CURRENT STATUS AND FUTURE DIRECTION OF LOW-EMISSION INTEGRATED STEELMAKING PROCESS

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Abstract

In 2006 the Australian steel industry and CSIRO initiated an R&D program to reduce the industry's net greenhouse emission by at least 50%. Given that most of the CO_2 emissions in steel production occur during the reduction of iron ore to hot metal through use of coal and coke, a key focus of this program has been to substitute these with renewable carbon (charcoal) sourced from sustainable sources such as plantations of biomass species. Another key component of the program has been to recover the waste heat from molten slags and produce a by-product that could be substituted for Portland cement.

This paper provides an overview of the low-emission Integrated Steelmaking Process, progress made over the past seven years and the program's future direction which includes proposed demonstrations of the technologies developed including large scale piloting and full scale plant trials.

Introduction

The global steel industry produced about 1.5 Gt of crude steel in 2012 with an emission of about 2.5 Gt of CO_{2-e}. This level of GHG emission is significant and represents about 5-6% of the total global emission. While the steel industry has reduced its energy consumption and hence GHG emission by about 50% over the past decades, it is conscious of high the volume of CO_2 emissions and has been actively developing a number of step change technologies to reduce its net emission by at least another 50%. About 10 years ago, the World Steel Association initiated an R&D program called CO_2 Breakthrough Program which focused on step change reduction in their emissions. This collaborative program has benefited from contributions by many steel companies, engineering firms and R&D institutes in Europe, Japan, Korea, North America, Australia, etc. The Australian CO_2 Breakthrough Program was initiated by BlueScope Steel in 2006, through collaboration with OneSteel/Arrium and CSIRO. This program aims to reduce net GHG emission by the steel industry through use of renewable carbon sources as fuels and

reductants, as well as the recovery and utilization of waste heat from molten slags. The key research questions behind this program have been:

- Can deep cuts into CO_2 emissions be made using current process equipment?
- Can charcoal provide a low-capital path to a low-CO_2 future?
- Can waste heat recovery from molten slag provide a further cut in CO_2 emission?

The combination of (1) sustainable supply of biomass and its processing to produce charcoal, bio-oil and other renewable energy; (2) utilization of charcoal as partial replacement for coal and coke products in iron and steelmaking; (3) recovery of high grade waste heat from molten slag and (4) conversion of molten blast furnace slag into a Portland cement substitute has been defined as the low-emission Integrated Steelmaking Process (ISP). In Figure 1, the conceptual "flowsheet" for the ISP is presented.
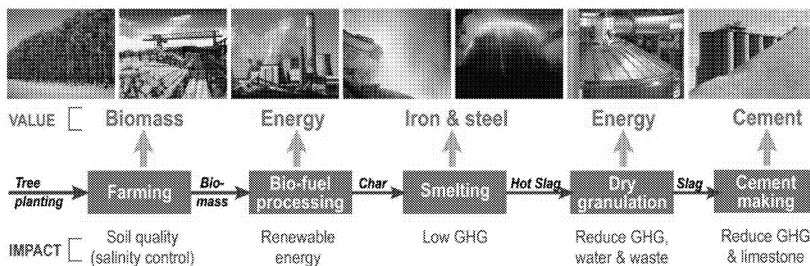

Figure 1: The conceptual flowsheet across the value chain for the low-emission Integrated Steelmaking Process (ISP).

The present paper provides a summary of the key findings from a series of investigations covering the full value chain, i.e. from the sustainable supply of biomass to production of charcoal, iron and steel as well as dry granulation of slag to produce feedstock for the cement industry and energy recovered from waste heat. The paper also provides an outline of the future direction of the ISP development program.

Supply of biomass from sustainable sources

One of the questions that we were faced with was "do we have sufficient supply of biomass resources in the short and medium terms to support the steel industry?" To address this and related questions a survey of existing resources and residues available from plantations in some regions of Australia had to be carried out. Thus the quantities of biomass available from some regions of Australia (northern, central, southern New South Wales, western Victoria, and southern South Australia) were estimated by Haque et al.[1]. These regions were selected due to their proximity to existing steel plants at Port Kembla, Sydney, Geelong and Whyalla. Our estimate was made based on information gathered through site visits, meetings with the various State forestry agencies, wood processing industries and where possible from the open literature.

The annual forestry and wood processing residues were estimated on an oven-dry basis to be 3.4 Mt and 2.3 Mt, respectively. The non-forestry residues were estimated to be around 1.2 Mt/year. Non-forestry residues included biomass from grain crops such as wheat and maize, olive

pomace, grape marc, almond waste and cut flowers waste. A significant part of non-forestry waste was from sugarcane bagasse, in-field cane crop residues, woody weeds (Camphor Laurel) and macadamia nut processing waste in Northern New South Wales. Assuming 30% charcoal yield of dry residues and 50% of total dry residues being available immediately, this equates to 3.7 Mt/year of dry biomass that can potentially generate about 1.14 Mt of charcoal per year.

These results indicate that currently the biomass residues from forestry and agricultural industries are sufficient to satisfy the short-to-medium term needs of the steel industry. In the longer term, some dedicated plantation of short cycle biomass species should be put in place to ensure a secure supply of biomass material from sustainable sources.

Life cycle assessment and techno-economic evaluation of biomass and charcoal supply for steel industry

The second question that arises is whether the biomass/charcoal option is environmentally and economically sound. To answer this question we have carried out some life cycle assessments (LCA) covering both environmental and economic dimensions. An initial social LCA on the biomass/charcoal scenario was recently completed by Weldegioris and Franks [2].

LCA methodology was used to estimate the greenhouse gas footprint of charcoal production from Mallee eucalypt biomass, and is described in detail elsewhere by Norgate et al [3]. The results of this LCA, showing the contributions of the various stages to the greenhouse gas footprint of charcoal production, are shown in Figure 2.
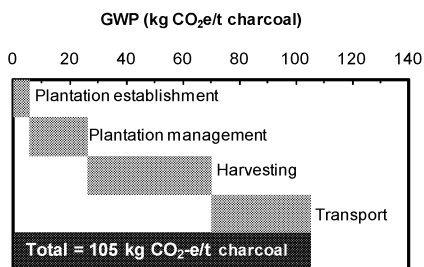

Figure 2: Stage contributions to Global Warming Potential (GWP) or greenhouse gas footprint of charcoal production (no by-product credits).

The greenhouse gas footprint for charcoal production was 105 kg CO_2-e/t charcoal, which reflects the fossil fuel used in its production (i.e. plantation management including fertilizer, harvesting and transport). Since the charcoal plant, which includes drying and pyrolysis of biomass, is fuelled entirely by combustion of biomass by-products, any emissions associated with these stages are not fossil fuel-based.

Greenhouse gas credits for the bio-oil and combustible bio-gas by-products produced during charcoal production (i.e. electricity is generated using the gas which replaces electricity generated from black coal, and bio-oil replaces diesel) can significantly reduce the greenhouse gas impact of charcoal production. It is worth noting that the credits will normally outweigh the 105 kg/t charcoal, meaning overall GWP is expected to be negative [3]. However, it should be appreciated that the magnitude of the by-product credits depends on the by-product yields in the

charcoal retort, which in turn are dependent on a number of factors, in particular, the nature of the pyrolysis process (fast or slow) and the biomass feed composition. Slow pyrolysis tends to maximize the charcoal yield, with less gas and bio-oil by-products produced, thus by-product credits are less with slow pyrolysis.

A techno-economic evaluation study was carried out on a hypothetical biochar plant with an annual capacity of 100 kt of charcoal. For this exercise a process flow sheet was developed and key items of equipment were identified and costs were collected from various sources [4,5]. The required raw material feed and final charcoal product output rates were estimated based on the flowsheet and product yields obtained from small scale slow pyrolysis of biomass at CSIRO (~0.3 t charcoal and 0.3 t of condensate per t of oven-dry biomass, with about 20% of the condensate being bio-oil).

The evaluation was based on the scenario that:

- The hypothetical charcoal plant is located at or near a sawmill and charcoal is transported to a steel plant that is about 300 km away.
- Raw biomass is collected, chipped, and dried close to the biomass source and transported 100 km to the sawmill and charcoal plant.
- The bio-oil product has a value of A$88/t (August 2013 price of crude oil in Australian dollar used and the energy content of bio-oil is 50% of crude oil. It is to be noted that if diesel price is used, the value of bio-oil will almost be double).
- The value-in-use of softwood charcoal as injectant into a blast furnace is about $89/t higher than a standard high volatile PCI coal [6] with estimated price of A$135/t [7] in 2013.
- A carbon credit of A$23/t CO_2-e is applied to the charcoal and by-products such as bio-oil.

The net cost of charcoal to a steel plant was estimated to be A$169/t, which increases with decreasing carbon price/tax and decreases as the price of PCI coal increases. It should be noted that we have not valued the excess combustible gas from pyrolysis process as quantities are uncertain.

It is worth mentioning that 45% of the total operating cost of A$446/t at the charcoal plant was for supply of raw materials and 16% for transport. Maintenance, interest on capital, labour and utilities accounted for the remaining 39% of the cost.

The estimated total capital cost of the charcoal plant was about A$1100/t of charcoal per year. A sensitivity analysis showed that for the same percentage change in base case value, changes in the raw material cost had the greatest effect on the operating cost followed by plant capital-related costs (maintenance and interest/depreciation) and raw material transport, with the labour cost having the least effect.

It should be emphasized that the making of charcoal and supplying it to the steel plant is financially viable if all the byproduct credits and benefits are taken into account.

Development of an energy and resource efficient pyrolysis process

The optimum substitution of charcoal for coal-based materials used for iron and steel making imposes a number of requirements such as acceptable price, density, contents of volatile matter and ash, and others (see Table 1). Furthermore, even at moderate levels of replacement, millions of tonnes of charcoal are needed annually for a large integrated steel plant. Existing charcoal making technologies cannot satisfy requirements for the quality of the product, its net price and the high production volumes [8]. Hence, the development of a new technology is

needed. The ability to convert smaller-sized wood (such as wood chips or wood pellets) to charcoal is to be an important feature of a new technology as it will permit the utilization of lower-cost materials (wood waste/residues) and densified wood pellets as a feedstock. Charcoal made from wood pellets has up to three times higher density than that of conventional charcoal, which is essential for some of its applications (Table 1). An important contribution to the economic efficiency of charcoal making can be made if a new technology permits the extraction of maximum value from its by-products, namely; pyrolysis condensate (also called bio-oil) and pyrolysis gas (syngas).

The main barrier in the way to processing large volumes of smaller-sized wood in a pyrolysis reactor is associated with the combination of low gas permeability of such material with its low thermal conductivity. The former makes heating through flow of hot gas impracticable and the latter diminishes the efficiency of external heating of the reactor. These difficulties can be overcome if the principle of autogenous pyrolysis is used. That is the arrangement of the process can be such that the material is heated to the maximum pyrolysis temperature spontaneously by the heat of internal exothermic reactions, which occur within the material even without any air supply to the reactor [9]. Based on this principle a pilot scale plant was developed at CSIRO. The flow diagram given in Figure 2 shows its main units. The reactor is a well insulated vertical shaft with a wood charging mechanism at the top and a charcoal discharging valve at the bottom. The simplicity of the mechanical design of the reactor, with no moving parts in its hot zone, ensures the minimization of its installation and maintenance costs. Additionally, cooling of charcoal in the bottom section of the reactor can be accelerated by circulating a non-combustible gas through it, which also permits the recovery of heat from charcoal [10]. The flow of the cooling gas is confined to the bottom section of the reactor and the gas does not permeate the material in the rest of the reactor. Other main units are the dryer, the screw conveyors to transfer wood chips or pellets to the top of the reactor, condensers and the afterburner.

The advantages of this technology are:

- High energy efficiency, as no high-grade heat is needed to bring wood to the maximum pyrolysis temperature under steady-state (low-grade heat is still needed for drying the material);

- High-yield of charcoal from wood, as the conditions in the reactor are favourable for that [8];

- High value of pyrolysis by-products, since;

  - pyrolysis gas is not diluted by any inert gases or combustion products; and

  - the condensate is not diluted by free moisture from wood (the material is supplied to the reactor bone-dry)

- No heat-transfer limitation to scaling up the reactor to large sizes, as no supply of external heat to the material is needed; production of 100,000 tonnes of charcoal per year by a single reactor unit may be achievable.

The pyrolysis pilot plant (internal diameter of reactor ~ 600 mm, maximum depth of material bed in the reactor ~ 2700 mm, nominal productivity of 800 t of charcoal per year, if operated continuously) is currently being commissioned and it has been demonstrated that in a batch mode operation the autogenous heating of the material can bring its temperature to above 450 $^{\circ}$C. It is

expected that a maximum temperature of 520 °C will be reached in continuous operation of the reactor.
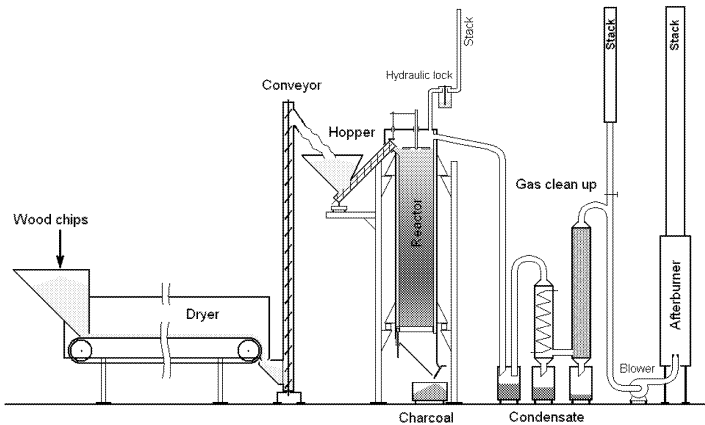

Figure 3: Process flow diagram of the pilot plant based on the principle of autogenous pyrolysis of wood.

Concept of designer chars for various applications in iron and steel making

Raw biomass is not suitable for iron and steelmaking applications because of its high moisture content, low carbon content and specific energy. Since pyrolysis is necessary to produce chars that are chemically similar to coal/coke, it is appealing to produce optimized products that are either superior to traditional fuels/reductants or that minimize any weaknesses in physical properties.

The substitution of charcoal for coal/coke in iron and steel making operations requires the preparation of charcoal with specific properties. Mathieson et al [6, 11-13] summarized the optimum quality criteria for charcoal substitution and showed that different applications require different charcoal properties, e.g. charcoal for sintering fuel should be of low volatile content (<3 %), high density, low reactivity and in the 0.3-3 mm size range. In comparison, charcoal as a blast furnace injectant should be higher in volatile matter (10-20 %), low in ash and low in alkalis. Recent research conducted at CSIRO as part of the Australian steel industry CO_2 Breakthrough Program has focused on controlling the pyrolysis process to produce charcoal with the desired properties. This concept has been called "designer charcoal".

Somerville et al [14] showed that the volatile content of charcoal can be controlled through the pyrolysis temperature (shown in Figure 4a). Charcoal density can also be controlled through pyrolysis temperature as well through the choice of biomass feedstock, i.e. dense wood (Figure 4b). The use of dense biomass fuel (DBF) pellets as a pyrolysis feedstock has been very effective at increasing the bulk density and particle density of charcoal. Densification of charcoal during pyrolysis and after pyrolysis have also been investigated. Similarly, alternative methods for controlling the ash content of the charcoal have been studied. These studies have shown selection of biomass species as well as different fractions of the plants could be used to

produce charcoals with different ash contents and compositions. Our study also suggests that soil chemistry affects the ash composition and content.

Charcoal with low levels of moisture and volatile matter has been prepared for successful recarburisation plant trials at the Sydney Steel Mill [14]. Dense charcoal has also been prepared for pilot scale iron ore sintering trials [15].
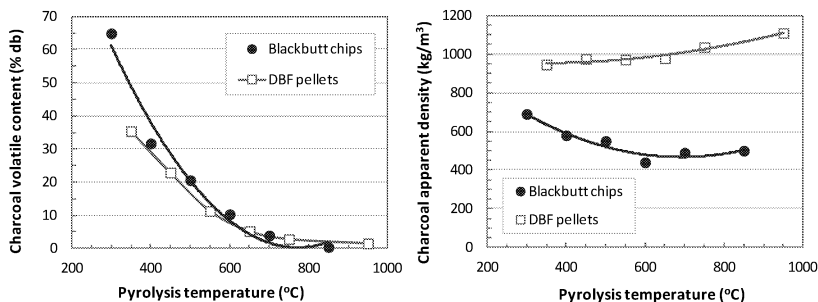

Figure 4: The effects of pyrolysis temperature on the (a) volatile content (% dry-basis) and (b) apparent density (particle density) of charcoal made from wood chips and dense biomass fuel (DBF) feedstocks.

Life cycle assessment of charcoal substitution for coal/coke

Life cycle assessments of the integrated, mini-mill and direct smelting steelmaking routes were carried out with charcoal (88.3% C, 31.1 MJ/kg, dry basis) substituted for coke, coal and carbon in various applications for each route by Norgate et al. [16]. For the integrated route, charcoal was assumed to replace coke (92% C, dry basis) and coal (75% C, dry basis) in the blast furnace on an equivalent fixed carbon basis and pulverised coal injectant (30 MJ/kg) on an equivalent energy basis. 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. The results of these LCAs in terms of the total potential reduction in greenhouse gas emissions from charcoal use compared to the coal/coke base case values for the three steelmaking routes are listed in Table 2.

Table 2: LCA based total potential reduction in greenhouse gas emissions resulting from substitution of coal/coke with charcoal for different steelmaking routes.

Steelmaking route	Total potential Reduction without by-product credits ($t\ CO_2$-e/t steel)	Total potential reduction with by-product credits ($t\ CO_2$-e/t steel)
Integrated BF–BOF	0.69 – 1.21	0.91 – 1.61
EAF mini-mill	0.028 – 0.056	0.037 – 0.075
Direct smelting	0.34 – 1.70	0.45 – 2.15

The physical significance of the results for the integrated route (sintering) in terms of greenhouse gas emissions is shown in Figure 5, where the various components contributing to the greenhouse gas footprint of the integrated route are shown, along with the reductions achieved from the use of charcoal in this process for the case without any by-product credits. The results shown in Figure 5 mean that without any by-product credits, the greenhouse gas footprint for the integrated route (sintering) is reduced from 2.17 t CO_2e/t steel to between 0.96 t CO_2e/t steel and 1.48 t CO_2e/t steel over the range of charcoal substitution rates considered.
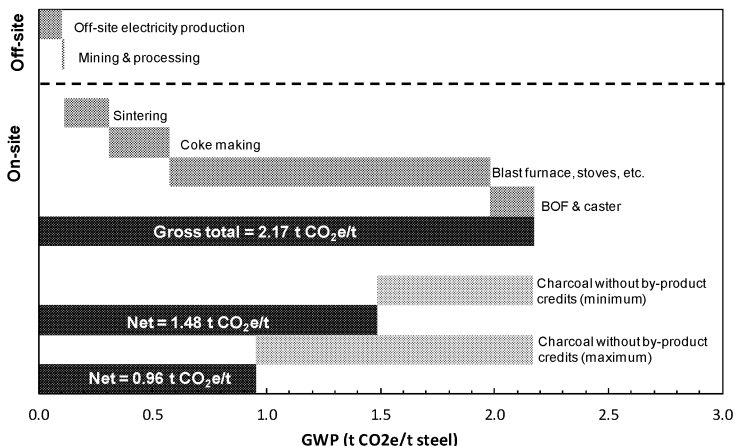

Figure 5: Global warming potential footprint of the integrated steelmaking route (sintering-BF-BOF) showing reduction with use of charcoal.

Value of Using Charcoal as a Substitute for Coal and Coke

Because of low ash, sulfur and phosphorus levels, charcoal can generally be considered to be chemically superior to coal-based fuels/reductants. This means that optimized charcoal products (see Table 1) should lead to fuel and other savings in ironmaking and steelmaking processes, as well as the advantages of using renewable carbon to combat net CO_2 emissions. These advantages mean that designer charcoal products may have greater value than traditional fuels/reductants in several of the applications. For example, Mathieson et al. [6,12] estimated that BF coke rate could be reduced by 23 – 30 kg/t-HM by using charcoal as the tuyere injectant and 4.5 – 9 kg/t-HM by charging 5 – 10% charcoal/ore composites. Our industrial trial [11] also indicated that charcoal was potentially a more efficient liquid steel recarburiser.

Mathieson et al. [6] illustrated the value-in-use (VIU) of various charcoal types compared with coal types for BF tuyere injection at 140 kg/t-HM. This is shown in Figure 6, along with the net CO_2 emissions involved. It will be observed that the three charcoal samples had calculated values 50% greater than the reference high-volatile bituminous coal, reflecting predicted lower BF coke rates and improved hot metal composition (Si, S and P).
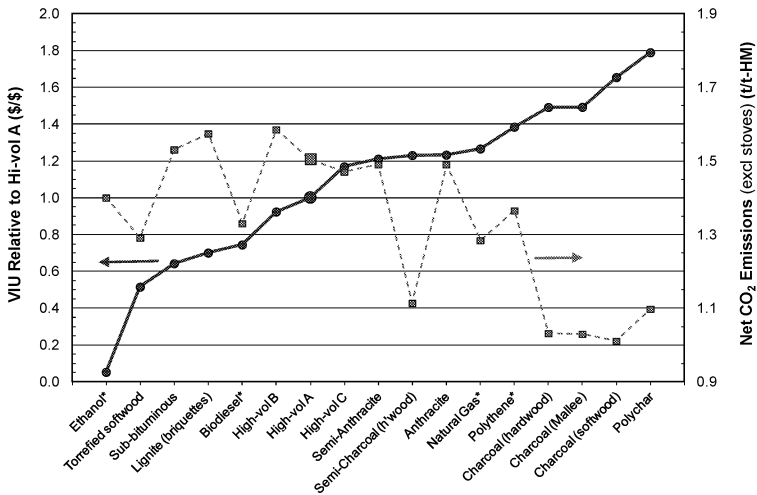
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Figure 6: Calculated VIUs for BF Injectants and Consequent Net Carbon Dioxide Emissions from the Blast Furnace. (Order of Injectants: Increasing VIU. * indicates injection at 60 kg/t-HM, rather than 140 kg/t-HM)

Current status and future directions of designer charcoal applications

Table 1 provides a summary of the charcoal applications proposed for ironmaking and steelmaking processes. Key quality parameters that optimize each application are given [13] as well as estimated net CO_2 emissions savings based on simple substitutions [6] (gate-to-gate). Additional savings of around 50% in net emissions are indicated by cradle-to-gate life-cycle assessments [3, 16] because it appears possible to produce charcoal with negative global warming potential if pyrolysis co-products (bio-oil and combustible gases) are captured and utilized.

The aggregate CO_2 emissions savings shown in Table 1 are calculated for Australian conditions and are $0.7 - 1.3$ t-CO_2/t-crude steel (31 to 57%) for the integrated BF-BOF steelmaking route, but only $0.04 - 0.06$ t-CO_2/t-crude steel for the EAF route ($8 - 12\%$), because of the dominance of CO_2 emitted for electricity generation in that sector. It will be observed that BF charcoal injection is the largest of the applications and has the potential to decrease net CO_2 emissions by up to 25% in the integrated route. This application is already practiced $100 - 200$ kg/t-HM in some Brazilian mini-BFs (up to 700 m^3 inner volume). The R&D phase has been completed for several of the applications making them ready for industrial trials or commercial operations.

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Table 1: Charcoal Applications Proposed for Ironmaking and Steelmaking [6, 12]

Application	Key Parameters	Net CO_2 Emissions Savings (t-CO_2/ t-crude steel)	Current Status	Next Step
Sintering solid fuel	Low VM: <3% High density*: >700 kg/m^3 Size: 0.3 - 3 mm	0.12 – 0.32 (5 – 15%)	Pilot scale testing [15]	Industrial trials
Cokemaking blend component	Low to mid VM: <10% High density*: >700 kg/m^3 Size: <1 mm Low alkalis	0.02 – 0.11 (1 – 5%)	Bench-scale R&D [17]	Pilot oven trials
BF tuyere injectant	Higher VM: 10 - 20% Low ash: <5% Low alkalis	0.41 – 0.55 (19 – 25%)	Theoretical analysis [6] & combustion testing [18]; Mini-BF commercial operations	Trial on large BF
BF nut coke replacement	Low to mid VM: <7% Higher density Size: 20 - 25 mm	0.08 – 0.16 (3 – 7%)	Mini-BF commercial operations [19]	Trial on large BF
Carbon/ore composites	Low VM: <5% Size: 80% passing 75 μm	0.06 – 0.12 (3 – 5%)	Bench-scale R&D [20]	Industrial trials
Steel recarburiser	Low VM: <3% Low moisture: <2% High density*: >500 kg/m^3	0.001 – 004 (0.3 – 1.0%)	Industrial trial [14]	Commercial operations
EAF charge carbon	Low to mid VM: <7% Size: 20 - 30 mm Low alkalis	0.02 – 0.04 (4 - 8%)‡	Proposed	Industrial trial
EAF foaming agent/ inject carbon	Low to mid VM: 2 - 7% Moisture: 1 - 7% Size: 0.5 - 5 mm Low alkalis	0.02 (4%)‡	Industrial trial [21]	Industrial trial with optimized charcoal

†   Applications not requiring very low moisture levels require relatively dry charcoal, say <12% moisture.
*   This is particle (not bulk) density, *e.g.* made from DBF pellets.
‡   Refers to savings in an EAF plant

Waste heat and value recovery from BF slag through dry granulation

Molten slags are high volume by-products from pyrometallurgical industries, with ironmaking typically producing 250-300 kilograms of slag for every tonne of hot metal produced, amounting to some hundreds of millions of tonnes of blast furnace slag each year worldwide (e.g. 230-270 million tonnes in 2010). Blast furnace slag is commonly granulated using water to produce a glassy product that can be used as a valued feed in cement production or to substitute for Portland cement. However, wet granulation consumes a large amount of fresh water (approximately one tonne of evaporative loss of water for one tonne of molten slag processed), can generate H_2S and/or acid mist causing air pollution, and more importantly, does not allow for recovery of a large amount of high grade waste heat in the slag (about 1.8 GJ of heat for every tonne of molten blast furnace slag cooled from a discharge temperature of 1500 to 100 °C). To overcome these shortcomings, dry granulation of slag has attracted extensive research efforts over the last 30-40 years to develop an alternative and more sustainable process than the conventional wet slag process.

In the dry process molten slag was first broken up into small droplets by several mechanical means such as air blast, rotary drum(s) and spinning disc/cup. Slag droplets were quenched and solidified using air to recover high grade heat released from the slag in a fluidized or moving bed. A number of dry granulation methods have been proposed and some trialled at pilot and demonstration plant scales in the 1980s, but none of them have been successfully commercialized. Nevertheless, there is a renewed interest in dry slag granulation since early 2000 due to increasing pressure and drive by the industry for more sustainable slag processing.

CSIRO started working on dry slag granulation (DSG) via a spinning disc in 2002. Following an extensive investigation, major breakthroughs have been made to resolve some common issues associated with slag atomization at a spinning disc, in particular the formation of slag "wool". A novel disc design has been developed to produce fine granulates without the formation of slag wool. A cyclonic air flow is employed to quench the hot granules to produce a highly glassy product. These breakthroughs make it possible to significantly reduce the droplet flying distance required, contributing to a compact reactor design that can efficiently recover heat. An integrated dry granulation and heat recovery process has since been developed and the concept has been proved through laboratory pilot trials at scales up to 5 t/h using a 3 m diameter pilot plant at CSIRO's Clayton laboratory as shown in Figure 7. The granulated products were highly glassy and suitable for cement manufacture [22] and the heated air stream reached 300°C during a relatively the short tapping time of about 1-2 min (which was limited by the amount of molten slag available at the laboratory).

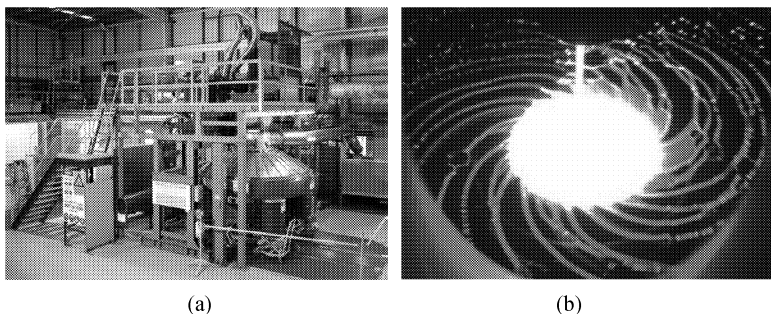(a)   (b)

Figure 7: (a) the 3 m diameter DSG pilot plant (5 tonne/h) and (b) a still image from a high speed video (1000 frame per second) of disc atomisation (slag 1450°C, 40 kg/min, 800 rpm)

Techno-economic and environmental assessment of dry slag granulation

A techno-economic and environmental assessment was carried out [23,24] to estimate the capital and operating costs (reported in 2012 Australian dollars A$) of a DSG plant to handle 300,000 t/y of slag (or 1 Mt/y steel) and to estimate its potential greenhouse gas benefits. The capital cost was estimated at A$9.1M. However, as CSIRO's DSG process is still at the pilot plant scale, this estimate is an order-of-magnitude cost only, as further development work on the process, particularly the heat recovery stage, is required before more definitive capital costs can be estimated. This estimate excludes any capital costs associated with utilization of the recovered waste heat. The operating cost of the dry slag granulation process was estimated to be A$4.80/t slag, with the major contributor being the labour component. Further details of the DSG process

economics are given by Norgate et al. [23, 24]. The estimated capital and operating costs for the slag dry granulation process are compared with the corresponding costs for the conventional wet granulation process (estimated by the authors based on various data sources) in Figure 8. The results in this figure indicate that both the capital and operating cost of the dry granulation process are roughly half of those for wet granulation, bearing in mind the preliminary nature of these costs.
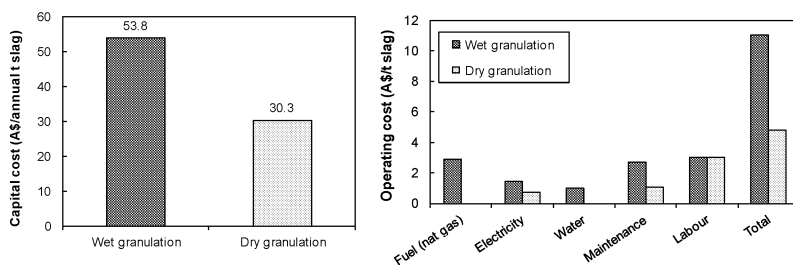

Figure 8: Comparison of capital and operating costs for dry and wet granulation.

Dry granulation also offers possible process credits which have the potential to improve the overall process economics compared to wet granulation and simple air-cooling of slag, as well as offering potential environmental benefits in the form of reduced greenhouse gas emissions. Compared to wet granulation these potential credits are the elimination of water for granulation and energy for slag drying, utilization of recovered waste heat, and avoided greenhouse gas (GHG) emissions and any associated carbon cost. The potential credits compared to air-cooling include the revenue derived from selling the granulated blast furnace slag to Portland cement producers for use as a cement clinker substitute, and the avoided GHG emissions and carbon costs associated with this substitution. The latter credit does not apply when comparing to wet granulation as both wet and dry granulated slags can be used in this way. Compared to wet granulation the process credits amounted to A\$15.7/t slag, while compared to air cooling the credits were A\$59.8/t slag. The combined avoided GHG emissions for dry granulation over wet granulation were 87 kg CO_2e/t slag, and 867 kg CO_2e/t slag compared to air cooling of slag. Calculation of these process credits are given in detail elsewhere [23, 24]. The Net Present Value (NPV) of the dry slag granulation plant without any process credits included was A\$33 M. With all potential process credits included, the NPV increased to A\$56 M compared to wet granulation and A\$126 M compared to air-cooling. Detailed calculation of these process credits and benefits have been provided elsewhere [23, 24]

Future direction of integrated heat recovery and DSG process

The work carried out to date has led to development of know-how that has addressed some of the issues that prevented further development and commercialization of the spinning disc based process in the past. We believe that our recent progress in understanding the fundamentals of the DSG process and the advanced computational fluid dynamic model developed and validated against our pilot plant results at CSIRO place us in an excellent position to take on the next stage in the scale up of the process and its demonstration under continuous operation at a steel plant with access to tonnage amounts of molten slag. We expect the commercialization of the process to follow within a few years after the demonstration phase. Given the growing interest in this

technology by the non-ferrous industry, one could see that dry granulation of base metals slags and mattes is the logical extension of this application in future years.

Concluding remarks

For the integrated BF-BOF route, the use of renewable biomass-derived chars in ironmaking and steelmaking has the potential to decrease net CO_2 emissions by 32-58% directly, and more under full life-cycle assessment. The potential in the EAF route is less, at around 10-15%, because its energy principally comes from the electricity grid and therefore depends on emissions in that sector. Through combining the carbon credits for waste heat recovery from molten slag and production of "green cement" from granulated blast furnace slag where viable, then the net reduction in CO_2 emissions for integrated BF-BOF route increases by 10% to about 42 to 68%.

The ISP represents an integrated, innovative and potentially very effective program to decrease the net CO_2 emissions from the steel industry using current process equipments. ISP is based on 7 years of productive collaboration.

The World Steel Association has recognised these innovative technologies, which do not depend on carbon capture and storage, as the best options for short and medium term CO_2 reduction within the steel industry and, when proven, they will be widely applicable throughout the world.

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