of 2.17 t CO_2e/t steel (sintering) and 2.40 t CO_2e/t steel (pelletising) are similar to the values reported in other LCA studies, eg. Orth et al [23] (2.20 t CO_2e/t steel), Scaife et al [24] (2.16 t CO_2e/t steel) and Birat [25] (2.0 t CO_2e/t steel). Likewise, the GWP value of 0.51 t

Table 4. Inventory data for steel production.

Mining				Earth rock	2.3 t/t iron ore
				Diesel fuel	0.0007 t/t iron ore
				Electricity	0.2 kWh/t iron ore
Processing, transport & handling				Electricity	8 kWh/t iron ore
Ironmaking	Int. route	Feed preparation	*Sintering*	Iron ore fines	0.93 t/t sinter
				Limestone[a]	140 kg/t sinter
				Coke	42 kg/t sinter
				Electricity	28 kWh/t sinter
				Water	0.13 t/t sinter
			Pelletising	Iron ore fines	1.04 t/t pellets
			- green ball preparation	Electricity	1.5 kWh/t green balls
				Water	290 kg/t ore
				Limestone	18 kg/t ore
				Dolomite	80 kg/t ore
				Coke breeze	8 kg/t ore
				Bentonite	10 kg/t ore
			- pellet induration	Electricity	45 kWh/t pellets
				Fuel (nat gas)[b]	750 MJ/t pellets
		Coke ovens		Coal	1.27 t/t coke
		Blast furnace		Lump & sinter	1.44 t/t hot metal (thm)
				Coke	415 kg/thm
				Coal	70 kg/thm
				Limestone	43 kg/thm
				Dolomite	23 kg/thm
				Oxygen	18 Nm^3/thm (25 kg/thm)
				Natural gas	15 kg/thm
				Electricity	25 kWh/thm
				Slag	280 kg/thm
	Direct smelting			Iron ore fines	1.44 t/t hot metal (thm)
				Coal	610 kg/thm
				Limestone	186 kg/thm
				Dolomite	0 kg/thm
				Oxygen	182 Nm^3/thm (260 kg/thm)
				Natural gas	0 kg/thm
				Air	1.73 t/thm
				Electricity	0 (ie. none imported)
				Slag	379 kg/thm
Steelmaking & casting	Int. route & direct smelting	BOF & casting		Hot metal	0.95 t/t steel
				Oxygen	53 Nm^3/t steel (75 kg/t steel)
				Limestone	40 kg/t steel
				Dolomite	35 kg/t steel
				External scrap	50 kg/t steel
				Electricity	43 kWh/t steel
	Mini-mill/EAF	EAF		Scrap steel/pig iron	1.0 t/t steel
				Carbon	
				- charge	9.0 kg/t steel
				- injectant	4.7 kg/t steel
				- recarburising	1.3 kg/t steel
				Limestone	72 kg/t steel
				Oxygen	33 Nm^3/t steel (48 kg/t steel)
				Electricity	410 kWh/t steel
				Electrodes	1.8 kg/t steel
		Casting		Electricity	20 kWh/t steel

a. Amount of limestone will depend on basicity.
b. Fuel requirement for pelletising depends on type of material being processed, eg. magnetite, hematite.

[5] 1.27 t coal/t coke (see Table 4).

Table 5. LCA results for various steelmaking routes (without charcoal substitution).

	Integrated route	Direct smelting/BOF	Mini-mill/EAF 90% scrap	Mini-mill/EAF 100% scrap
Gross energy requirement	*Sintering*			
Renewable (GJ/t steel)	0.0	0.0	0.0	0.0
Non-renewable (GJ/t steel)	21.0	19.4	6.9	4.8
Total (GJ/t steel)	21.0	19.4	6.9	4.8
	Pelletising			
Renewable (GJ/t steel)	0.0			
Non-renewable (GJ/t steel)	20.9			
Total (GJ/t steel)	20.9			
Greenhouse gases (GWP)	*Sintering*			
Renewable (t CO_2e/t steel)	0.00	0.00	0.00	0.00
Non-renewable (t CO_2e/t steel)	2.17	2.12	0.71	0.51
Total (t CO_2e /t steel)	2.17	2.12	0.71	0.51
	Pelletising			
Renewable (t CO_2e/t steel)	0.00			
Non-renewable (t CO_2e/t steel)	2.40			
Total (t CO_2e /t steel)	2.40			

CO_2e/t steel given in Table 5 for the mini-mill/EAF route (100% scrap) is similar to the value of 0.54 t CO_2e/t steel reported by Sandberg et al [26] for this route.

As well as the base case scenarios shown in Table 5, LCAs of each route were also carried out with charcoal (88.3% C, 31.1 MJ/kg, dry basis) substituted for coke and coal in the various applications previously identified for each route. For the integrated route, charcoal was assumed to replace coke (92% C, dry basis) and coal (75% C, dry basis) in the blast furnace at 20% and 100% substitution rates on an equivalent fixed carbon basis, as well as fully replacing coal (30 MJ/kg) and natural gas (53 MJ/kg) injectant on an equivalent energy basis. As pointed out earlier, 100% substitution of charcoal for coke is probably only possible in small blast furnaces, and while there are similarities between charcoal and coke blast furnaces, there are also a number of differences [27]. Despite these differences, the same inventory data in Table 4 were used for both 20% and 100% substitution rates. Given the indicative nature of the study, this assumption was not considered to have a significant effect on the overall results. In the direct smelting route, charcoal was assumed to replace coal (81.3% C, dry basis) in the bath smelting reactor on an equivalent fixed carbon basis over a range of substitution rates up to 100%, while for the mini-mill/EAF route, charcoal was assumed to fully replace charge, injectant and recarburiser carbon (85% C) in the EAF on an equivalent fixed carbon basis. Transport of charcoal to the steel plant was not included in the LCAs as this is very site-specific, and furthermore was not expected to have any significant effect on the results[6]. The results of these LCAs are given in Tables 6-8 in terms of the reduction in non-renewable GER and GWP over the base case values in Table 5 with charcoal by-product credits included. The physical significance of the results in Table 6 in terms of greenhouse gas emissions for the sintering case is shown in Figure 4, where the various components contributing to the greenhouse gas footprint of the integrated route are shown, along with the by-product credits from 20% replacement of coal with charcoal in this process.

Figure 5 shows the reduction in non-renewable GWP for the three steelmaking routes at 100% charcoal subsitution rate compared to no charcoal substitution. The results for 100% charcoal substitution with no electricity and eucalyptus oil co-product credits are also included in Figure 5 for comparative purposes. While not shown in Figure 5, the reduction in non-renewable GWP for the integrated route with only 20% charcoal substitution and no charcoal by-product credits was 0.33 t CO_2e/t steel. This compares with a reported value [12, 24] of 0.56 t CO_2e/t steel for the same scenario. However, if the latter value is corrected for the different charcoal production yield used by the authors in this study as outlined earlier, the reduction in non-renewable GWP is the same[7] as

[6] It was estimated that transporting charcoal 500 km by road (diesel) would add only about 6 kg CO_2e/t steel to the overall result, while by rail(diesel) the amount would be about 1 kg CO_2e/t steel.
[7] 0.56 t CO_2e/t steel x 0.134/0.225 = 0.33 t CO_2e/t steel.

Table 6. Reduction in non-renewable GER and GWP for integrated route with charcoal substitution (with by-product credits).

	Charcoal substitution rate (%)	
	100	20
Gross energy requirement (GJ/t steel)		
Sintering	48.0	12.5
Pelletising	48.4	12.9
Greenhouse gases (t CO_2e/t steel)		
Sintering	4.46	1.17
Pelletising	4.62	1.32

Table 7. Reduction in non-renewable GER and GWP for direct smelting/BOF route with charcoal substitution (with by-product credits).

	Charcoal substitution rate (%)				
	100	80	60	40	20
Gross energy requirement (GJ/t steel)	56.2	45.0	33.7	22.5	11.3
Greenhouse gases (t CO_2e/t steel)	5.30	4.24	3.18	2.12	1.06

Table 8. Reduction in non-renewable GER and GWP for mini-mill/EAF route with charcoal substitution (with by-product credits).

	100% charcoal	
	100% scrap	90% scrap
Gross energy requirement (GJ/t steel)	1.5	1.5
Greenhouse gases (t CO_2e/t steel)	0.15	0.14

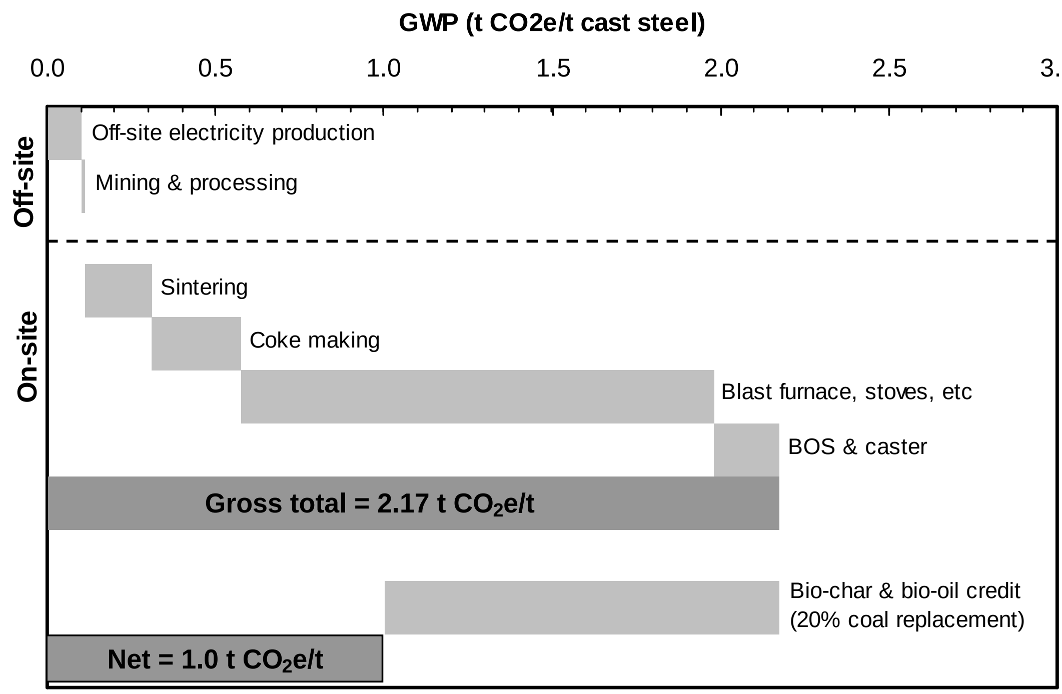

Figure 4. GWP footprint of the integrated steel route (sintering) showing reduction from 20% replacement of coal with charcoal.

that reported above. Using the integrated route (sintering) as an example, the results shown in Figure 5 mean that the non-renewable GWP is reduced from 2.17 t CO_2e/t steel to 0.85 t CO_2e/t steel and -2.29 t CO_2e/t steel without and with the by-product credits respectively, for 100% charcoal substitution. The negative value indicates an overall GWP credit. The corresponding values for 20% charcoal substitution are 1.84 t CO_2e/t steel and 1.0 t CO_2e/t steel (see Figure 4) respectively.

It can be seen from Figure 5 that the direct smelting/BOF route offers the greatest potential for reducing non-renewable greenhouse gas emissions by the use of charcoal compared to the

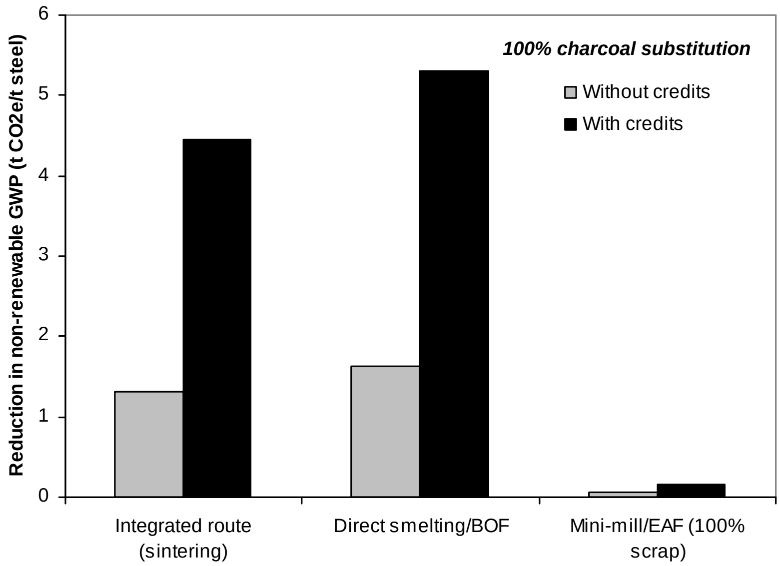

Figure 5. Reduction in non-renewable GWP due to charcoal use.

integrated and mini-mill/EAF routes, with reductions of 5.3, 4.5 and 0.15 t CO_2e/t steel for the three routes respectively (cf. 1.6, 1.3 and 0.05 t CO_2e/t steel with no charcoal electricity and eucalyptus oil co-product credits). It should be appreciated that the two charcoal by-product credit scenarios considered (ie. no by-product credits and electricity and bio-oil by-product credits from an integrated charcoal plant) represent likely minimum and maximum reductions in non-renewable GWP respectively for the various steelmaking routes. More definitive values for charcoal by-product credits will only be forthcoming when further development work on charcoal production with by-product generation has taken place and the results published.

6. DISCUSSION

One of the critical issues likely to affect the uptake of charcoal in steelmaking will be biomass availability. The biomass and charcoal retort yields given earlier correspond to an overall green (ie. 44% moisture) biomass requirement of 10.6 t/t charcoal. For a wood only feed to the charcoal retort, this figure decreases to 8.6 t/t charcoal due to the higher retort yield (23.2% cf. 13.4%). Figure 6 shows the plantation area required for biomass production versus steel production rate by the integrated route (currently about 70% of the world steel production or about 870 Mt is produced by this route) for green biomass plantation yields of 10, 20 and 30 t/ha/y with 20% subsitution of coke with charcoal and an overall biomass utilisation of 10.6 t/t charcoal. At a plantation yield of 30 t/ha/y the required plantation area for 870 Mt/y of steel is about 43 Mha, while for a yield of 10 t/ha/y it increases to about 127 Mha. At 100% substitution rate the corresponding numbers are 158 and 474 Mha respectively. Average yields of 15 t/ha/y have been reported for well-managed timber plantations where fertiliser is applied [28-29], while a base case value of 19.2 t/ha/y was used in the charcoal production LCA earlier, based on data reported by Wu et al [18].

One of the main issues being addressed in the European ULCOS (Ultra Low CO_2 Steelmaking) project is biomass availability from industrial-scale forest plantations. While the global potential for biomass production is large, there is only a finite area of land available without compromising food production [29-30]. Based on plantations of fast-growing eucalyptus species in various tropical countries, ULCOS researchers reported that Brazil would have 46 Mha available in 2050, while several central African countries would also have 46 Mha available. However, transportation is likely to be a significant issue affecting the cost of charcoal delivered to steel plants under this scenario.

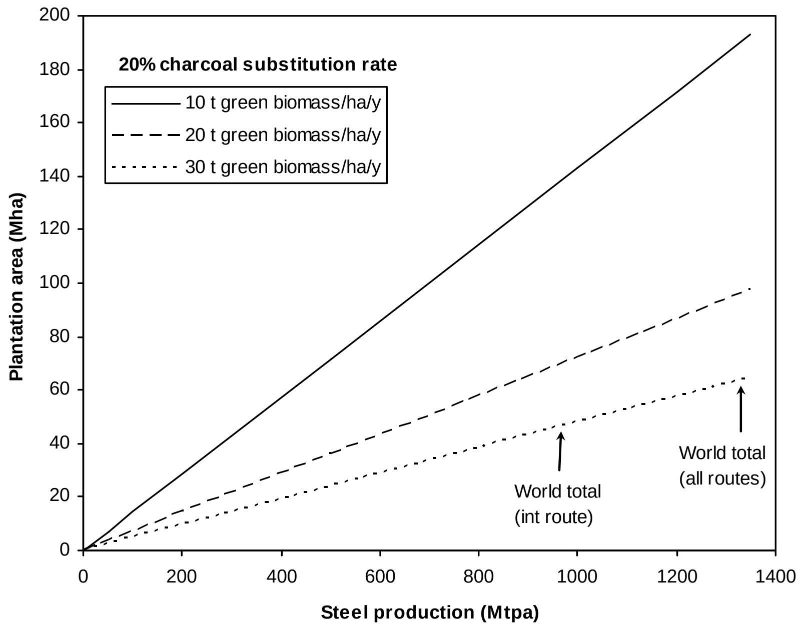

Figure 6. Plantation area required for charcoal production (20% substitution).

7. CONCLUSIONS

The potential for reducing the greenhouse gas emissions by the use of biomass-derived charcoal in place of coal or coke in a number of steelmaking applications has been assessed using the results from "cradle-to-gate" life cycle assessments of charcoal production and steel production by a number of processing routes. The results indicated that the use of charcoal in the direct smelting/BOF route offers the greatest potential for greenhouse gas reductions, followed by the integrated route. These reductions amounted to 5.3 and 4.5 t CO_2e/t steel respectively, with 100% substitution of charcoal for coal or coke with electricity and eucalyptus oil co-product credits included for charcoal production. Without these credits, the values were 1.6 and 1.3 t CO_2e/t steel respectively.

Estimates of the biomass plantation area required to produce charcoal for steelmaking purposes suggest that it is possible that an appreciable amount of the world's steel production can utilise charcoal in place of coal or coke over the coming decades. However, transportation is expected to be a significant issue affecting the cost of charcoal delivered to steel plants.

8. REFERENCES

1. K. Baumert, T. Herzog and J. Pershing. Navigating the Numbers: Greenhouse Gas Data and International Climate Policy, (2005). World Resources Institute.
2. R. Gupta. Woodchar as a sustainable reductant for ironmaking in the 21st century. *Mineral Processing & Extractive Metallurgy Review*, 24, (2003), 203.
3. M. Wadsley. Greenhouse gases and extractive metallurgy. Greenhouse gases in the Metallurgical Industries: Policies, Abatement and Treatment, Met Soc CIM, Toronto, (2001), 3.
4. J. Burgess. Biomass and renewables as alternative energy sources and reductants in the minerals industry. Green Processing Conference, AusIMM, Fremantle, (2004), 9.
5. M. Dell'Amico, P. Fung, R. Lovel, J. Manuel and M. O'Connor. Green iron ore sintering. Green Processing Conference, AusIMM, Fremantle, (2004) 73.
6. Norgate, T and Langberg, D. Environmental and economic aspects of charcoal use in steelmaking. *ISIJ International*, 49, (2009), 587-595.
7. IISI (International Iron and Steel Institute). World Steel in Figures 2010, http://www.worldsteel.org (accessed July 2010).
8. N. Goodman. Operations at the HIsmelt Kwinana plant. AIST Conference, Indianapolis, May 2007 (www.hismelt.com.au).

9. H. Nogami, J. Yagi and R. Sampaio. Exergy analysis of charcoal charging operation of blast furnace. *ISIJ International*, 44, (2004), 1646.
10. R. Lovel, K. Vining and M. Dell'Amico. Iron ore sintering with charcoal. Iron Ore Conference, AusIMM, Fremantle, (2005), 1.
11. V. Strezov. Iron ore reduction using sawdust: Experimental analysis and kinetic modelling. *Renewable Energy*, 31, (2006), 1892.
12. SERDF. Sustainable steelmaking using renewable forest energy. NSW Sustainable Energy Research and Development Fund, (2001).
13. J. Brosnan and D. Spratt. Silicon production by Simcoa Operations Pty Ltd at Kemerton, WA. Australasian Mining and Metallurgy, AusIMM, (1993), 1241.
14. P. Fung, M. Kirschbaum, R. Raison and C. Stucley. The potential for bioenergy production from Australian forests, its contribution to national greenhouse targets and recent developments in conversion processes. *Biomass and Bioenergy*, 22, (2002), 223.
15. C. Stucley. Wood processing for energy and char. Green Processing Conference, AusIMM, Newcastle, (2006), 77.
16. Enecon Pty Ltd. Integrated tree processing of Mallee eucalypts. November 2001, http://www.enecon.com.au (accessed April 2006).
17. C. Syred, A. Griffiths, N. Stred, D. Beedie and D. James. A clean, efficient system for producing Charcoal, Heat and Power (ChaP). *Fuel*, 85, (2006), 1566.
18. H. Wu, Q. Fu, R. Giles and J. Bartle. Energy balance of mallee biomass production in Western Australia. Bioenergy Australia 2005 – " Biomass for energy, the environment and society", Melbourne, (2005), 19.
19. T. Norgate, S. Jahanshahi and W. J. Rankin. Assessing the environmental impact of metal production processes. *Journal of Cleaner Production*, 15, (2007), 838.
20. T. Norgate, S. Jahanshahi and W. J. Rankin. Alternative routes to stainless steel – a life cycle approach. Tenth International Ferroalloys Congress (INFACON X), Cape Town, (2004), 693.
21. T. Norgate and W. J. Rankin. Greenhouse gas emissions from aluminium production – a life cycle approach. Greenhouse gases in the Metallurgical Industries: Policies, Abatement and Treatment, (Met Soc CIM), Toronto, (2001), 89.
22. IISI (International Iron and Steel Institute). World Steel life Cycle Inventory, 2000 (www.worldsteel.org).
23. A. Orth, N. Anastasijevic and H. Eichberger. Low CO_2 emission technologies for iron and steelmaking as well as titania slag production. *Minerals Engineering*, 20, (2007), 854.
24. P. Scaife, J. Nunn, A. Cottrell and L. Wibberley. Towards sustainable steelmaking. *ISIJ International*, 42, (2002), Supplement, S5-S9.
25. J-P. Birat. Greenhouse gas emissions of the steel industry – avenues open for a responsible and sustainable management of emissions. Greenhouse gases in the Metallurgical Industries: Policies, Abatement and Treatment, (Met Soc CIM), Toronto, (2001), 89.
26. H. Sandberg, R. Lagneborg, B. Lindblad, H. Axelsson and L. Bentell. CO_2 emissions of the Swedish steel industry. *Scandinavian Journal of Metallurgy*, 30, (2001), 420.
27. A. Chatterjee. Beyond the Blast Furnace, CRC Press, (1993), 195.
28. G. Berndes, M. Hoogwijk and R. van den Broek. The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy*, 25, (2003), 1.
29. S. Nonhebel. Renewable energy and food supply: will there be enough land? *Renewable and Sustainable Energy Reviews*, 9, (2005), 191.
30. J. Moreira. Global biomass energy potential. Mitigation and Adaption Strategies for Global Change, 11, (2006), 313.