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Canada

ADVANCED SOLID BIOFUELS

Strategies for Decarbonizing the Iron and Steel Industry

INTRODUCTION

The forest sector plays a vital role in supporting employment across various regions in Canada, significantly contributing to the economic activities of local communities.

Beyond traditional wood products, the forest sector holds immense potential as a key supplier of biomass which can be sourced from harvesting and milling operations. Once thermally treated, woody residues offer renewable alternatives for high-temperature industrial processes that require both energy and carbon inputs. These products are increasingly being explored as sustainable substitutes for fossil fuels and petroleum-based reductants in industries such as pulp and paper, iron ore processing, metal refining, and cement production.

The use of woody biomass not only helps reduce greenhouse gas emissions but also promotes the circular economy by utilizing by-products and waste materials from the forest sector. Moreover, developing bio-based products such as biochar and biocarbon creates opportunities for innovation and job creation, and contributes to the diversification of the forest industry.

CONTEXT AND NEED FOR DECARBONIZATION OF THE CANADIAN IRON AND STEEL SECTOR

Iron and Steel production is one of the most energy-intensive industrial activity. Its high-temperature requirements and dependence on fossil carbon sources make it especially challenging to decarbonize.

The iron and steel industry is exploring a range of decarbonization strategies, which include enhancing energy efficiency, transitioning to low-carbon fuels such as bioenergy, implementing new technologies such as direct reduction iron (DRI) for ironmaking and cold bonding for iron ore pelletizing plants, and adopting carbon capture and storage (CCS) technologies to further reduce CO_2 emissions.

This brochure provides an in-depth look at advanced solid biofuels as sustainable alternatives to fossil fuels in the iron and steel sector. It delves into the potential of biochar and biocarbon, produced from sustainably sourced biomass, to provide a practical pathway to decarbonizing the industry.

The Canadian iron and steel industry, including mining and pelletizing operations, is a major consumer of fossil fuel-based solid carbon, such as anthracite, bituminous coal, coke breeze and pet coke. It is estimated that this sector alone utilizes 4.8 Mt of these materials per year in Canada. Solid carbon is used for various process requirements, notably providing energy and reductant capabilities.

In 2020, Canada's steel industry emitted approximately 12 MtCO_2eq, with an additional 3 MtCO_2eq from iron ore mining and pelletizing, while consuming 171 petajoules of energy, primarily from fossil fuels like coal and coke.

HIGHLIGHTS AND RECOMMENDATIONS

DECARBONIZATION OF CANADA'S STEEL INDUSTRY

- **In 2020, the iron and steel sectors consumed 171 PJ of fossil fuels and emitted approximately 15 $MtCO_2eq$. Meeting Canada's 2030 and 2050 climate goals will require a targeted reduction in fossil fuel reliance within the industry.**

- The adoption of biocarbon and low-carbon intensity hydrogen is promising to reduce the emissions from the iron and steel industry. Biocarbon and hydrogen can be complementary fuels/reducing agents, offering flexible, context-specific pathways to decarbonization. For example, high-temperature slow pyrolysis can co-produce high-quality biocarbon and bio-based hydrogen, maximizing carbon efficiency.

ADVANCED SOLID BIOFUELS AS COAL AND COKE SUBSTITUTES

- Solid biofuels such as torrefied biomass (biocoal), biochar, and biocarbon, produced via thermochemical processes, present viable alternatives to traditional coal and coke in the steel industry. These biofuels can reduce GHG emissions significantly and contribute to a cleaner, more sustainable steel production process.

- The properties of these biofuels depend on factors such as the type of biomass and thermochemical conversion technology. Understanding all the process parameters is critical to optimize the yield and control the quality of biocarbon products for demanding industrial applications.

- Given the current quality and availability limitations of biocarbon, partial blending with traditional fossil fuels offers a practical interim solution for reducing emissions. Research into optimal blending ratios helps achieving significant emissions reductions while ensuring process stability.

- Further research and development are essential to improve conversion processes, reduce costs, and better understand how biocarbon properties affect iron and steel production. Pilot-scale and demonstration projects are underway in Canada to assess the scalability of biocarbon production in real-world steel production environments. These initiatives will generate valuable data on performance, cost, and best practices.

- Partnerships between forest companies, biocarbon producers, and iron and steel companies are needed. A reliable biomass supply chain is essential to meet industrial demand and scale up biocarbon adoption effectively.

Approximately 1.9 Mt of coal and 2.9 Mt of metallurgical coke are used annually in iron ore and steel production facilities in Canada.

- Assuming a theoretical substitution rate of 100% for coal and 25% for metallurgical coke, 14 Mt of dry biomass would be required per year, which would provide GHG emission reductions of up to 8 MtCO_2e per year. However, with the likely increases of DRI processes and the potential adoption of cold bonding technologies in Canada, biocarbon needs should be reduced significantly over the next decades.
- When feasible, locating biocarbon production facilities near steel mills enables the co-production of syngas and biocarbon, both of which are essential for steelmaking. This approach can also foster industrial symbiosis by facilitating efficient heat recovery from steel production processes, thereby improving energy efficiency and reducing emissions.

> “GHG emission reductions potential of up to 8 MtCO_2e per year requires 14 Mt of dry biomass per year.”

ADVANCED SOLID BIOFUELS: QUALITY PARAMETERS OF BIOCHAR AND BIOCARBON

Biocoal and biocarbon are advanced solid biofuels derived from biomass, increasingly recognized as renewable alternatives to fossil fuels for industrial applications, especially in the metallurgical and energy sectors.

The International Organization for Standardization groups both biochar and biocarbon under the term «pyrogenic biocarbon» and is developing standardized specifications to promote their broader adoption.

There are no internationally adopted definitions, although the term biochar is generally used for soil-based applications and biocarbon as a reductant and as a biofuel in heavy industries, especially in the metallurgical sector.

Although biochar and biocarbon are both produced through thermochemical conversion of biomass in oxygen-free or limited environments, they differ in properties due to variations in production conditions, especially the temperature and processing time.

These differences directly influence the carbon content, energy density, and overall suitability of the product for industrial applications.

The quality and effectiveness of biochar and biocarbon for high-demand industrial uses depend on key characteristics that reflect their degree of carbonization, energy density, material stability, and ash content.

The accompanying images (Figure 1) and the Van Krevelen diagram (Figure 2) provide a visual understanding of how these materials evolve with increasing processing severity, highlighting the quality parameters essential for their use in industrial processes.

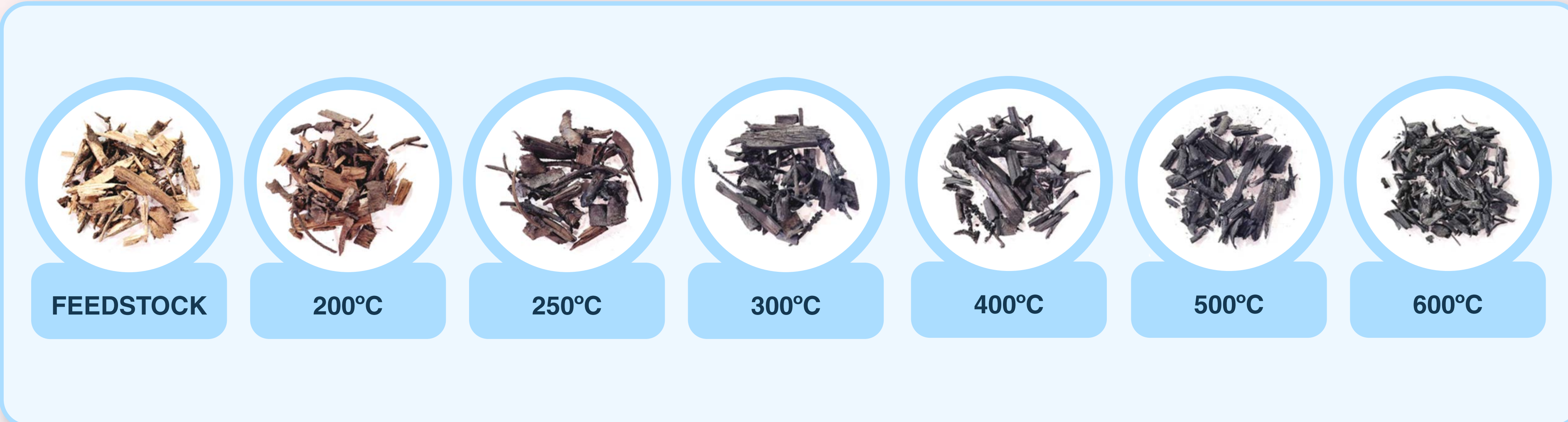

Figure 1: Visual progression of forest residues through pyrolysis at increasing temperatures (200°C to 600°C)

VISUAL PROGRESSION OF BIOMASS CARBONIZATION

Figure 1 shows the transformation of forest residues (branches, tops, and bark) as they undergo slow pyrolysis at progressively higher temperatures (200°C to 600°C). The images reveal changes in colour and structure, indicating increased carbon content and energy density as the biomass converts into biochar at moderate temperatures and biocarbon at higher temperatures. This visual progression demonstrates how thermochemical processing enhances the carbonization level, making these materials suitable for various industrial applications.

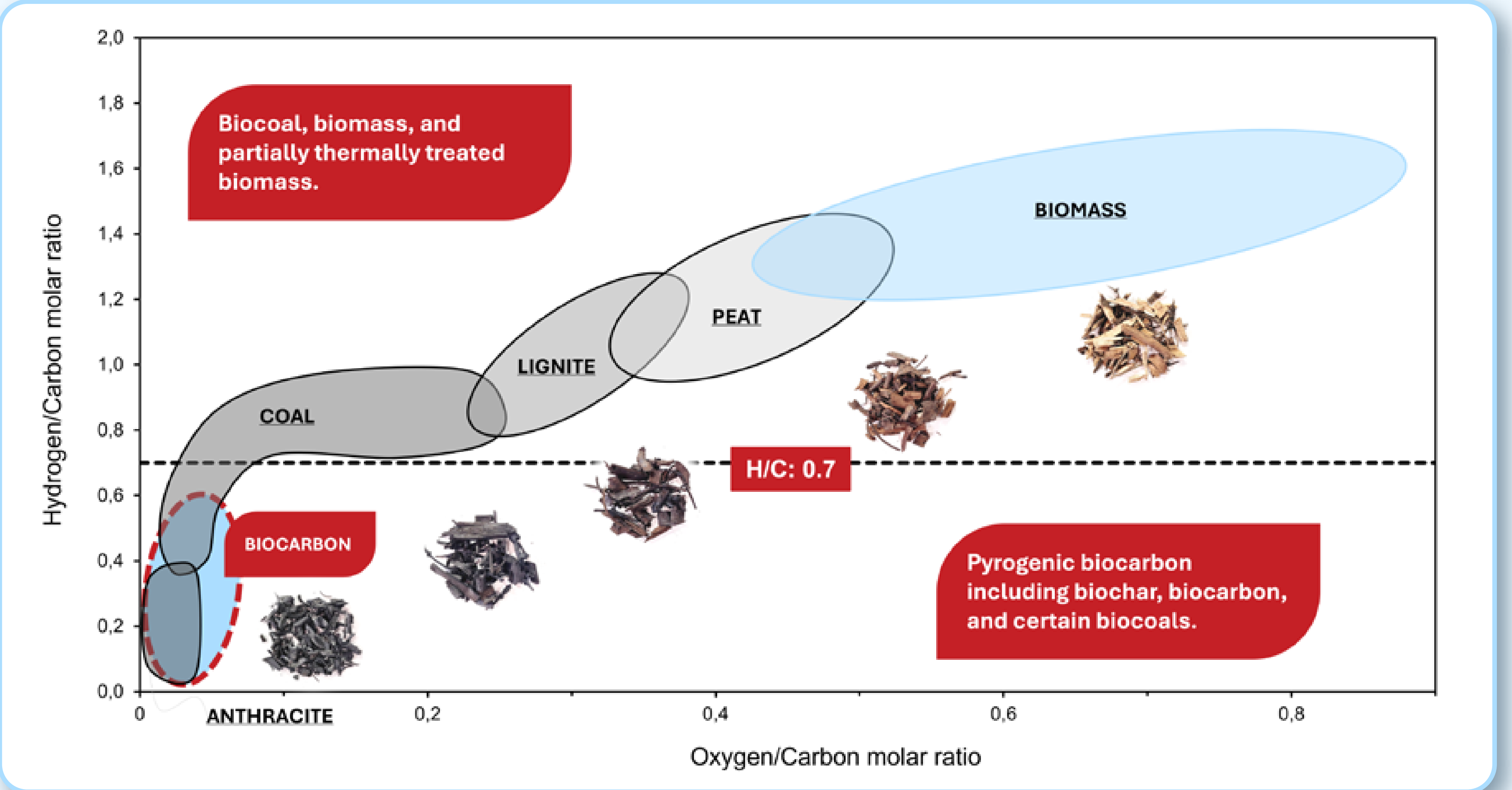

Figure 2: Classification of materials by compositional differences - Van Krevelen Diagram

The *Van Krevelen diagram* is a valuable tool for visualizing compositional differences between carbon-rich materials by plotting their hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) molar ratios. With increasing process severity, carbon-rich materials transition to intermediates, like biocoal, and eventually to products with higher chemical and thermal stability such as biochar and biocarbon. Once biomass is sufficiently carbonized/thermally treated, it can be categorized as pyrogenic biocarbon to differentiate it from other partially treated materials.

BIOCOAL

Appears in region of the graph with higher H/C ratio (typically above 0.7), indicating a lower degree of carbonization due to milder pyrolysis conditions typical of torrefaction. Its properties are closer to low and medium rank coals, making it more suitable for industrial heating and energy generation.

INDUSTRIAL HEATING AND ENERGY GENERATION

BIOCHAR

Defined by its high carbon stability and H/C ratio below 0.7 according to voluntary industry standards such as the European Biochar Certificate (EBC). This low H/C ratio reflects the material's high aromaticity, making it suitable for long-term carbon sequestration and soil amendment applications.

LONG-TERM CARBON SEQUESTRATION AND SOIL AMENDMENT APPLICATIONS

BIOCARBON

Produced at higher process temperatures and a processing time to achieve the necessary fixed carbon content and thermal stability. These conditions result in a material with a highly aromatic structure and a correspondingly low H/C ratio that tends to be less than 0.7 as well. Biocarbon occupies a specialized niche as an industrial reductant and energy source in metallurgical processes and other high temperature applications.

INDUSTRIAL REDUCTANT AND ENERGY SOURCE IN METALLURGICAL PROCESSES

While the boundaries between biocoal, biochar, biocarbon, and fossil coals are not rigidly defined, their properties vary significantly based on feedstock and processing conditions. The final application (agriculture or industry) tends to influence the terminology used to define biocarbon vs biochar.

By carefully adjusting key production parameters such as the feedstock type, temperature, and residence time - producers can fine-tune the balance of stability, functionality, and economic value in the final product. This adaptability is particularly critical in tailoring materials for diverse applications, ranging from soil enhancement to high-performance industrial processes.

ADVANCED SOLID BIOFUELS: PRODUCTION PROCESSES

Advanced solid biofuels are produced through various thermochemical processes that convert biomass into carbon-rich materials suitable for industrial applications. Each production process (slow pyrolysis, fast pyrolysis, and gasification) operates under specific temperature and residence time conditions, yielding distinct products such as torrefied biomass, biochar, biocarbon, bio-oil, and syngas.

These processes influence the material's carbon content, energy density, and suitability for use in energy-intensive industries like steelmaking. Below is an overview of the key production processes for these materials, highlighting their unique contributions to decarbonization. If solid biofuels are the main targeted products, torrefaction and carbonization (slow pyrolysis) are the preferred technologies.

Feed hopper with screw conveyor

Production of biocoal

Continuous rotary torrefier

Slow pyrolysis pilot plant at CanmetENERGY in Ottawa.

PRODUCTION PROCESS	PROCESS CONDITIONS	EFFICIENCY & YIELD	QUALITY CHARACTERISTICS
SLOW PYROLYSIS TORREFACTION	200-300°C, oxygen-limited extended residence time	• Yields solid products such as biocoal, with up to 85% of original biomass weight (on a dry basis) • Typical higher heating value: 17-24 MJ/kg • The typical carbon content is around 50% (40-60%)	• Lower carbon content and energy density than pyrolyzed biocarbon • Improved grindability and homogeneity and lower moisture compared to the biomass feedstock
SLOW PYROLYSIS CARBONIZATION	350-800°C, oxygen-free extended residence time	• Produces biochar or biocarbon with 25-60% yield by biomass weight • Typical higher heating value: 24-32 MJ/kg • Carbon content : 70-90%	• Low and high fixed carbon content are achievable, low volatile matter, suitable for high-temperature industrial processes • Additional processing may enhance durability • Small amount of pyrolysis oil and vinegar alcohol are produced
FAST PYROLYSIS	400-600°C, oxygen-free very short residence time	• Bio-oil as primary product, solid yield of 10-30% by biomass weight • Typical higher heating value of solid material: 24-28 MJ/kg	• Biocarbon has moderate carbon content (60-80%) and relatively high volatile matter • Suitable for use as a supplementary reductant rather than a primary fuel in the iron and steel processes
GASIFICATION	700-1100°C, oxygen-limited short residence time	• High syngas yield: ~70-85% of biomass • Biocarbon yield is lower but significant in large-scale settings • Syngas higher heating value: 60-70% of natural gas	• Biocarbon is highly carbonized and can be tailored for metallurgical uses • Syngas offers bio-based hydrogen and fuel flexibility

Each production process offers unique benefits, creating solid biofuels with distinct properties suitable for different industrial applications, from moderate-energy uses to high-temperature metallurgical processes. The chosen process and feedstock influence the product's carbon content, energy density, and stability. The gasification process can potentially be integrated in iron and steel facilities by simultaneously producing a syngas that can be used as a reducing agent for DRI processes and highly carbonized biocarbon. Similarly, slow pyrolysis processes can be used to simultaneously produce a good quality biocarbon (in a larger volume compared to gasification) with a pyrolytic oil as a coproduct.

DECARBONIZATION OPPORTUNITIES WITH ADVANCED SOLID BIOFUELS

The iron and steel industry has traditionally relied on coke, a derivative of coal, to fuel energy-intensive processes/equipment such as sintering, blast furnaces (BF), and electric arc furnaces (EAF) *Figure 3*. Advanced solid biofuels, including biochar and biocarbon, offer promising alternatives with the potential to significantly reduce carbon emissions. However, each production process comes with unique requirements and challenges, making substitution with bio-based fuels a complex and application-specific endeavor.

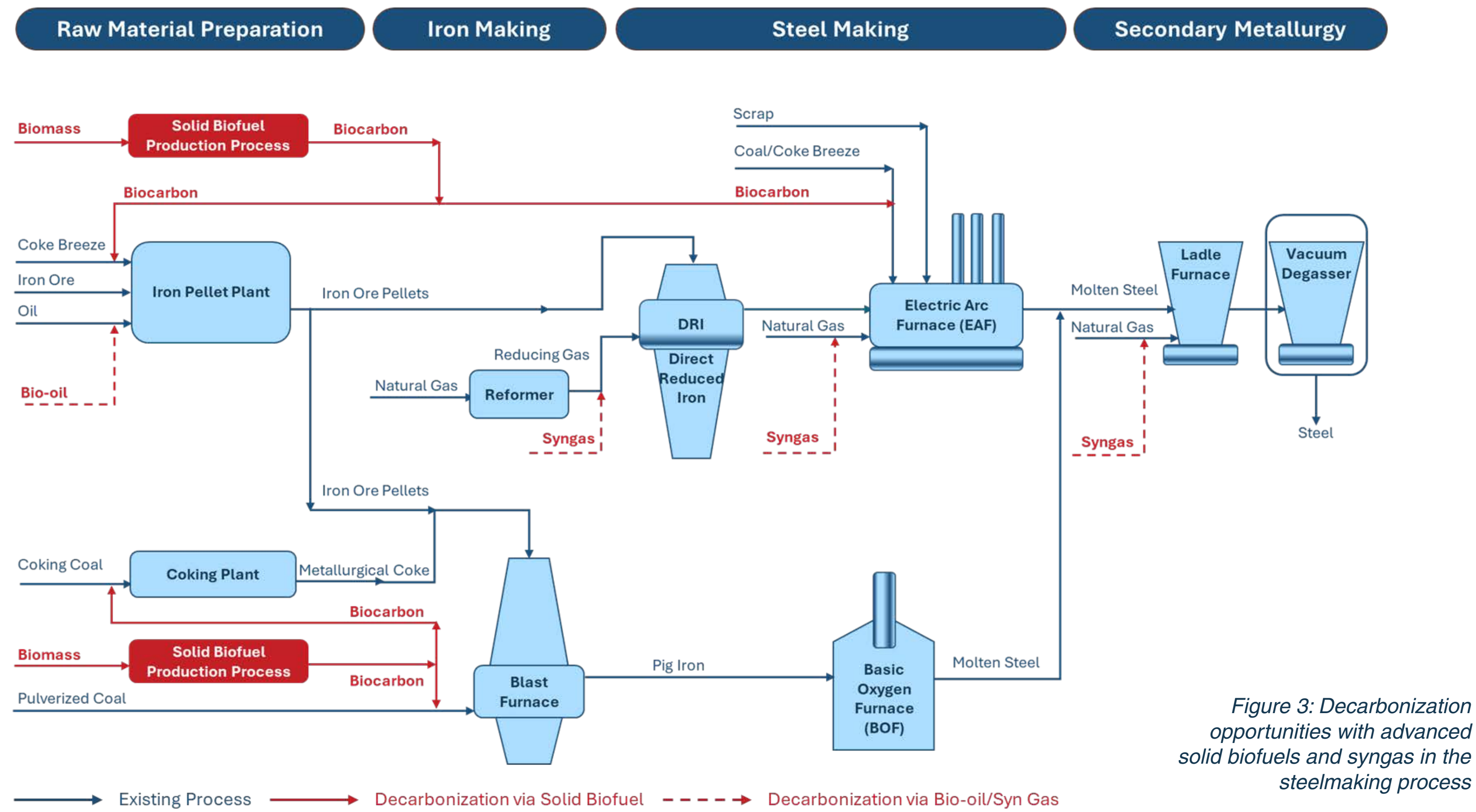

Figure 3: Decarbonization opportunities with advanced solid biofuels and syngas in the steelmaking process

The actual percentage of advanced solid biofuels that can replace coal/coke in each steelmaking facility depends on the specific biocarbon production technology, quality of the raw feedstock, quality of biocarbon, iron and steel production routes, and operational flexibility. While full replacement is possible in some processes, partial replacement is more realistic for BFs due to the technical challenges posed by the structural role of coke.

INDURATION PROCESS (IRON PELLET PRODUCTION) – SUBSTITUTE COKE BREEZE

The induration process plays a pivotal role in preparing iron ore pellets for direct reduction iron (DRI) processes or blast furnaces. This process involves heating green pellets in an induration furnace to harden them and achieve the necessary mechanical strength and permeability for downstream processing. Traditionally, fossil fuels such as heavy fuel oil and coke breeze have been the primary energy sources for achieving the high temperatures required in induration furnaces. Coke breeze is mixed with iron ore fines and additives to produce iron ore pellets while heavy fuel oil is used for furnace air heating.

BIOCARBON POTENTIAL: *Biocarbon generally has lower density compared to coke breeze. It also burns faster. Current research is focused on enhancing biocarbon's energy density, combustion properties, and thermal resilience to meet requirements for the induration process.*

BLAST FURNACE (BF) – SUBSTITUTE METALLURGICAL COKE, PCI, AND NUT COKE

Coal and coke usage: In blast furnaces, metallurgical coal plays a critical role as both a reducing agent and a medium that maintains permeability, facilitating efficient gas flow within the furnace. Its high carbon content, strength, and resilience at extreme temperatures (around 1,600°C) make it indispensable for smelting iron ore. Nut coke, a smaller variant, is often blended in to enhance furnace efficiency. Additionally, Pulverized Coal Injection (PCI) is employed to reduce coke consumption, lower operational costs, and optimize overall furnace performance.

BIOCARBON POTENTIAL: *While biocarbon can partially replace coke, its lower density and mechanical strength may affect furnace efficiency. However, substituting up to 20% of coke with biocarbon is achievable, potentially reducing CO_2 emissions without compromising furnace performance. Advances in biocarbon densification and pelletization are improving its durability, making it a more viable option for blast furnace use. Although a complete replacement is challenging due to structural requirements, partial substitution of biocarbon is achievable and can lead to significant emission reductions.*

DIRECT REDUCED IRON (DRI) – SUBSTITUTE COAL OR NATURAL GAS FOR H_2/CO PRODUCTION

Coal and natural gas usage: In Direct Reduced Iron (DRI) processes, iron ore is reduced to sponge iron using carbon-based agents, typically CO and H_2 derived from natural gas, without the need for melting. This results in lower energy consumption compared to blast furnaces. The shaft-furnace DRI process does not require solid carbon unless it is more economical to gasify coal for syngas production rather than using natural gas in a reformer to generate reducing agents (H_2 and CO). While coal is used in rotary kiln DRI processes in some countries, it is not employed in Canada.

BIOCARBON POTENTIAL: *Biocarbon is not required as a reducing agent in the shaft-furnace DRI process. However, to reduce the carbon intensity of the DRI process, a biomass gasification unit can be implemented to produce syngas, which could replace the natural gas used in the reformer. The syngas composition can be adjusted by injecting hydrogen as needed. Additionally, the biocarbon co-produced by the gasification unit could be utilized in the Electric Arc Furnace (EAF) process, further enhancing sustainability.*

ELECTRIC ARC FURNACE (EAF) – CARBON SOURCE IN SCRAP-BASED STEEL PRODUCTION

Coke usage: In Electric Arc Furnace (EAF) steelmaking, carbon plays multiple roles: it serves as an energy source, a reducing agent, a slag foaming agent, and an alloying element. Coal is commonly added alongside scrap metal or injected into the furnace to facilitate slag foaming, which helps regulate furnace temperature and enhances energy efficiency. While the amount of carbon used in the EAF process is relatively small compared to the Blast Furnace-Basic Oxygen Furnace (BF-BOF) production methods, it remains an essential component for optimal operation.

BIOCARBON POTENTIAL: *Biocarbon shows significant promise as a renewable alternative to coal in EAFs, both as a charge material and for injection purposes. Studies on partial coal replacement with biocarbon in EAFs have yielded positive results, with minimal modifications required to existing equipment or processes. Biocarbon can also function as a slag foaming agent, although higher quantities may necessitate adjustments to the injection systems. Ongoing research is focused on determining the ideal biochar grades and slag compositions to ensure stable, efficient processes, which could facilitate the broader adoption of biocarbon in EAF applications.*

FACTORS INFLUENCING BIOCARBON ADOPTION

01 ADVANCED SOLID BIOFUELS QUALITY AND CHARACTERISTICS

- **CARBON CONTENT**
  Biocarbon generally has a lower carbon content compared to coke, lowering its efficiency as a reducing agent in steelmaking.

- **MECHANICAL STRENGTH**
  In blast furnaces (BFs), coke's strength is essential for supporting the furnace structure and maintaining gas permeability. Biocarbon typically has lower mechanical stability, which limits its potential for a complete substitution in BFs.

- **REACTIVITY**
  While higher reactivity of biocarbon can improve reduction reactions, it can also cause faster degradation at high temperatures, posing operational challenges.

- **BULK DENSITY**
  Biocarbon bulk density is much lower than the solid fossil fuels. Consequently, modification can be required on fuel feeding and storage systems.

02 BIOMASS REQUIREMENT FOR BIOCARBON PRODUCTION TECHNOLOGIES

- **SUSTAINABILITY AND SUPPLY CHAIN**
  Biocarbon production depends heavily on a stable, sustainable biomass supply, mostly using forest and agricultural residues. Investment in biomass collection and processing infrastructure will be essential to meeting demand, with sustainable sourcing practices.

- **ASH CONTENT AND COMPOSITION**
  Ash composition is critical in steelmaking, as certain elements (e.g., sodium, potassium, phosphorus, chlorine) can disrupt processes. Even though biocarbon typically has less ash than coal, agricultural residues with higher ash content are less preferred compared to woody biomass.

- **VOLUME AND QUALITY OF BIOMASS**
  The type and quality of biomass directly affect the biocarbon produced. The use of low-quality feedstock such as bark is generally not suitable for high-quality biocarbon production. Consistent and reliable biomass supply is essential for efficient, high-quality biocarbon production suitable for industrial use.

03 TECHNICAL, ECONOMIC, AND LOGISTICAL CHALLENGES

- **TECHNICAL LIMITATIONS**
  Compared to coal, biocarbon's lower strength and different composition pose challenges, particularly in BFs. While densification techniques like pelletization can improve biocarbon's properties, they are not yet sufficient for complete coke substitution.

- **TECHNOLOGICAL ADVANCEMENTS**
  New technologies are improving biocarbon's structural properties, including enhanced densification techniques and hybrid processing methods that increase its strength and stability for high-temperature applications. As these technologies evolve, biocarbon's potential to replace coke in blast furnaces grows stronger.

- **SCALABILITY**
  Meeting the steel industry's demand for biocarbon requires significant scaling of production, which depends on substantial investments in biomass supply chains and conversion infrastructure. Without reliable large-scale production, biocarbon adoption will remain limited.

- **ECONOMIC VIABILITY**
  The production costs of biocarbon are currently higher than those of coal, primarily due to the costs associated with biomass collection, processing, and transportation. Scaling up production to achieve competitive pricing remains a significant challenge. However, the rising carbon price is making biocarbon increasingly economically viable.

- **CERTIFICATION AND STANDARDIZATION**
  Industry-wide certification is essential for gaining confidence in biocarbon's quality. The International Organization for Standardization is developing standards for pyrogenic biocarbon, ensuring consistency in quality and performance across applications. These standards will play a critical role in facilitating biocarbon adoption by making it a dependable and trusted option for steelmakers.

BENEFITS TO THE FOREST INDUSTRY

The forest industry is facing a range of significant challenges, including duties on Canadian softwood lumber bound for the United States, increased competition from other countries, and rising wood fiber costs mostly due to wildfires and pest outbreaks, among other causes.

Furthermore, the closure of several pulp and paper mills has disrupted conventional value chains, such as converting wood chips into pulp and using bark residues for heat and power.

The surplus of processing residues from sawmills has led some to curtail lumber production, highlighting the urgent need to find new uses for these byproducts.

Advanced solid biofuels offer a promising solution by enabling the forest sector to convert underutilized forest residues, process residues, and damaged trees into biocarbon.

This process opens the door to a rapidly growing market, driven by current interest and rising demand from Canadian iron ore and steel industries, as well as other sectors like cement, lime, aluminum, and power generation.

This presents the forest industry with a unique opportunity to diversify its markets while supporting industrial decarbonization efforts.

The production of advanced wood pellets, biochar, and biocarbon could significantly contribute to meeting national GHG reduction targets, while simultaneously fostering a new, sustainable value chain for the forest sector.


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