

Biotechnologies: A Pathway to Net-Zero CO₂ Emissions Steel?

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INTRODUCTION

Iron and steel decarbonization is at the forefront of global greenhouse gas (GHG) abatement discussions. Social and legislative pressures to achieve “net-zero” have accelerated steel producer efforts to find solutions to reduce GHG emissions. Initiatives to transform the traditional methods of fossil-fuel based iron- and steelmaking abound examples include hydrogen injection in the blast furnace, hydrogen-based direct reduced iron, and carbon capture and storage (CCS) of off-gases. Implementation of these transformational technologies poses significant technical and economic challenges. This has led to the exploration of other decarbonization pathways, including biotechnologies, as part of the push to produce “net-zero” steel.

Biotechnologies refers to the utilization of biological processes, at the cellular and biomolecular level, to generate desirable products or outcomes, such as those that can heal, feed, or fuel people, and the planet [1]. Not all biomasses are equal, and not all biotechnologies are suitable for every iron and steel process. Biomass can be used in the steel value chain as a reducing agent and energy source. Other emerging biotechnology applications include microalgae production via photosynthetic to capture CO₂ in off-gases [2], and bioethanol synthesis via microbial fermentation of a CO rich off-gas. These biologically based end-of-pipe treatments use microorganisms to valorize steelmaking carbon emissions while abating them.

This paper describes the production and use of biomass or biocarbon as a fossil-fuel replacement and the production of microalgae from process off-gases in the steel value chain. Specific applications in the blast furnace-basic oxygen furnace (BF-BOF) and electric arc furnace (EAF) steelmaking routes are described.

BIOMASS AND BIOCARBON VALUE CHAIN OVERVIEW

Biomass refers to organic material derived from animals, plants, and/or microorganisms. These are commonly sourced from by-products or industrial wastes or grown specifically for a desired application. Figure 1 Biomass applications are diverse and include heat production, fuel conversion, transportation, construction, carbon capture and storage through biomass production, and chemical processes (Figure 1) [3].

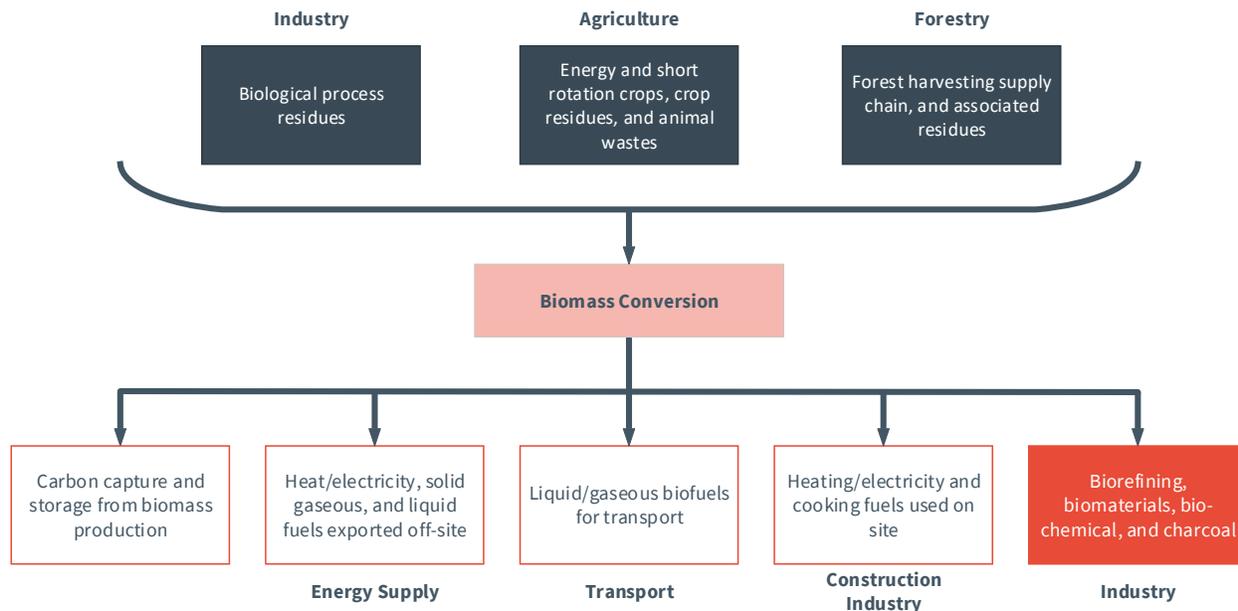


Figure 1: Biomass Value Chain and Applications [3]

The final use of biomass depends on the type and properties of the organic material. Not all biomass types are suitable for all industrial applications, and the scale of the steel industry further limits potential biomass applications.

Biomass Sources and Types

For biomass to be considered a source for applications in iron and steel processes, the biomass must be available in large quantities all year round and should have comparable properties to coal and/or coke. The most used biomass in iron and steel production is wood as its properties make it a good candidate for partial and occasionally complete coal/coke substitution. The ideal wood source has a short growth cycle, such as eucalyptus trees or bamboo. Only regions with a suitable climate and sufficient available land can grow the quantities of wood needed for large scale iron and steel production. The wood must be sustainably sourced for the resulting biomass to be a biogenic source of carbon. Wood harvesting rules that respect human rights and manages the forest/plantation in a sustainably way must be in place to yield biogenic carbon post processing.

The forestry industry yields an abundant amount of waste wood. Forestry waste includes the various unsalable parts of trees, constituting 50 to 75% by volume prior to harvesting, and remains a potential source of biomass as a biogenic source of carbon [4]. In most regions, the forestry industry is located far from iron and steel production centers and transportation of this waste wood to the steel plant adds a layer of complexity and cost.

Another source of wood is waste from the wood processing and construction industries found in urban centres. This includes manufactured wood products, such as plywood and furniture. A challenge associated with urban waste wood is the need to remove contaminants such as nails, paint, and glue prior to processing.

The agricultural industry is a promising source of biomass: short rotation crops such as corn, rapeseed, and sugar cane are used for the energy and transportation industries, and residues such as bagasse, corn stalks, and straw plus animal wastes can be used for biocarbon and energy production [3]. These crops and the resulting agricultural waste are seasonal, creating a challenge for year-round sourcing. For these reasons, the energy and liquid fuel producers consume crops and their residues, and animal wastes are processed for biogas production through anaerobic digestion.

Challenges common to all types of biomasses are transportation and scale. Transportation of biomass is costly because of its low density and safety concerns due to its potential for self-heating and generating combustible dust. The resulting dust can possess a human health hazard.

Biomass typically requires processing prior to use in most industrial applications. For coal replacement in iron and steel applications, the form of processed biomass most widely used is biocarbon. The biomass value chain is presented in Figure 2 and further described in the following sections.

Biocarbon

Biocarbon, which is a product of interest for iron and steel applications, results from charring raw biomass. The charring process produces three (3) outputs: biogas, liquid biofuels, and solid biocarbon. The relative yields of these three (3) products are a

function of the processing conditions. The common thermochemical conversion techniques used for large scale production are torrefaction, pyrolysis, and gasification.

Torrefaction involves the slow heating of biomass to 200–300°C in inert or low oxygen environments, this maximizes the solids produced [5]. In contrast, during pyrolysis the biomass temperature reaches 300–800°C in an inert or low oxygen environment [5]. There are two approaches to pyrolysis: slow and fast. Slow pyrolysis favors a high biocarbon yield and requires the slow heating of biomass for anywhere between 15 minutes to several hours. Fast pyrolysis favors a higher yield of pyrolysis biofuels and biogas via the rapid heating of biomass to higher temperatures for a few seconds. Finally, gasification is the thermochemical decomposition of biomass in oxygen-lean environments, or in the presence of steam. This maximizes the production of non-condensable gases (e.g., CO and H₂), also known as syngas [5]. The temperature range for thermochemical decomposition can vary from 600°C to >1,800°C.

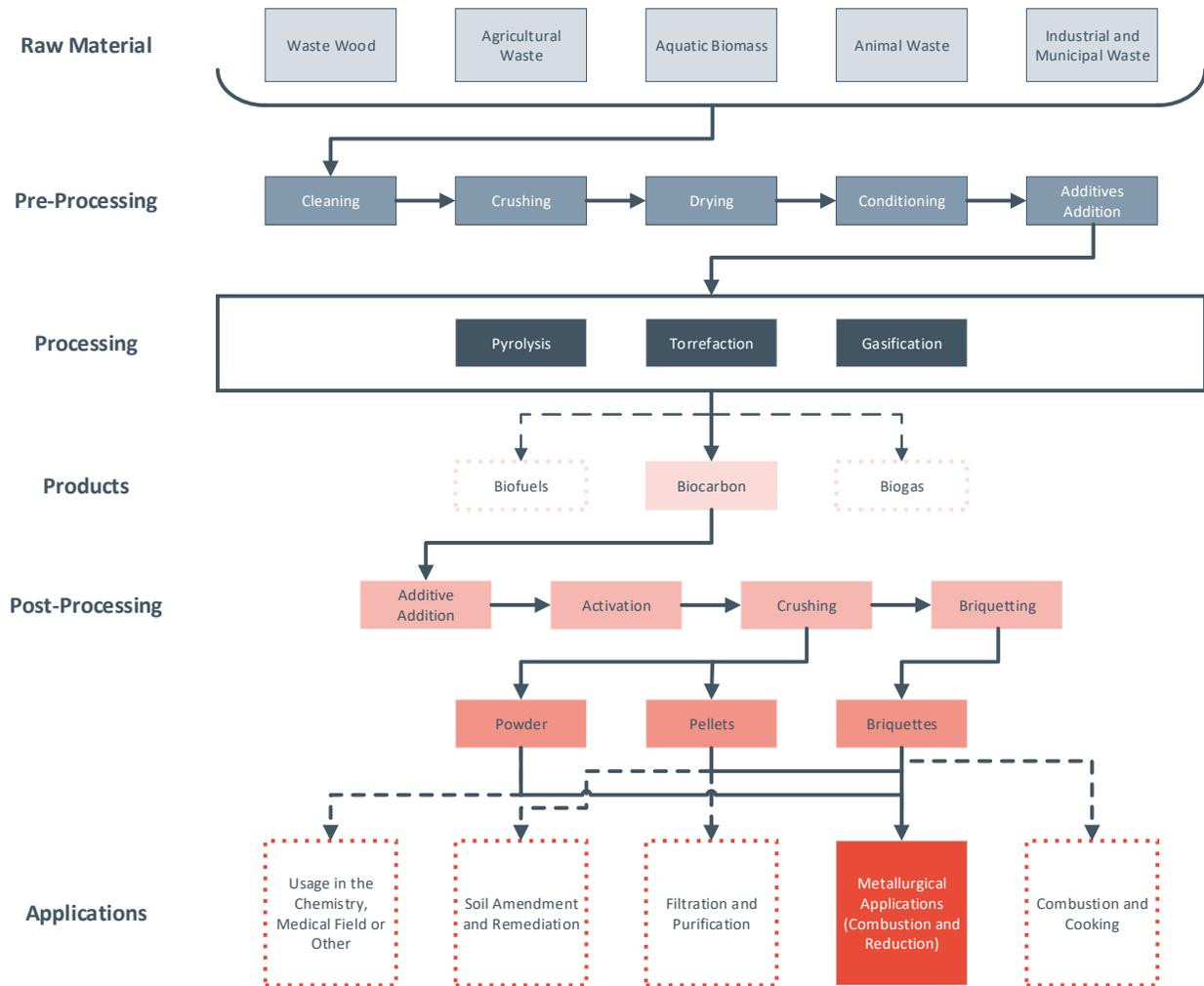


Figure 2: The Biocarbon Value Chain for Industrial Applications

Slow pyrolysis is used for biocarbon production as it drives off most of the volatile matter while maintaining a higher yield of biocarbon. The resulting biocarbon properties can be like those of coal (Table 1). The biocarbon resulting from torrefaction has a lower fixed carbon and calorific value compared to pyrolysis biocarbon; torrefied wood volatile matter is higher as cellulose does not fully decompose at torrefaction operating temperatures.

Table 1: Biomass Properties Compared to those of Coal and Coke

	Charring Conditions		Fixed Carbon (%)	Ash (%)	Volatile Matter (%)	Calorific Value (MJ/kg)
	Temperature (°C)	Cycle Time (h)				
Wood Eucalyptus Bark	N/A	N/A	20–24	5–6	70–74	18
Torrified Wood	200–300	0.2–0.5	25–30	1–3	75–85	23–25
Eucalyptus Biocarbon	500	3	60–90	18	24	23
Coal	N/A	N/A	75–85	<12	20–30	>30
Coke	1,200	18–20	85–90	8–12	<1.5	>30

Fixed carbon is an important property of biomass as it indicates the carbon available for reduction and correlates with a higher calorific value. The ash contains trace elements that can be harmful to the final product such as phosphorus. Ash and volatile matter content also increase the reactivity of the biocarbon. Volatile matter can be reduced through pre-processing of the biomass. For metallurgical applications, high fixed carbon is desired as the biomass is used both for reduction of iron oxides and provides process energy. Iron- and steelmaking typically targets biomass with low ash and low volatile matter content as high reactivity may limit the uses of this biomass.

Microalgae

Microalgae have emerged as a promising source of biomass due to its fast growth rate and flexible growth conditions. These single cell photosynthetic microorganisms are found in water, and they convert CO₂ into usable biomass. Thousands of microalgae species exist in nature; few species are cultivated in open ponds and closed photobioreactors. Open ponds are used for microalgae growth due to their simplicity. These types of ponds are profitable to operate while producing small quantities of microalgae for sale. Open ponds can be implemented in a greenhouse or outdoors in temperate climates. Closed photobioreactors are tanks, or closed tubular or flat panel bioreactors that use sunlight and/or artificial light to grow microalgae under controlled conditions. This allows for growth conditions that increase yield and improves microalgae quality, all-be-it with higher operational and investment costs.

BIOTECHNOLOGY APPLICATIONS IN THE IRON AND STEEL VALUE CHAIN

Biomass and Biocarbon Utilization in Iron- and Steelmaking

Biocarbon is used to fully replace coke in Brazilian mini-blast furnaces. This application has generated interest due its success displacing carbon emissions associated with coal and coke by biogenic carbon. Coal replacement by biomass and/or biocarbon is limited by technical and efficiency constraints as well as supply chain considerations. In most cases, biomass must be pyrolyzed to be used in iron- and steelmaking. The coal to biocarbon replacement ratio is not on a 1:1 ratio as a greater mass of biocarbon is required to compensate for its high moisture, and its lower carbon content and heating value. This section of the paper considers the use of biocarbon in the context of iron- and steelmaking value chain while minimizing impacts on operations and product quality.

Biocarbon use in cokemaking has been studied as a decarbonization strategy. The replacement of coking coal by biocarbon is technically challenging due to the impact on final coke properties, namely coke reactivity (CRI) and hot strength (CSR). Laboratory tests from CANMET have achieved up to 10% replacement of coking coal by biocarbon with an acceptable loss of coke properties [6]. The maximum coking coal substitution by biomass is estimated from the laboratory test results to be 5% of the coal blend before coke properties deteriorate. Coke quality decreases due to biocarbon's higher reactivity related to its higher volatile matter and higher concentrations of K, Ca, Na, Fe, and Mg in the ash. The resulting coke CSR is reduced by the natural fiber directionality of biomass materials in the resulting coke particles. The authors' view is that for large scale blast furnace applications, biocarbon would only replace the cheapest non- and soft-coking coals. Coke production still requires the same amount of high-quality coking coal to engulf the biocarbon particles and partly compensate for the coke CSR loss. The authors are aware of the addition of a small amount of wood chips to the coking coal blend at selected North American coke plants.

In the sinter plant, biocarbon with high fixed carbon and low volatile matter can partially substitute for coke breeze in the sinter mix. In trials, coke breeze replacement by biocarbon was limited to ~25% as beyond this sinter quality is negatively impacted [3]. A reduced peak temperature when using biocarbon led to the formation of weak sinter, and productivity decreased due a greater amount of sinter return fines. Biocarbon negatively impacts the sinter blend granulation/micro-pelletizing process because of biomass' high porosity and affinity for moisture. Compared to coke breeze, biocarbon reduced sinter bed

permeability due to biocarbon's low crushing strength. The use of biocarbon does reduce NO_x and SO_x in the sinter plant off-gas, as biocarbon contains lower concentrations of N and S compared to coke breeze. Raw biomass' high moisture, low carbon content, and low calorific value prevents its direct use in sintering.

In the pellet plant, biocarbon can fully replace fossil fuels and coke breeze/anthracite used when producing iron ore pellets from hematite ores. Biocarbon's similar calorific value and physical properties compared to anthracite, coke breeze, and coal make it a viable candidate for substitution. A concern using biocarbon as a solid fuel replacement is biocarbon's higher volatile matter compared to anthracite. This can have a negative impact on the fired pellet quality and lead to reduced fired pellet product yield. Biocarbon substitution also depends on the pelletizing technology used. Coal-fired grate kilns are more readily able to use of a significant volume of biocarbon in the kiln burner. This substitution would lower SO_x emissions from combustion due to the negligible sulfur content of biocarbon compared to coal. Pellet producers have demonstrated the ability to replace anthracite with biocarbon in industrial pelletizing, fired pellets were produced from hematite ores using only biocarbon as a solid fuel.

Brazilian mini blast furnaces can operate with 100% biocarbon because of the scale of their operations. With their small volume, mini blast furnaces can cope with the increase in reactivity and lower strength of biocarbon, as well as the related fines generation and furnace pressure drop compared to a larger blast furnace operation.

At the blast furnace, fossil carbon is added in the form of pulverized coal injection (PCI) via the furnace tuyeres, nut coke, and coke. Coal used for PCI can be fully replaced by biocarbon without major impacts on the top gas temperature and hot blast oxygen enrichment [3]. A new opportunity is the use of biocarbon to enhance nut coke effects when added to the ferrous burden. Currently, nut coke additions are limited by the availability of screened coke and the addition rate is typically 30–50 kg per tonne hot metal. Higher nut coke rates of up to 100 kg per tonne of hot metal have been demonstrated in industrial practice and decreased the furnace coke rate on a 1:1 basis. Biocarbon has sufficient strength to behave in a similar fashion as nut coke. The addition of "bio nut coke" can provide another avenue for the use of biogenic carbon in the blast furnace by increasing nut coke plus bio nut coke to 100 kg per tonne hot metal. "Bio nut coke" addition rates of 60 kg per tonne hot metal reduce the furnace coke rate by a similar amount, decreasing fossil carbon consumption by 7% with steelmaking CO_2 emissions reduced by 160 kg CO_2 per tonne liquid steel.

When adding the maximum theoretical amount of biocarbon at every unit operation in the integrated steel plant value chain, just over 50% of the carbon emissions would become biogenic (Figure 3).

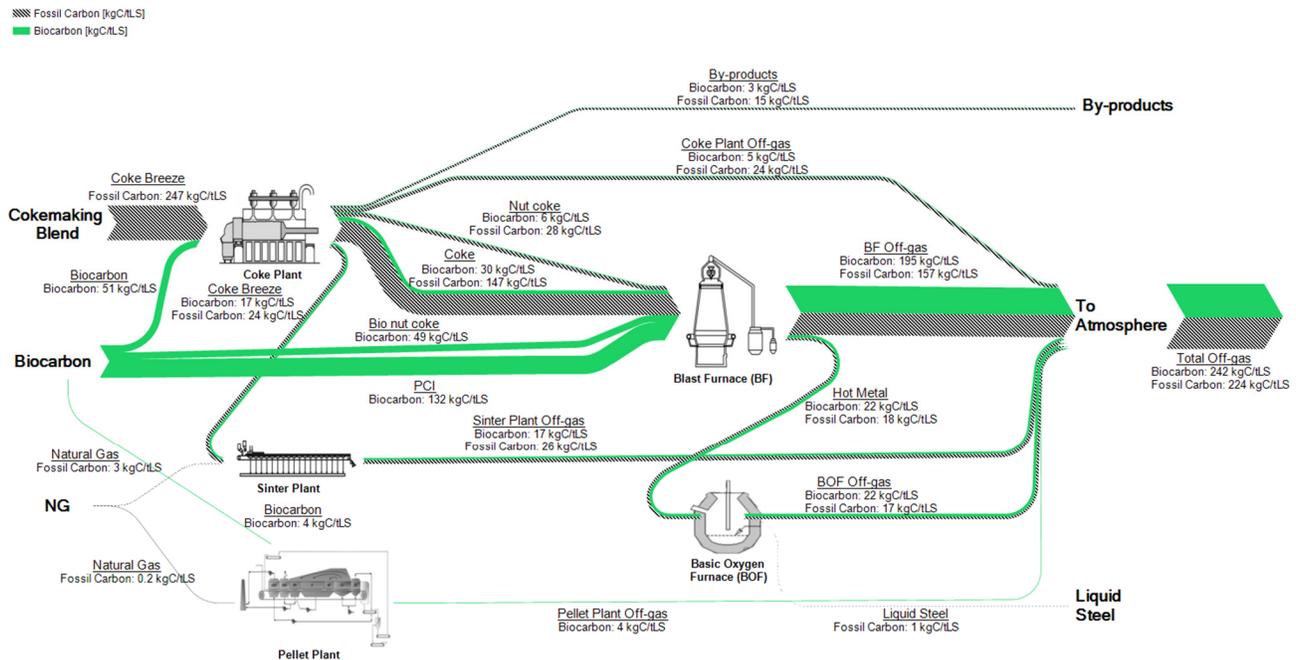


Figure 3

Figure 3: Carbon Flow and Biocarbon Potential in an Integrated Steel Plant

This balance considers a BOF hot metal consumption of 890 kg hot metal per tonne liquid steel; the consumption figures used to develop the carbon balance are based on the European Union Best Available Techniques for Iron and Steel Production with the main assumptions detailed in Table 2 [7].

Table 2: Integrated Steel Plant Carbon Balance Assumptions

Assumption	Units	Value
Pellet / Sinter / Lump	% of ferrous burden	33 / 67 / 0
BF Fuel rates		
Coke	t-coke/t-LS	300
PCI	t-PCI/t-LS	150
Nut Coke	t-nut-coke/t-LS	40
Hot Metal to Scrap Ration in BOF	t-HM/t-LS	0.89

Using substantial amounts of biocarbon in large-scale blast furnaces is unproven and concerns can be foreseen. The higher alkali in biocarbon ash compared to coal and coke will increase the alkali loading which can cause scaffolding and impair operations. Another concern is the presence of phosphorous particularly from agriculture based biocarbon due to the use of fertilizers as these contaminants are undesirable. Blast furnace operators can deploy well-known countermeasures to deal with these challenges; the impact on the ultimate consumption of biocarbon will only be determined by industrial blast furnace trials.

In electric arc furnace (EAF) steelmaking, charged and injected coal is a critical aspect of EAF operations. Biocarbon replacement for both applications have been evaluated at the industrial scale. Field tests have shown no impact of biocarbon on the finished steel quality. As the primary purpose of charge carbon is to reduce iron oxides, the biocarbon reactivity must be sufficiently low for it to participate in iron oxide reduction rather than burning with air in the EAF freeboard. Conversely, a high reactivity is critical for injection carbon to support slag foaming and stability.

Microalgae Production from Iron- and Steelmaking Off-Gases

There is growing interest in microalgae for applications such as bio-fuel production, soil-remediation, and industrial off-gas treatment. Compared to more traditional chemical-based carbon capture and storage technologies (CCS), microalgae growth includes both the separation and the sequestration of the CO₂. Biological CO₂ capture methods take advantage of the naturally occurring photosynthetic process that not only absorbs CO₂ but also produces O₂. On Earth, most CO₂ fixed via photosynthetic organisms is performed by seagrass, algae, and cyanobacteria. In fact, these organisms' photosynthetic efficiency and annual carbon fixed is ten (10) times greater than terrestrial plants.

The advantage of microalgae over traditional CCS methods is dependent on the gas stream treated. Microalgae are best suited to capture CO₂ from dilute streams, typically 5–16% CO₂, compared traditional chemical-based carbon capture methods that have proven cost effective to implement for streams with over 90% CO₂. The carbon capture efficiency of microalgae technologies can range from 50–90% CO₂ capture. The resulting dried microalgae can be sold to a variety of industries, or potentially be recycled back into iron- and steelmaking operations as circular carbon.

The conditions for microalgae growth depend on the cultivated species. While there are different varieties of microalgae, the species spirulina and chlorella are the most common ones cultivated for industrial applications due to their capacity to better capture CO₂ [8]. Ideal gas conditions for microalgae growth are a combination of pH, temperature, gas composition, and presence of contaminants. Table 2 lists the optimal microalgae growth conditions along with typical off-gas compositions from various iron and steel processes.

Table 3: Microalgae Growth Conditions Compared to Various Iron and Steel Process Off-Gas Compositions

	CO ₂	CO	NO _x	SO _x	Temperature	Volumes
	Vol %	Vol %	g/t-product	g/t-product	°C	Nm ³ /t-steel
Optimal Microalgae Growth Condition	5–16	-	<150 ppm	<150 ppm	20–35	-
Sinter Plant	6	0.8	300–1,030	220–970	175	1,900
Pellet Plant	≤5	0	150–550	11–200	135	690
Coke Oven Flue Gas	22	1.1	80–200	90–400	200	370
Blast Furnace Stoves	23	0	1.6–150	6–170	225	940
Basic Oxygen Furnace Gas	16	63	8–60	4–15	40	110
Power Plant	23	1	90–400	80–200	160	2,200
EAF Off-gas	5–20	5–10	10–460	5–200	300–1,200	100–300
Reheat Furnace	6–30	0	100–200	5–850	180	230

Water acidity is an important parameter for microalgae growth as it impacts growth rate and hence productivity. Most microalgae species favor conditions closer to a pH of 7, with few exceptions [9]. High concentrations of dissolved CO₂ in water decrease pH leading to impaired photosynthesis: at low pH, microalgae must divert energy to maintain its intracellular pH [10].

Industrial scale microalgae technology providers, such as Carbon BioCapture, Pond Tech, and Danieli, indicate that a gas stream with 5–16% CO₂ is optimal for microalgae growth. NO_x and SO_x concentrations must be controlled when growing microalgae as these gases also cause water acidification that negatively impacts growth rate and hence productivity [10]. Low NO_x and SO_x concentrations do not impair the growth; studies show that at concentrations below 150 ppm, NO_x and SO_x are favorable for microalgae growth [10]. As noted in Table 2, the CO₂ concentration in steel plant flue gases varies depending on the source and likely will require dilution before being sent to a microalgae plant. NO_x and SO_x concentration may vary significantly between off-gas streams, requiring dilution or imposing limits on stream usage for microalgae growth.

The effects of high CO concentrations on microalgae growth are unknown and should be investigated if treating CO rich steel plant off-gas. Microalgae and all photosynthetic organisms produce tiny amounts of CO during the generation and degradation of photosynthetic pigments, up to 400 g-CO/t-organic matter [11]. This indicates that low concentrations of CO are unlikely to harm microalgae. Off-gases containing high concentrations of CO should be combusted to generate CO₂ that can be subsequently captured by the microalgae. If the post-combustion concentration of CO₂ exceeds the upper limit optimal for microalgae growth, the off-gas must be diluted with air.

Gas temperature must be precisely controlled for optimal microalgae growth with the system temperatures between 20–30°C [8]. Microalgae sensitivity to temperature can result in complete losses of cultures when the temperature varies 2 °C above optimal [8]. High reactor temperatures decrease the CO₂ solubility and subsequently microalgae productivity is reduced [10]. Iron- and steelmaking off-gases are above 50°C, requiring cooling before being used for microalgae production.

Heavy metals, such as mercury and lead are a concern: studies have demonstrated that heavy metals contained in off-gas can accumulate in microalgae resulting in a productivity decrease [8],[10]. Bioaccumulation of heavy metals limits the subsequent use of microalgae in health and food products as their ingestion and exposure are detrimental to human health [10]. A complete understanding of heavy metals in the feed gases is required if microalgae is grown for health and food products. Alternative uses of microalgae such as biofuels or soil remediation and re-use as biomass in steelmaking may have greater tolerance for heavy metals.

Table 2 outlines the off-gas compositions and flow parameters of different iron- and steelmaking processes. The off-gas temperatures are too high for microalgae growth meaning that the streams would need to be dilute or otherwise cooled to achieve ideal temperature for growth. Streams with higher concentration of CO₂ such as blast furnace stoves, coke oven flue gas, and basic oxygen furnace flue gas would require dilution before being sent through the microalgae photobioreactors to mitigate the impact on the system acidity. Microalgae is better suited for gas streams which CO₂ is more dilute for instance sinter plant, EAF, and reheat furnace off-gas. Alternatively, these dilute streams can be mixed with the CO₂ rich gases to dilute the CO₂ present to target levels. Combustion and mixing of other off-gases can be a strategy to reach the target CO and NO_x required for microalgae production.

Technology providers Danieli and Carbon BioCapture have demonstrated microalgae growth from reheat furnace and power plant off-gas, respectively [12], [13]. The use of other steel plant off-gases is unexplored. Tests should be performed to understand the suitability of these process gases for microalgae growth. For instance, the presence of soot in coke oven flue gas on microalgae growth rates is unknown.

Microalgae can be sold for diverse applications such as health, cosmetics, food, cattle feed, and soil remediation. Steel producers are often interested in using microalgae as a coal substitute as it would allow for a circular carbon economy, but there are both technical and cost challenges in this regard. When comparing biocarbon from microalgae versus biocarbon derived from trees and crops, microalgal biocarbon has a lower carbon content, higher surface area, higher ash content, and higher concentrations of inorganic elements (P, K, Ca, and Mg). The lower carbon content requires a higher tonnage of microalgae-derived biocarbon to deliver an equivalent amount of carbon for reduction or energy. Microalgae's higher concentration of inorganic elements increases coke CRI which leads to a reduction in coke CSR. High phosphorus content in microalgae may pose a challenge for steelmakers who have limits on phosphorus input. For the reasons mentioned above, the authors' opinion is that the sale of microalgae to external markets such as biofuel production and soil remediation would be the best use of any microalgae produced from steel plant off-gases.

The Use of Biotechnologies in Emerging for Iron and Steel Applications

The authors note that biotechnologies feature in emerging technologies being developed by global iron ore and steel producers to reduce CO₂ emissions:

- EAF steelmakers are partnering with biocarbon producers to replace their fossil-based charge and injected carbon as a Scope 1 emissions mitigation strategy. In the USA, Steel Dynamics announced a strategic partnership with AYMUM, a biocarbon producer [14].
- Vallourec is commercializing Carboval™, a modern pyrolysis kiln focused on efficiently producing biocarbon for mini-blast furnace pig iron applications [15].
- Vale is constructing a 500 ktpa TecnoRed™ ironmaking plant that will use bagasse as a biogenic carbon source replacing coal. A new pyrolysis technology is being developed as part of the overall TecnoRed project [16].
- ArcelorMittal will soon produce bioethanol from blast furnace gases in Belgium. In another project, waste urban wood will produce biocarbon to replace pulverized coal injected into ArcelorMittal blast furnaces [17].
- Rio Tinto announced development of a pilot plant for their BioIron™ process that produces direct reduced iron using agricultural wastes [18].

These applications illustrate the diverse uses of biotechnologies that are on-going and that the authors expect will expand as the steel industry transforms to reduced CO₂ emissions.

BIOTECHNOLOGY SCALABILITY CASE STUDY

Two scenarios are presented: a scenario describing the production of 100,000 tonne per annum (tpa) of biocarbon for use in steel plants and a scenario investigating the capture of 100,000 tpa of CO₂ as microalgae produced from steel plant off-gases.

Production of 100,000 tpa of Biocarbon

The most common slow pyrolysis technology is the traditional beehive kiln that has been used in Brazil and elsewhere for centuries. Traditional kilns represent 70% of the Brazilian biocarbon production and produce the biocarbon used in the Brazilian mini blast furnaces. Carbonization using beehive kilns is inefficient since they operate on a batch basis and by-products are typically not collected. Biocarbon plants using kilns produce from 200–1,000 tpa of biocarbon and have a typical biocarbon yield of 28–30% [19]. The pyrolysis gasses are released to atmosphere and contain incomplete combustion byproducts, notably CH₄ and CO [19]. Methane (CH₄) has a high global warming potential resulting in biocarbon produced from traditional beehive kiln having associated GHG emissions.

The pyrolysis industry has been developing new processes that are more efficient converting wood to biocarbon and do not release unburnt gases. These new processes are design to be continuous, automated, and fully energy self-sufficient allowing for a greater charcoal yield from wood and better control on biocarbon properties such as fixed carbon content. By-products are collected and partially re-used in the pyrolysis process which increase the complexity of the pyrolysis plant compared to the traditional beehive kilns. Pyrolyzed off-gas pass through heat exchangers for heat recuperation and are sometimes used for drying of the raw wood before being flared. The biocarbon yield achieved by these emerging technologies varies between 30–35%. These innovative technologies provide higher production rates: individual units can produce from 15,000–25,000 tpa of biocarbon. Examples of new steel focused pyrolysis kilns are Vallourec's Carboval process and Vale's TecnoRed Carbonization Process [15], [16].

Figure 4 compares the GHG emissions of biocarbon produce by traditional beehive kilns and new process technologies. Most emissions from beehive kilns are non-biogenic as they are from incomplete combustion, e.g., methane. New process

technologies have lower emissions as the biofuels by-products are collected and not release to atmosphere. All the CO₂ emissions associated with the pyrolysis process can be considered biogenic as per the GHG protocol (ISO 14064).

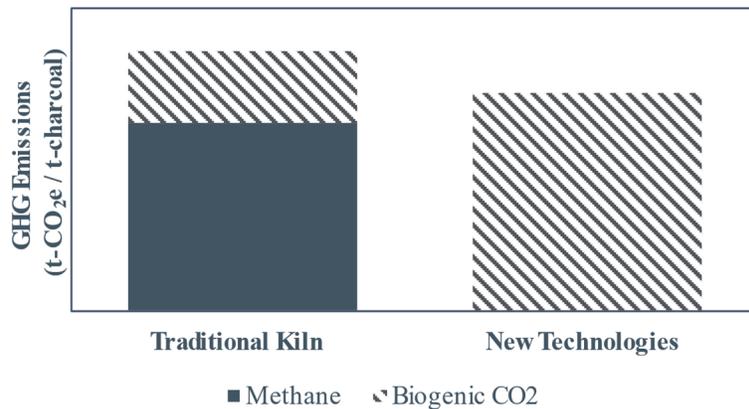


Figure 4: Qualitative Emissions Comparison of Charcoal Produced from Traditional Kilns and New Technologies

For this analysis, eucalyptus wood is considered as it is the main biomass source used for Brazilian mini-blast furnaces. To produce 100,000 tpa of biocarbon using traditional kilns requires 320,000–350,000 tonnes of eucalyptus wood annually. This would decrease to 280,000–310,000 tpa when considering new pyrolysis technologies. A sustainable eucalyptus plantation requires a seven (7) year cycle, so the total land requirement to produce 100,000 tpa of biocarbon is 18,000-20,000 hectares. This is equivalent to 27,000 football/soccer fields for traditional kilns and is expected to reduce to 23,000 football/soccer fields when recently developed technologies are deployed.

The production of biocarbon is location dependent as biomass is challenging to transport. Two scenarios are possible: production of biocarbon adjacent to the biomass source, as is practiced in Brazil, or production of biocarbon close to the end-users. As not all types of biomasses are available in all regions, the biomass sourcing approach must be adapted accordingly.

Sequestration of 100,000 tpa of CO₂ Using Microalgae

An optimized microalgae growth system sequesters 1.83 kg of CO₂ per kilogram of dry microalgae produced; hence capturing 100,000 tpa of CO₂ produces ~55,000 tpa of dry microalgae [12]. Given a carbon capture efficiency of 50–90% for an optimized microalgae capture system, between 111,000–200,000 tpa of CO₂ would be processed to capture 100,000 tpa of CO₂. This volume of CO₂, 100,000 tpa, represents 2–3% of the annual Scope 1 CO₂ released by a 2.5 Mtpa integrated steel plant. For a 1.5 Mtpa EAF plant, the capture of 100,000 tpa of CO₂ represents 33% of the Scope 1 CO₂, making a microalgae facility more interesting for an EAF steel producer. A microalgae production facility sized for this volume of gas would require 3–6 hectares of land, equivalent to 4–8 football/soccer fields.

The primary barriers to large-scale microalgae CCS are carbon capture efficiency and channels to market for the product. Carbon capture efficiency depends on the microalgae species produced and process optimization developed by technology providers. Since microalgae cells are naturally opaque and need light to grow, the tank design must maximize light penetration to create photosynthesis conditions required to grow microalgae. This land requirement is highly dependent on the design of the photobioreactors; these reactors must leverage as much natural light as possible to reduce land requirements. The photobioreactors must be located close enough to off-gas sources such that large volume of the dilute off-gas can be easily delivered to the microalgae facility. Iron- and steelmaking plants are typically located in urban regions and are frequently land constrained. A solution investigated to address this challenge is decoupling of the CO₂ capture and the microalgae production. This decoupling approach has been evaluated by Danieli for a reheat furnace where the intermediate carbon capture step is independently completed using an absorption tower to dissolve CO₂ in water and the resulting solution is pumped to a remote microalgae production facility [12].

Technology selection is driven by regional conditions. When the technology leverages sunlight for microalgae growth, regions with temperatures consistently above freezing are needed. When microalgae growth is performed in a closed system with artificial light, there is more flexibility regarding plant location. That said, artificial light technologies have higher capital and operating costs and depend on green electrical power to be considered a CO₂ abatement solution.

The operating cost of microalgae facilities based on natural and artificial light from light emitting diodes (LED) are compared in Figure 4Figure 4.

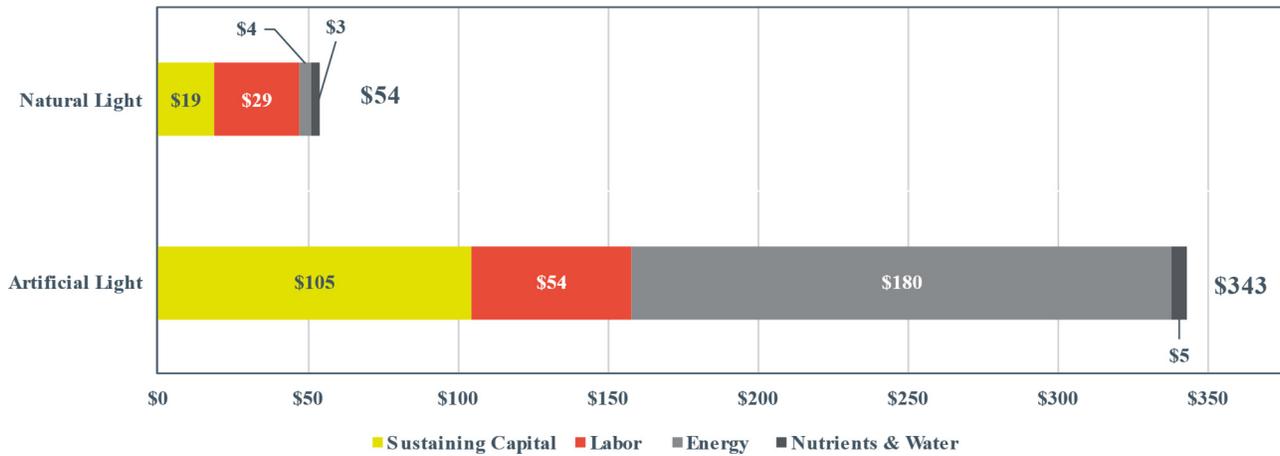


Figure 4: OPEX for Microalgae Production per tonne-CO₂ Captured

These estimates are based on key performance indicators given by microalgae technology suppliers, namely energy, nutrients, water, and labor requirements. The most important cost different between technologies comes from the electrical energy required. While artificial light systems provide 24/7 production, revenue from microalgae sales must be extremely high to support the additional production costs. This limits the microalgae produced from artificial light to high value products for human and animal consumption rather than lower value products such as biofuels. One strategy for a steel plant would be to deploy both technologies: a small microalgae plant using artificial light and producing high value-added products and a much larger natural light facility serving the low value applications. Markets for large scale microalgae consumption are immature; channels must be developed for large volume markets for steel industry microalgae production to be viable.

BIOTECHNOLOGY SYNERGIES

Biotechnologies can be deployed synergistically across downstream and upstream iron- and steelmaking process. Applications such as biocarbon as injected fuel in the blast furnace do not prohibit biotechnology implementation downstream for carbon capture from the various process off-gases. Implementation of the biotechnologies discussed in this paper also opens the door to synergistic deployment with other technologies, for example utilization of the pyrolysis gases produced as an in-plant green fuel or treatment of CO rich off-gas streams to produce bioethanol via fermentation.

Pyrolysis by-products can be used as another biogenic source of carbon in the making of iron and steel. The main by-product of interest is the biogas, a non-condensable syngas rich in CO, H₂, and CH₄. Biogas can be blended into mixtures for applications in blast furnaces, direct reduction, and pellet plants. Biogas usage has its own challenges as its direct compression is difficult given its CO₂ content of around 30 wt.% and the necessity to clean raw biogas to meet environmental regulations and protect the downstream processes.

While microalgae may be suitable for carbon capture of low CO₂ concentration off-gas streams, CO is not captured during microalgae photosynthesis. Fermentation technologies that convert CO present in off-gas into bioethanol can be considered as either pre-treatment prior to microalgae production or co-treatment if CO and CO₂ are separated prior to treatment.

For example, acetogenic bacteria can be used in a bioreactor to ferment CO rich syngas to bioethanol [20]. One of the largest barriers in bioethanol production is the production of acetic acid, as acidification decrease bioethanol yield [20]. Another challenge is low solubility of CO in water. Benefits of using acetogenic bacteria over chemical techniques include high specificity and no strict H₂/CO ratio requirement [21]. Like microalgae, process conditions such as temperature and pressure are easily maintained, and gas pre-treatment and metal catalysts are not needed [21]. With a continuous supply of off-gas containing CO, CO₂ and H₂, the bacteria species used can produce other types of biofuels such as butanol and hexanol [22]. One potential idea to fully synergize with the microalgae technology is to use both types of microorganisms in series to remove the CO followed by CO₂, to maximize carbon capture.

CONCLUSION

Biotechnologies offer unique pathways to reduce fossil-fuel usage in both integrated BF-BOF and EAF steelmaking plants. Biocarbon and biogas can be incorporated into existing steelmaking operations replacing for example injected coal in the blast furnace, charge carbon in EAF steelmaking, and natural gas for heating. Treatment of dilute off-gas is possible using fermentation to capture CO, and photosynthesis to capture CO₂. The resulting bioethanol has value added applications in the fuel and chemical markets while microalgae can be sold for human and animal products, for soil remediation or to produce

biofuels. Both bioethanol and microalgae could be re-used in the steel process as circular carbon, that said for the moment sales outside the steel plant appear more profitable. Challenges to deploy biotechnologies include technical maturity, space to produce bio-resources, and climate conditions to support biotechnologies.

The use of biocarbon in EAF steelmaking and the subsequent production of microalgae from the EAF off-gas can potentially eliminate EAF Scope 1 emissions. Biomass can have a significant impact on Scope 1 CO₂ emissions of the traditional BF-BOF steelmaking but only if massive quantities of biomass can be economically and sustainability sourced. Microalgae production from reheat off-gas, as demonstrated by the proof of concept developed by Danieli, offers a solution for minor steelmaking emissions that must be abated to reach net zero emissions.

Emerging technologies including Vale's TecnoRed™ and Rio Tinto's BioIron™ processes plan to use biomass as a coal substitute. Steel Dynamics and others are developing biocarbon supply chains to replace charge carbon in EAF steelmaking. ArcelorMittal will soon produce its first bioethanol from blast furnace gas in Belgium. These examples confirm biotechnologies emerging role as part of the technical solutions to CO₂ emissions. As biotechnologies are in early development and with a low technology readiness level, the authors anticipate further adoption as steel producers deploy innovative technologies on their journey to net zero CO₂ emissions steel.

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