CLIMATE CHANGE – GREEN BLAST FURNACES

Nicholas Standish [1*]

[1] Emeritus Professor University of Wollongong, Northfields Ave Wollongong, NSW 2522, Australia

[*] Correspondence: mst97899@gmail.com

Abstract: Recent paper on Climate Change in this journal considered Green Steel and argued for a DRI-EAF route using charcoal from tree branches in forest plantations that are maintained by workers using hand tools. And this will continue even more in proposing charcoal's major use in blast furnaces. There are many operating iron blast furnaces in Indonesia and worldwide using coke and as the process is capital intensive they must be operated for a long time. This means that most blast furnaces with their coke ovens will continue producing iron and large amounts of CO_2 for many years yet, making zero carbon unattainable. An obvious question is: Can coke in the iron blast furnace be substituted by the more climate friendly charcoal? And if yes, will it be economic and will the blast furnace be as productive as now? Following an exhaustive literature study this paper answers the question positively. It is demonstrated that there are two fundamentally different requirements of carbon in blast furnaces that people have not appreciated and instead followed a hundred year tradition in treating them as one. This paper exposes them as two different carbons, namely: the cohesive zone carbon and the shaft zone carbon. This is perhaps the first time that this has been done, as so far these two quite different evidence-based theory requirements of a blast furnace carbon have been invariably introduced as a single carbon, namely: coke in coke BFs and charcoal in charcoal BFs. It is also demonstrated that large blast furnaces can operate with this dual carbon burden not too differently from a 100% coke or a 100% charcoal carbon burdens. It is also good economics as cheaper charcoal is substituted for expensive coke.

Keywords: Indonesia; Charcoal; GHG emission; Blast furnace; Cohesive zone

1. Introduction

It is well documented that the amount of CO_2 generated since the start of industrial revolution has been rising. This rise was kept at bay by the two earth's natural sinks, namely land sink (forests and agriculture) and water sink (oceans and lakes). However, as forests were cut down for timber and to free land for houses and industry the land sink has been steadily decreasing and reducing its ability to absorb more and more of the CO_2 generated, so the CO_2 content in the atmosphere has been rising over time.

Many climate scientists believe that increased CO_2 will cause amplified global warming and more extreme weather events affecting human health. Be that as it may, but right now more CO_2 closer home is definitely a problem in accelerating materials' corrosion and causing "concrete cancer' – and with high humidities in Indonesia even more so!

The recently published paper titled Climate Change in Indonesia: Green Steel [1], strongly argued for a DRI-EAF route using charcoal from tree branches in forest plantations that are maintained by workers using hand tools and create millions of jobs throughout the country.

Using charcoal makes a lot of practical sense because this way we get double benefit – one: increasing CO_2 absorption by forests by not cutting trees down and two: decreasing

the overall CO_2 of the DRI process by regenerating the emitted CO_2 with charcoal and reusing the so-formed CO.

For Indonesia this has much higher benefit still because its AFOLU (Agriculture, Forestry and Other Land Use), at 53% emission [2] is just more than double that of the worldwide average of 24% [3].

Commenting on this, Zaki [3] also said "It is ironic that forests, which should serve as carbon sinks, have instead become major emission sources due to land burning, forest conversion, and peat degradation."

Over the years in Indonesia there have been many forest laws issued that should have stopped their degradation, but they were apparently not strong enough legally [4] so degradation continued. Hopefully the Presidential Regulation No. 5/2025 of 21 January 2025 on Forest Area Management, issued by President Prabowo and creating a new task force headed by the defense minister, the TNI commander and the attorney general will be effective. As expected this law has its critics cautioning that it militarizes environmental governance and risks repressing communities defending their land.

It should be pointed out that President Prabowo continues making efforts to see Indonesia reduce its GHG (Green House Gas) emission as quickly as possible; he even reduced the zero target year from its 2060 to 2050 at the G20 Summit 2024 in Brazil (to be reversed back again to 2060), and right now (October 2025) President Prabowo announced full support for Brazil's TFFF (Tropical Forest Forever Facility) by stating: "Brazil has established an investment fund that aims to conserve tropical forests. Brazil pioneered this movement, and we support it. We will commit whatever amount Brazil has invested there Indonesia will invest here." [Note: TFFF aims to set up a $125 billion global investment fund to provide tropical countries with permanent income in exchange for protecting their forests].

To sum up so far. AFOLU emissions released by lands and forests in Indonesia produce twice as much greenhouse gases than other emissions and reducing them via charcoal in making iron and steel gives twice the benefit. As was demonstrated in the recent paper [1], this can be done immediately for DRI production and assisted by hydrogen if it is economic.

However, there are many operating iron blast furnaces worldwide using coke - some are new and some are being relined right now at high cost. For example in Australia, Bluescope Steel has announced in October 2025 a reline of its Port Kembla No 6 BF at a cost of $1.15 billion.

The reason for this is that the BF process is capital intensive, and to be cost effective it must be operated for a long time or to use the ironmaking terminology, have a "long campaign". Modern BFs have campaign lives of 20 years, or more.

Economically this means that most blast furnaces with their coke ovens will continue producing iron and large amounts of GHG emissions, making zero carbon targets unattainable.

The question is: can coke in the iron blast furnace be substituted by charcoal? And if yes, will it be economic and will the BF be as productive as now? The answer is yes! It has been done in Brazil for decades in small size blast furnaces. For example, in 2020 – 31.42 million tonnes came from integrated mills using charcoal. [5]. One BF of 350 m³ or cum, is producing 600 tpd of iron. By contrast, modern coke blast furnaces are 2,000 – 6,000 cum producing 5,000 – 15,000 tpd (tonnes per day) of iron.

Therefore, we need to establish if coke can technically be substituted by charcoal in existing blast furnaces, most of which are large, and whether it can be done by a full

substitution as in Brazil or not, and how effective and economic these substitutions are likely to be.

2. TECHNICAL BACKGROUND

To establish if coke can technically be substituted by charcoal, we start with first principles.

The basic principle, as pointed out in the previous paper [1], is that no matter how, or where you do it - to make iron from its ore, generally hematite, Fe_2O_3, you need to remove its oxygen, and for every one tonne of Fe made this requires theoretically 161 kg of carbon, or in actual practice to account for losses, inefficiencies, incomplete reactions, etc about double that. As quantities under ideal conditions may interfere with final conclusions – and are simple to calculate from standard chemical stoichiometry and thermodynamics, we will postpone quantities till later, and go directly to essential basics and industrial data to support answers to our question.

2.1 Blast Furnace

A Blast Furnace (BF) is a tall cylindrical furnace. Layers of small size iron ore (6-20mm) and large size coke (25-60mm) are charged at the top and move down counter to upcoming hot, reducing gases, generated in the bottom. Much of the carbon's chemical energy is not fully used in reduction and leaves the BF as CO. Ore particles in moving down, are reduced, then melted in the bottom and the molten iron collected in the hearth to be periodically tapped.

These materials form alternating layers in the furnace and are supported on a bed of incandescent coke below. Hot air at high pressure is blown into the lower part of the furnace. The coke combusts, producing heat and carbon monoxide (CO) gas which passes through the porous bed. The CO removes the oxygen from the iron ore forming CO_2 and the heat melts the charge, producing hot metal.

Hot metal is a solution of molten iron at approximately 1480 °C, which contains 4 percent carbon and some other elements like Si, Mn, Ti, etc. This hot metal flows to the bottom of the furnace, through the coke bed and is periodically "tapped" from the furnace into torpedo cars and transported to the BOF shop where it is refined into steel.

A traditional Blast Furnace Plant consists of five major parts 1 – The Blast Furnace itself, 2 – The Coke Ovens, 3 – The Stoves, heated by the BFG (Blast Furnace Gas) assisted by the richer COG (Coke Oven Gas) to increase the blast temperature to as high as 1300ºC, 4 – The Slag Granulation and on-treatment sold as clinker for cement making, and 5 – The Stockhouse, to store, blend and send materials to the top BF charging gear, historically bells, but since 1975 BLT (Bell-Less Top). This, plus tuyere injection, high top pressure and its TRT (Top pressure Recovery Turbine), enhanced control architecture, etc, are designed to save the expensive coke of some $US500/tonne.

2.1.1. Subsidiary Notes

1) Blast furnaces are tall, about 50m all up. This why in all countries – except English! – it is called Hochoffen,고로, Alto Horno, Vysoka Peč, 高炉, Haut Fourneau, etc. 2) BFs are always tall – irrespective of production quantities, and the reason is what I call "cooking time", which means under the blast furnace conditions, starting with 'raw' particles (iron oxide) and finish with 'ripe' particles (iron metal) it takes the same time. Blast furnace production is then obtained by increasing the furnace cross-sectional area. 3) DRI reactors, e.g. Midrex, Hylsa, etc, are essentially blast furnace shafts, and are also tall for the same reason. 4) Ferrous burden (pellets, sinter or lump ore) size is small because its usual (economic) reducibility has always been the norm. It is true that reducibility of natural ores are fixed over a narrow band, but reducibility of sinter and pellets can be varied over a wide range. 5) BF coke size is large because its usual (traditional) physical properties have always been the norm. Coke is the only raw material

that descends into the lower part of the blast furnace (BF) in its original form; therefore, it is of utmost importance to improve the coke properties for its use in BF.

From all of the above information we can conclude that:

 The BF is essentially a heat engine + chemical reactor — with useful output of gas energy. When talking of blast furnaces, I like to stress that to really understand it we must look at the blast furnace in a number of its roles. This is shown in a series of following figures.

2.2. Physical Blast Furnace

Figure 1 is what I call a physical BF. It shows: "Granular zone" also called "lumpy zone", cone-shaped "Cohesive zone" with its "coke slits' or 'coke windows', "Active coke zone" and "Stagnant coke zone", better known as 'deadman'. It is important to thank our Japanese colleagues who shared their findings of quenched operational blast furnaces – eight with water and one with nitrogen – starting with Higashida in 1968.

The finding of the greatest importance is that all furnaces showed that layers of ore and coke, set at the stockline on the top do not mix but remain as layers right to the bottom.

The second finding of great importance was that all furnaces, showed an existence of a cohesive zone of different shapes.
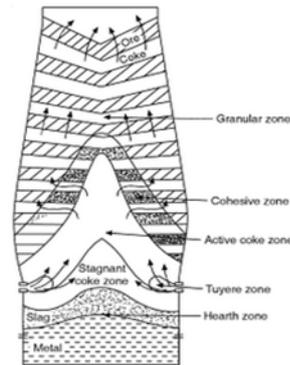

Figure 1. Physical BF

Subsequent quenched furnaces, including one of best productivity, showed that the best shape is an inverted V-shape, or cone. Incidentally, the best way to ensure a good conical shape is to get a central gas flow, which in practice means to charge large coke in the centre. It is also essential to ensure that an equal blast from each tuyere is maintained, otherwise the inverted cone becomes deformed in some way and furnace productivity suffers.

From the fundamentals of fluid flow that fluids always flow from high to low pressure, a horizontal jet of fluid, in our case gas from tuyeres, will always take a curved path to the lower pressure at the top AND from the basics of granular materials a horizontal jet of gas aimed at a granular mound is like hitting a semi-solid wall, so it gives in and goes up and at the next open 'window' does 'a dog leg' to flow to the top following a path of least resistance.
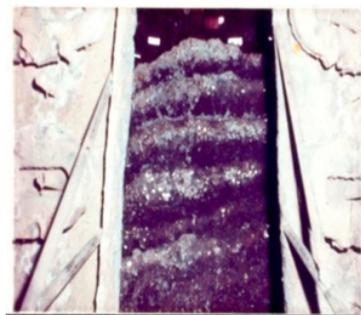

Figure 2. Cohesive zone. Chiba No 2

Figure 2 is a photo of an actual cohesive zone in an actual operating BF after water quenching and excavating the burden. In showing this photo, I need to thank the former Kawasaki Steel Company for allowing me to use it for educational purposes.

It shows the quenched Chiba No 2 after it was excavated and a slice of its stack cut off, and a photo taken looking up from the casting floor. On the outside you can see plate cooler covers and at the far up top inside, you see two openings where plate coolers were removed.

The cohesive zone shows distinct layers of ore and coke, with the ore semi-molten (light colour) and 'coke windows' clear. Not seen here, but this cohesive zone is similar right around and conical enough – something that is good for BF operation.

As fundamentals do not change, the same phenomena described in Figs 1 and 2 should apply to charcoal blast furnaces.

2.3. Thermal Blast Furnace

Figure 3 is what I call a thermal BF, with heat and temperature distribution along the height of the blast furnace. Temperature distribution is shown in Fig 3(a) in idealized fashion of the many measurements in actual blast furnaces starting in about mid-1960s.
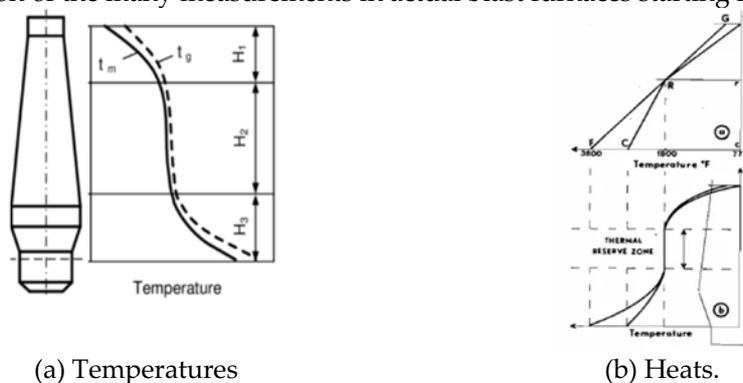

(a) Temperatures   (b) Heats.

Figure 3. BF Thermal behaviour

Interestingly, theory on this was developed by BI Kitaev in USSR in early 1950, but being in the Russian language was not available in the West until much later.

In fact, the work assembled in his book was considered so important that the book was translated and edited by Professor PA Young with the title "Heat Exchange in Shaft Furnaces" [8].

In Fig 3(b) the upper diagram is the often forgotten 'Reichardt Diagram' of 1927. Yet, it was the first scientific diagram: 1) describing heating of the cold solids charged at the top of the blast furnace by the gas generated at its flame temperature at the tuyeres and 2) provide heat required by the exothermic reactions of reduction of iron oxides and the endothermic coke gasification.

These fundamental principles will also be fundamental for charcoal.

2 .4. Chemical Blast Furnace

Figure 4 is what I call a chemical BF where chemistry is followed.

As shown in Fig 4, there is a chemically 'Coke Inert Region' and a chemically 'Coke Reactive Region'. The boundary between these two regions is theoretically governed by the thermodynamic equilibrium of Carbon and Oxygen. These are simply stated as:
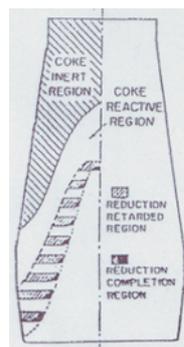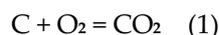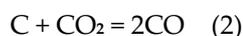
Figure 4. Chemical BF

$$C + O_2 = CO_2 \quad (1)$$

Which is, of course, the combustion reaction and produces heat and high temperature. But thermodynamically CO_2 is unstable at high temperature, so it immediately reacts with carbon as:

$$C + CO_2 = 2CO \quad (2)$$

Incidentally, this is the only oxide reaction that increases entropy [one mole of reactant gas (CO_2) produces two moles of product gas (CO)], so clearly seen in Free Energy Diagrams (Ellingham diagrams) as the only line that slopes down among all others that go up.

Equation (2) is the well-known endothermic Boudouard equation. Its reverse is the Bell's "soot-forming" equation well-known and proven in fire place chimneys.

Although it was stated above that the boundary between the two regions in Fig 4 is theoretically governed by the thermodynamic equilibrium of eqn (2), in real life blast furnace practice chemical kinetics, or rates of reactions, take precedent and carbon reactivity dominates.

Using simple word equation we have the rate for our eqn (2) as:

$$\text{Formation of CO} = \text{Rate Constant} \times \text{Driving Force} \quad (3)$$

Since the driving force, i.e. concentration of CO_2 in the gas at the same levels in the shaft are same the production of CO by eqn (2) depends only on rate constant, which for carbons is called 'reactivity'.

As ordinary charcoals are more reactive than ordinary cokes is the reason to see in technical literature statements like "Charcoal in BFs is thermally favourable for indirect reduction owing to its higher reactivity" or ""Charcoal has a higher reactivity than coke and reduces the reserve zone temperature which improves efficiency".

It should be noted that without also stating restrictions, statements like this are highly inaccurate and should not be made. The reason is that without at the same time referring to the ferrous burden's reducibility makes the above statements worthless.

Next we consider the "Coke Reactive Region" which from above means that eqn (2) is kinetically favourable and takes place as soon as a CO_2 appears from reduction of FeO forming 2CO by contact with carbon (coke).

For most efficient BF operation we would like to see all of the ore reduced to Fe before melting. There are good reasons for that – the most practical of all is summarised as:

"Blast Furnace Has Never Had Any Problems Melting Iron".

This was clearly demonstrated first time back in 1970 when Jack Peart and Frank Pearce of Stelco charged some DRI from their new SLRN (<u>S</u>telco <u>L</u>urgi <u>R</u>epublic <u>N</u>ational) kiln into their BF. The result was, to quote 'It was like the furnace had diarrhoea – we couldn't get the torpedo cars in fast enough to take the metal out'.

As a reminder of what is involved in getting the ore reduced to Fe we look in the previous paper [1] to see that reduction of Hematite to Iron proceeds in steps, ie

$$Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe \quad (4)$$
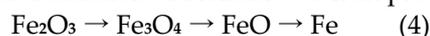
This is illustrated in Fig 5 for early stage of the reduction which shows that the reduction proceeds topochemically, or onion-like to use every day expression.
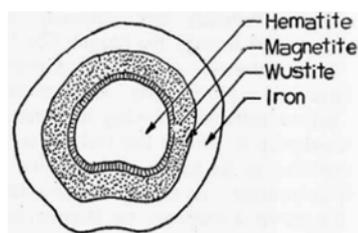
Figure 5. Iron ore reduction

There are only two reductants that thermodynamics tells us can take the oxygen away from the iron oxides. They are CO and H_2.

In the first case the product is CO_2 that is the problem GHG gas and in the second case it is H_2O. As is well known, for centuries it was the CO produced from coke in the blast furnaces that reduced Fe_2O_3 to Fe (iron) in Fig. 5. The BF way of iron ore reduction has been the mainstay of quantity iron production and is still the economically unrivalled process of world-wide iron and steel making industry, but as shown in the previous paper [1], DRI processes are beginning to be considered.

In the end stage of reduction, as indicated in Fig 6, only the FeO is left inside surrounded by Fe metal.

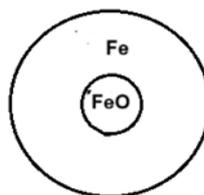The reaction is then: $FeO + CO = Fe + CO_2$ (5)

Figure 6. Near end reduction

In following this reaction, we see that the CO molecules have to diffuse through longer and longer distance through the increasing iron layer to reach the FeO. There, the CO reacts with FeO to form Fe and CO_2 molecules which have to diffuse out counter to CO molecules coming in, through longer and longer distance of the iron layer and interfering with CO molecules moving in to react with the remaining FeO, to finally reach the outside and join the upflowing gas.

Time taken to do this, τ, gets longer and longer to convert the last of the FeO to Fe. The equation is:

$$\tau = \frac{\rho R^2}{6bD_eC_g}$$

(6)

Where: ρ - the density of solid reactant, R - is the particle radius, b - the stoichiometric coefficient, Cg - the concentration of the gaseous reactant in the main body of fluid, and De - the diffusion coefficient

Once FeO and CO make contact chemical reaction takes place with the rate given as a simple:

$$r = kCg$$ (7)

where k is the rate constant.

Both De and k are temperature dependent so that increased temperatures help kinetics. Unlike in DRI practice [1] where if higher temperatures lead to sticking or swelling, temperatures are adjusted lower to avoid it. In BF practice this is not possible and any stuck together agglomerates will just continue moving down.

This why in practice there is always FeO left inside ore particles before melting zone is reached and provided the amounts are small there is no problem.

Consequences of the ore particles not being well reduced by the time the cohesive zone is reached should be kept in mind.   .

1).What happens is that the remaining FeO melts (MP = 1420°C), the liquid FeO immediately contacts the hot CO and immediately reacts, viz. $FeO + CO = Fe + CO_2$.

2).This Fe having a higher melting point (MP = 1535°C) immediately solidifies and simultaneously the thermodynamically unstable CO_2 just formed reacts with C, viz. $CO_2 + C = 2CO$ – the most endothermic reaction in the BF and takes the heat from the system, and instead of the just formed solid Fe remelting it freezes and, even some just molten FeO freezes too.

3). Of course, the blast furnace has big inertia and can deal with such situations, but too much retained FeO will definitely cause irregularities and increase hot metal costs and is to be avoided.

And being fundamental all of this will also be fundamental for charcoal.

2.5. Blast Furnace Permeability

At this time, it is important to consider the fact seen in Figs 2-4 that a BF has a cohesive zone with 'coke windows' so essential for getting the hot gases made in the raceways to travel up to heat and reduce the iron oxides to Fe metal. Naturally, 'coke windows' must be clear and free of any inclusions that would reduce its flow area. To reach the BF top and do heating and reducing work efficiently the solids in the shaft must have good permeability for these gases.

In practice permeability in blast furnaces has generally meant pressure loss and invariably calculated using Ergun's equation consisting of viscous and kinetic pressure losses, as shown in equation (8) where the terms have their usual meaning.

$$\Delta P_f = 150 \ (1\text{-}\varepsilon)^2/\varepsilon^3 \times \mu v L_s)/\phi d_p \ + 1.75 \ (1\text{-}\varepsilon)/\varepsilon^3 \times (\rho L v_s^2)/\phi d_p \qquad (8)$$

The particle size term (ϕd_p) is a reminder that particle shape (ϕ) has an effect on ΔP_f.

Because only the kinetic term is important in blast furnaces the equation used is eq (9) below:

$$\Delta P_f = 1.75 \ (1\text{-}\varepsilon)/\varepsilon^3 \times (\rho L v_s^2)/(\phi d_p) \qquad (9)$$

I like to define permeability in a more useful way and focussing on the packing rather than the gas, so I say, "Permeability is the ability of a packing to pass gas through it" and so that we can compare permeability of packings, add "under standard conditions of ΔP = 1 atm, A = 1 m², L = 1 m and ρ = air @ STP. So, our equation of permeability, Q cum/s, is then:

$$Q = K \ [(\phi d_p) \ \varepsilon^3 \ (1\text{-}\varepsilon) \ \psi]^{1/2} \qquad (10)$$

where ψ is a new term called geometric factor with values 0 – 1. The simplest way to look at ψ is to think of a vertical tube filled with packing and air flowing from the bottom. If air flows up unhindered and out freely ψ = 1. If you close the top of tube air flow stops completely and ψ = 0. For other extents of flow hindering ψ = 0 – 1.

It is noted that ΔPf in eq (9) is for normal flow pressures. However, if the pressures are reasonably high, as in modern blast furnaces, then the flow is sufficiently compressible for the driving force to be expressed as:

$$\Delta P_f = [(P_2)^2 \ - (P_1)^2] \qquad (11)$$

Of course, this does not change the permeability of the system defined in eqn (10).

Recalling the finding of quenched blast furnaces of the greatest importance is that layers of ore and coke set at the stockline do not mix but remain as layers right to the bottom, we note the existence of ore-coke interfaces and explain that for blast furnace ore and coke layers there is an interface every time small size ore is layered on top of the large particle size coke layer and that there is no interface when coke layer is on top of the ore layer. So, for coke on top of ore ψ = 0 and for ore on top of coke ψ > 0.

It is important to be reminded that these interfaces are fundamental result of granular materials' theory of particle segregation with size difference predominating over density and shape. It may be useful to quote a simple segregation rule [9], namely:

For size segregation to occur two requirements must be met simultaneously- there must exist:

1. difference in particle size, and
2. relative motion between particles.

From which clearly:　　　　　　　　　　　　　　　　　　　　　　　　　　　.

ELIMINATE EITHER ONE and YOU ELIMINATE SEGREGATION.

Details of quantifying the value of ψ from particle sizes have been available in blast furnace literature for 50 years [10], so it seems unusual that Ergun's equation [eq (8)] is still widely used instead of eq (10) which represents reality better. It should be remarked that a few papers exist which do discuss, or rather, introduce 'interfaces' as something that could increase furnace pressure drop.

Our 1975 work in Wollongong on ore/coke interface [11] is foundational and seems to be more often used indirectly via subsequent literature rather than explicitly. For example, Propster and Szekely [12] reported laboratory results with layers of different particles and concluded that for small on large conditions the interfacial regions will contribute appreciably to the overall flow resistance.

More recently, Song [13] used cold model experiments with multilayer burden that revealed the pressure drop occurred the most at the layer interface. To find out why he used glass balls and coke particles and showed that the porosity decreased at the interface as the glass balls filled the space between the large sized coke particles. He also found that nut coke mixing ratios of 20 and/or 30% were good for furnace permeability.

These findings are based on experiments done at cold condition (room temperature) only. In blast furnace the burden starts its travels from stockline at the top with ore and coke layers in the throat ending in the bottom part, encountering various physicochemical gas-solid reactions at high temperature in between, plus the reduced ore melting in the cohesive zone area.

All investigations and reports on the effect of ore-coke interfaces on BF permeability in the literature have been done either experimentally on a small scale or with mathematical modelling on industrial scale furnaces.

An exception was when in 1978 I was asked to suggest a design for a simple way to measure BF burden permeability that a real O/C interface was obtained. Figures 7(a) - (c) show this and the results of measurements on a real undisturbed sample from the stockline of a full size rig of Port Kembla No 5 BF built for operators to practice Paul Wurth BLT charging.

It is very important to state that the sample of the full ore layer on coke with an O/C interface in Fig 7(b) was taken from the actual full scale PK BF No 5 stockline after it was layered down by the PW BLT without any disturbance of the particles as they were in that position at the stockline and all subsequent measurements of its size consist and pressures, with actual measurements in Fig 7(c) did not involve disturbances of any kind!

It is also necessary to state that under actual operating conditions the burden is charged against an upcoming hot gas so the very fine ore particles would be elutriated and report in the dust catchers. The ore-coke interface, as such, would still be clearly identifiable and more so in high top pressure blast furnaces.
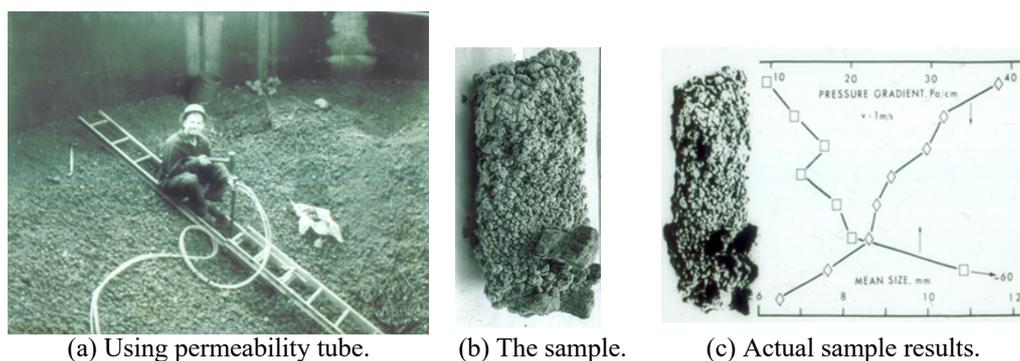
(a) Using permeability tube.   (b) The sample.   (c) Actual sample results.

Figure 7. Measuring permeability down ore layer at PK No 5 SL and its particle size distribution   and pressures on an undisturbed sample withdrawn from the SL shown.

The outer surface of the sample in Fig 7(b) already tells the story starting with layer angle, then of larger particles of sinter with some pellets here and there, then smaller particles above and within the upper part of the coke layer. It is noted that coke sizing specification used in the burden was 25 – 60 mm with 5% max of +60 mm, but it is obvious that a few were really well above 60 mm!

The measurements of actual mean size and pressure gradient of the ore in the sample in Fig 7(c), without disturbing the sample in any way, show ore mean particle size of 12 mm at the top surface decreasing to 6.5 mm at the bottom. The pressure gradient starts at 10 Pa/cm at the top, with a gradual increase to 20 Pa/cm for about 2/3 of the height and then in the last 1/3 - which can be seen to be an interface a huge 60 Pa/cm.

Saying this in another way is that the gas flow in one third of an ore layer experiences resistance three times higher than its resistance in the rest two thirds of it!

3. APPLICATION TO LARGE BF TO USE CHARCOAL BURDEN

3.1. Preliminaries

As noted earlier, most papers on charcoal in large blast furnaces deal with charcoal injection. The reason is to save the expensive coke – and the injection rates spoken of are in 200-300 kg/thm by weight.

This paper considers replacing major part (300kg/thm) of the carbon of BF burden with charcoal, not a small part (20kg/thm) reported to have been tried with good results [21,22], nor as additions to coking blends [23]. In this respect replacing major part of the carbon of BF burden with charcoal appears to be presented here for the first time in the blast furnace industry.

Preceding material established unambiguously that small BFs in Iron and Steel industry, especially in Brazil, have been successfully operating in practice with 100% charcoal for many years. Likewise, an exhaustive search of literature carried out at the same time showed that apart for recent interest in substituting some of the currently used injectants, like pulverised coal, with charcoal, there have been no publications of using 100% charcoal in the burden of large (>2000cum) blast furnaces.

The material presented here in previous chapters also showed that theory of iron making in any type of reactor follows the same rules of chemistry, thermodynamics, kinetics, fluid flow, engineering and reactants contacting, be it Midrex, Hylsa, ZESTY, etc

for making of solid iron, or with melting to make pig iron in coke and charcoal blast furnaces.

In summary – and an important one that should be highlighted and kept in mind is:

The two zones, i.e. 'coke inert zone' and 'coke reactive zone'
are the product of Boudouard reaction rates – NOT equilibrium,
so their rate constants can be changed.

3.2. Bringing Everything Together

To sum up so far. AFOLU emissions released by lands and forests in Indonesia produce twice as much greenhouse gases than other emissions and reducing them via charcoal in making iron and steel gives twice the benefit and even more with using charcoal to reform CO_2 produced.

As was demonstrated in the recent paper [1], reducing CO_2 can be done with DRI production immediately and assisted by hydrogen if it is economic. However, there are many operating high capital cost iron blast furnaces in Indonesia and worldwide using coke, so economically this means that most blast furnaces with their coke ovens will continue producing iron and large amounts of GHG emissions.

As charcoal is CO_2 neutral – and is also carbon - can it substitute coke in the coke iron blast furnace?

To answer it, we need to establish if coke can technically be substituted by charcoal and whether it can be done by a full substitution as in Brazil or not, and how economic is it likely to be.

It has been demonstrated in this paper so far that small charcoal blast furnaces have been producing iron for decades – and more importantly that their internal state, including the cohesive zone, are similar to coke blast furnaces.

It is true that the larger is the coke blast furnace the better quality its coke must be and by analogy the same must apply to large charcoal blast furnaces. And here it must be stressed that the science has moved on, and our views should too.

What this means is that charcoals (biochars) can now me made with properties that are not too different from coke. In fact, there have been companies very recently in many countries who have developed charcoal making processes of 'metallurgical charcoal'. One was mentioned in the previous paper [1] as the CSIRO 'Metallurgical Charcoal', others are 'Pyrochar' claimed to be 'replacement to coal in primary metals manufacture' [14], and especially 'BioCarbon' [15] that has developed charcoal based, coke replacement products

for EAF steelmaking and ferroalloy production, and said to be working towards achieving properties approaching BF coke.

With all the facts, evidence and theory presented above backing us we can confidently consider the following proposal.

We have a large BF in a steel plant. The BF produces 4,000,000 thm/year. As its burden we intend to use:

1. imported iron ore pellets (6-20mm),
2. a fixed amount of 125 kg/thm of coke made in the plant's coke ovens (20-50mm), and
3. 300 kg/thm of charcoal having similar properties to the coke (20-50mm).

Air is preheated to 1200°C in hot blast stoves with BFG and COG. To balance the BF's energy, carbonaceous material, including charcoal fines, are tuyere injected.

Energy-wise the products BFG and COG at 18.0 PJ/year and 3.0 PJ/year is sufficient to heat the coke ovens themselves and hot blast stoves for 8.6×10^6 m3/year blast at 1200°C and 2.5 atm(abs).

Cost-wise the answer is simple. We are substituting the same amount of cheaper charcoal with 2% ash for the more expensive coke and its 14% ash, so it will not be surprising if the costs are lower!

For this blast furnace operation, as can be seen, we are using two different carbons, namely: 1) the cohesive zone part and 2) the shaft zone part. This appears to be the first time that this has been done, as so far these two quite different evidence-based theory requirements of a blast furnace carbon have been invariably introduced as a single carbon, namely: coke in coke BFs and charcoal in charcoal BFs.

The coke comprising the 125 kg/thm of "cohesive zone coke" would be strong, unreactive and shatterproof – not unlike the "cupola coke" which is just like that. The cohesive zone coke will be added with the 300 kg/thm of charcoal and layer charged. In moving down, this layer will first be contacted by the upcoming hot gas to be heated to reserve zone temperature. As both coke and charcoal have similar effective thermal conductivities, reaching uniform temperature will be no different for the various sizes to what it is now.

In the reserve zone the CO_2 product of iron ore reduction will be mostly reacted with the more reactive charcoal than with essentially unreactive coke. This is simply a consequence of a higher reactivity of charcoal compared with coke in the word equation for reaction rate shown in eqn (3), viz:

$$\text{Formation of CO} = \text{Rate Constant} \times \text{Driving Force}$$

Since the driving force, i.e. concentration of CO_2 in the gas is the same at the same level in the shaft, the regeneration rate of CO_2 by gasification of carbon, or $CO_2 + C = 2CO$ depends only on rate constant, or reactivity.

This is absolutely expected from theory. The finding by the Aachen team mentioned earlier "that coke reactivity in CO_2 atmosphere decreases when charcoal particles are attached on the coke surface, which evidently protects coke from the solution loss

reaction." is therefore unsurprising. Nevertheless, it is important because it is a practical BF confirmation of using both carbonaceous materials at the same time, as proposed here.

As to the best particle sizes chemistry and permeability counter each other. Chemistry says small size – permeability says large size. This means we need to find the best compromise.

3.2.1. Chemistry says small size

As shown earlier in eqn (4), the reduction of Hematite to Iron proceeds in steps, ie

$$Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$$

This was illustrated in Fig 5 for early stage of the reduction which shows that the reduction proceeds topochemically, or onion-like to use an everyday expression, and in Fig 6, for near the end of reduction when only FeO is left inside surrounded by Fe metal.

It was also shown that because of diffusion of CO from outside gas through the Fe shell to reach the FeO, react according to eqn (5), namely $FeO + CO = Fe + CO_2$ and the product CO_2 to diffuse back through the Fe shell to finally reach the outside gas is a very difficult task.

An additional benefit of using hydrogen, besides its product being a friendly H_2O, is that both H_2 and H_2O molecules are much smaller than both CO and CO_2 and increase the reduction rate significantly.

Actually, as discussed earlier, it is again pointed out that any increase in reduction rate means an increase in the diffusion coefficient, to get the reactants together quicker to get benefits of high reaction rate coefficient.

It was also pointed out earlier that with the best will in the world, in actual blast furnace practice – and in DRI practice, too – there will always be FeO left inside ore particles before melting zone is reached and provided the amounts are small there is no problem.

To end this part of chemistry and particle size it is worth repeating the consequences of the ore particles not being well reduced by the time the cohesive zone is reached, namely: .

1). The remaining FeO melts (MP = 1420°C), the liquid FeO immediately contacts the hot CO and immediately reacts, viz. $FeO + CO = Fe + CO_2$.   .

2). This Fe having a higher melting point (MP = 1535°C) immediately solidifies and simultaneously the thermodynamically unstable CO_2 just formed, reacts with C, viz. $CO_2 + C = 2CO$ – the most endothermic reaction in the BF, and takes the heat from the system, and instead of the just formed solid Fe remelting it freezes and, even some just molten FeO freezes too.

3). Of course, the blast furnace has big inertia and can deal with such situations, but too much retained FeO will definitely cause irregularities and increase hot metal costs and is to be avoided.

The answer to this dilemma of reducibility of ferrous part of the burden is to design pellets with high reducibilty while keeping their strength properties the same. This idea is not new, and many ways have been tried, from adding saw dust to pellets to making iron carbon composites ("Ferrocoke") by adding coke particles to ore [16], and so on.

However, for some reason none of these ideas have been implemented 'en masse' as a standard procedure.

As the science has moved on fast in the last few years, it is quite likely that an economic and a practical method will be found to increase reducibility of pellets, which may well involve use of catalysts.

<u>And being fundamental all of this will also be fundamental for charcoal.</u>

3.2.2. Permeability says large size

Now we consider the other half of the compromise, namely particle size and permeability.

Theory and its useful practical equation, incorporating a new term, ψ, called an interface factor, was presented earlier in eqn (10).

Note in eqn (10) the huge importance of bed porosity (ε), also known as voidage, compared with d_P, the particle size. For example, for a bed porosity of 0.5, the effect is $[\varepsilon^3 (1-\varepsilon)]^{1/2} = [0.5^3 (1-0.5)]^{1/2} = [0.5^4]^{1/2} = 0.5^2$, whilst for particle size its effect on permeability is only $(d_P)^{1/2}$.

As an example, consider the porosity or voidage (ε), of various mixtures of three ore sizes, namely: 7mm, 14mm and 28mm. The measured porosities, plotted on the ternary diagram in Fig. 8, so that any point inside the triangle is a mixture of these three size ores, show a map of 'isopores', ie lines of mixtures of these three sizes of ore that have the same porosity.

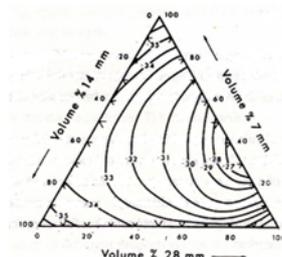This is the same interpretation as that of a daily weather map of isobars.

Figure 8. Ternary porosities

To explain further: each corner corresponds to 100% of each of the three sizes, with the side opposite being 0%. Each side therefore corresponds to a mixture of two sizes. For example, the bottom side of the triangle in Fig 8 corresponds to mixtures of 14mm and 28mm – no 7mm!

If we now draw, say, 10 lines parallel to the bottom side of the triangle going up to the top corner of 100% 7mm ore, each of these lines will correspond to 10% of the 7mm ore, first line up is 10%, next line up is 20%, and so on – each time the other two sizes are the difference from 100%. The point in the middle of the triangle is a mixture of 1/3rd, 1/3rd and 1/3rd, or 33.3% 7mm, 33.3% 14mm and 33.3% 28mm – of course!

It can be seen that he lowest porosity in this three sizes ore mixtures in Fig. 8, occurs in a binary mixture of 28mm particles and 7mm particles at ε = 0.26. Although to many people this may seem strange, it is expected from granular materials theory. In other

words, no matter how many different size particles a mixture has, the minimum porosity would always be in a binary mixture of the largest and the smallest particles and always at around 30% of the smallest size particles.

Figure 9 shows permeabilities of mixtures of three sizes, for generality labelled L, M and S, or Large, Medium and Small. Being a ternary system, each corner is 100% and everything else explained before for Fig 8 is the same, except, of course, that the lines inside are lines of equal permeabilities or "isoperms" calculated by eqn (10). In this case, for simplicity the permeability (Q) of beds of large particles at the 100% L corner is the highest (Q =10), reducing to Q = 1 for beds of small particles at the 100% S at the top corner.
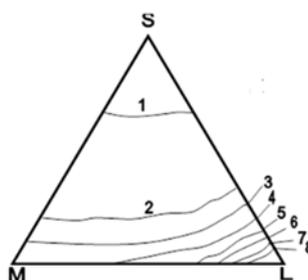

Figure 9. Ternary permeabilities

It is quite clear from Fig 9 that the highest permeabilities are at the large size corner (L) – then the permeability decreases very, very rapidly around the L corner and then remains essentially low for the rest of the other 85% of mixtures.

In view of the crowding of isopores at the largest particle size corner in Fig 8, we can say that the crowding of isoperms at the largest particle size corner L, in Fig 9, should not be unexpected.

As a result of this we can formulate a Permeability Rule, namely:

<u>For high permeabilies do not mix small size particles with large particles but keep them away from each other as much as possible.</u>

Apart from its critical role of providing permeability for hot gases to travel from the bottom to the top of the BF, coke in blast furnaces also serves a number of fundamental purposes.

They are, in round figures: 1) Heat source - 60%, 2) Reducing agent - 30% and 3) Carburising agent - 10%.

To complete our task of finding best particle size compromise we need to take up the behaviour of carbon particles in the cohesive zone, deadman and the hearth to maintain good permeability for gases and liquids (iron and slag) and to carburize iron before it is cast.

Fortunately, there have been recent papers on dissection results of these zones in large blast furnaces, 2200 m3 [17] and 2800 m3 and 5500 m3[18], all in PRC.

The dissections found that total region porosity of deadman was 0.3 with centre of 0.25. Therefore, improving the porosity of the central deadman is important to make the high temperature tuyere gas reach the centre zone of the hearth. With large blast furnaces hearth diameters are large, too, 15m for the 5500 m³ one, so with raceways depths of

around 1.5m, the hot gas has to travel about 6m through a coke bed to reach the centre. This also explains the observed lower molten iron velocity in the centre compared with its higher velocity near the side wall

Porosities of ore and coke layers in the shaft of a BF are typically 0.4 and 0.5, and M40 for big BF must be +80% and M10 must be -6%.

Other parameters of BF burdens are:

Ore – Size: 6-20mm. Strength: -3.15mm 2%max. Swelling Index: 13-18%. Reducibility: 65%.

Coke – Size: 25-80mm. Strength: M40 >85%, M10 <7%. CSR >65%. CRI <25%.

In the dissected 2200 cum BF[17] the average voidage of the deadman in the hearth was 41.1%, the mean size of the charged coke was 54.9 mm and that of the dissected hearth was 34.5mm in the centre and gradually decreased to 27.6 mm at the wall. Also, the closer to the bottom of the hearth vertically, the smaller the coke size was from 34.6mm to 27.8mm, or almost identical variation as horizontally.

The M40 of hearth coke was observed to have decreased by about 13% compared with feed coke, and M10 had increased by 63% compared with the coke in the upper part.

For the 2,800cum BF[18], deadman coke was 28.2mm centre, and 25.4mm at the wall. The M10 and M40 of the feed coke was 88% and 6%, respectively. Compared with feed coke, the M40 of hearth coke was observed to decrease by about 13% and the M10 increased by 144%. The M10 increased with the increasing distance to the tuyere level while the M40 decreased with the distance.

In the 5,500cum BF[18], the average porosity of the deadman coke at the edge, the middle and the centre areas was 0.33, 0.30 and 0.25, respectively. Hearth coke average M10 was 14% and M40 was 77%.

So, for these large blast furnaces, the reduction of coke size and its strength from the stockline to the hearth was something normal and expected. However, as the dissection results showed, the reduction in both were mild, except for M10 which was high, and also expected – and the reason is the number 3) of coke's fundamental purposes listed earlier, namely: carburizing agent.

As a reminder, carburization in the hearth occurs primarily via:

$$Fe(liq) + C(solid) \rightarrow Fe\text{-}C(liq) \qquad (11)$$

and is endothermic under blast furnace conditions, meaning it absorbs heat. The enthalpy change (ΔH) depends on the form of carbon. In any case it is small 0.4-0.6 GJ/t, compared with the huge total BF heat flow of 13-15GJ/thm, and as noted before, the blast furnace has a large thermal inertia and can readily deal with it.

The rate of carburisation, eqn.(11), depends on: (i) carbon activity difference between molten iron and the solid carbon source - and charcoal being more active than coke, would show higher rates - and (ii) surface area. And as small size particles have a large area/unit

weight explains why M10 of the coke in dissected hearth of BFs referred to above, was high.

It is also important to note that theory shows that, on average, granular particles contain the same number of internal cracks or defects per unit volume.

A. Specifying large size feed coke for blast furnaces, believing that it will not break up on the way to the hearth and decrease voidage, is something entrenched hard in the ironmaking industry.
B. The other belief that the voidage of large size particles is always greater than that of the small size particles is one of the most deeply entrenched misconception in practice. The reason is mistaking void size and void volume – the two are quite different concept.

Therefore, all the evidence-based results, presented in this paper support the proposal for BF burdens to consist of a ferrous part and two carbon parts, namely:

1. coke for the cohesive zone and hearth and
2. charcoal for heating and reduction.

The ferrous part can be pellets or sinter with appropriate physical and chemical properties and a reducibility to match the charcoal's reactivity. The size range of these should be governed by how high a reducibility can be achieved on a continuous basis.

The carbonaceous part will be: 1 - Unreactive coke of cupola quality in the size range 20 – 50 mm and, 2 - Charcoal compacts, of similar physical and chemical properties to coke ovens coke and a reactivity to match the ferrous part's reducibility. The size range of this charcoal should also be 20 – 50 mm.

It is expected that the cohesive zone structure and the deadman and their performance would not be too different from those now. However, the burden being lighter because for the same carbon content a 10-12% lower ash in charcoal would make the buoyancy force of the liquid metal in the hearth greater and lead to a higher coke-free layer at the bottom.

This could actually have a positive effect as recently reported by Wang et al [20] that "maintaining a higher floating height of the deadman is more beneficial for the overall protection of the hearth".

Finally, for our 4,000cum BF example the CO_2/thm in the top gas is 265 kg from charcoal and about 140 kg from coke and injectants and this 140kg of CO_2 can be converted to CO in charcoal gasifiers (see [1]) to make the BF be a true "green BF".

4. SCOPE LIMITATIONS AND FUTURE WORK

4.1. Scope of the Present Study

The present work presents what is almost certain the first to document a "dual-carbon" blast furnace burden combining two carbons 'cohesive zone' coke portion and a larger share of dense charcoal 'stack' portion. This assignment of carbons recognises distinct functional roles of carbons within the furnace that have been traditionally served by one – coke in coke BFs and charcoal in charcoal BFs. The study is backed by both blast furnace up-to-date theory and practice and a focus is on metallurgical compatibility with established blast furnace constraints.

The study can not – and does not - demonstrate operational maturity, extended campaign performance, or site-specific optimisation. What it does demonstrate is that the proposed configuration is physically aligned within known blast furnace theory and operating envelopes, thereby justifying further investigation for optimisation.

With all the ironmaking industry facts, evidence and theory presented here backing us we can confidently say that a dual-carbon blast furnace will work. On the other hand with Paul Wurth/SMS syngas stack injection of EASyMelt [24] process for which theory and the 1970 ironmaking industry facts of Hirohata No 4 BF do not back it, we can confidently say that it will not work!

4.2. Limitations

Several limitations consistent with every new concept are acknowledged.

- Technology Readiness Level (TRL):
The concept corresponds to an early TRL, in that it has never been done, as such, though all the individual parts have been done and it is already known what would happen . This is why it is recommended to do it in an actual blast furnace.

- Materials Behaviour:
While the functional use and properties of conventional coke and conventional charcoal in blast furnaces are historically established, their behaviour can not be currently predicted with any precision and is still managed empirically in practice. Actually, the coke in this dual-carbon charge is 'cupola coke'used in foundries for 100 years, so much is known about it.

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Cohesive Zone and Campaign Behaviour:
Cohesive zone geometry can only be determined by quenching and excavation. In operation its geometry and stability are inferred operationally or mathematically, rather than directly. Its extended campaign behaviour of the dual-carbon configuration therefore cannot be unambigously demonstrated within the scope of this work.

- Energy Balance Quantification
Although enhanced endothermicity of conventional charcoal due to its increased reactivity is well known, that of compacted charcoal of the dual-carbon charge of this operation is unknown, but expected to be not too different from that of normal BF coke. As such analysis would require campaign-specific operating data it is beyond the scope of conceptual study.

 - Economics and Supply Chain
The paper does not present a detailed techno-economic assessment or a comprehensive biomass supply-chain analysis. Statements regarding potential cost advantage are intended as first-order indications rather than quantified economic claim.

These limitations are explicitly recognised to ensure clarity regarding the scope and intent of the study.

4.3. Future Work and Development Pathway

The results of the present study define a clear pathway for future improvements, research and development.

4.3.1. Subsystem-Level Experimental Validation

- Dense charcoal reactivity and attrition testing.
- Gasification behaviour above the cohesive zone.
- Raceway and hearth heat balance sensitivity to carbon distribution.

4.3.2. Process Modelling and energy Balance Closure

Development of a zone-based furnace model to enable:

- Quantification of thermal redistribution effects.
- Evaluation of thermal load vs control variables.
- Sensitivity analysis of thermal resilience under operating conditions.

4.3.3. Operational Monitoring and Control Studies.

Integration of the dual-carbon concept into existing BF control framework could be explored using:

- Top gas composition and pressure drop data.
- Burden distribution and descent.
- Dynamic response analysis to blast and burden fluctuation.

4.3.4. Techno-Economic and Sustainability Assessment.

A full techno-economic assessment, incorporating dense charcoal and cupola quality coke – production, logistics, handling infrastructure and maintenance impacts on additional - and reduced equipment, should be conducted on a site-specific basis. In parallel, regonal sustainability assessment addressing land use, governance and supply-chain resilience are required to inform responsible deployment.

4.4. Concluding Note.

The dual-carbon blast furnace concept presented here for the first time can not be proposed as a fully developed turn-key industrial solution to 'green blast furnace', but as 100% technically and practically supported actual operating parts making up the whole coherent framework that aligns with established blast furnace theory while enabling substantial reduction in fossil carbon dependence. The identified limitations are only those of scale and not of substance and define investigation priorities for optimisation rather than feasibility barriers and provide a structured basis for advancing the concept toward implementation to operating level of technological readiness.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

There are many operating iron blast furnaces in Indonesia and worldwide using coke and being capital intensive they must be operated for a long time. This means that most blast furnaces, nowadays large, with their coke ovens will continue producing iron and large amounts of CO_2 for many years yet, making zero carbon unattainable.

It was shown in the recent paper in this journal [1] that sponge iron can be produced in large 2.5 mty DRI reactors using charcoal and that making charcoal using tree plantations and no automation would give employment to millions of Indonesian workers.

AFOLU (Agriculture, Forestry and Other Land Use), emissions released by lands and forests in Indonesia produce twice as much greenhouse gases than other emissions [2, 3] and reducing them via charcoal, particularly in making iron and steel gives twice the benefit.

In October 2025, President Prabowo announced full support for Brazil's TFFF (Tropical Forest Forever Facility) by stating: "Brazil pioneered this movement to save forests, and we will commit whatever amount Brazil has invested there - Indonesia will invest here."

All government laws and regulations already exist and this paper gives strong technical evidence that a dual-carbon BF operation will work. It specifically demonstrates, almost certainly for the first time, that there are two fundamentally different carbons in blast furnaces namely: the cohesive zone carbon and the shaft zone carbon.

It is also demonstrated that large blast furnaces can operate with this dual-carbon burden not too differently from a 100% coke or a 100% charcoal carbon burdens.

Clearly, this can be viewed as good economics as we are simply substituting the same amount of cheaper charcoal carbon for the more expensive coke carbon.

5.2. Recommendations

Because ironmakers are naturally cautious of any new changes in operation and overly traditional in their thinking, it is recommended that a test of the proposed dual-carbon burden be made directly in a medium size coke blast furnace (≈1,000cum) with a stepwise replacement of coke with dual-carbon quality charcoal.

The reason for not starting with laboratory tests and progressing up in scale is threefold: 1) we already have these laboratory results, 2) we already know their BF shaft reactions, and 3) we need to test dual-carbon burden cohesive zone behaviour which has never been done before and therefore is not available anywhere in the world.

Acknowledgements

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