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Retrofitting Blast Furnaces for Producing Green Steel and Green Urea

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Abstract: ***This paper proposes a process to produce green steel, green slag cement, and green urea by retrofitting the existing blast furnaces for using torrefied biomass, biochar, and bio-coke derived from carbon-neutral biomass. Top gas recovery is proposed to extract hydrogen and carbon dioxide, with 100% oxygen replacing air by converting the blast furnace into an oxygen blast furnace. No internal modifications are required to the existing blast furnace, including the blast furnace stoves. Only associated auxiliary systems are modified or added. The modified blast furnace is highly flexible in its raw material quality and product mix, without sacrificing overall productivity and thermal efficiency. For every tonne of rated production capacity of an existing blast furnace, nearly 0.50 tonne of green urea can be produced at attractive economics. India can become self-sufficient in urea production without relying on imports by retrofitting most of its operating blast furnaces. It is a bioenergy carbon capture and storage method in which the generated green carbon dioxide gas is sequestered, leading to negative carbon emissions. The air pollution from the oxygen blast furnaces is completely avoided except for excess green carbon dioxide, if not sold or sequestered.***

Keywords: BECCS, Bio-Coke, Oxygen Blast Furnace, Top Gas Recovery

Nomenclature:
ASU: Air Separation Unit
BECCS: Bioenergy Carbon Capture and Storage
BF: Blast Furnace
BOF: Basic Oxygen Furnace
CRI: Coke Reactivity Index
CSR: Coke Strength after Reduction
DRI: Direct Reduced Iron
EAF: Electric Arc Furnace
FCEV: Fuel Cell Electric Vehicles
HHV: Higher Heating Value
OBF: Oxygen Blast Furnace
PSC: Portland Slag Cement
PCI: Pulverised Coal Injection
RAFT: Raceway Adiabatic Flame Temperature,
SEF: Standard Enthalpy of Formation
TB: Torrefied Biomass
TGR: Top Gas Recovery
TGT: Top Gas Temperature
VGF: Viability Gap Funding

I. INTRODUCTION

Ironmaking through blast furnaces (BFs) is a centuries-old technology that has been continuously improved to accommodate varying raw material availability and reduce production costs. Presently, BFs with hot metal production capacities of up to 15,000 tonnes per day are in operation. Nearly 70% of global crude steel and 54% of the Indian crude steel are produced by BFs [1]. Global annual steel production was around 1.9 billion tonnes in 2024. The steel industry accounts for nearly 7% of global carbon dioxide (CO_2) emissions from fossil fuels, mainly coal/coke. Global urea production is around 180 million tonnes in 2024. Nearly 1% of global greenhouse gases are emitted during the production of urea and other nitrogen-containing fertilisers. In addition to BF-BOF (basic oxygen furnace) ironmaking, there are direct-reduced iron (DRI) production methods using natural gas, hydrogen, and coal. These DRI processes generate syngas (a mixture of carbon monoxide and hydrogen) from coal or natural gas to convert iron ore to DRI, which is further refined to steel in electric arc furnaces (EAF). Iron ore is also directly reduced to DRI using hydrogen. Steel scrap is also recycled in EAFs. To limit global warming to 1.5-2 °C, green steel production is encouraged by replacing fossil fuels with non-fossil biomass, green hydrogen, and renewable electricity. DRI-EAF steel production based on the use of fossil fuels can be economically converted to green steel production by using green syngas produced from biomass or green hydrogen (H_2) and green electricity [2]. Green syngas/ H_2 can be produced economically from biomass gasification, and cheaper green electricity that can be generated from renewable energy sources such as solar and wind power [3]. However, substantial fossil fuel-based BF capacity with a good remaining productive life is in operation and cannot be retired without a heavy financial burden [4]. This paper examines the feasibility of green steel production by retrofitting existing BFs to use torrefied biomass (TB), biochar, and biomass-derived green coke. In addition to rated BF productivity, there is also the possibility of producing green urea (NH_2CONH_2) by using hydrogen and CO_2 gases from the BF, along with the byproduct nitrogen gas from the air separation unit (ASU).

II. DATA

BF is a counter-current heat exchanger/furnace or an updraft reactor with gases/blast flowing upward against the descending burden (mixture of iron ore, coke, and flux). At the bottom, the molten hot steel is collected, and liquid slag (formed by reaction of flux/lime with gangue/waste material present in the iron ore and coke) floats on the liquid iron since the slag density is lower than that of the liquid iron (nearly 8 tonne/m^3). Coke, flux, and iron ore lumps/pellets are loaded separately into the BF from the top, forming layers. Hot blast (air and/or oxygen) is supplied from the bottom through the tuyeres located around the circumference of the BF. The descending coke in the BF comes in contact with the hot blast, undergoes partial combustion, and liberates heat and CO gas. The

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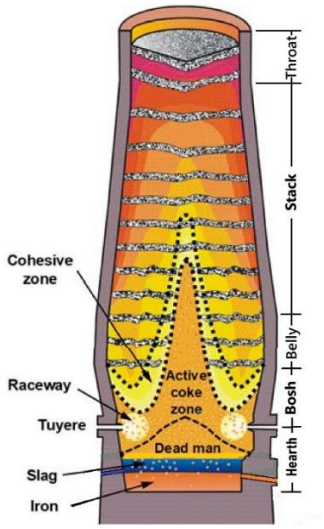
combustion/flame zone located in front of the tuyeres is called the raceway. At the bottom centre of BF, a conical-shaped space filled with hot burden is formed, which is called deadman and is surrounded by the active coke zone, which is further surrounded by the cohesive zone, as shown in Fig.1. The deadman mass is floating on the molten iron, surrounded by the liquid slag at its bottom. Typically, a large BF is approximately 30 m tall. The residence time of the burden in the BF ranges from 5 to 8 hours [5].



[Fig.1: Cross-Section of a Blast Furnace]

The following chemical reactions are applicable in ironmaking using BF-TGR.

(R1) $3Fe_2O_3(s) + CO(g) \rightarrow 2Fe_3O_4(s) + CO_2(g)$ - 40.8 kJ/mole at 850 °C

(R2) $Fe_3O_4(s) + CO(g) \rightarrow 3FeO(s) + CO_2(g)$ + 34.9 kJ/mole at 850 °C

(R3) $FeO(s) + CO(g) \rightarrow Fe(s) + CO_2(g)$ - 16.6 kJ/mole at 850 °C

(R4) $Fe_2O_3(s) + 3\,CO(g) \rightarrow 2Fe(s) + 3\,CO_2(g)$ - 50.73 kJ/mole at 850 °C

(R5) $Fe_3O_4(s) + 4\,CO(g) \rightarrow Fe(s) + 4\,CO_2(g)$ - 14.9 kJ/mole at 850 °C

(R6) $3Fe_2O_3(s) + H_2(g) \rightarrow 2Fe_3O_4(s) + H_2O(g)$ - 5.9 kJ/mole at 850 °C

(R7) $Fe_3O_4(s) + H_2(g) \rightarrow 3FeO(s) + H_2O(g)$ + 56.6 kJ/mole at 850 °C

(R8) $FeO(s) + H_2(g) \rightarrow Fe(s) + H_2O(g)$ - 16.9 kJ at 850 °C

(R9) $Fe_2O_3(s) + 3H_2(g) \rightarrow 2Fe(s) + 3H_2O(g)$ - 2 kJ at 850 °C

(R10) $Fe_3O_4(s) + 4H_2(g) \rightarrow Fe(s) + 4\,H_2O(g)$ + 5.9 kJ/kmol at 850 °C

(R11) $3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2$ -26.3 kJ/mole at 850 °C

(R12) $4Fe_3O_4(s) + O_2 \rightarrow 6Fe_2O_3(s) + H_2O(g)$ - 237.2 kJ/mole at 850 °C

(R13) $FeO(l) + C(l) \rightarrow Fe(s) + CO(g)$ + 156.5 kJ/mol at 25 °C

(R14) $2C + O_2 \rightarrow 2CO$ - 110.5 kJ/mol at 25 °C

(R15) $CO_2 + C \rightleftharpoons 2CO$ +172.6 kJ/mol at 25 °C

(R16) $CO + H_2O \rightarrow CO_2 + H_2$ - 41.2 kJ/mol at 25 °C

(R17) $C + H_2O \rightleftharpoons CO + H_2$ + 131 kJ/mol at 25 °C

(R18) $C + 2H_2 \rightarrow CH_4$ - 74.9 kJ/mol at 25 °C

(R19) $SiO_2(l) + 2C \rightarrow Si(l) + 2CO$ above 1300 °C

(R20) $Si\,(l) + FeO\,(l) \rightarrow Fe(l) + SiO_2\,(l)$ above 1300 °C

(R21) $N_2 + 3H_2 \rightarrow 2NH_3$

(R22) $2NH_3 + CO_2 \rightarrow NH_2CONH_2 + H_2O$

As they descend in the BF, the layers of iron ore, coke, and flux move radially inward into the cohesive zone, where they undergo most of the reduction process. The upward moving reducing gases (CO, H_2) from the raceway react with hematite/magnetite to form wustite and DRI. The reduction of iron ore/hematite (Fe_2O_3) takes place in stages: first (*R1 and R6*) to magnetite (Fe_3O_4) and then (*R2 and R7*) to wustite (FeO) by reacting with CO or H_2 gases below 1000 °C in the stack zone of the BF. Wustite does not exist below 570 °C [6]. Some ore is directly converted to DRI in solid form (R4, R5, R9, and R10) without being melted into molten iron. Wustite (*R3 and R8*) is reduced to Fe to a significant extent in the cohesive zone. All these reduction reactions are indirect types, in which the gas comes into contact with the solid iron ore. Direct reduction (*R13*), the direct consumption of solid carbon without converting it to CO gas, can occur to a limited extent when liquid coke comes into contact with liquid wustite in the active coke zone. Liquid slag forms in the cohesive zone from gangue and flux. Liquid silicon (Si) in the liquid slag also reacts with liquid wustite (R19 and R20) in the direct reduction process. The content of wustite in the final slag is less than 0.5 weight %, and the total recovery of Fe is more than 99.7%. Liquid slag and molten iron do not mix, and liquid slag floats on the molten metal [5].

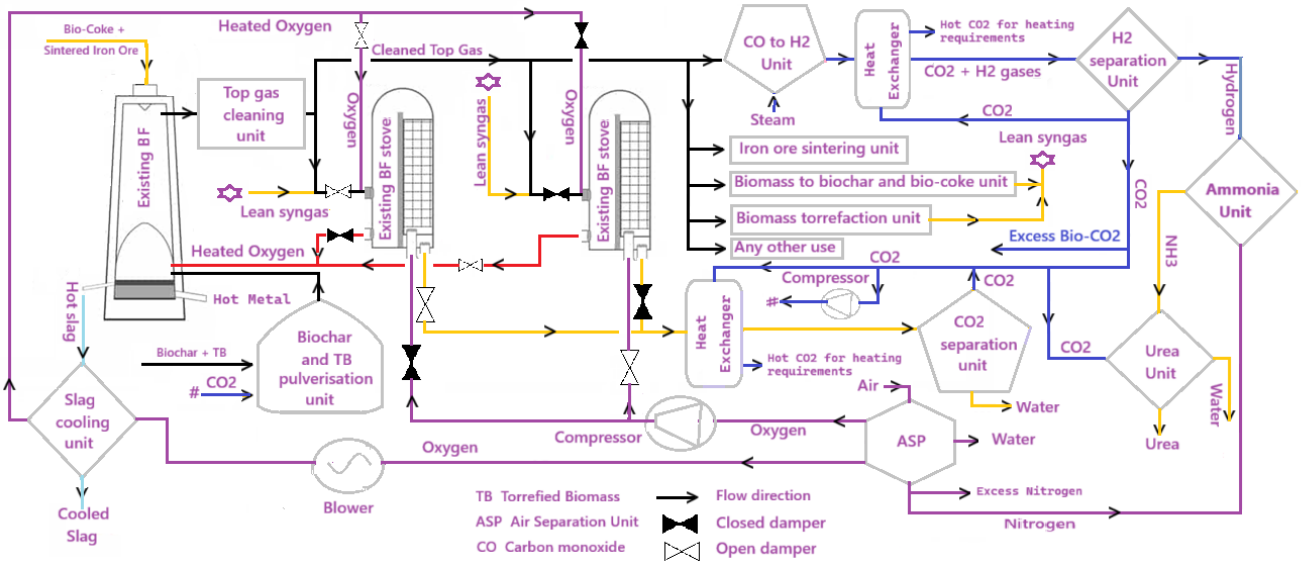
At the top of the BF, the descending burden is thoroughly dried, free of moisture. CO gas reacts with moisture (*R16*) to form H_2 and CO_2, undergoing the water-gas shift reaction with iron ore acting as a catalyst [7]. The BF gas/BF top gas contains substantial CO and H_2, as the ore reduction process occurs only above the minimum CO concentration for product CO_2 (H_2 for product H_2O), which can be used for heating the blast or separated for other uses [8]. Also, the residence time of gases in the BF burden is around 10 seconds, which is inadequate to react with iron oxides at full potential [8]. To enhance the BF's fuel efficiency, the blast air is heated to above 1000 °C in the preheat stoves by burning the BF's top gas before releasing it to the atmosphere [9]. The temperature of the gas exiting the BF at its top is called the top gas temperature (TGT) and ranges from 150 to 300 °C.

III. DISCUSSION

As it is not possible to measure the flame temperature in the raceway, theoretically calculated flame temperature or raceway adiabatic flame temperature (RAFT) is maintained around 2150 °C for optimum productivity and stable performance of the BF. RAFT can be enhanced to increase BF productivity, but it would reduce BF refractory life due to excessive erosion. The cohesive zone height also extends into the BF stack zone, leading to unstable BF operation. RAFT is calculated based on the input materials and their characteristics, such as permeability, etc. It determines the hearth gas temperature, thereby affecting heat transfer, reduction, slagging, desulfurization, hot metal temperature and composition, etc. Too high RAFT will also cause initial gas volume expansion in the hearth, leading to a large

amount of SiO_2 volatilisation, which increases resistance to the burden column, impeding the downward movement of the burden, and even causing the BF to run poorly or stall. Too-low TGT, caused by high RAFT, is also unfavourable to blast furnace productivity, as it leads to clogging in dust separation filters and cold-end corrosion in the presence of moisture and SOx gases. When hydrogen-rich fuel is injected, the RAFT becomes low while the TGT remains high. A TGT that is too high will increase heat loss from the furnace, enhance the coke ratio (coke consumption per tonne of hot metal), and shorten the service life of the furnace top charging equipment and bag filters. Well-developed mathematical models are available to predict BF performance with respect to variations in the quality and quantity of input fuels, iron ore, blast composition, etc. [10].

Pulverised coal injection (PCI) is also done into the BF through the tuyeres to reduce the consumption of costly, and scarce coke. Coke is produced from coking coals, whose availability is limited and is imported from a few countries at a higher cost, thereby increasing the production cost of steel from the BF-BOF route.



[Fig.2: Line Diagram of Green Steel and Green Urea Production Plant]

Coke use in BF cannot be avoided entirely with PCI, as it is essential for creating passage/permeability to the upward-moving BF gases in the cohesive zone through the burden. There is also a limit to using the PCI without enriching the blast air with O_2 to maintain the RAFT at an optimum level. The char generated from pulverised coal particles tends to clog the coke's pores, reducing BF capacity [10]. In some countries, natural gas is also fed to the BF through the tuyeres to reduce the coke consumption. It is possible to increase the RAFT by increasing the hot blast temperature and using enriched air with O_2 or 100% O_2 [11]. With PCI, it is not feasible to use 100% O_2 as a blast since coal contributes excess heat, leading to excessive RAFT. So, air is partially enriched with O_2 to maintain optimum RAFT. Similarly, steam/CO_2 injection or moisture in blast air/oxygen can be used to reduce RAFT to the optimum level. H_2O / CO_2 breaks into H_2 / CO and O_2, consuming thermal energy but reducing external O_2 demand. The thermal energy contribution capacity of the fuels is vital to maintain optimum RAFT [12]. In the raceway zone, where the flame temperature exceeds 2100 °C, CO_2 and H_2O are not stable (*R15 and R17*) for achieving complete combustion. Hydrocarbon fuels, when burned with oxygen, undergo partial combustion, producing CO and H_2 gases. Heat is liberated only when carbon reacts (*R14*) with oxygen to produce CO in an exothermic reaction. The carbon-to-hydrogen ratio of coke, coal, biochar, natural gas, torrefied biomass (TB), etc., is to be adequate for maintaining optimal RAFT conditions [10]. The standard enthalpy of formation (SEF) of the fuel is also relevant, as the fuel should not require more energy to split into its constituent elements. The SEF of a fuel is the change in enthalpy during the formation of one mole of substance from its constituent elements. Natural gas (CH_4) has a negative SEF (*R18*) because it is formed by the exothermic reaction of carbon with H_2. Coke, biochar, and coal are mostly in elemental form with negligible SEF, and hydrogen content generally does not exceed 4% by weight, resulting in a very high carbon-to-H_2 ratio. TB has nearly 45% carbon and 6% H_2, with a lower C/H_2 ratio, and its SEF is approximately –1100 kcal/kg. The net heat liberated from the gasification of carbon in TB into CO is marginal after the SEF is met. The carbon content in TB can be increased by adding biochar, which provides additional thermal energy during gasification and reduces coke consumption [13]. The ash content in TB is comparable with the ash content (nearly 8% by wt) in coke or good quality coal. It has been found that the fineness requirement for pulverised TB/biochar is not as stringent as that for pulverised coal to achieve complete gasification in the BF [14]. Biochar, which is 85% carbon by weight, is as effective as good-quality coal for injection into BF in all respects [15].

The main requirement for green steel production is to replace air with O_2 to eliminate substantial nitrogen from the BF gases, thereby increasing CO_2 concentration for economic separation by the acid gas removal process [16]. A line diagram of green steel and green urea production is shown in Fig.2. The residual gas rich in H_2

can be used in the production of ammonia (NH_3) with the available nitrogen from the ASU. ASU is used to generate the required O_2 for feeding to the BF in place of air. NH_3 is further converted to green urea using the bio-CO_2 gas separated from BF gases. Most of the carbon present in the fuels (coke, TB, biochar, etc) is consumed for producing iron from the iron ore. Hydrogen present in the fuels is recovered from the top gas to produce ammonia. Nitrogen in blast air has pros and cons in the BF. It helps in transferring thermal energy from the lower portion (bosh) to the upper portion (stack) to maintain the TGT. It reduces the BF's thermal efficiency due to chimney losses, releasing hot nitrogen into the atmosphere. Being an inert gas, it does not take part in chemical reactions except in the formation of NOx, which causes air pollution. Oxygen blast furnace (OBF) is a BF where 100% O_2 is used as the blast in place of air to eliminate nitrogen in the top gas recovery (TGR) system. When existing BF is converted to the OBF with pulverised TB injection, the gas mass flow in the BF is unchanged by enhancing the gases produced from the gasification of TB and biochar to the extent of eliminated nitrogen gas. Thus, the draft loss in the BF is kept the same or less [17]. The product gases (CO and H_2) from gasification have higher specific heats than nitrogen gas, enabling them to transfer sufficient thermal energy to the upper part of the OBF to maintain an optimum TGT. The required thermal energy in the raceway is provided by the coke and pulverised biochar to maintain the optimum RAFT for the trouble-free operation of the OBF. Pulverised TB contributes to surplus CO and H_2 gases, which are part of OBF exhaust gases. Before separating the CO_2 from the OBF exhaust/top gases, CO is converted to hydrogen gas by reacting with steam (R16). Thus, H_2 gas is extracted from the OBF exhaust gas for further enrichment and onward use in the production of NH_3 and urea [18]. Only 10% by weight of H_2 is required (*R21* and *R22*) in the urea production. The capacity to produce urea from biomass fuels is nearly 50% of the hot metal production capacity of a BF using coke as its fuel.

Table I: Proximate and Ultimate Analysis of a Few Biomasses

Type of dry Biomass	Fixed Carbon	Volatiles	Ash	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	HHV
Units	% by wt	% by wt	% by wt	% by wt	% by wt	% by wt	% by wt	% by wt	kJ/gm
Rice husk	15.80	63.60	20.60	38.30	4.36	35.45	0.83	0.06	14.89
Sudan grass	18.60	72.75	8.65	44.58	5.35	39.18	1.21	0.01	17.39
Wheat straw	19.80	71.31	8.90	43.20	5.00	39.40	0.61	0.11	17.51
Mango Wood	11.36	85.64	2.98	46.24	6.08	44.42	0.28	-	19.17
Corn stover	19.25	75.17	5.58	43.65	5.56	43.31	0.61	0.01	17.65
Water Hyacinth	0.00	80.40	19.60	40.30	4.60	33.99	1.51	0.00	14.86
Poplar	16.35	82.32	1.33	48.45	5.85	43.69	0.47	0.01	19.38
Eucalyptus	17.82	81.42	0.76	49.00	5.87	43.97	0.30	0.01	19.42
Biomass (average)	-	-	-	47.91	5.74	40.98	0.52	0.05	19.11
Eucalyptus char	70.32	19.22	10.45	76.10	1.33	11.10	1.02	0.00	27.60
Coal – Pittsburg Seam	55.80	33.90	10.30	75.50	5.00	4.90	1.20	3.10	31.75
BF Coke	86.19	1.54	12.27	85.68	0.18	0.27	0.96	0.84	29.52

Biomass is converted to (TB) by subjecting it to mild pyrolysis, where biomass is heated to 250 to 300 °C in the absence of air/oxygen. TB is a nonhygroscopic, brittle, soft and dry material free from moisture. TB is also suitable for long-duration storage without any mass loss or biological decomposition. Biomass, a fibrous substance, is not ideal for use as pulverised fuel because it tends to cake rather than form a powder. To overcome the grinding problem, biomass is converted to TB for injection into the BF as pulverised fuel. Pulverisation of TB requires lower power consumption than coal. As given in Table I, dry biomass mainly contains carbon (40 to 50% by weight), oxygen (40 to 45% by weight), hydrogen (5 to 7% by weight), ash (average below 10% by weight), sulphur (average below 0.5% by weight), nitrogen (average below 1% by weight), etc [19]. As given in Table II, the ash generated from biomass combustion mainly contains Al_2O_3, SiO_2, CaO, MgO, Fe_2O_3, sodium, potassium, phosphorus, chlorides, etc [20]. The hydrogen content in biomass is at least 5 % points higher than in coke [19]. Hydrogen, by weight, has six times the reduction capacity of iron ore compared to carbon [21]. Its sensitivity/kinetics is three to four times that of CO in reducing the iron ore to iron, though its reaction is less exothermic compared to CO (*R4, R5, R9, and R10*) [22]. H_2 reacts with iron ore at higher temperatures with greater sensitivity than CO [23], [6]. O_2 content in biomass is much higher than in coke/coal, which helps reduce the O_2 feed required to the BF from the ASU. CaO, MgO, and Fe_2O_3 are also valuable materials acting as flux or iron ore. Sodium, potassium, and phosphorus in biomass are usually within the tolerable limits of BF. Chlorides and sulphur in TB, biochar, and bio-coke are also generally within the tolerable limits compared to coke/coal. Chlorides cause hot end corrosion in BF, and SOx gases generated from sulphur cause cold end corrosion in top gas recovery/handling equipment.

Basicity of slag is the ratio of basic oxides (CaO + MgO) and acid oxides (SiO_2+Al_2O_3) in the slag. As SiO_2 converts to Si at higher hot metal temperatures, the slag's basicity increases, leading to a decrease in its volume [24]. Basicity of the slag in the OBF is maintained at optimum by reducing the flux material (limestone, dolomite, etc) addition to the OBF due to lower Al_2O_3 and SiO_2 content in the biocoke, biochar, and TB fuels. Thus, there is a possibility of reducing the flux material consumption [25]. However, Al_2O_3 and SiO_2 are the predominant gangue minerals in iron ore and meet the minimum requirements for slag formation. The ability of slag to retain alkalis (sodium and potassium) is called the alkali capacity of the slag. Excess alkalis form scabs, which can peel off, upsetting the thermal condition of the BF. Potassium salts collected in the slag evaporate at slag temperature and then travel back up in the BF as gases, where they react and are absorbed by the burden in the lower temperature region of the BF. Recycling results in much higher internal potassium salt concentrations than those entering or leaving the BF [24]. When biocoke, biochar, and TB with high potassium content are used in

the OBF to produce green steel, there is a risk of potassium contamination, which is a disadvantage. Potassium and sodium salts are highly soluble in water [26]. Biochar can be water-washed and dried to remove potassium and sodium salts to a substantial extent, or suitable additives can be added to enhance the slag's alkali capacity, if required. Most of the phosphorus accumulates in hot metal.

Table II: Composition of Ash Generated from a Few Biomasses

Type of Biomass	SiO_2	CaO	K_2O	P_2O_5	Al_2O_3	MgO	Fe_2O_3	SO_3	Na_2O	TiO_2	Cl	High in
Units (% of ash)	% by wt	% by wt	% by wt	% by wt	% by wt	% by wt	% by wt	% by wt	% by wt	% by wt	% by wt	
Rice husk	92.19	0.09	0.05	No data	0.09	0.41	0.10	0.41	1.64	No data	No data	SiO_2
Rice straw	74.67	3.01	12.30	1.41	1.04	1.75	0.85	1.24	0.96	No data	4.06	SiO_2, K_2O
Wheat straw	55.3	6.1	25.6	1.3	1.9	1.1	0.7	4.4	1.7	0.1	4.26	SiO_2, K_2O, SO_3
Miscanthus	58.78	11.90	3.65	5.44	1.83	2.25	3.42	0.45	No data	No data	No data	SiO_2, P_2O_5
Corn stalk	38.70	11.11	24.47	7.05	0.92	1.10	0.93	2.12	0.17	0.10	No data	K_2O, P_2O_5
Chicken litter	13.26	26.61	16.54	23.74	2.81	5.72	1.84	0.82	5.74	0.43	No data	P_2O_5, K_2O
Willow	6.1	46.09	23.4	13.01	1.96	4.03	0.74	3.00	1.61	0.06	No data	P_2O_5, CaO, SO_3
Eucalyptus	No data	57.74	9.29	2.35	No data	10.91	No data	No data	1.86	No data	No data	CaO, MgO
Poultry litter	2.69	65.17	6.36	17.46	0.31	No data	0.57	No data	2.48	0.02	5.67	CaO, P_2O_5
Coke (Australia)	57.3	3.50	0.60	0.57	26.5	0.57	5.40	2.78	0.25	1.12	0.03	Al_2O_3, SO_3

To avoid the use of fossil coke in the BF, green coke can be produced from biochar and bio-oil generated by biomass pyrolysis [27]. The high-temperature, oxygen-rich volatile gases produced by biomass pyrolysis are condensed to form biooil. The biochar is briquetted to the required size after mixing with the biooil. The briquets are again cured at nearly 1000 °C to form oxygen bonds in solid carbon, and the generated light gases are used to meet the energy requirements of the curing process [28]. The biocoke briquettes have properties similar to those of coke in terms of abrasion resistance, coke strength after reduction (CSR), and coke reactivity index (CRI), with acceptable ash content. Coke/biocoke are more stable in an OBF-TGR, as the gasification of pulverised TB and biochar yields more CO and H_2, with less CO_2 and H_2O, which prevent Bourdon and water-gas reactions (R15 and R17) with coke in the cohesive zone. Thus, biocoke with biochar and TB can be used to produce green hot metal from existing BFs without sacrificing productivity or thermal efficiency. All the needed thermal energy is met by biocoke, and the biochar added to the OBF. Optimum RAFT and TGT are achieved by injecting hot O_2 (1200 to 1500 °C) free from moisture in place of air. Since excess CO and H_2 are maintained in the top gas to extract H_2 in the TGR system, the dew point temperature would be lower than TGT to eliminate the possibility of cold-end corrosion. The capacity of the TGR system to extract H_2 is decided by the quantity of pulverised TB that can be injected into the OBF without adversely affecting its hearth conditions. The total mass injection into the OBF is reduced due to the elimination of N_2 gas in the blast. Bio-coke dust in place of fossil coke dust can also be used in the sintering plant to produce iron ore pellets. The hot liquid slag extracted from the OBF is cooled by the O_2 gas, which is used for burning the top gas in the BF stoves, as shown in Fig.2. Alternatively, it is possible to convert biomass into TB by using the heat energy of the slag [29]. Compressed CO_2 gas is used to transport and feed pulverised TB and biochar into the OBF [30]. Excess N_2 gas from the ASU can be exchanged for O_2 gas from nearby water electrolysis-based NH_3 production plants, and excess bio-CO_2 gas is sold for sequestration and other uses. The entire OBF-TGR process becomes a bioenergy carbon capture and storage (BECCS) process when the generated bio-CO_2 is sequestered, leading to negative carbon emissions. When bioenergy is extracted from biomass and the generated bio-CO_2 is sequestrated, it is called a BECCS process.

At present, scrap steel is used in the DRI-EAF route to produce usable steel. Scrap steel can be used in an exothermic reaction (R11) with steam to produce hydrogen and magnetite [31]. It is called steam-iron process [32]. The required steam can be generated from the reaction heat (*R11*). High-purity hydrogen and magnetite are generated in the process [31]. The generated H_2, with a bit of further purification, can be used as fuel in fuel-cell electric vehicles (FCEVs). Such magnetite can also be used in ironmaking as pellets without enrichment. Distributed H_2 production from steel scrap on a medium or minor scale is economically feasible near consumption centres, such as cities and towns, for FCEV needs, etc. In the future, the availability of adequate scrap steel for ironmaking is uncertain due to competition from scrap-based green H_2 units. The availability of good-quality iron ore at affordable prices is becoming increasingly complex, and the rich magnetite derived from scrap steel can supplement the ironmaking industry in the future [34]. Cheaply available magnetite ore, without the need to convert to hematite (R12), can also be used in OBF-TGR plants, as H_2 gas can effectively reduce magnetite to wustite [35]. Using magnetite pellets made from naturally available magnetite in the BF would not affect the BF's burden permeability [35]. With the integration of urea/hydrogen production in an OBF-TGR plant, inferior quality iron ore can also be used in the OBF by reducing the iron output with a corresponding increase in urea/hydrogen output for the same quantity of fuel/heat input to the OBF. When fewer iron oxides are to be converted into the metal, less CO gas is consumed, or more CO gas is available to the TGR system for conversion to hydrogen. Also, more slag is formed in the BF due to the greater gangue content in inferior iron ore. Slag is not a waste material; it is a byproduct used to make superior-quality slag/PSC cement. Thus, green cement is also a byproduct of OBF. Theoretically, it is feasible to produce slag cement by feeding flux material (limestone and dolomite) along with gangue matter (with minor iron content) in an OBF-TGR plant to produce H_2 or urea and slag cement in huge quantities. OBF-TGR plants are highly flexible in their use of raw materials and product mix, without sacrificing

overall productivity, unlike in conventional BF plants. Other metals, including rare earth metals, can be produced by reducing their respective minerals/ores with CO or H_2. An OBF-TGR plant can be transformed into a general-purpose high-temperature updraft metallurgical furnace for multiple applications from an ironmaking BF predominantly.

IV. CONCLUSION

The main advantages of using biocoke, biochar, and TB in OBF-TGR plants are:

- Green steel is produced at a reduced cost to sell at a premium price
- Green urea is generated from the H_2, bio-CO_2, and N_2 gases to sell at a premium price. Green urea production capacity can be established by retrofitting existing BFs at a cost below that of natural gas-based urea plants. The production cost of green urea would be less than its imported cost. One tonne of dry biomass can yield nearly one tonne of urea.
- Green slag cement is produced as a byproduct.
- Coking coal imports are replaced by abundantly available local biomass. A year-round biomass supply chain can be developed to procure at an affordable cost, as there is no dearth of live/fresh biomass.
- OBF-TGR plant is highly flexible, without foregoing the overall productivity, to use the low-quality iron ore that is available from a medium distance.
- No major modifications are needed to the BF except adding auxiliary units such as ASU, CO_2 or H_2 separation units, biochar and TB unit, and biocoke production unit.
- Conventional coke production batteries are not used. Any coke-oven gas used in the sintering and other units is replaced with OBF top gas. Power generation with coke oven gas is replaced by green, renewable power purchased from the grid at an affordable cost.
- It is a BECCS process with negative greenhouse gas emissions if the generated bio-CO_2 gas is sequestrated. When slag cement is converted to concrete, additional carbon capture and sequestration of CO_2 from air is also achieved.
- No polluting gases like SOx, NOx, particulate matter, PM10, PM2.5, and ozone are released to the atmosphere, causing air pollution. The ironmaking industry can transition to a zero-pollution industry by using biomass-derived products.

Instead of producing green urea, it is also possible to enhance the existing BF productivity (capacity to produce hot metal) by at least 40% with 100% O_2 use and injection of syngas (CO and H_2) extracted from the top gas of the OBF provided there is adequate local demand to dispose the generated bio-CO_2, and the nitrogen gas available from the ASU [10].

There is no technical hurdle in transforming the steel industry to achieve carbon neutrality. Grey steel production can be gradually transformed into green steel by initially replacing fossil pulverised coal with biochar and TB, and later replacing fossil coke with bio-coke. National governments should encourage/induce the steel industry to produce green steel by giving viability gap funding (VGF) to establish lab-scale R&D units, pilot plants, retrofitting the existing BF and DRI units into green steel production, and new green steel plants by offering an assured market at a premium price over the price of fossil fuel-based steel. Governments shall also encourage by offering assured, viable prices for the collection and transport of biomass from various sources to consumption centres, as well as for the installation of biochar, biocoke, biooil, and TB production units.

DECLARATION STATEMENT

The references cited, especially [8], [10], [11], [13], [15], [19], [25] and [30], are older and are explicitly noted as such. Nonetheless, these works remain essential for the current study as they are pioneering in their respective fields.

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