Biocarbon Rising:

From Concept to Commercialization

ASSESSING OPPORTUNITIES FOR SCALE, DECARBONIZATION, AND INDUSTRY LEADERSHIP IN BC

NorthX

Acknowledgement

This report is the result of collaboration between NorthX Climate Tech (NorthX), formerly the British Columbia (BC) Centre for Innovation and Clean Energy (CICE), and Energy Super Modelers and International Analysts (ESMIA). Our teams have worked closely to obtain and validate input and perspectives required to provide an overview of the fundamentals of biocarbon.

We would like to thank all the participants that have contributed to the development of this report through research, content development, and pre-screening of its outcomes. These stakeholders were intended to represent the full breadth of the energy transition value chain, including technology developers, existing utility operators, think tanks and accelerators, research organizations, regulatory bodies, industrial suppliers, Indigenous Rights Holders, and other commercial developers and end-users.

We acknowledge with respect and gratitude that this report was produced on the traditional, ancestral, and unceded territories of the Coast Salish peoples, including the xwməθkwəy’əm (Musqueam), Skwxwú7mesh (Squamish), and səl’il’wətaʔɬ/ sel’íl’ witulh (Tsleil-Waututh) Nations, whose deep connections with this land continue to this day. NorthX is committed to advancing economic reconciliation by fostering meaningful partnerships with Indigenous Rights Holders and ensuring shared economic benefits through its projects and operations.

Notice to reader

NorthX has collaborated with ESMIA to produce a report on the fundamentals of biocarbon.

This report highlights economic opportunities, avenues for commercial-scale carbon sequestration, and solutions to reduce the carbon intensity of incumbent fuels. The report drives forward short-term and tangible decarbonization pathways, positioning BC to lead the way. While the report emphasizes the significant role biocarbon can play in meeting emissions targets like carbon dioxide removal (CDR), biocarbon is not a replacement for other decarbonization such as electrification. To address and mitigate climate change in BC, these elements and more will need to be synergistically incorporated to meet regional, national, and international needs.

For NorthX, research reports like this (Biocarbon Rising: From Concept to Commercialization) are a key part of the data gathering that underpins our investment thesis, shaping future funding opportunities. Our intelligent, risk-taking framework empowers us to confidently lead investment into disruptive, climate technology innovation. By leveraging the knowledge gathered through a combination of deep-dive reports, community engagement, and world-class subject matter experts, NorthX uniquely validates future pathways to net zero by identifying the optimal, high-impact convergence point of breakthrough decarbonization solutions and real-world readiness for implementation.

Thank you to ESMIA, GECA Environnement (GECA), and to all who actively collaborated in our research, content development, and prescreening of the report.

NORTHX CLIMATE TECH:

NorthX Climate Tech is a catalyst for climate action. We stand at the intersection where potential meets opportunity, funding the climate hard tech solutions that transform industries and build lasting prosperity. Rooted in British Columbia but global in vision, we unite visionaries, investors, industry, and partners to scale technologies that drive deep decarbonization and economic growth for Canada. Like the "X" on a map, we pinpoint that pivotal moment when potential is immense, but capital is scarce, that place where local strengths become global solutions.

ESMIA:

ESMIA is a leader in integrated 3E (energy-economy-environment) systems modelling and analysis for strategic decision-making on complex issues such as energy transition and energy security. ESMIA offers a scientific approach, guided by sophisticated models and high-quality data, which allows energy and climate goals to be achieved without compromising economic growth. ESMIA provides a comprehensive suite of modelling services: i) develop state-of-the-art turnkey models for organizations worldwide, ii) assist clients in building their own models, iii) deliver studies on energy pathways and energy policies leveraging its proprietary models.

SUPPORT FROM GECA:

The project team acknowledges the important support of GECA, a world-renowned firm of experts in the transformation of waste (biomass, digestates, forest residues, plastics, etc.) into value-added products like biochar, bio-oil, and renewable natural gas using thermal processes (pyrolysis, torrefaction, gasification). Operating in over 30 countries, GECA accelerates projects through strategic, scientific, and technical consulting. As a global leader in biochar carbon credit development and trading on the voluntary market, GECA also supports R&D, production planning, and environmental reporting for biocarbon projects. GECA created PyroList, a platform connecting buyers and sellers in the biocarbon sector. GECA is widely recognized for its research and expertise in biocarbon technologies.

Disclaimer

NorthX, ESMIA, and GECA do not assume any responsibility or liability for losses incurred by any party because of the circulation, publication, reproduction, or use of this analysis contrary to its intended purpose. The analysis is provided as of October 2024, and we disclaim any undertaking or obligation to advise any person of any change in any fact or matter affecting this analysis, which may come or be brought to our attention after that date. In the analyses, we may have made assumptions with respect to the industry performance and other matters, many of which are beyond our control, including government and industry regulation. No opinion, counsel, or interpretation is intended in matters that require legal or other appropriate professional advice. It is assumed that such opinions, counsel, or interpretations have been, or will be, obtained from the appropriate professional sources. To the extent that there are legal issues relating to compliance with applicable laws, regulations, and policies, we assume no responsibility.

Contents

Contents

Executive summary

This report provides a comprehensive overview of the biocarbon value chain—from concept to commercialization—including feedstock pathways, conversion technologies, market outlooks, and emerging opportunities for industry. Leveraging the North American Times Energy Model (NATEM) through a Techno-Economic Optimization Analysis, the report delivers insights to inform stakeholders on the potential and economics of the biocarbon sector. While these findings are focused on BC's context, they offer a scalable model for other jurisdictions with similar resource potential. The following executive summary outlines key questions addressed in detail throughout the report, including:

- What is biocarbon?
- Which feedstocks are most feasible for large-scale biocarbon production?
- What production technologies and end-use products are most commercially viable?
- What are the drivers for commercial scale deployment, and what investment is needed?
- What is the current and future market potential for biocarbon?
- What are the opportunities for industry?
- What is biocarbon's role in decarbonization?
- What actions can be taken to scale biocarbon production and use by 2050?

What is biocarbon?

Biocarbon is defined as the solid, liquid, and gaseous products generated from the aerobic or anaerobic thermal decomposition of biomass residues. These products include: biochar, bio-coal and torrefied pellets, hydrochar, bio-oil, wood vinegar, and synthesis gas (syngas).

Which feedstocks are most feasible for large-scale biocarbon production?

The five biomass categories identified as having the highest potential for conversion to biocarbon are: co-products from primary and secondary wood processing, forest harvest residues, dead wood, construction, renovation and demolition wood, and agricultural residues. A key feedstock consideration is moisture content, as most current conversion technologies require low moisture levels—typically below 10%—for efficient processing. Biomass is composed of three main components: lignin, cellulose, and hemicellulose. Generally, cellulose tends to yield bio-oil, hemicellulose favors syngas production, and lignin predominantly produces biochar. Currently, dry (<10% moisture content), woody, lignin-rich biomass is considered the most suitable feedstock for biocarbon production.

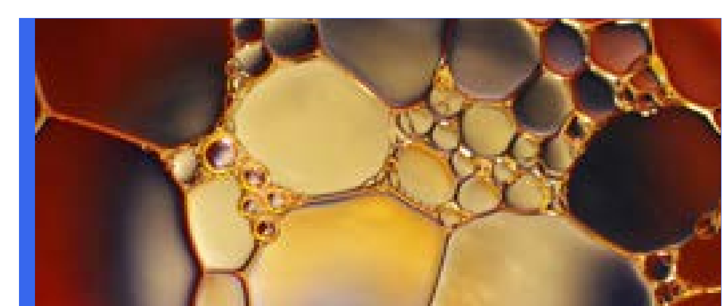
Modelling suggests the use of wood processing plant residues or comparable feedstock for biocarbon needs to increase from 1 million tonnes (MT) to 2 MT by 2035. While BC and Canada's abundant biomass resources provide a competitive advantage for feedstock supply, doubling sustainable feedstock utilization presents a substantial challenge due to competition for reliable, low-cost biomass.

What production technologies and end-use products are most commercially viable?

The main biocarbon production technologies are pyrolysis, carbonization, hydrothermal processing, and gasification. These technologies range from Technology Readiness Level (TRL) 5 - 9. These processes yield solid (e.g. biochar and bio-coal), liquid (bio-oil), or gaseous (syngas) outputs. Currently, the most commercially viable and widely adopted production technology is slow pyrolysis due to its versatility and operational flexibility. The primary output of slow pyrolysis is biochar. To remain economically feasible, however, feedstock costs must be kept between $45 - 60 CAD per tonne.

The emerging technologies that show the most promise are slow pyrolysis processes that produce both biochar and syngas, fast pyrolysis systems with high bio-oil output, and gasification systems followed by methanation for renewable natural gas (RNG). Fast pyrolysis and methanation are at a lower TRL than slow pyrolysis and require early investment to reach commercial scale in the next five years. For commercial viability, processes that produce biochar with minimal carbon loss during production (i.e. high carbon conversion efficiency) are favored.

When it comes to end-use products, modelling indicates that biochar used as a material additive will see the highest consumption between 2024 and 2050. After 2035, gasification-derived syngas and upgraded bio-oil have the potential to become significant decarbonization tools, particularly for industrial heat and transportation sectors.



What are the drivers for commercial scale deployment, and what investment is needed?

The biocarbon industry supports net-zero goals by enabling both carbon sequestration and emissions reduction through fuel switching to lower carbon intensity (CI) alternatives. Main drivers include net-zero commitments, carbon markets and incentives, social licensing, technological development, economic viability, and access to affordable feedstock.

The Intergovernmental Panel on Climate Change (IPCC) asserts that any pathways to limit global warming to 1.5°C require not only reducing emissions but also removing CO_2 from the atmosphere. Carbon sequestration is a key component of these pathways [1]. Extrapolations from the NATEM model show a sequestration potential of 46 million tonnes (MT) CO_2e by 2050, along with the capacity to reduce emissions by 17 MTCO_2e in hard-to-abate sectors such as industrial heat and transportation. Achieving these outcomes will require sustained increases in investment totaling approximately $450 million (M) CAD (2022 dollars) annually by 2050. Biochar production requires 65% of this required investment.

Carbon markets and incentives are key to commercializing biocarbon. In regulated systems, carbon avoidance credits can be earned by lowering feedstock carbon intensity (e.g. with bio-coal or upgraded bio-oil). In carbon dioxide removal (CDR), the largely unregulated voluntary carbon market (VCM) remains a primary enabler of business models. In 2023, CDR.fyi reported biochar accounted for 93% of CDR deliveries. Robust measurement, reporting, and verification (MRV) is essential for market confidence, compliance, and long-term success.

Gaining public support through social licensing is a critical aspect of successful biocarbon project development. Raising awareness about the benefits of biocarbon technologies and actively engaging communities in the planning and implementation processes helps ensure broad acceptance and participation. Key engagement strategies include enhancing public education, involving local communities to address concerns and build trust, and fostering collaboration among stakeholders such as industry, academia, government, and community groups. Cross-jurisdictional partnerships can also contribute to long-term project success. Central to this approach is economic reconciliation, which should be prioritized to ensure biocarbon initiatives align with community goals and deliver shared benefits. This includes meaningful, equitable partnerships, transparent credit models, and strong revenue pathways for Indigenous Rights Holders in the biocarbon sector.

To effectively scale, investment rates in biocarbon production must reach approximately $157 - 198 MCAD (2022) / yr by 2035. Technological development is key to large-scale production. To effectively process diverse feedstocks and optimize biocarbon yields, innovations are needed to handle high-moisture-content biomass, control product moisture levels to meet downstream processing requirements, and develop new applications, such as biocarbon-compatible catalysts, that enable accelerated market uptake.

The high initial costs of biocarbon technology deployment and the uncertainty of return on investment (ROI) are substantial challenges to economic viability, where projects need to have the right mix of financial support to succeed. Two examples of project funding that have a higher risk of failure include those financing projects through 100% pre-purchase of carbon removal credits, or those that finance with 50% grants and 50% bank loans. Contractual agreements, careful equipment selection, and consultation with carbon credit experts are key to reducing risk and providing assurance to investors.

Access to sustainable, reliable biomass feedstock is essential for the development of biocarbon production in BC, with wood processing plant residues currently serving as the primary source. However, competition with the pellet industry poses significant challenges, especially as modelling shows BC feedstock utilization could reach 99% by 2050. Access to cost-effective feedstocks may be limited due to existing export demands and long-term pellet contracts. To increase supply, BC may need to incentivize the use of forest slash piles and increase retention of domestic sawmill residues. Alternative feedstocks like woody debris from landfills and refuse-derived fuel (RDF) may also be viable with appropriate incentives but product quality may become more variable.

What is the current and future market potential for biocarbon?

Since the IPCC highlighted biochar production as a Negative Emissions Technology (NET) in 2018, interest in biochar and its co-products (bio-oil and syngas) has surged. Modelling indicates a biocarbon market shift in Canada from use as energy towards greater incorporation of biochar's material sequestration capability and the decarbonization of liquid and gaseous fuels. Market growth is led by solid biocarbon, with 420,000 tonnes of solid biocarbon (biochar, bio-coal, and torrefied pellets) expected to be produced in BC in 2025.

Biochar is currently the leading tool for negative emissions, priced at $188 CAD / tonne in 2023 on the voluntary carbon market (VCM). The global market size was estimated to be $777.1 million CAD (MCAD) in 2023 with an expected compound annual growth rate (CAGR) of 13.9% to 2030. In Canada, the total production of solid biocarbon (including announced projects) is around 1.2 million tonnes per year (MT / yr), with actual production reaching about 250,000 tonnes per year (t / yr).

Looking to the future, BC has significant potential to expand biocarbon consumption, with projections of 3x by 2035 and 8.5x by 2050 (reaching 129 petajoules per year (PJ / yr)). Biochar is expected to dominate the biocarbon market and will likely be used for carbon sequestration through agricultural soil, mining soil reclamation, construction, and other emerging markets. Bio-coal products are expected to be used for industrial heat, however, near-term uptake is dependent on adoption by heavy industry. Although the growth of bio-oil and syngas markets is slower, their importance in producing drop-in fuels and decarbonizing industrial heat is projected to lead to increased market penetration over time.

What is the opportunity for industry?

Biocarbon is expected to have the greatest consumption and opportunity in the agricultural, transportation, and industrial sectors. Biocarbon demonstrates material carbon sequestration potential of 46 $MTCO_2e$ in BC. It is also seen to increase combined transport and industrial heat decarbonization capacities by up to approximately 17 $MTCO_2e$ by 2050.

Based on global market projections, biochar shows considerable potential (over bio-coal) in its use within the CDR industry, where its global sequestration potential is estimated to be 0.4 - 6.6 gigatonnes per year ($GTCO_2$ / yr). This corresponds to 1.1% to 17.6% of global CO_2 emissions in 2023 (37.4 GT). Industrial applications of biocarbon include soil remediation, reclamation of abandoned mine lands, and integration into durable building materials such as cement and asphalt. If successful, the carbon removal duration could range from 100 to 1,000 years.

The current applications for bio-oil are as replacements for conventional fuel oils in commercial and industrial heating applications, combustion for power generation (boilers and gas turbines), and upgrading for use as transportation fuels. Whereas the applications for syngas are industrial heat, as well as the production of ammonia, methanol, hydrogen, liquid fuels, and electricity.

Overall, industrial applications are dependent on access to new site developments and low carbon feedstocks. Without these, biocarbon production will shrink to 33% of its current scale and may face significant competition from the biofuels industry.

What is biocarbon's role in decarbonization?

Biocarbon has the potential to rapidly and significantly contribute to BC's decarbonization goals and offers a near-term deployment option. Among these impacts, biocarbon shows significant promise in carbon sequestration and reducing industrial heat and transportation emissions. By 2035, biocarbon could sequester 9 $MTCO_2e$, reduce industrial heat emissions by 1.4 $MTCO_2e$, and decarbonize up to 1 billion liters (BL) of renewable diesel (1.3 $MTCO_2e$) or bio-jet fuel (0.5 $MTCO_2e$). By 2050, sequestration potential increases to 46 $MTCO_2e$, industrial heat emissions reductions grow to 7 $MTCO_2e$, and transportation decarbonization reaches 10 BL of renewable diesel (10 $MTCO_2e$), or bio-jet fuel production of 10 BL (3 $MTCO_2e$).

What actions can be taken to scale biocarbon production and use by 2050?

Modelling shows that biocarbon has considerable potential for growth after 2035. However, if action is not taken by 2035, then production is expected to decline, reducing the probability of BC being able to fully utilize biocarbon as a resource in meeting its net-zero goals.

To advance the biocarbon industry, stakeholders (innovators, industry leaders, investors, academia, policy makers, and Indigenous Rights Holders) must achieve several targets by 2035 and 2050:

Economic reconciliation

Engage early and ensure project outcomes align with community needs and objectives. Build meaningful, equitable partnerships, transparent credit models, and robust revenue pathways into project development.

Carbon sequestration

Scale biochar to sequester at least 1 MT of CO_2e in BC (close to half a million tonnes of high-quality biochar) by 2035 and 2.7 MT of CO_2e by 2045. Develop a robust market for biochar applications in agriculture, mining soil reclamation, construction, and other emerging markets, reaching specific market-wide consumptions of 0.4 MT by 2035 with over 25,000 tonnes used as construction additives. Enable growth of 6 - 8% for the biochar market in the medium-term. Policy incentives also should contribute to increasing the cost-effectiveness of feedstocks being used for carbon sequestration with biochar, reaching parity with wood pellet exporting.

Decarbonizing transport

Facilitate bio-oil upgrading facilities to exceed 25% annual growth before 2035, prioritizing drop-in fuel (DIF) production to decarbonize hard to abate transport.

Decarbonizing heat

Target biomass-derived syngas for industrial heating applications to achieve short payback periods, achieving a market potential of 5 PJ by 2035.

Required investment

Secure long-term contracts for biocarbon consumption, aiming for 0.4 MT of biochar and 20 PJ from bio-oil and syngas (combined) by 2035. Investments of over $60 MCAD (2022) / yr by 2035 to grow syngas to RNG production to displace natural gas. By 2045 investment rates need to achieve over $190 MCAD (2022) / yr with a third being allocated towards slow pyrolysis technologies alongside investments in upgraded bio-oil refining catalysts.

Access to reliable feedstock

Establish a reliable, cost-effective supply chain for feedstock that doubles the use of wood processing plant residues or comparable feedstock from about 1 MT in 2024 to over 2 MT by 2035. Achieve a feedstock price range of $45-60 CAD / tonne.

Introduction

What is biocarbon?

Biocarbon is defined as the solid, liquid, and gaseous products generated from the aerobic or anaerobic thermal decomposition of biomass residues. Many people are familiar with charcoal, a solid form of biocarbon used for heating or cooking but are unfamiliar with its other forms:

SOLID BIOCARBON
• Biochar • Bio-coal/torrefied pellets • Hydrochar
LIQUID BIOCARBON
• Bio-oil • Wood vinegar
GASEOUS BIOCARBON
• Synthesis gas (syngas)

Together, these products offer sustainable alternatives to traditional fuels, fertilizers, and construction materials—while also delivering significant environmental benefits. These include long-term carbon sequestration, waste reduction, pollution control, and improving soil health through amendment and remediation.

The objective of this study is to inform interested parties about the fundamentals of biocarbon technologies, its current market outlook within Canada, and its potential applications as an impactful contributor to provincial, national, and international net-zero goals.

Below illustrates this report's structure alongside the scope of the analysis conducted.

Chapter 01: Technology fundamentals

- Technology descriptions with TRL comparison.
- Feedstock availability with impacts on production pathways.
- Current technology uses within the market.

Chapter 02: Market opportunities

- Current market applications within Canada.
- Future applications for biocarbon with projected product splits.

Chapter 03: Biocarbon's decarbonization potential

- Biocarbon consumption projections.
- Decarbonization potential for hard-to-abate industries.
- Considerations and requirements for biocarbon impact to be realized.

Chapter 01: Technology fundamentals

Chapter highlights:

01

BIOCARBON CURRENTLY FACES TECHNOLOGY BARRIERS

Technology readiness level: 5 - 9

02

CURRENT TECHNOLOGIES REQUIRE LOW MOISTURE LEVELS IN THE FEEDSTOCK

Required feedstock moisture: 10%

03

BIOCARBON TECHNOLOGY USED

Pyrolysis is the dominant biocarbon technology worldwide

04

FEEDSTOCK OF CHOICE FOR BIOCARBON

Dry woody and lignin-rich biomass

How is biocarbon produced?

The history of biocarbon production goes back thousands of years and has a wide range of useful applications. Today, it is produced through specialized thermal processing technologies that convert biomass residues into various biogenic products.

The main production technologies are pyrolysis, carbonization, hydrothermal processing, and gasification. Table 1, at the end of this section, summarizes the various technologies with their Technology Readiness Levels (TRLs), process conditions, and byproduct yields.

Pyrolysis

Pyrolysis is the process of heating organic material in an oxygen-limited environment to produce a mixture of solid, liquid, and gaseous byproducts. Modern pyrolysis processes range from small-scale artisanal kilns to highly engineered and controlled industrial thermal decomposition systems that can produce a wide variety of useful products:

- Biochar (solid): Long-lasting, porous carbonaceous material that can, depending on its characteristics, be buried in the ground and provide negative emissions while increasing the health and fertility of agricultural or forest soils [2].
- Bio-oil (liquid): Can be upgraded for use in combustion applications (substituting diesel, gasoline, and jet fuel), deconstructed into chemical feedstocks (acids and phenols), or injected underground for long-lasting carbon sequestration (Biomass Carbon Removal and Storage (BiCRS) or biomaterial injection) [3][4].
- Syngas (gas): Can be upgraded for use in combustion applications or converted into renewable natural gas (RNG).

TECHNOLOGY INSIGHTS

Pyrolysis-produced biochars are characterized by their additional environmentally sustainable production, quality, and usage features. To qualify what is considered “biochar” vs. charcoal or torrefied bio-coal, the European Biochar Certification (EBC) and World Biochar Certification (WBC) guidelines agree that only biomass pyrolysis processes at 350°C to 1000°C in a low-oxygen environment can create the characteristics of biochar.

Pyrolysis can be categorized into torrefaction (mild pyrolysis), slow, intermediate, fast, and microwave pyrolysis, differing in feedstock, temperature, heating rate, residence time, and product yield. All types require low feedstock moisture (~10%), necessitating drying of fresh biomass residues before processing [5]. Pyrolysis process temperatures and heating rates determine the main outputs:

- <500°C with slow heating rates produce charcoal, torrefied pellets, or biochar.
- 450 - 800°C with moderate to high heating rates produce bio-oils.
- >800°C with high heating rates produce syngas.

The flexibility of process temperatures and heating rates allows the same facility to generate a variety of products depending on how the process is controlled [6]. Microwave pyrolysis is the exception as it is an emerging alternative that offers more controlled and uniform heating, producing high-quality biochar and bio-oils [7]. This exclusion may also apply to torrefaction as its use tends to be optimized for the generation of solid biocarbon in the form of bio-coal.

Occurring anaerobically at 200 - 300°C, torrefaction is the only pyrolysis method that produces no liquid products whereby 20% of feedstock mass is lost as moisture and volatile compounds. Its product is a dry, homogenous, storable, water-resistant solid (known as bio-coal or charcoal). This can be combusted with low carbon intensity or further processed via gasification and Fischer-Tropsch to produce low carbon liquid fuels. Torrefaction solid products can 100% replace coal in power plants and heating intensive applications such as ironmaking and steel production—offering a significantly greater decarbonization opportunity compared to the current co-firing limit of ~10% with wood pellets [8][9][10].

Carbonization

Carbonization is similar to slow pyrolysis but aims to maximize solid carbonaceous fuel production like charcoal, rather than liquid or gaseous co-products. It is also similar to torrefaction but occurs at higher temperatures (>350°C vs. 200 - 300°C) and produces a more energy dense fuel. Charcoal, intended as a fuel, has more volatiles or tars and is less porous than biochar, breaking down quickly in soil. Recently, a specialized form called flash carbonization has been developed.

Flash carbonization is a specialized thermochemical treatment process for biomass residues to produce biochar. The production takes place in a packed

bed reactor that is pressurized with air (1 - 2 bar). It can produce a relatively high biochar yield (up to 50%) in less than 30 minutes at moderate temperatures (400 - 650°C) [11].

Hydrothermal processing

Hydrothermal processes have emerged as an alternative to the conversion of second-generation biofuel sources (wood and agricultural residues, aquatic biomass, animal manures, inedible oils, sludges, etc.) into useful carbonaceous solids, liquids, and gases. The distinguishing feature of these processes is in their ability to treat wet biomass residues (up to 90% moisture content), thus eliminating the energy intensive drying step of pyrolysis and gasification [12][13]. There are three main types of hydrothermal processing based on temperature and pressure ranges—hydrothermal carbonization (HTC), hydrothermal liquefaction (HTL), and hydrothermal gasification (HTG).

Hydrothermal carbonization (or wet pyrolysis) has emerged as an alternative to traditional pyrolysis processes as it can receive wet biomass residues. HTC is a thermochemical process in which a mixture of wet biomass and water is treated under 20 - 100 bar of pressure and relatively low temperatures of 100 - 300°C to produce a high-yield, “hydrochar” [14]. The hydrochar leaves the process as a carbonized paste and is made into a pulverized powder through mechanical compression and excess drying, achieving a moisture content of 5 - 25%. This powder can be pelletized and stored the same way as torrefied pellets or fossil coal [15]. Hydrochar’s use as a coal substitute has recently been investigated and its qualities fall into the following coal-fired steam applications: domestic and non-domestic power generation and cement kiln operations [16][9][10].

Hydrothermal liquefaction takes place at higher temperatures and pressures than HTC at 275°C – 400°C and 50 - 250 bar. The main output of the HTL process is bio-oil, along with a typically smaller share of hydrochar. Bio-oil yields from HTL can range from 10 - 65% depending on the type of biomass being processed and process parameters (temperature, pressure, heating rate, and solvent ratio) while the hydrochar output can range from 2 - 40% [17][13][18][19][20]. Bio-oils produced from HTL vs. pyrolysis usually have: a higher heating value (~35 MJ / kg vs. ~23 MJ / kg), lower oxygen (O_2) content (~16% vs. ~36%), lower moisture content (~5% vs. ~25%), and are more thermally stable. This makes them more suitable for direct use as fuels in many stationary applications, and potentially easier to upgrade as renewable replacement fuels for gasoline, diesel, and jet fuel [21][22].

Hydrothermal gasification occurs at the highest temperatures and pressures among hydrothermal processes, bringing water to a near or fully supercritical state, where it exhibits properties of both a liquid and a gas [23][24]. The process usually occurs very quickly and produces syngas comprised of mostly hydrogen (H_2) and methane (CH_4) (conventional gasification produces syngas with H_2 and carbon monoxide (CO)).

Gasification

Gasification typically occurs at higher temperatures than pyrolysis and uses a controlled amount of air to produce syngas as the main output. Syngas has up to half the energy density of natural gas (5 - 20 MJ / m^3 vs. ~40 MJ / m^3) and is composed of mainly CO (30 - 60%) and H_2 (25 - 30%) with smaller amounts of CO_2 (5 - 15%) and CH_4 (0 - 5%). The gasification process itself is exothermic, so it is typically more energy efficient than pyrolysis (endothermic) [25].

Syngas can be used in multiple ways. In its raw form, it can be used as a fuel for gas turbine combined heat and power production, or it can be used as a natural gas replacement in pre-existing kilns, calciners, and solid-fuel boilers in industrial facilities. Raw syngas can be further processed into ammonia, methanol, or liquid transportation fuels via gas-to-liquids processes (i.e. drop-in fuels (DIFs)), and it can also be converted to RNG via methanation.

Technology summary

Each technology has its unique place within the biocarbon market. Pyrolysis, for instance, is a versatile process that can be adjusted to produce biochar, bio-oil, and syngas with lower product selectivity and therefore, has the potential for greater process complexity. Hydrothermal processes are less versatile than pyrolysis but offer the advantage of processing wet lignin biomass, eliminating the need for drying. Gasification's selectivity is even smaller by primarily producing syngas, a versatile fuel that can be used or further processed for various 'hard-to-abate' industrial applications. The differences between these technologies, including their process conditions and product yield potential, are summarized in Table 1.

Biocarbon production technologies, operating conditions, and byproduct yields

TECHNOLOGY [26]	TRL	PROCESS CONDITIONS				PRODUCT YIELDS (%)		
		TEMPERATURE	OXYGEN (%)	RESIDENCE TIME	HEATING RATE	BIOCHAR	BIO-OIL	SYNGAS
HYDROTHERMAL CARBONIZATION (HTC)	6 to 8	100 - 300°C	0% oxygen, 20 - 100 bar pressure with water	1 hrs - 16 hrs	Slow (10 - 30°C / min)	45 - 95% (hydrochar / bio-coal)	5 - 20%	0 - 5%
TORREFACTION	8 to 9	200 - 300°C	0 - 10%	10 - 120 min	Slow (<20°C / min)	60 - 80% (charcoal / bio-coal)	0%	20 - 40%
HYDROTHERMAL LIQUEFACTION (HTL)	5 to 8	275 - 400°C	0% oxygen, 50 - 250 bar pressure with water	5 - 120 min	Moderate (30 - 110°C / min)	20 - 40% (hydrochar / bio-coal)	35 - 65%	0%
SLOW PYROLYSIS (SP)	8 to 9	300 - 500°C	0 - 2%	10 min - several days	Slow (1 - 10°C / min)	20 - 80% (35% avg)	30 - 40%	20 - 40%
INTERMEDIATE PYROLYSIS (IP)	8 to 9	400 - 600°C	0%	1 - 15 min	Moderate (1 - 10°C / sec)	30 - 40%	35 - 50%	20 - 30%
MICROWAVE PYROLYSIS (MP)	5 to 6	350 - 650°C	0%	1 min - 60 min	Fast (25 - 50°C / min)	15 - 80%	8 - 70%	12 - 60%
FLASH CARBONIZATION (FC)	5 to 7	400 - 650°C	Air used to maintain process pressure and temperature	<30 min	Very fast (1,000°C / sec)	50% (biochar / charcoal)	0%	50%
HYDROTHERMAL GASIFICATION (HTG)	5 to 9	375 - 700°C	0% oxygen, 90 - 400 bar pressure with water	<1 - 60 min	Moderate - very fast	0%	0%	65 - 100% (H_2 and CH_4)
FAST PYROLYSIS (FP)	8 to 9	300 - 1,250°C	0%	0.5 - 5 seconds	Very fast (100°C - 1,000°C / sec)	5 - 38% (12% avg)	50 - 75%	10 - 25%
GASIFICATION	8 to 9	600 - 1,500°C	Less than stoichiometric (6 - 6.5 kg air / kg dry wood)	10 - 20 seconds	Moderate - very fast	2 - 20%	< 5%	85%

Table 1 - Biocarbon production technologies, operating condition, and byproduct yields. Adapted from Safarain, Energy Reports, 2023

What feedstocks can be used?

BC ranks among the top forested jurisdictions in the world, with ~60% of its land covered in forests. The total forested area in BC has remained relatively stable at around 55 million hectares (Mha), and it has one of the lowest deforestation rates globally (6,200 ha per year) [27]. As one of the world's largest exporters of sustainable wood products, BC's forest industry is a key economic driver, historically accounting for 30% of the province's total commodity exports.

BC produces about 20% of solid biocarbon in Canada and despite BC's abundant biomass resources and a robust public commitment to sustainable biomass development, there are still challenges related to its market adoption. Examples include variable or uncertain biomass feedstock availability, reliable biomass accounting, high biocarbon production costs, limited end-use applications, and an awareness gap that hinders technological and business model development. The following sections evaluate and discuss these challenges to provide a clear understanding of the market opportunity.

When analyzing feedstock availability, five biomass categories were identified as having a high potential for conversion to biocarbon based on their characteristics and the substantial annual tonnages generated (Table 2). There are other potential biomass feedstock categories in BC that could be used for biocarbon production including aquatic biomass, animal and municipal waste, and sewage sludges. The potential for these feedstocks is not addressed explicitly as they generally have high moisture content (MC) and require substantial amounts of energy for drying or can only be used in specific conversion processes (e.g. HTL).

2023 availability of feedstocks in BC

FEEDSTOCK	2023 AVAILABILITY IN BC
Co-products from primary and secondary wood processing	8 million dry tonnes
Forest harvest residues	2.4 million dry tonnes
Dead wood	780,000 dry tonnes
Construction, renovation, and demolition (CR&D) wood	348,000 dry tonnes
Agricultural residues	121,000 dry tonnes

Table 2 - 2023 availability of feedstocks in BC

Co-products from primary and secondary wood processing

The products of primary and secondary wood processing plants include wood chips, sawdust, and shavings. Bark generated during primary processing operations also falls into this category, as do residues generated solely during secondary processing. The use of the terms "secondary processing" or "secondary transformation" encompasses both the second and third stages of wood processing. These products are primarily obtained during sawmill, veneer, or pulp and paper mill operations. Forest harvest residues (or residual forest biomass) refer to the logging residues left in the forest following forestry operations. These residues include only non-commercial wood material resulting from forest management activities or from short-rotation plantations conducted for energy production purposes. Forest harvest residues are often referred to colloquially as "slash piles". Another type of forest harvest residue is bark deposits, which result from the accumulation over several years of bark produced by the debarking operation at sawmills and paper mills. Similar to forest harvest residues, dead wood refers to all the non-living woody biomass, either standing on the ground or in the soil. Dead wood includes fallen trees, branches, twigs, dead roots, and stumps of sufficient size (>10 cm). Dead wood can form through different processes including age or natural death, competition for resources, severe weather conditions, forest fires, or insect infestation or damage.

CR&D wood encompasses all wood residues that have been used in applications other than energy production. This includes residues from the construction industry or wooden pallets used by the handling industry. This material is found in sorting centers, eco-centers, landfills, or at large private landowners who accumulate stocks of CR&D wood with the intention of reselling them at a competitive price. Urban wood waste and refuse derived fuel (RDF) made from a mix of CR&D and municipal solid waste (MSW) can also be categorized under CR&D.

Agricultural residues

Agricultural residues or by-products are defined by the BC Ministry of Agriculture and Food (MAF) as agricultural vegetative debris, manure, soiled animal bedding, dropped or spoiled feed or silage, composting residues, used mushroom growing substrate, and soilless media. Agriculture in BC encompasses a wide variety of crops: grains and oilseeds, field vegetables, forage, berries, grapes, mushrooms, tree fruits, and flowers and nursery plants.

How do feedstocks impact the production of biocarbon?

As demonstrated in the technology descriptions, the production of biocarbon is a complex endeavor. The feedstock selection, the process selection, the process temperature, the process heating rate, and the residence time of the feedstock can all impact the product(s). The characteristics of the end products themselves can vary dramatically between facilities or even within facilities as processes are tuned or feedstocks changed.

For all process types, the quality of the biocarbon outputs depend on the composition of the biomass feedstock used for its production. Biomass is made up of three main components: lignin, cellulose, and hemicellulose.

Generally, when processing biomass with the various thermo-chemical conversion technologies, cellulose produces a high bio-oil yield and a low biochar yield. Hemicellulose favors the production of syngas and bio-oils with higher content of water, ketones, and phenols. Finally, lignin is the major contributor to biochar (rather than charcoal) and can also generate bio-oil with a high oxygen content (low heating value, chemical instability) and high viscosity [28][29]. Infographic 1 summarizes the biomass feedstock inputs that can be processed with each biocarbon production technology, the moisture content requirements for the feedstock, and the end use applications for the different outputs.

Biocarbon production technologies, input feedstocks, moisture content required, and end uses for outputs

Infographic 1 – Biocarbon production technologies, input feedstocks, moisture content required, and end uses for outputs

INFOGRAPHIC OVERVIEW

1:FEEDSTOCKS
Feedstocks are shown at the centre of each plot.

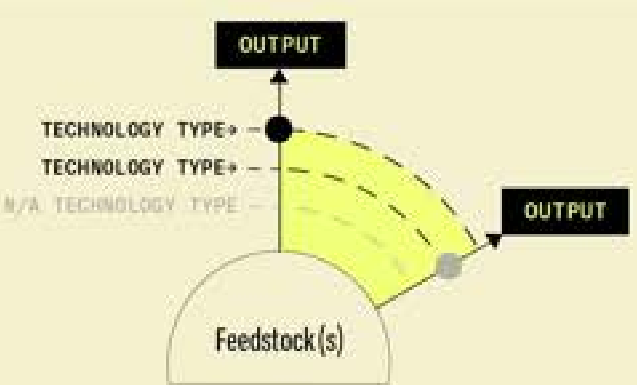
2:END USE PRODUCT FOR OUTPUT
Biocarbon products are shown in black boxes dividing the plots.

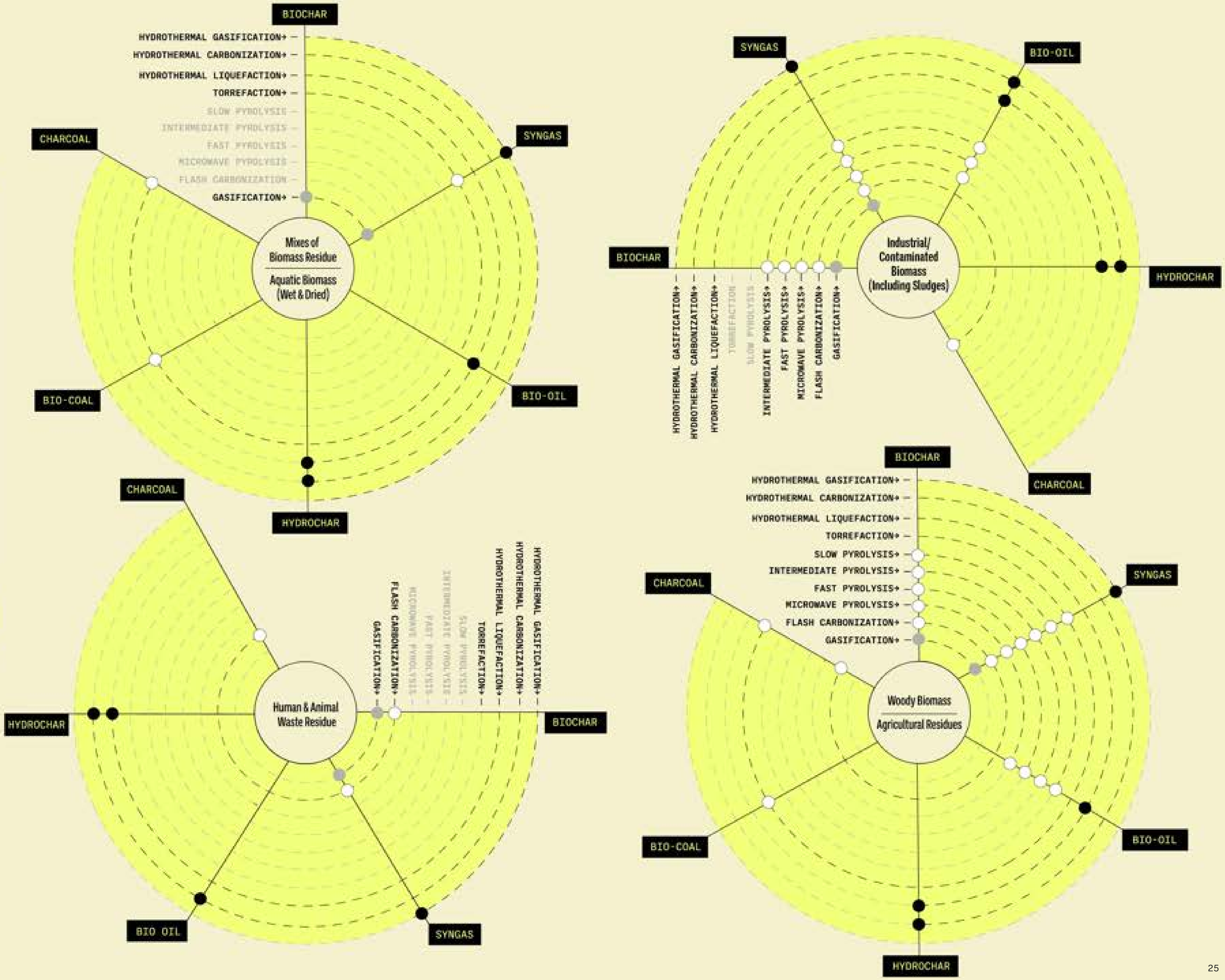
3:TECHNOLOGY TYPE
Feedstock processing technologies are listed at the beginning of the plots connected to a pathway. The ability for a technology to produce an end product with the feedstock(s) is indicated with a dot at the intersection of the technology pathway and end product.

4:MOISTURE CONTENT
The dot colour represents the moisture content requirement for the feedstock(s) in relation to the technology.See the legend for the three different moisture content ranges.

INFOGRAPHIC LEGEND

MOISTURE CONTENT		
● 70 - 90%	UP TO 35%, IDEALLY 10 - 15%	○ <10%





What technologies are used commercially?

A technology survey of biocarbon production technology developers and suppliers in Canada, United States of America (USA), and Europe was conducted by GECA, a Canadian biochar and pyrolysis consulting group. Only technologies at the proven pilot or more advanced stages of development were considered. In North America, 43 biocarbon technology providers were identified in Canada and 66 in the USA. In Europe, 115 different technology developers and suppliers were identified as either in production or in advanced stages of development or demonstration and were located mainly in Germany, France, Denmark, Sweden, and the Netherlands, see Figure 1.

Across all regions, pyrolysis was the most common technology type, followed by gasification. In Canada and the USA, torrefaction technology comes third, while in Europe, hydrothermal technologies show more significant supply.

These trends suggest that hydrothermal technologies may become more prominent in North America over the next decade as their average TRL advances toward full commercial readiness. Additionally, the need for more diverse feedstocks—potentially with higher moisture content—may drive further adoption to meet market demand.

It is likely pyrolysis will remain a significant biocarbon technology due to its ability to produce a variety of products, despite its lower selectivity for any single product. However, uncertainty around environmental changes (increases in regional humidity or precipitation), logistical requirements (access to viable feedstock), and general market risk (desirable products and specifications) will dictate where these technologies are established and how quickly they are adopted into the commercial landscape.

Number of biocarbon technology producers in the USA, Canada, and Europe

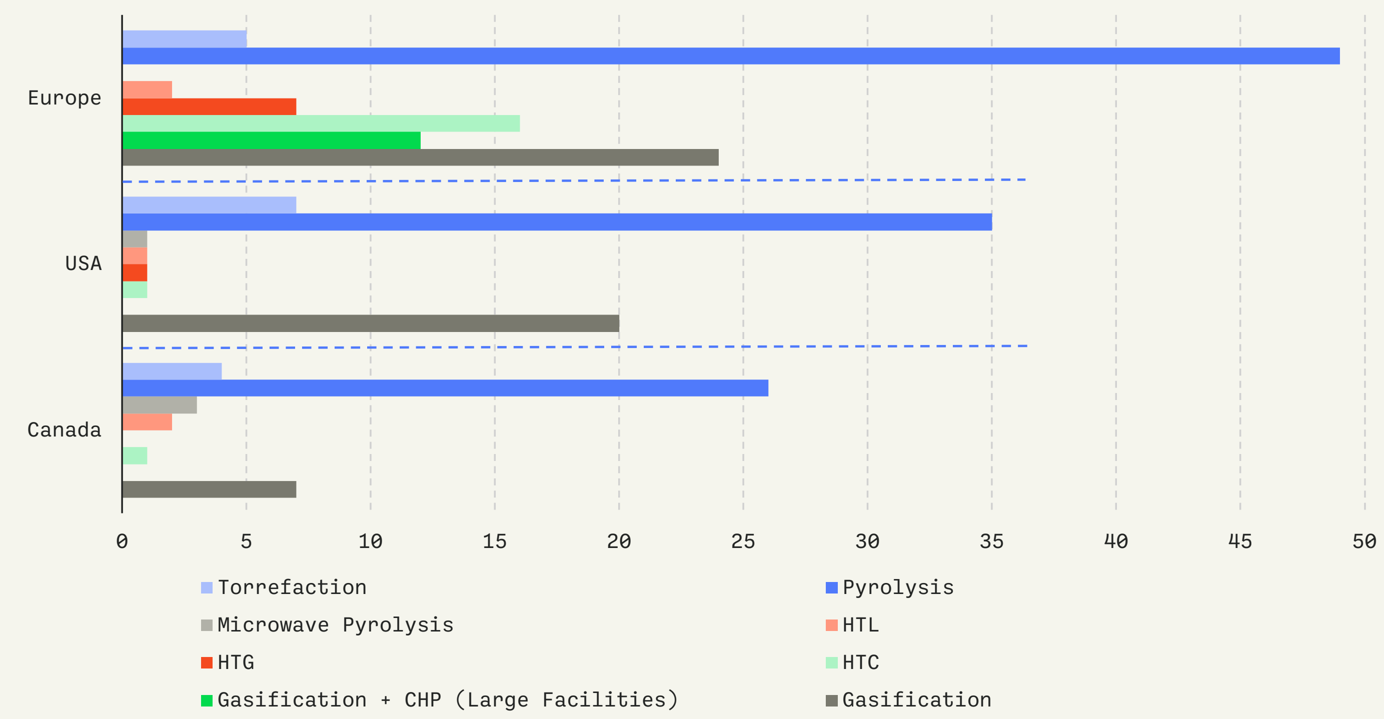


Figure 1 – Number of biocarbon technology producers in USA, Canada, and Europe by technology type

Chapter 02: Market opportunities

Chapter highlights:

01

DEVELOPING MARKETS

Transport and industrial heat

02

VOLUNTARY CARBON MARKET

Biochar is currently the leading tool for negative emissions at $188CAD / tonne (2023)

03

FUTURE PRODUCTION

Production rate reaches 129 PJ / yr by 2050

04

BIOCARBON MARKET GROWTH

Market growth led by solid biocarbon

Chapter 02: Market opportunities

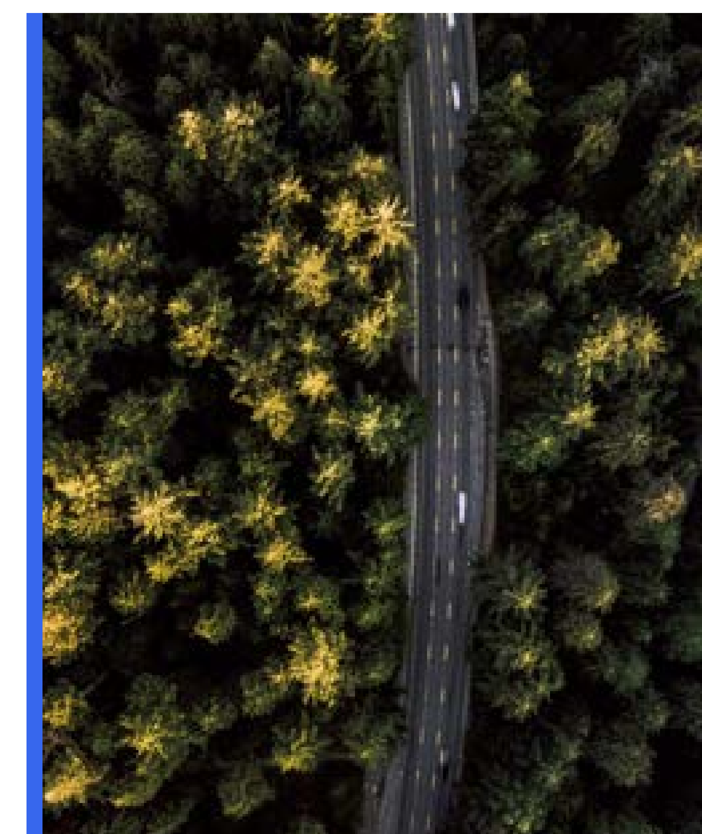
This chapter examines the role of biocarbon in supporting BC's decarbonization goals, with a focus on its current applications and market potential.

As outlined in the previous chapter, there are a range of technologies and feedstocks that can be used to produce biocarbon products to varying degrees of similarity. A significant factor not yet discussed are the viable market applications of these products and how they could change to meet to the decarbonization efforts of BC and Canada more broadly.

In theory, the biocarbon sector is a versatile industry which follows many of the same processing concepts as the oil and gas (O&G) sector: it processes highly varied and complicated inputs into a variety of commercial hydrocarbon-based feedstocks and products. In principle, this positions the industry well to decarbonize many hard-to-abate sectors such as mining, baseload energy production, construction, and essential mineral processing such as steel or iron production. However, this is not the reality. Unlike the O&G sector, the biocarbon industry has several factors acting against it, many of which are circular in nature (non-exhaustive):

1. Its primary resources are derived from living ecosystems or other land- and resource-intensive economic activities such as forestry and agriculture. This creates a trade-off between cultivation, conservation, and preservation. Therefore, this leads to the utilization of waste biomass and materials, the quality of which is hard to standardize.
2. The acquisition of resources is often expensive, labor-intensive, and requires considerable pre-treatment. This often results in reliance on another plant for co-processing or a 'resource collector' (such as a pulp and paper facility), both of which are sensitive to market changes and therefore increases project risk.
3. Biocarbon competes with incumbent, well-established, and economically superior industries such as O&G and mining, which have significant economies of scale already realized.
4. Asserting into established industries with prefabricated specifications make blending, substituting, and replacing feedstocks or products technically and/or economically undesirable.
5. The volumes required to make meaningful reductions in carbon intensity across the value chain are significant and make the necessary scaling economically challenging.

Despite these factors, biocarbon products provide a unique opportunity for the growth of low carbon alternatives that should be explored and market potential evaluated. The following section details the applications of biocarbon products, how they are currently used within the market, and how the wider market adoption may change on the journey to BC's 2050 net-zero milestone.



What applications apply to biocarbon?

MARKET INSIGHTS

From the biocarbon products described, both biochar and bio-oil are seen as carbon negative and are currently captured within the VCM.

Biochar: In 2018, the IPCC included the production of biochar via pyrolysis as a promising Negative Emissions Technology (NET) in the 15th IPCC special report on Global Warming of 1.5°C [49].

Bio-oil: In September 2024, the first bio-oil geological storage carbon removal protocol was released by carbon removal standard developer and registry, Isometric. [78].

The market applications for biocarbon are based on the mix of solid, liquid, and gaseous products produced by technologies discussed in the previous chapter. For solids, these are bio-coal (torrefied pellets or briquettes), biochar, and hydrochar. For liquids, these are bio-oils and wood vinegar ("liquid smoke" or pyroligneous acid). For the gas portion, this is syngas. These broadly split into the following market categories:

- Solid: Heat and power decarbonization, fine mineral substitution (soil remediation, agriculture and cement blending), and carbon sequestration.
- Liquid: Production of renewable transportation fuels, process heating, production of chemical feedstocks, and carbon sequestration.
- Gas: Production of renewable domestic heating fuel, process heating, and synthetic fuel feedstock.

Within the market, biocarbon has two main purposes: the generation of low carbon intensity feedstock (chemical or mineral), whereby revenue is generated in sales to commercial and industrial enterprises; and carbon sequestration, which generates revenue on the VCM for carbon dioxide removal (CDR). Each of these products has its own unique market potential, barriers, and opportunities within the commercial and industrial market. As a result, individual facilities that produce biocarbon might focus on one specific market or multiple markets at the same time to minimize risk, much like an oil refinery.

For example, a pyrolysis facility looking to pursue multiple markets can use biomass residues to produce:

1. Biochar that can be sold for use in agricultural applications and to generate carbon credits on the VCM (or potentially compliance carbon markets in the future).
2. Syngas can be used for process or facility heat, or upgraded to produce gaseous fuels.
3. Any liquid output can be collected and separated to generate bio-oil. This oil can then be used for direct use as crude, undergo further upgrading into transportation fuels, or be processed into wood vinegar. Wood vinegar can be sold as a replacement for chemical herbicides, natural pesticides, and as a growth stimulant for plants.

What is biocarbon's current market opportunity?

This section details global market potential and application trends within BC and Canada for solid, liquid, and gaseous biocarbon. Table 3 below outlines the global market size and growth associated with each main biocarbon product, illustrating their comparative impact on the market.

Biocarbon market size and growth

	SOLID [30] [31]		LIQUID [32]	GASEOUS [33] [34] [35]
MARKET PRODUCT	Biochar	Bio-coal	Bio-oil	Syngas
MARKET VALUE (CAD)	$777 M (2023)	$33 M (2021)	$86 M (2021)	42 M (2022)
CAGR (UNTIL 2024-2030)	13.90%	16.40%	4.30%	8.9%
POTENTIAL MARKET VALUE (CAD)	$2.3 B (2030)	$129 M (2030)	$126 M (2030)	64 M (2027)
CARBON REMOVAL CREDIT PRICE (AVERAGE CAD/TONNE)	$188 (2023)	N/A*	$724 (2023)	N/A*

N/A: Not applicable as a negative emissions technology

Table 3 - Biocarbon market size and growth

In recent years, biocarbon has exhibited promising potential and growth in commercial production and sales within commodity and voluntary credit markets. This is particularly true for BC and Canada, as it has enabled the development of multiple commercial solid biocarbon facilities over the next 1 - 3 years, where biochar will be the main product.

Market potential: Solid biocarbon

Biochar has seen a surge of interest over the past decade. In 2023, there were over 6,800 scientific publications related to biochar, an exponential increase since 2010 when there were just ~100 papers published [36]. It's global market size was estimated to be $777.1 million CAD (MCAD) in 2023 with an expected compound annual growth rate (CAGR) of 13.9% to 2030 [30].The International Biochar Initiative's (IBI) 2023 Global Biochar Market Report highlights the fact that in 2023, global biochar production reached ~350,000 tonnes, an increase of 91% compared to 2021, when they conducted a similar survey [2].

Outside of carbon sequestration and the VCM, there are over 100 potential uses for biochar in various industries, including agriculture, forestry, cement production, metallurgy, mining, advanced materials, and catalyst precursors.

All of which are dependent on the biochar grade or quality, which is determined by process conditions, feedstocks, and feedstock condition.

According to research done by GECA, the total production of Canadian biochar for actual and announced producers is around 1.2 million tonnes per year (MT / yr), with actual production reaching about 250,000 tonnes per year (t / yr). It is expected that, in the next few years, the number of producers and tonnage will increase dramatically to a projected 400,000 t / yr, as several plants are already under construction.

Biochar production in North America is expected to grow rapidly over the next 5 years, which will reduce its price. This growth is partly due to biochar being a byproduct of renewable energy production activities such as syngas and RNG production, and biomass power plants. Based on these analyses, GECA estimates the selling price of biochar to decrease by about 20% by 2035 and by 50% by 2050.

As can be seen in Figure 2 and Figure 3, most of the current and future (3 - 5 years) solid biocarbon production in Canada is concentrated in the four most forested provinces: BC and Alberta (AB) in the west; Ontario (ON) and Quebec (QC) in the east. BC is likely to become the largest producer of solid biocarbon in Canada in the next few years, with 40% of production. Market forecasts from GECA estimate that the number of announced solid biocarbon plants in Canada will double in the next 3 - 5 years. However, this forecast does not include small producers that are likely to appear over time.

Planned and actual solid biocarbon production in Canada by number of facilities and tonnage

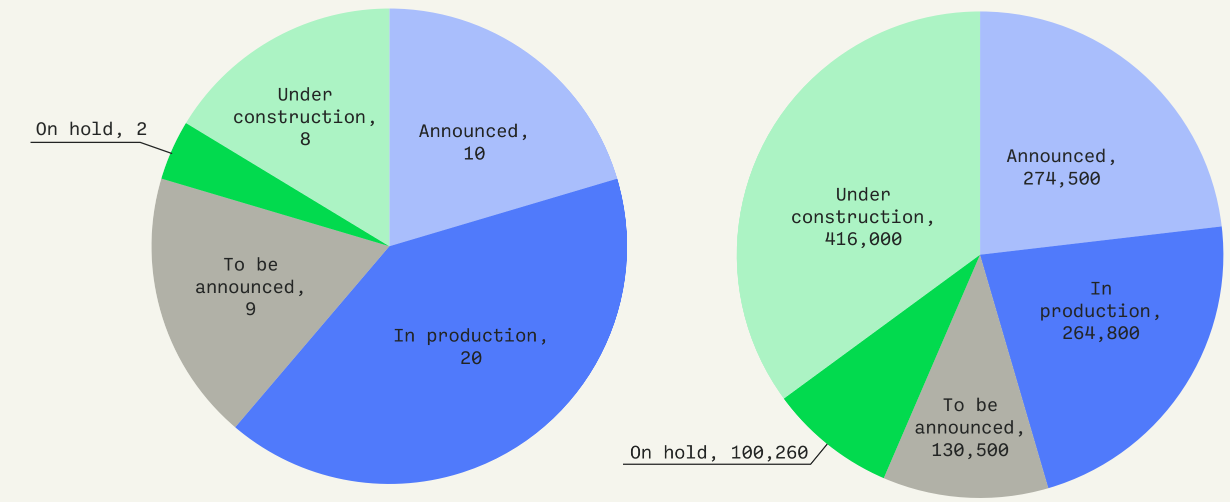


Figure 2 - Planned and actual solid biocarbon production in Canada by number of facilities (left) and by tonnage (right)

Annual tonnage of actual and future solid biocarbon production by province in Canada

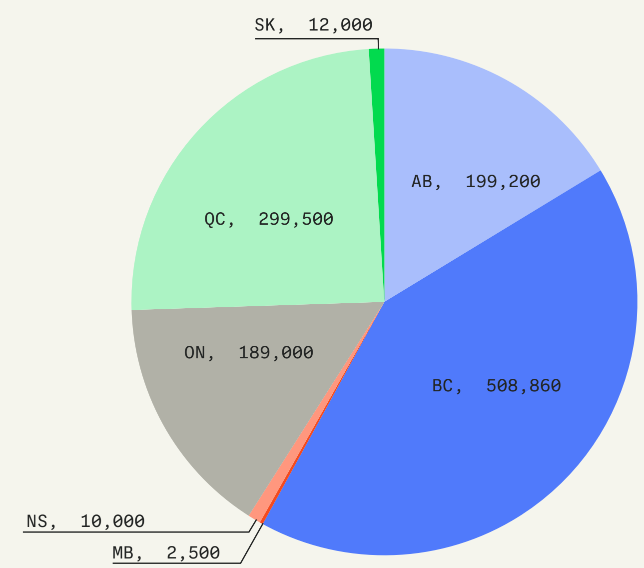


Figure 3 - Annual tonnage of actual and future solid biocarbon production by province in Canada

To meet this increase in production demand, approximately 65% of solid biocarbon production will need to come from forest and agricultural residues, with the majority for biochar and the remainder for pellets and briquettes. These products are expected to supply the VCM (the largest market for solid biocarbon, which is satisfied by biochar), followed by energy production (torrefied pellets), and agriculture and soil remediation. The remaining markets include activated carbon products (e.g. filtration systems), according to research conducted by GECA.

The market size for bio-coal (torrefied wood pellets and briquettes) is difficult to quantify since it is in the earlier stages of development. Currently, bio-coal represents a small fraction of the total wood pellet production globally. One market analysis firm, SkyQuest, estimated a market value of $32.8 MCAD for bio-coal in 2021, with a CAGR of 16.4% to 2030 [31].

To put this estimate in context, in 2023, total wood pellet market size was estimated to be $12.8 billion CAD (BCAD), with an expected CAGR of 6.2% by 2030 [37]. The total global demand for wood pellets was estimated to be around 44 MT, with the top 10 exporters of wood pellets representing 50% of the market. Canada was the second largest exporter, after the USA, with 3.5 MT of wood pellets exported. BC represented 76% of Canada's total wood pellet exports, at 2.2 MT exported [38][39]. Based on market value, torrefied wood pellets would make up less than 0.5% of these volumes, or less if assuming higher pricing.

The main feedstocks for conventional wood pellets are forest harvest and wood processing residues. Bio-coal can also be produced from woody biomass and agricultural residues, with the main applications being power generation and industrial heating. There is also increased interest in using bio-coal in cement and metallurgy applications for their emissions reduction potential [40][41]. To that effect, a recent study in BC found that a transition from conventional wood pellets to torrefied pellets could have significant emissions and energy consumption savings.[1]

Overall, solid biocarbon products have a distinct advantage to decarbonize hard-to-abate sectors through the direct substitution of high carbon intensity feedstocks by using industry known and popular technologies, e.g. slow pyrolysis. Its applicability to industry has enabled a varied range of potential use-cases whereby GECA has produced a detailed market and end-use assessment as part of this report, see Appendix 1. The purpose of this

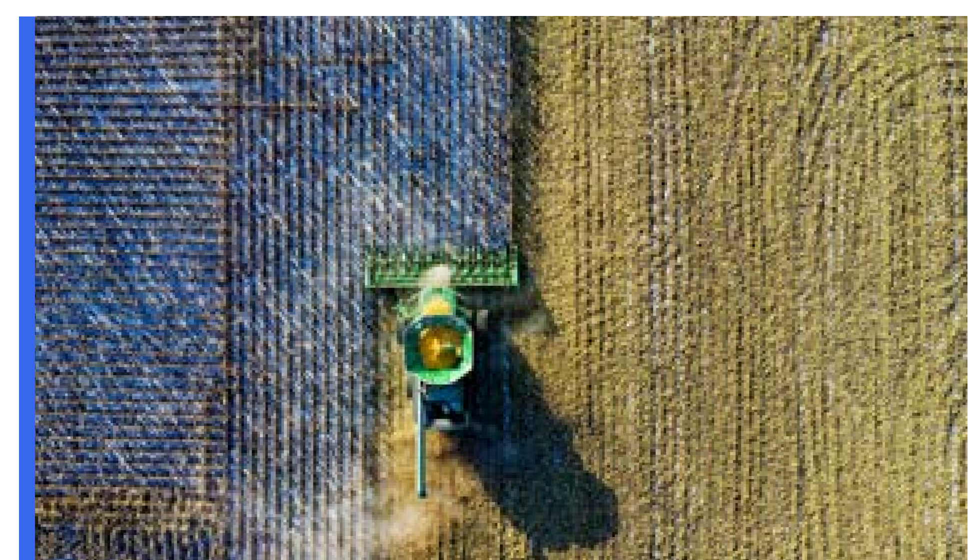
1 An environmental and economic assessment of BC produced torrefied wood pellets vs. conventional pellets produced, detailing the impact of residue wood harvesting, transport, and replacing of coal in European, Asian, and Canadian power plants. It was found that a transition to torrefied wood pellets could have a 30% reduction in emissions footprint, along with a 30% reduction in primary energy consumption footprint, compared to conventional pellets [73].

assessment is to outline the role and specifications solid biocarbon would need to satisfy to be a part of an identified market. Of these applications, Table 4 shows the most common applications for solid biocarbon with their current and projected expected consumer price per tonne (2024 to 2050). Within Table 4 and Figure 4, market prices are highly variable, which reflects their nascent role in the market. However, towards 2050 this variability declines as products become more prevalent within the BC market and benefit from developments in economic supply chains and production. As a result, prices are expected to decline by an average of 20% by 2035 and 49% by 2050, compared to 2024 levels.

Solid biocarbon expected consumer price ($CAD / tonne)

MARKET	PRODUCT	2024	2035	2050
AGRICULTURE AND SOIL IMPROVEMENT (A&SI)	Biochar	200 - 700	150 - 550	100 - 350
ANIMAL HUSBANDRY	Biochar	400 - 1500	325 - 1200	200 - 750
ENERGY	Bio-Coal	375 - 475	300 - 950	200 - 600
METALLURGY	Biochar Bio-Coal	350 - 650	275 - 525	175 - 325
CONSTRUCTION	Biochar	400 - 700	325 - 550	200 - 350
HORTICULTURE	Biochar	400 - 750	325 - 600	200 - 375
VOLUNTARY CDR MARKET (VCM)	Biochar	600	900	480

Table 4 - Solid biocarbon expected consumer price ($CAD / tonne)



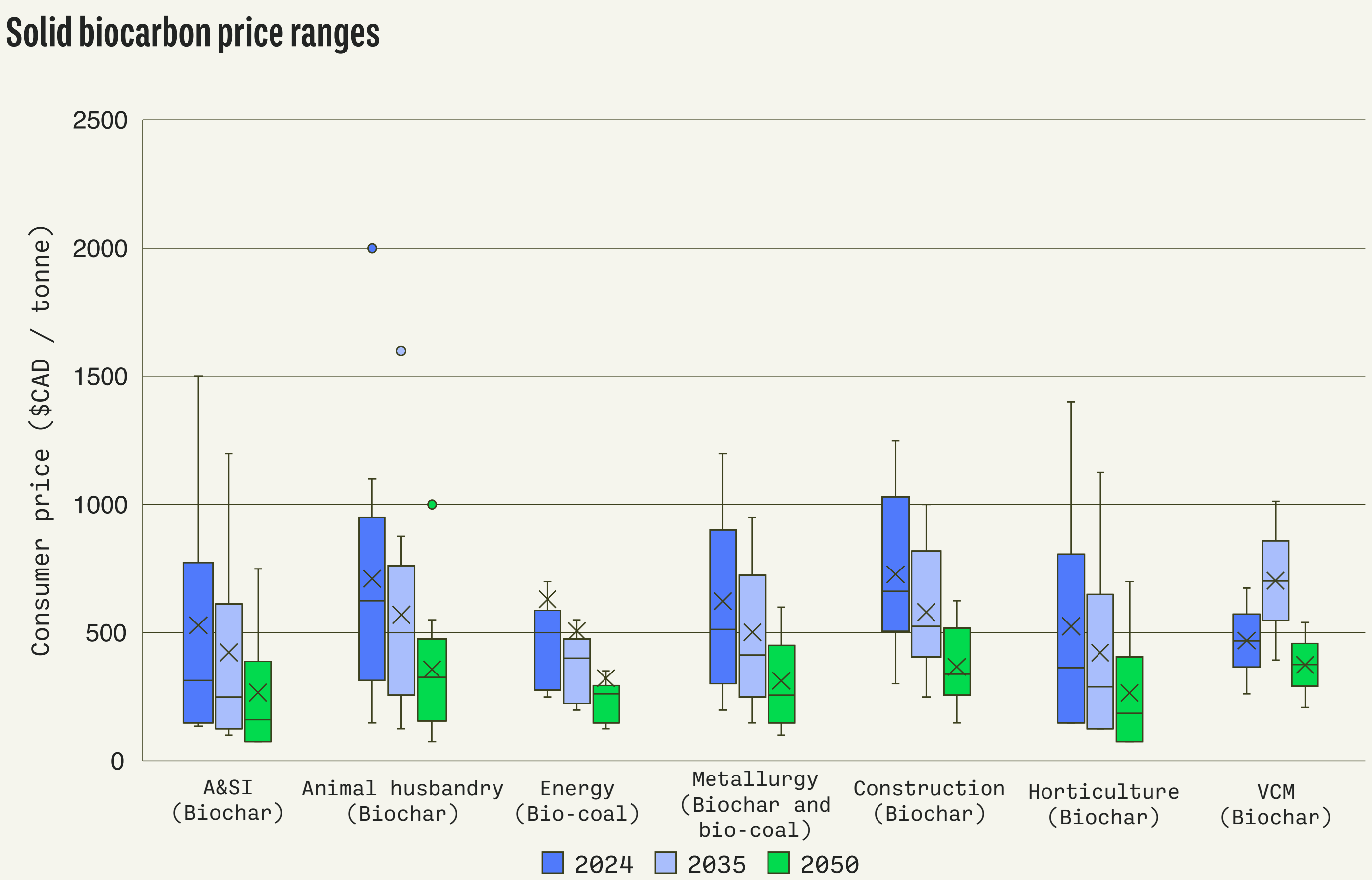


Figure 4 - Solid biocarbon price ranges (cross: average price, inner-box line: median price, box: inner quartile price range, lines outside box: overall price range, single points outside box: price outliers)

Despite the contrast in market size, both biochar and bio-coal demonstrate immediate ways in which industry within BC could reduce the carbon emissions and intensity of their products. However, biochar shows considerable potential (over bio-coal) in its use within the carbon dioxide removal (CDR) industry, where its sequestration potential is estimated to be 0.44 - 6.6 gigatonnes per year ($GTCO_2$ / yr). This corresponds to 1.1% to 17.6% of global CO_2 emissions in 2023 (37.4 GT [42]).

However, this benefit will likely only be realized under specific applications. A practical example of how this could be achieved is by utilizing biomass feedstock to produce biochar and then disposing it within inert environments (e.g. soil remediation, abandoned mine lands, and incorporation into durable building materials, like cement and asphalt). If successful, the estimated removal duration of carbon from the carbon cycle could be between 100-1000

years [43][36]. Therefore, the potential for sequestering a portion of biomass carbon through the production of biochar is increasingly seen as a practical and impactful solution for removing carbon (from the carbon cycle) at scale. Overall, this presents a considerable opportunity for biochar within the VCM sector.

Market potential: Liquid biocarbon

The market size for bio-oil was estimated to be $457 MCAD in 2021, with the majority (~75%) of that "bio-oil" using plastics and rubber tires as a feedstock. Bio-oil produced from biomass residues was estimated to be about 19% of the total, at $86 MCAD in 2021, with an expected CAGR of 4.3% to 2030. As the scope of this report only considers biocarbon products, only bio-oil (from biomass sources) will be discussed.

A common derivative of bio-oil is wood vinegar, which can be produced as a byproduct of slow pyrolysis, fast pyrolysis, or hydrothermal carbonization. This byproduct has a market size of around $6.7 MCAD in 2023, with an expected CAGR of 7.1% to 2030 [44]. Its main applications are varied, but it is commonly used in agriculture as a growth agent and insecticide. Other uses include as a food preservative, in medicine, in animal husbandry for disease prevention, odor control, and the ecological preservation of wood [45].

Outside of wood vinegar, the main applications for bio-oil are as replacements for conventional fuel oils in commercial and industrial heating applications, combustion for power generation (boilers and gas turbines), and upgrading for use as transportation fuels [32]. Although bio-oils demonstrate potential, the requirements for upgrading and their higher contaminant content (higher oxygen and water levels) present barriers to faster growth rates due to the denaturing of process catalysts. Even from a blending perspective, the chemical composition of bio-oils (from HTL or pyrolysis) inhibits the economic adoption into refineries as a substitute or blend for fossil-based crude, which would be the most direct route to market.

Although bio-oil is recognized as having potential within the VCM, its BC adoption has been limited. However, bio-oil has potential in its carbon credit generation for the production and selling of low carbon intensity fuels, such as renewable diesel or gasoline. These credits are commonly known as 'avoidance credits'.

Market potential: Gaseous biocarbon

The market size for syngas was estimated to be $65.8 BCAD in 2021, with an expected CAGR of 6 - 12.5% by 2030 [34][35]. However, most of the global syngas production was through the reformation of natural gas. Syngas produced through biomass gasification represents only a small percentage of the total syngas market ($42 MCAD in 2022), with expected CAGR's ranging from 8.9% to 15%, depending on the source [33][46].

In general, the main applications for syngas are industrial heat, as well as the production of ammonia, methanol, hydrogen, liquid fuels, and electricity [35]. In May 2023, a study was published investigating the economics of biomass gasification to produce energy and fuels. It identified 37 biomass gasification facilities globally, four of which are in Canada. Twenty-two of the facilities producing syngas were being used to generate electricity and/or heat, and seven were producing liquid fuels via Fischer-Tropsch synthesis.

As there were only three facilities identified producing RNG from biomass gasification, the reductions in capital expenditure observed with liquid fuels (economies-of-scale) were not reflected with RNG. However, the study did note that specific costs for RNG facilities were on par with those of liquid biofuels facilities. The study also suggested that specific incentives and subsidies will be required to further scale RNG synthesis technologies (TRL 4 - 8) in order to meet the demand for low carbon fuels sourced from biomass gasification (to complement the RNG produced through anaerobic digestion) [47].

What about the voluntary carbon market (VCM)?

MARKET INSIGHTS

1) BCR credits are sold by producers who either engage in direct sales outreach themselves or leverage a brokerage that claims between 5 - 25% of revenues from credit sales [74].

2) In their 2024 Market Outlook Summary report, CDR.fyi reports that 79% of purchasers expect to pay over $137 CAD per tonne for durable CDR, and 75% report price per tonne as a primary factor [75].

The VCM is a nascent industry that revolves around building a market for CDR in support of reaching net zero. This market has experienced significant fluctuations over the past two decades, driven by varying levels of demand, industry regulatory changes, and the perceived reliability of different CDR technologies with their associated monitoring, verification, and reporting (MRV) techniques. This is not to be confused with carbon avoidance credits, whereby the credit is provided by decreasing the carbon intensity of feedstock; bio-coal and upgraded bio-oil products would be examples of this.

The VCM is an important market, as it is one of the main mechanisms to support the adoption of CDR business models[2]. Others include businesses using CDR to offset their own emissions, and the disposal of CO_2 as a waste service, where revenue is generated from both voluntary credit buyers and the companies producing the carbon waste.

2 VCM Compliance: 1 tonne CO_2=1 credit

From a market perspective there are two main parts to the VCM, purchases and deliveries. Purchases are the tonnes of CO_2 purchased by a party (these can be pre-purchases as well), the price of which will vary depending on the technology, company and contract (e.g. spot and long-offtake agreements). Deliveries are the verified tonnes of CO_2 captured and stored by a specific technology and company, i.e. CO_2 has been successfully removed from the carbon cycle. According to CDR.fyi, in 2023, biochar carbon removal (BCR) was the leading CDR delivery method in the VCM, representing 93% of deliveries[3]. See Table 5 for a CDR performance comparison between biochar and other technologies.

2023 CDR technology summary

CDR TECHNOLOGY [48] 2023 PURCHASES: 4.5 MT 2023 DELIVERIES: 0.1 MT	$CAD/TONNE (AVERAGE)	CAD CHANGE SINCE 2022	PURCHASES	DELIVERIES
BIOMASS REMOVAL	159	+21%	0.66%	4%
BIOCHAR	188	-38%	7%	93%
BIOENERGY WITH CARBON CAPTURE AND STORAGE	430	N/A*	63%	N/A*
ENHANCED WEATHERING	532	-15%	4%	0.2%
DIRECT AIR CAPTURE	715	-43%	20%	0.1%
BIO-OIL	724	-16%	3%	1.3%

*N/A: No data available

Table 5 - 2023 CDR technology summary

3 The top 3 companies in BCR deliveries were Pacific Biochar (California), Wakefield Biochar (Georgia), and Aperam BioEnergia (Brazil) with the remaining 21% of BCR deliveries coming from over 40 different suppliers located in around the world with many in developing countries/the Global South.

From the data provided, the CDR market indicates that biochar is considered an attractive method for removing CO_2 from the carbon cycle. However, the varying amounts of carbon in woody feedstocks and the limitations on which ones are suitable or harvestable introduce variability and uncertainty in predicting biochar's carbon sequestration potential. These factors will ultimately affect its credit price. Therefore, as MRV and other CDR technologies improve, biochar may become a solution that is primarily adopted in regions with a high availability to biogenic feedstock.

The price of BCR credits depends on numerous factors. Table 6 shows current and projected pricing estimates for low, medium, and high-quality biochar for 2024, 2035, and 2050. It should be noted that these estimations are based on the best available data but are subject to change as the sector continues to evolve, especially for distant time horizons (2050).

Biochar VCM price estimation from wood waste

	2024 - 2035: BIOCHAR QUALITY - CREDIT IMPACT			2035 - 2050: BIOCHAR QUALITY - CREDIT IMPACT		
	LOW -> HIGH			LOW -> HIGH		
CARBON TO HYDROGEN RATIO	<1.43	~ 2	>2.5	<1.43	~ 2	>2.5
BIOCHAR PRODUCTION EFFICIENCY	Low	Average	High	Low	Average	High
CREDITS PER TONNE OF BIOCHAR	1	2	3	<1	2	3
$CAD PER TONNE OF CO_2E	100	175	250	150	200	375

Table 6 - Biochar VCM price estimation from wood waste

What is the future market potential?

In terms of BC's decarbonization, the biocarbon industry clearly demonstrates potential to help BC reduce its carbon emissions. However, it requires biocarbon to deliver on two objectives: (1) sequester carbon dioxide from the atmosphere and (2) provide meaningful solutions for hard to abate industries, enabling them to minimize their carbon intensity—both of which need to be material and reliable.

The Intergovernmental Panel on Climate Change (IPCC) asserts that limiting and reversing the impacts of climate change requires the reduction of economic emissions alongside the adoption of negative emission technologies [49]. This is in direct alignment with Canada's carbon management strategy whereby carbon management technologies (including those that are carbon negative) are seen as important tools to reduce and remove emissions [50]. The inclusion of these negative emission technologies in BC leave limited options due to the lack of (a) available capture and storage or utilization options and (b) the implementation of credible business models. The previous section outlines how biocarbon could be poised to deliver both, but it needs to be optimized.

Considering this objective, according to NorthX's CDR Techno-Economic Assessment (TEA)[4] and Carbon Management report[5], 30% of emissions within BC stem from hard-to-abate sectors, including agriculture (livestock methane from manure), buildings (efficient heating), transportation (air and shipping), and industrial activities (heating and production of steel, cement, and petrochemicals). Of these, biocarbon is poised to be the most effective in transportation, industrial, and agricultural activities.

To evaluate its contribution, ESMIA conducted a techno-economic optimization analysis on biocarbon using its North American Times Energy Model (NATEM) optimization model, illustrating the 'art of the possible' when it comes to its impact by 2035 and 2050. However, it should be noted that these conclusions are possibilities representing the 'least-cost behavior' of how the biocarbon industry could grow within the BC economy.

Modelling results for biocarbon

Below is a discussion on the potential pathways of biocarbon to 2050, which will be done through discussion of the of two modelled scenarios: (1) biocarbon outcomes if the market continued its current trajectory (REF) and (2) biocarbon outcomes if the BC economy optimized for net zero (NZBC). For details regarding the scenarios, see Appendix 2.

The modeling conducted by ESMIA shows that biocarbon has considerable potential for growth after 2035, see Figure 5. However, if action is not taken by 2035, then production is expected to decline, reducing the probability of BC being able to fully utilize biocarbon as a resource in meeting its net-zero goals.

Gap in total biocarbon production between reference and net-zero scenarios in BC

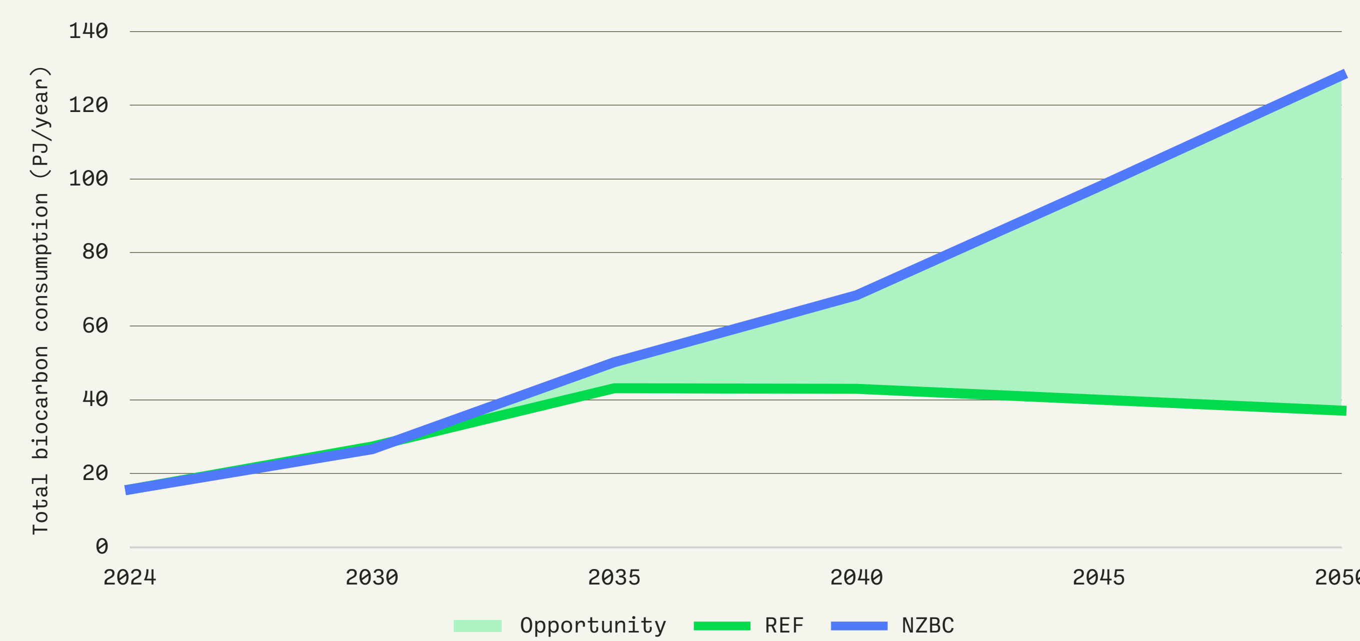


Figure 5 - Gap in total biocarbon production between reference (REF) and net-zero (NZBC) scenarios in BC

4 Report Title: Catalyzing Carbon Dioxide Removal at Scale

5 Report Title : BC Carbon Management Blueprint

In 2025, 420,000 tonnes of solid biocarbon are expected to be produced in BC (assuming the Global Bio-Coal Energy facility comes online). In the modelling, this number is expected to double by 2035, representing an annual growth rate of 7%. Although this is lower than the expected short-term global market CAGR of 14%, literature reviews have shown that many project announcements have not led to completed facilities.

The share of biocarbon consumption as of 2025 is heavily dominated by biochar (87%), while upgraded syngas makes up the remainder. As shown in Figure 6, by 2035, the share of biochar is expected to decrease to 60% in the reference case and 53% in the net-zero scenario. Syngas, including upgraded syngas (RNG), remain in second place with 28 - 31% and bio-oil taking the remainder with 12 - 16%. With advanced technologies, the mix shifts in favor of syngas (particularly upgraded syngas) with a drop in biochar.

Share of biocarbon consumption by output in 2035 for reference and net-zero scenarios

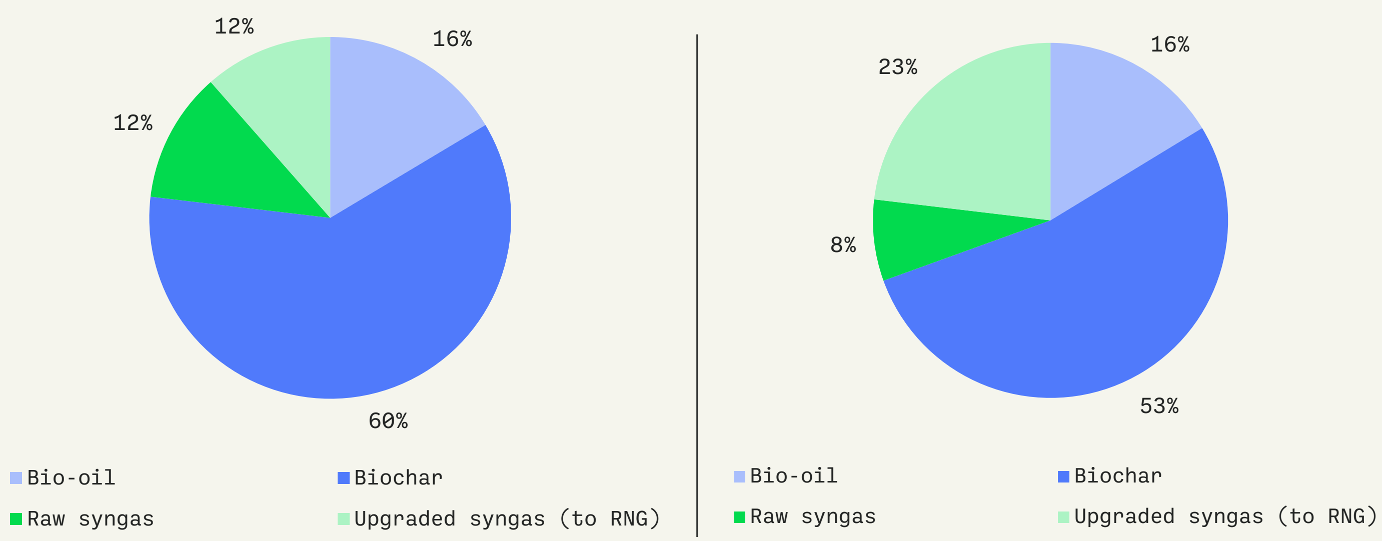


Figure 6 - Share of biocarbon consumption by output in 2035 for reference and net-zero scenarios

The total volume of biochar production projected by the model for 2035 is about 70% higher than the total from projects announced, demonstrating potential for further development in the next 5 - 10 years. The market size for biochar after 2035 depends highly on what technologies reach commercial scale and their costs, future climate and energy policies, and availability of relatively low-cost feedstock. With current policies and technologies currently at high maturity, long-term market growth is limited.

However, with more advanced technologies, such as fast pyrolysis (with high quality bio-oils), and declining costs for slow pyrolysis, growth for biochar remains strong, expected to reach 1.8 MT by 2045[6].

By 2050, in the net-zero scenario, the share of biochar remains similar, with a projected increase of 2 - 5%, depending on the scenario. Bio pyrolysis oil moves up to second place, with 31% of the mix. However, its role is diminished with advanced technologies, where bio-oil and syngas take up a similar share. These trends indicate that there is a growing role for bio-oil both in the short-to-medium term as well as the long term, and that the mix is likely to be more diversified than it is today. This aligns with the launch of Arbios Biotech's Chunto Ghuna low carbon biofuel plant in Prince George: 50,000 barrels of bio-oil in BC, planned for 2025 (representing about 0.3 Terajoules (TJ) annually) [51].

In general, the technologies that tend to be favored in modelling are those with the most competitive levelized costs, as well as those with the highest fixed carbon factors. In the reference scenario, this may allow greater revenue per tonne of biochar sold for carbon offsets. In the net-zero scenario, it could allow for a greater amount of carbon sequestration per tonne of biomass. In addition, analysis of feedstock use across scenarios suggests that lower cost feedstock (around $45 - 60 CAD per tonne ($CAD / t)) is needed for biocarbon production to be cost-effective; this may be a limiting factor for long-term growth.

The reference scenario leads to greater growth of bio-oils in the short to long-term, as fast pyrolysis tends to produce a larger share of bio-oils. With increasingly stringent climate policies in the future represented by the net-zero scenario (e.g., increasing price on carbon, increasingly stringent regulation of transportation fuels beyond 2030), the biocarbon market is expected to grow to about 8.5x its current size, or an average annual growth rate of 8.6%.

The net-zero scenario in the long-term leads to advanced technologies favouring slow pyrolysis, with syngas over fast pyrolysis with bio-oil production, possibly as there is greater potential for its use with carbon capture and storage (CCS) as a negative emission technology. Gasification with methanation for upgraded syngas production also shows moderate uptake across scenarios, which is reflected by recent activity in industry (e.g. Nexterra Energy Systems). Finally, should market factors constrain growth of biocarbon production processes like pyrolysis, there may be an opportunity for HTL for production of renewable liquid fuels, as demonstrated by Arbios Biotech.

6 Biochar energy density: 30 MJ / kg

In terms of the industrial sector, a study by FortisBC suggests that syngas could be used in lime kilns in the pulp and paper industry [52], which is confirmed by the modelling. In 2035, we see about 4.3 petajoules (PJ) being consumed in the scenario results. The use of upgraded syngas in industrial sectors also continues to grow in net-zero scenarios, where it can replace natural gas in heating and boiler processes, in several sectors including other manufacturing.

Other promising markets shown for biocarbon are the production of renewable fuels from bio-oil upgrading and a potentially transitory role in the building sector, where upgraded syngas (RNG) can replace natural gas, as mandated by the Greenhouse Gas Reduction Regulation (GGRR). In net-zero scenarios, bio-char shows potential beyond agriculture, including use in cement replacement and other material-based sequestration. On the other hand, the use of biochar for energy, such as industrial heating, shows limited uptake in BC since coal and coke[7] play a marginal role in the industrial energy supply mix.

In terms of consumption, the reference scenarios confirm that there is robust growth potential in the carbon market until 2035, after which it stabilizes and then decreases in size because of the expected cost of voluntary CDR credits, peaking around 2035. However, in the net-zero scenario, this market is taken over by other consumption sectors as soon as 2026. This result demonstrates the possibility of local market development for biochar with more stringent policies driving emission reductions (e.g. a higher carbon price). For example, the biochar offset protocol that is being developed by the BC Ministry of Environment and Parks (MEP) will allow use of these credits in the Output Based Pricing System (OBPS) market in BC.

Overall, these results suggest a change from the trends seen in the biocarbon market in Canada today: from a strong energy market towards greater incorporation of biochar's material sequestration capability and the decarbonization of liquid and gaseous fuels. Therefore, demonstrating that biocarbon has the potential to rapidly and significantly contribute to BC's decarbonization goals, and offers a near-term option for deployment.

7 Coke definition: a coal-based fuel with a high carbon content. It's an import industrial product mainly used within industrial furnaces, e.g. iron ore smelting.

Chapter 03: Biocarbon's decarbonization potential

Chapter highlights:

01

CURRENT PROCESS OF CHOICE

Slow pyrolysis

02

INVESTMENTS NEED TO INCREASE

Total investment of $451 MCAD (2022) / yr required

Biochar production needs 65% of required investment

03

REQUIRED TECHNOLOGY ADVANCEMENTS

Gasification and fast pyrolysis

04

AFFORDABLE FEEDSTOCKS

Waste process wood at $45-60 CAD / tonne

05

BIOCARBON IMPACTS BY 2035 | 2050

Carbon sequestration

9 MT CO_2e | 46 MT CO_2e

Industrial heat

1.4 MT CO_2e | 7 MT CO_2e

Transport

1BL | 10 BL
(road, rail, and marine)

1.3 MT CO_2e | 10 MT CO_2e

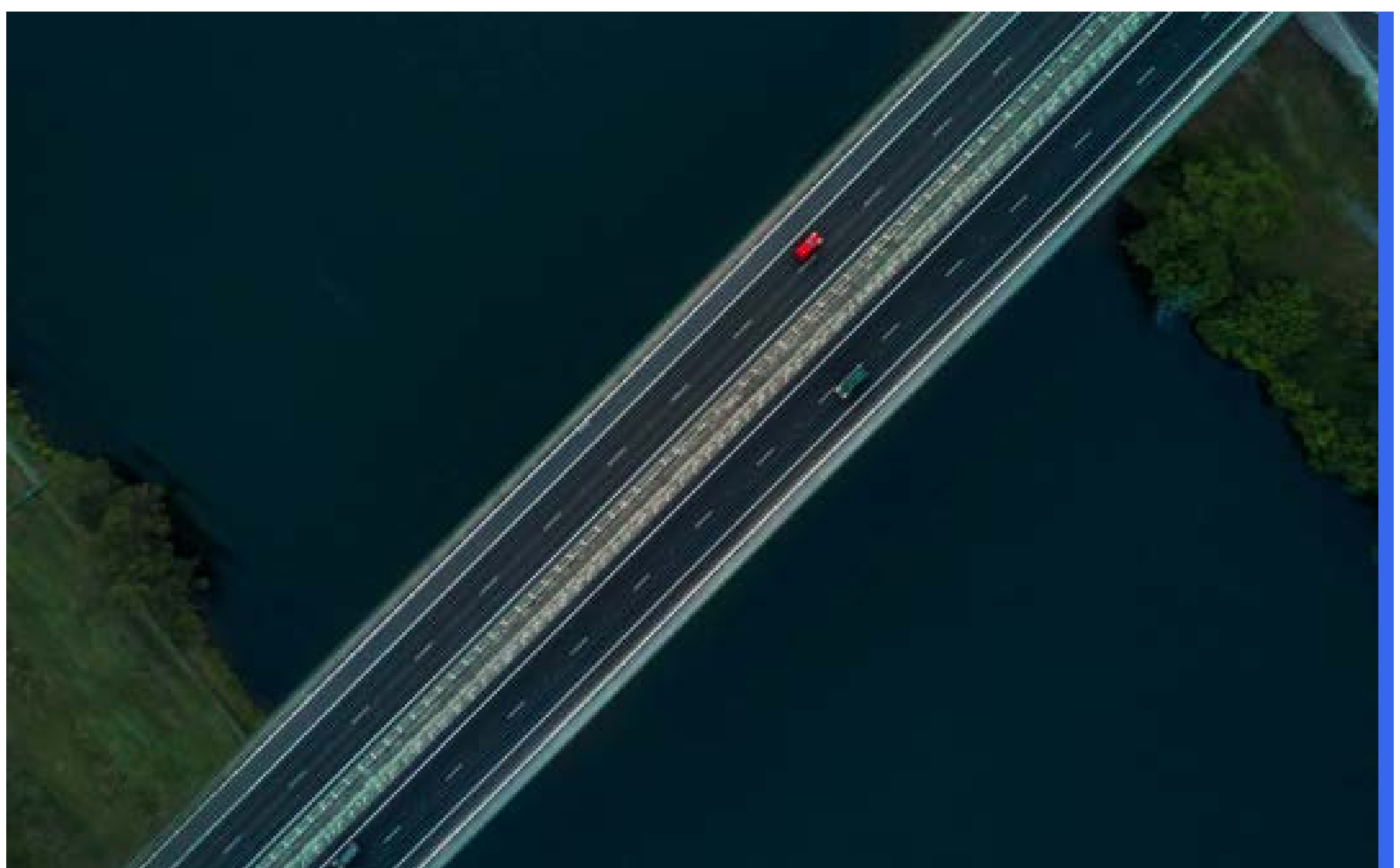
1BL | 10 BL
(aviation)

0.5 MT CO_2e | 3 MT CO_2e

What is the opportunity for industry?

This chapter seeks to outline the opportunity for industry, and the key considerations for commercial scaling. Figure 7 shows a summary of the modelled results for biocarbon adoption by estimating their degrees of certainty, while outlining their pathway from feedstock to end-use. As the biocarbon market grows towards the NZBC scenario, there are several key conclusions that emerge to bridge the opportunity gap:

1. Opportunity for industry: Biocarbon demonstrates material carbon sequestration potential of 45.7 $MTCO_2e$. It's also seen to increase combined transport and industrial heat decarbonization capacities by 10.2 - 17.3 $MTCO_2e$ by 2050 depending on the application, adoption, and assuming current BC policy targets are maintained.
2. Production considerations: Without access to new site development and low carbon feedstocks, biocarbon production will shrink to 33% of its current size and is at risk of being cannibalized by the biofuels industry.
3. Consumption considerations and regulatory mechanisms: Modelling shows that demand is sensitive to provincial policies including the Greenhouse Gas Reduction Regulation (GGRR) and BC Low Carbon Fuel Standard (LCFS).
4. Required investment: Between 2024 and 2050 the required investment into biocarbon is significant, requiring an investment increase of $330 MCAD (2022) / yr (REF to NZBC) by 2050.



Biocarbon feedstock to end-use model results summary

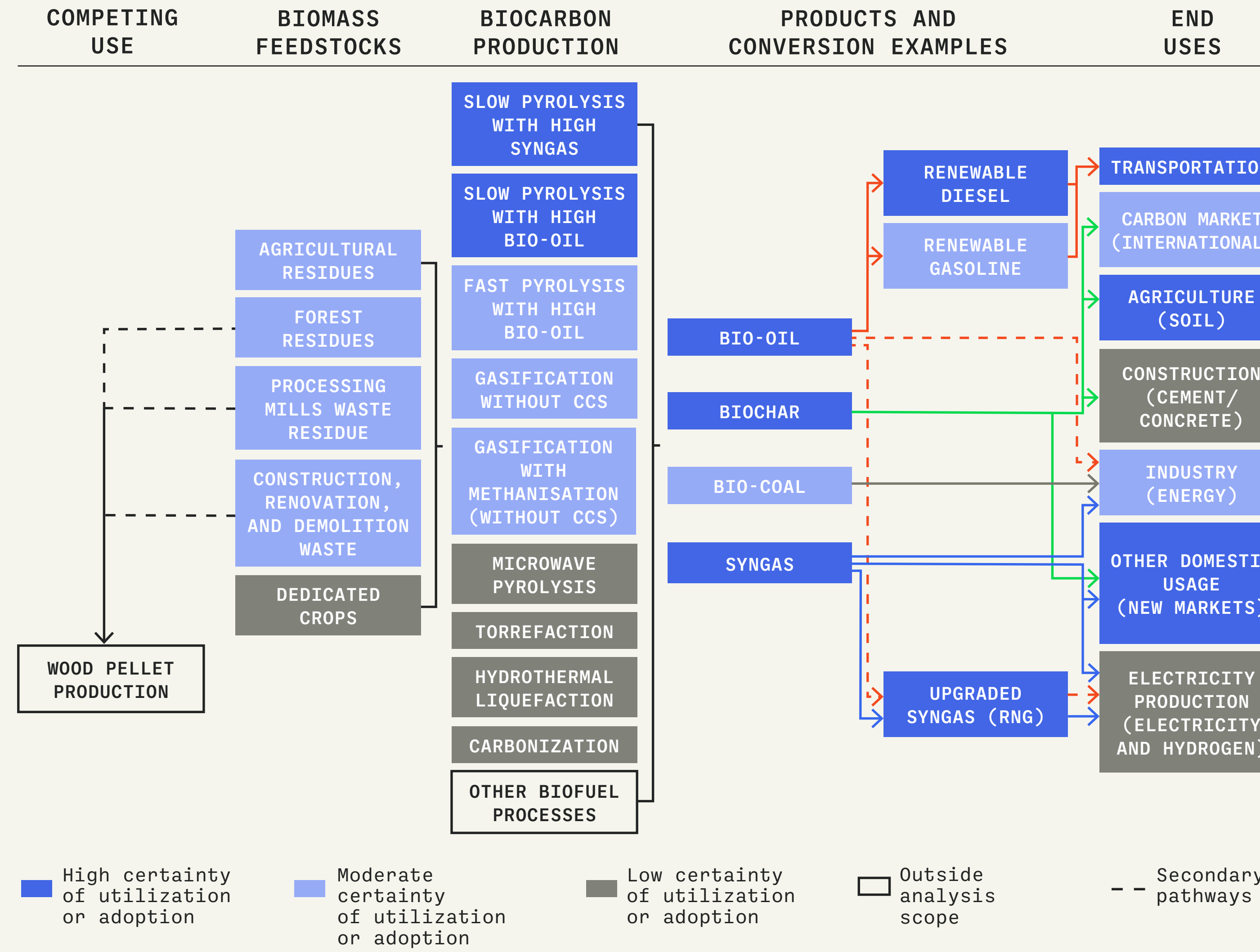


Figure 7 - Biocarbon feedstock to end-use model results summary

If action is taken and the NZBC scenario is realized, the relative increases in biocarbon applications are seen to contribute significantly to emission reductions within the BC economy, most tangibly within material additives (S-solid), biofuel upgrading (L-liquid), and industrial heat (G-gaseous); see Figure 8. The critical actions required in order for the opportunity gap to be bridged are reported in Table 7 in the Action plan for biocarbon development in BC.

Biocarbon consumption projection

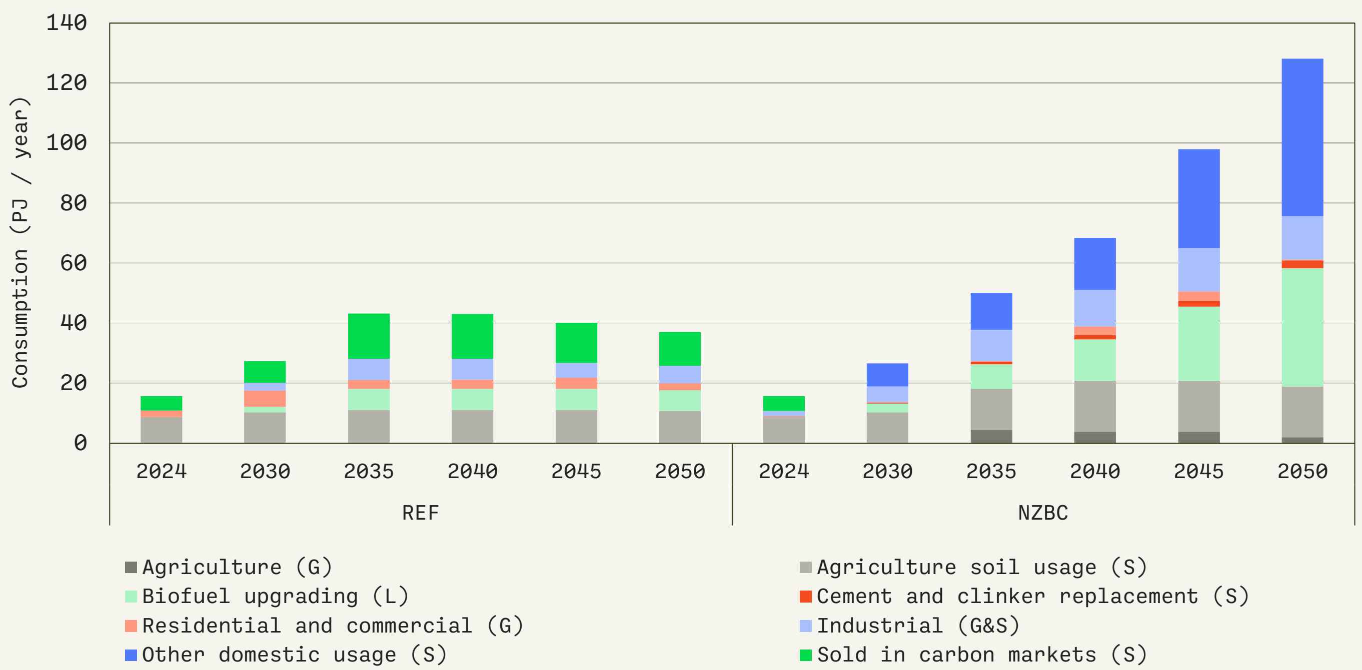


Figure 8 - Consumption of biocarbon in PJ by sector and end-use in BC for the REF and NZBC scenarios

Carbon sequestration: Biochar for material additives

Biochar is by far the most utilized biocarbon product, occupying 54% of total biocarbon consumption by 2050 (on a PJ / yr basis), with the majority used for CO_2 sequestration. This translates to the production of 2.4 MT / yr of biochar[8]. Prominent end-uses include agriculture soil and possibly mining soil reclamation (or other material uses), as well as cement and clinker to a lesser extent[9,10]. Sequestration rates from Figure 9 indicate that biochar has the potential to sequester approximately 45.7 $MTCO_2e$[11] by 2050, with rapid growth after 2030[12].

It should also be noted that the above is based on service business models, whereby biochar is advanced to become a replacement and reclamation product. If these do not commercialize within BC, agriculture and the VCM will be the only national markets biochar could partake in. Although some biochar is being adopted within the construction industry, its uptake is limited as costs are currently prohibitive (see Table 4 and Figure 4 in Chapter 02). However, when using the VCM it should be considered that although the sequestration would be delivered in BC, and in reality, the BC environment will benefit, the administrative credit will go to the purchaser and therefore could leave the province or country.

Therefore, developing new end-use markets and off-takers for biochar will encourage biochar to remain in BC for CO_2 sequestration. Aside from agriculture, cement production, and mining reclamation, there are opportunities to produce high-value products for individual consumers (e.g. garden soil mixes), animal litter, and animal feed.

8 Calculation: 75 PJ / yr = 2.5 MT / yr solid biocarbon (total); 2.6 PJ / yr bio-coal=>0.086 MT / yr ; CO_2 Seq. Biochar=2.4 MT / yr.

9 Cement and clinker replacement=Approx. 2 PJ = 83,636 tonnes (upper weight replacement of 5%).

10 Clinker strength is expected to be reduced by 57% with biochar substitution.

11 Does not include lifecycle emissions, see Appendix 3.

12 Average 1.6 tonnes CO_2e captured for 1 tonne of biochar across 2024 - 2050.

Carbon sequestration potential of biochar

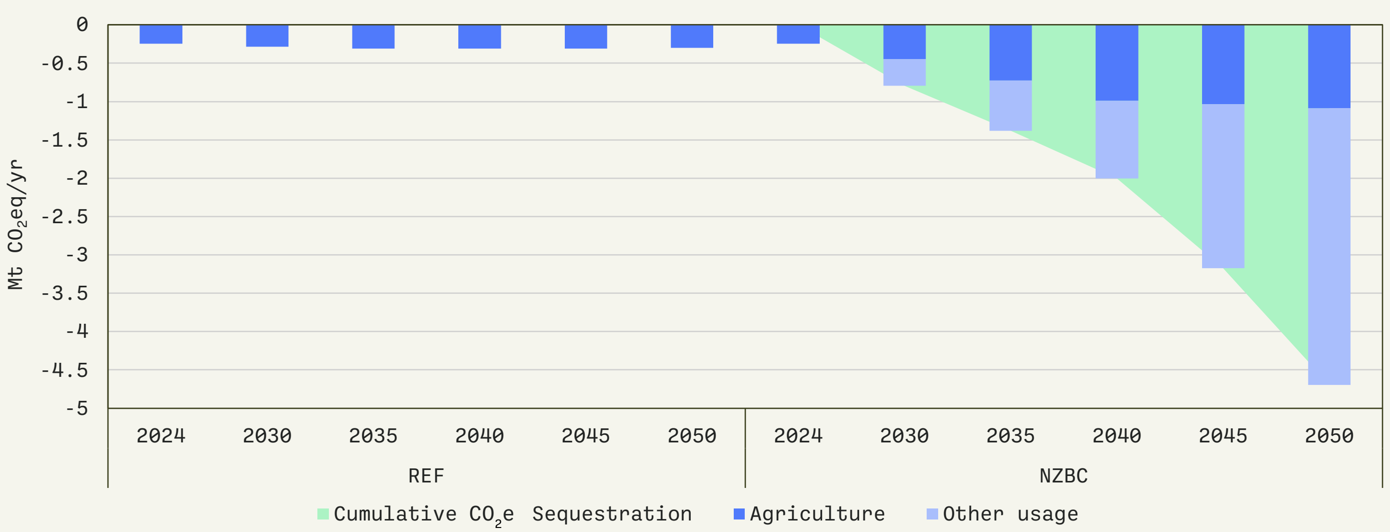


Figure 9 - Million tonnes of CO_2e emissions sequestered by biochar in BC (REF and NZBC)

Decarbonizing transport: Upgrading bio-oil

Bio-oil is used to reduce carbon emissions in parts of the transportation sector where electrification is not practical (e.g. marine shipping). It is anticipated that this trend will continue for all light-duty road transport vehicles, including those using fuels other than gasoline. Biofuel upgrading could supply upwards of 10 billion litres (BL) of renewable diesel (10.3 $MTCO_2e$ avoided) or 10 BL of bio-jet fuel (3.2 $MTCO_2e$ avoided) to the clean fuel market by 2050 (assuming 100% of bio-oil upgrading goes to renewable diesel or bio-jet fuel until 2050, 362.5 PJ cumulatively)[13]. These emission reductions could increase further depending on the degrees of carbon intensity (CI) achieved. However, this could be lower depending on the quantity of byproducts produced in the refining of the upgraded bio-oil (e.g. renewable gasoline).

For example, the BC government has reported industry renewable diesel and alternative jet fuel production CI values of 10 grams of CO_2e per megajoule of fuel consumed (gCO_2e / MJ) and 36 gCO_2e, respectively (high ends of the ranges provided). These are far below the CI 2030 BC targets for diesel and jet fuel. If scaled, bio-oil upgrading (of these fuels) has the potential to reduce transport

13 (1) Due to data availability calculations for bio-oil uptake started with 2030 and assumed BC policy targets for allowable diesel and jet-fuel carbon intensities are not reduced from 2030 [76]. (2) Bio-oil fuel uptake assumed to be 100% in the NZBC scenario where no renewable gasoline is produced.

Chapter 03: Biocarbon's decarbonization potential

emissions by 19.2 - 30.6 $MTCO_2e$ (19.2 for bio-jet and 30.6 for renewable diesel), depending on the level of end-use adoption [53][14].

As the transportation of feedstock is the most carbon intensive aspect of biocarbon production (see Appendix 3),[15] the commercialization of bio-oil upgrading could help reduce the carbon intensity of feedstock and product transportation. Minimizing transport emissions would improve the carbon sequestration impact of biochar and the use of biomass in general. Bio-oil derivatives would likely come in the form of drop-in fuels (DIF). However, advancements in the production of bio-oil would be necessary, in which the analysis suggests that fast pyrolysis would be prioritized.

There is significant potential for the production of bio-oil from the fast pyrolysis of wood residues in BC, however, a few important hurdles remain:

- Quality of bio-oil produced from pyrolysis needs improvement for better integration into fuel upgrading processes.
- Commercial operation of bio-oil production for refineries needs to be demonstrated.
- New markets and off-takers for biochar, produced as a co-product of bio-oils, need to be developed. Specific policies that incentivize biofuel and biochar production from biomass residues may be required, as the current LCFS targets are not sufficient to drive further growth and achieve deep decarbonization.
- Removal and sequestration processes should be evaluated for BC, such as the injection of bio-oil into deep geological formations. This represents a new paradigm for bio-oil that focuses on its carbon reduction potential, without combustion. In this case, the quality of the bio-oil is not as important as it is not being upgraded into renewable fuels/DIFs.

Decarbonizing heat: Syngas and bio-coal

The adoption of syngas revolves around the decarbonization of industrial, agricultural, commercial, and residential heat, whereby both raw syngas and RNG are utilized. Like bio-oils, the adoption of these fuels shows significant potential for emission reductions, with some variability. Overall, the modelling estimates that around 302[16] PJ of gaseous biocarbon will be produced over

14 Recorded industry values are not offered as official guidance on emission reduction potential of bio-oil as they are highly contextual to the process used, the feedstocks collected and the delivery of the outputs.

15 The carbon intensity of biochar or any biocarbon production needs to be assessed on a case-by-case basis as the GHG impact will vary with feedstock, transport distances and the process adopted.

16 Assumption: 90% of produced gas is consumed to account for process gas being left in situ. within pipelines, or process piping.

the 2050 time horizon, 74% of which will be RNG (224 PJ). Carbon intensities will depend on the producer, making it difficult to predict exactly. With this in mind, the full adoption of biocarbon syngas could see carbon reductions of 7[17] - 16.2[18] $MTCO_2e$, 43 to 99.5% reduction from equivalent usage with natural gas.

Unlike bio-oil upgrading, the production of low CI gas is already being adopted at the commercial level. The current incentive of $31 CAD / MJ of RNG production makes sense economically for upgrading biogas produced from the anaerobic digestion of agricultural and other organic wastes. However, according to some stakeholders, it barely represents production costs for high-quality syngas production and methanation at current TRLs and available feedstock costs. A short-term opportunity for biomass gasification and syngas production is onsite production and direct utilization (without upgrading) as a fuel replacement for natural gas in industrial heating processes.

There are also opportunities to use bio-coal and torrefied pellets as a replacement for coal or coke, or to replace wood pellets exported for electricity production. See estimated costs for specific applications in Table 4. The modelling suggests that in BC, despite a production capability of up to 10.8 PJ / year of bio-coal and biochar (as per the Global Bio-Coal Energy project, 360,000 t / yr from 2025 to 2050), only 2.6 PJ of bio-coal will be produced in 2050 (~87 thousand tonnes) while the rest would be biochar[19]. This suggests the use of solid biocarbon for energy is less attractive than its use for carbon sequestration. There may be a few reasons for this:

1. Increased electrification requirements are being met mainly with new wind capacity, suggesting that the use of biomass or biocarbon for electricity production is not cost-effective.
2. Industrial uses in heavy industry, such as in heating processes in cement, iron, and steel, may indeed be cost-effective (as seen in the modelling results). However, these are relatively small markets in BC, and only partial replacement by biocarbon (depending on its properties) may be possible in certain applications.
3. Carbon accounting for biochar (or biomass in general, as per the current National Inventory Report (NIR)) implies that its use as an energy source produces neutral (i.e. zero) emissions, whereas biochar use as a material leads to negative emissions, since carbon is sequestered.

17 Using allowable CI from GGRR [71]: 30.8 gCO_2e / MJ (both RNG and raw syngas).

18 Using target CI reported by Fortis [77] and GECA LCA (see appendix 3): 0.27 gCO_2e / MJ (RNG) and 0.29 gCO_2e / MJ (raw syngas).

19 Energy density of bio-coal: 30 MJ / kg; not counted towards decarbonization values due to negligible uptake.

Production considerations

There are two factors that influence the production of biocarbon by 2050, low build limits (representing market barriers, for example) and access to affordable feedstock. Other 'what if' modelling conditions such as advanced technologies (AdvTech), high build-out (HighBuildBio), and forest residue consumption (HighBioQt) only changed the distribution of products, rather than materially impacting the overall production quantities. Their impact on each biocarbon product is summarized in Figure 10.

Biocarbon product consumption across modelling scenarios

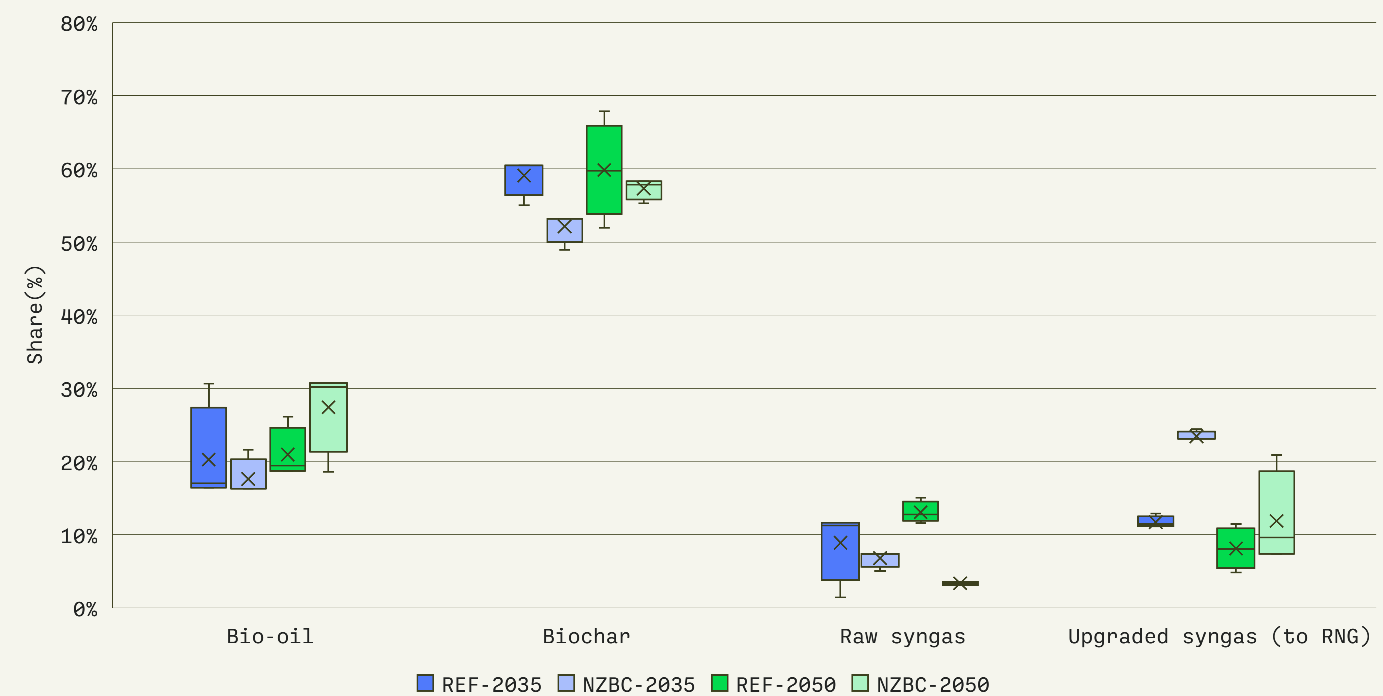


Figure 10 - Range in share of biocarbon outputs by year and four base scenarios: HighBioQt, HighBuildBio, AdvTech, and REF or NZBC (cross: average share, inner-box line: median share, box: inner quartile share range, lines outside: overall share range).

Low build limits

Low build limits effectively make biocarbon production a 'non-starter' and, unfortunately, it is within the realm of possibility. Although it may not come from policy or regulation, the current barriers of social licensing, technological development, and economic viability may be enough to make future development prohibitive.

Social licensing: Gaining public support for biocarbon projects is an important factor that should not be overlooked. There is a need to raise awareness about the benefits of biocarbon technologies and engage communities in the development process to ensure acceptance and participation. Some engagement examples include:

- Awareness and education: Public understanding of biocarbon benefits and applications needs enhancement.
- Community engagement: Involving local communities in biocarbon projects to address concerns and gain support.
- Multi-stakeholder collaboration: Engaging industry, academia, government, and communities in collaboration may be required for the success of some projects.
- Cross-border initiatives: Exploring partnerships across provincial, regional, and federal borders may need to be explored for maximizing project success and longevity.
- Economic Reconciliation: Economic reconciliation needs to be at the center of biocarbon projects and revenue opportunities. Engaging early and ensuring project outcomes align with community needs and objectives is vital. Project development with meaningful, equitable partnerships, transparent credit models, and robust revenue pathways present a significant opportunity for Indigenous communities to be feedstock and production stewards for the biocarbon industry.

Technological development: While BC has a strong innovation ecosystem, the challenge remains to scale up biocarbon technologies and integrate them with existing industrial, energy, and agricultural systems. Continuous technological development and adoption of best practices are necessary to overcome these hurdles. This may require a regular feedback forum, where new innovations and best practices are shared so that technologies can become more efficient, production can become more sustainable, and environmental impacts can be minimized.

While certain biocarbon-related technologies (such as slow pyrolysis, some forms of fast pyrolysis, and gasification) are relatively mature (TRL 8 - 9), scaling them up with diverse feedstocks still poses technological risks associated with strict moisture requirements. As can be seen in Chapter 01: Technology fundamentals, these technologies have strict moisture requirements which necessitates a pre-drying stage if dry feedstock cannot be sourced. Failing to achieve either is a significant process constraint which could make product quality control an issue. Therefore, to have diverse feedstocks these technologies need to expand their allowable moisture content to establish greater quality certainty for customers and offtakers.

There are also emerging versions of these technologies with less technological maturity (e.g. microwave pyrolysis, HTL, gasification plus methanation, and fast pyrolysis for high-quality bio-oil production) that present other technological risks and scaling uncertainties. For example, HTL allows for a significantly higher feedstock moisture content (70 - 90% vs. <10%) and thus can have around twice the feedstock diversity. However, its product (bio-oil) requires substantial upgrading due to the resultant O_2 and H_2O content incompatible with bio-crude and blended refining catalysts.

To fully capture the potential of biocarbon in BC, a clear path to integration within existing industrial and energy systems at scale needs to be identified. Specifically, attention needs to be given to enabling technologies to either (a) handle high moisture content, (b) better control the moisture contents of products to make them compatible with external processes, or (c) innovate processes that use biocarbon products (e.g. catalysts) to allow an accelerated uptake.

Economic viability: The high initial costs of biocarbon technology deployment and the uncertainty of return on investment (ROI) are substantial challenges. The 2022 PICS Report on BC's need for a CO_2 removal strategy highlights the need for robust financial models and incentives to make biocarbon projects economically viable in BC [54].

Additionally, the biocarbon industry reports that viable projects need to have the right mix of grants, bank loans, junior debt, carbon removal credit pre-purchase, and equity financing. Two specific examples of project funding that have a high chance of failure are [55]:

- Projects that attempt to finance through 100% pre-purchase of carbon removal credits, as this presents too much risk for the buyer at current market prices. With this financing strategy, there is a lack of additional stakeholders to ensure the project is completed on time and according to plan.

- Projects that attempt to finance with 50% grants and 50% bank loans, as they can suffer from a funding stalemate where the bank requires a certain amount of capital available before issuing a loan and the grant programs often ask for matching project funds available to the grantee before issuing the grant funds.

Therefore, factors to help ensure project economic viability include:

- Securing legal documents or contractual agreements for biomass feedstock access that include historical production logs.
- Having a selection of biocarbon production equipment with costs and a clear understanding of capabilities.
- Connecting with local universities, research centers, and farmer community working groups that are focused on soil amendment.
- Consultation with carbon credit experts to provide assurance to investors or funding organizations about project revenues.

Access to affordable feedstock

Access to sustainable, reliable biomass feedstock is crucial for biocarbon production and project development. Wood processing plant waste is the key feedstock being utilized for biocarbon production. However, competition with pellet production limits utilization by 2035, which will be more impactful as BC works towards the NZBC scenario. In this scenario, total feedstock utilization (for all uses) increases to 99% in 2050, and biocarbon production is expected to contribute to 17% of feedstock utilization in 2035 and consume 45% of available feedstock by 2050.

The modelling results show that the primary cost-effective feedstocks for biocarbon production in the next 10 years and beyond are wood processing plant residues, followed by CR&D, and forest harvest residues. In BC, access to processing plant residues and forest harvest residues for biocarbon production may be a challenge, as it will be in competition with pellet production. Additional available sources of biomass residues that can be targeted for biocarbon production are woody debris diverted from landfill and refuse derived fuel (RDF).

Currently there are incentives in the United Kingdom (UK), some European countries, and Japan to import wood pellets for energy production. As a result, BC currently exports 2.5 to 3 MT of wood pellets per year, whereby mill residues and forest harvest residues are important feedstocks. For the biocarbon industry in BC to grow, it must compete with pellet production. This will require increasing the supply of low-cost feedstock, either by expanding

Chapter 03: Biocarbon's decarbonization potential

or incentivizing the use of forest harvest residues and slash piles, or by encouraging a portion of sawmill residues to remain in the province for local use, with pricing that reflects their climate benefits.

Existing long-term wood pellet supply contracts may remain a challenge for diverting feedstock to the domestic market. Additionally, incentives may need to be developed for biocarbon production that uses woody debris diverted from landfills (e.g. furniture, pallets, and broken lumber) or RDF as feedstock.

Although many production technologies are flexible with the types of feedstocks they can process, some end-uses for biochar or syngas have tight requirements and may not allow for flexibility in feedstock. For example, bioenergy feedstock sizing and moisture content are important for biocarbon production performance. Product and regulatory flexibility could allow producers to adapt to rapidly changing market conditions and varying demand for biochar, bio-oil, or syngas, so long as certain environmental and emissions standards are maintained.

Consumption considerations and regulatory mechanisms

Specifically, the analysis shows that biocarbon consumption is sensitive to the removal of existing clean fuel policies. However, some are more impactful than others. For example, the GGRR is seen to be a strong influencer for the adoption of syngas and RNG (for heating applications) for the short-term. The LCFS, on the other hand, doesn't have the same influence; the LCFS impacts the uptake of biofuels in the short-term, and not the utilization of bio-oil specifically as it has other markets it can still partake in (e.g. chemical feedstocks).

Although not explicitly modelled, changes in federal and provincial regulations relating to biochar could impact its consumption. For example, biochar is not yet included within the soil carbon sequestration protocol, which, in addition to its exclusion from the carbon capture and underground storage (CCUS) investment tax credit (ITC), may prevent the necessary incentive to drive biochar as a short-term win for carbon sequestration. See Appendix 4 and 5 for more information on the application regulations for biochar, bio-oil, and syngas and modelling assumptions made at the provincial and federal level.

Cost

To secure biocarbon's role in decarbonization, investment in different process types will be required; see Figure 11. Across both reference and net-zero scenarios, investment rates in biocarbon production reach around $157 - 198 MCAD (2022) / yr by 2035. The technologies that show the most promise are:

- Slow pyrolysis facilities that produce both biochar and syngas.
- Fast pyrolysis systems with high bio-oil output.
- Gasification systems followed by methanation for RNG.

It is important to note that fast pyrolysis and methanation is at a lower TRL than slow pyrolysis and could benefit from early investment to reach commercial scale in the next five years. Furthermore, processes that generate biochar with high fixed carbon factors (high carbon conversion efficiencies) are favored.

Deployment of upgrading facilities will be required for both syngas and bio-oil. Investment of $6.5 - 9.5 MCAD (2022) / yr is required in 2035 to ensure that commercial facilities will be ready to process these biocarbon products and meet the needs of the market:

- Bio-oil: 100% upgrading is projected to produce renewable drop-in fuels (gasoline and diesel, and bio-jet, if applicable).
- Syngas: Industrial heating applications.

Although net-zero pathways show strong growth for upgraded syngas applications, investment is needed in pyrolysis technologies producing some share of bio-oils as well as those producing syngas. The trends are somewhat different in the reference versus net-zero scenarios in that the reference case tends to favour technologies producing bio-oils (although this is partly offset by the GGRR requirement), whereas the net-zero case tends to favor more biochar and syngas production.

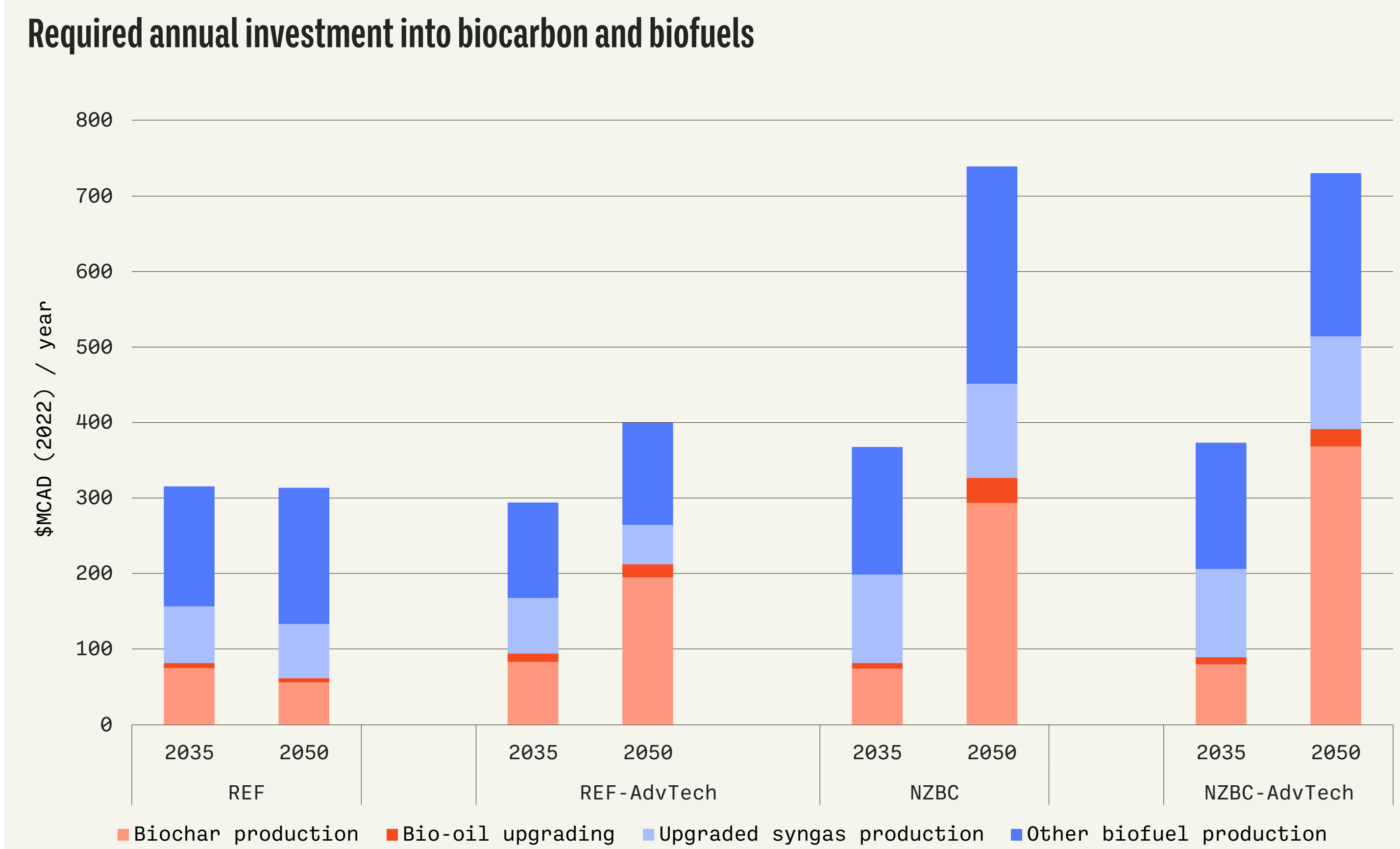
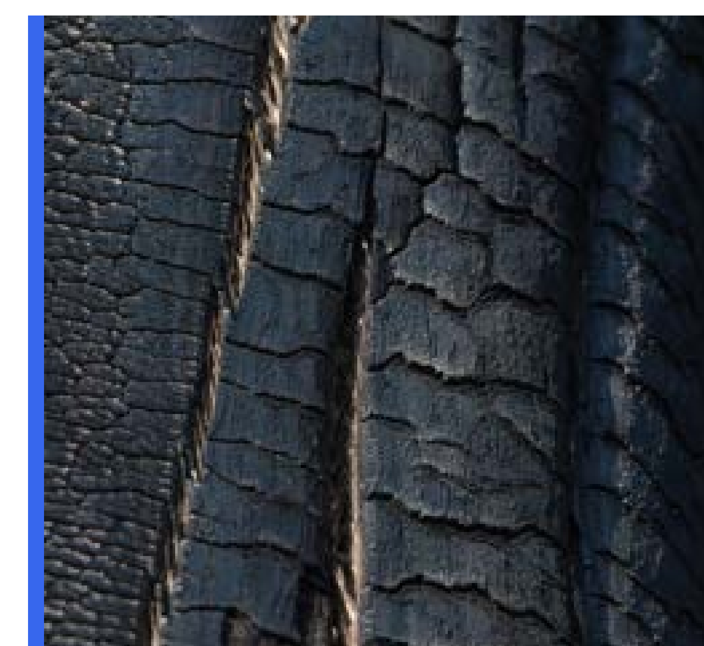
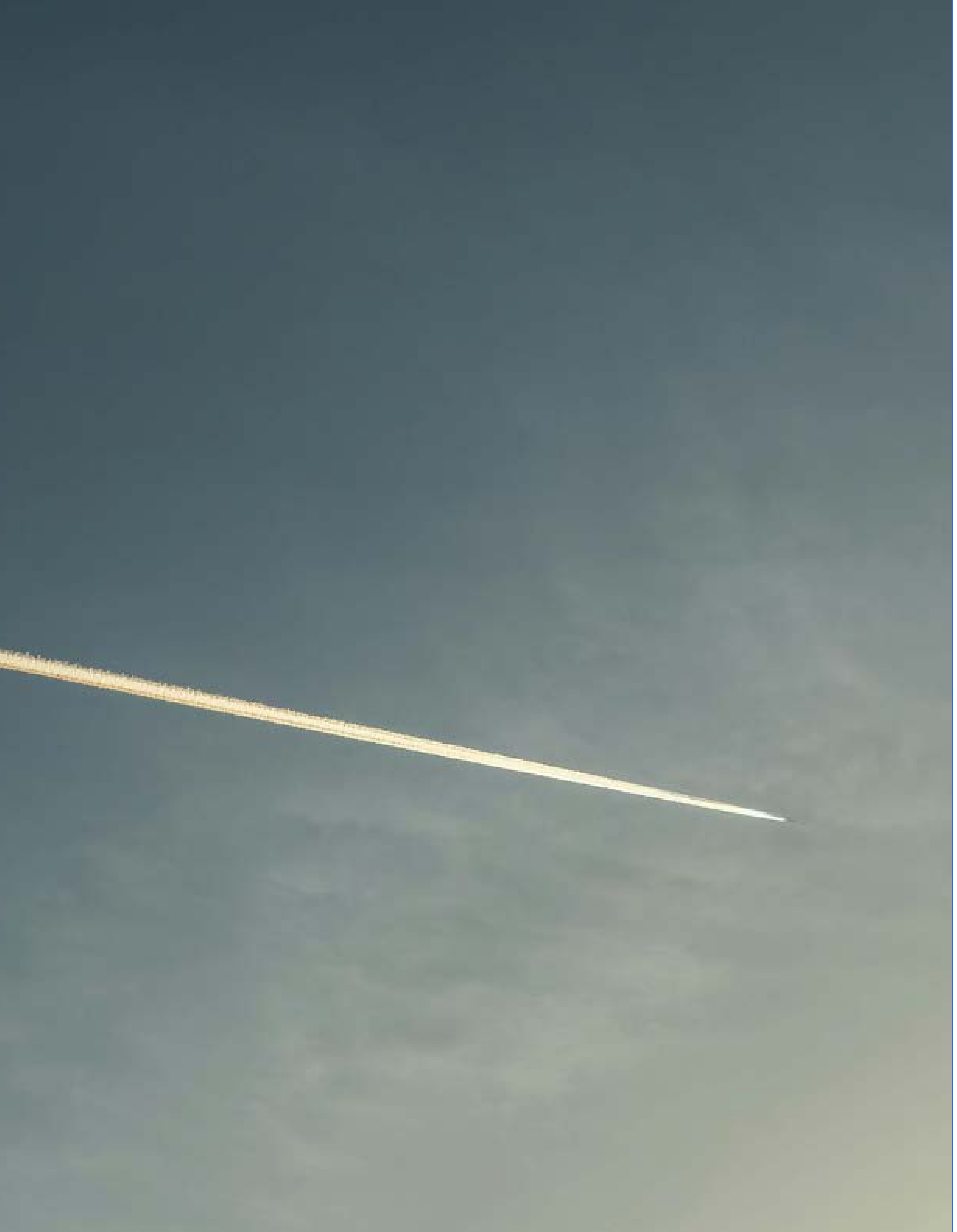


Figure 11 - Annual investment in $MCAD (2022) / year in biocarbon production in BC for four scenarios

In either case, we see investment in fast pyrolysis for bio-oil production, which is estimated to have a TRL of 8 - 9 today. Therefore, it could benefit from early investment to ensure that commercial deployment may begin in 2027 - 2030. Finally, we see continued growth in other biofuel technologies, which represent different biomass feedstock conversion processes, as well as investments in the transport of biomass, which are required to support bioenergy production. Investment in these technologies is expected to reach $159 - 180 MCAD (2022) / yr in 2035 and then grow to $169 - 288 MCAD (2022) / yr by 2050 (depending on the scenario).





Action plan for biocarbon development in BC

The following action plan (Table 7) outlines the steps needed to enable British Columbia to maximize the potential of biocarbon within the net-zero BC (NZBC) scenario. It focuses on building a sustainable, flexible, and efficient biocarbon industry over the next two decades, with a particular emphasis on actions required in the next 10 years.

These actions aim to advance the maturity of the biocarbon sector and establish the necessary frameworks, technologies, and markets to support strong long-term growth and drive decarbonization—helping to close the opportunity gap illustrated in Figure 5.

KEY THEMES OF THIS ACTION PLAN INCLUDE:

01	Economic reconciliation
02	Carbon sequestration
03	Decarbonizing transport
04	Decarbonizing heat
05	Required investment
06	Access to reliable feedstock

Action plan for biocarbon development in BC

Table 7 - Action plan for biocarbon development in BC

Economic reconciliation

ISSUE	GOAL	ACTION
PROJECT DEVELOPMENT → CONTINUOUS		
Biocarbon project development is inherently land-based, making it closely tied to the rights, knowledge, and leadership of Indigenous Peoples. First Nations, Inuit, and Metis communities in Canada are stewards of their traditional territories, and their sovereignty, land rights, and knowledge systems must be central to any development approach. In BC alone, there are over 200 First Nations, highlighting the importance of co-developing biocarbon opportunities in ways that advance both climate goals and economic reconciliation. Recognizing Indigenous leadership and enabling equitable participation is essential to building lasting, just, and effective biocarbon solution.	Engage early and ensure project outcomes align with community needs and objectives. Build meaningful, equitable partnerships, transparent credit models, and robust revenue pathways into project development.	Ensure that any industrial development plans on traditional lands, or the use of forest residues, adhere to Indigenous land-use planning, cultural values, Free, Prior, and Informed Consent (FPIC), United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) principles, and contribute shared knowledge and economic benefit. Risk analysis and environmental impacts of proposed projects should align with community values and existing environmental and conservation strategies.
Annual growth in biocarbon facilities should attain 10 - 15% in the short term. Community benefits from new resource development projects often do not accrue naturally and need to be prioritized and negotiated.	Ensure early partnerships and ownership agreements with Indigenous communities. This includes early access to jobs and priority for other economic benefits that can be realized at the community level.	Where biocarbon projects are located near Indigenous communities, there is an opportunity to pursue equitable partnerships that reflect community interests, values, and priorities. Where there is interest and capacity, these projects could be Indigenous-led or co-developed, building on examples like the Arbios Biotech Chunto Ghuna low-carbon biofuel plant in Prince George. Ensure that local employment and training opportunities are accessible to Indigenous community members.

Carbon sequestration

ISSUE	GOAL	ACTION
END-USE MARKETS → 2035		
There is a significant gap in material applications for biochar, which are needed to drive a growing market demand instead of relying on carbon markets alone.	Develop a robust market for high-value biochar applications, targeting an unclaimed market of approximately 0.4 MT of biochar by 2035.	Invest in and support emerging high-value applications for biochar and ongoing research, particularly in heavy industries such as mining, where biochar can be utilized for site reclamation in BC.
Biochar will require the development of new end-use markets to support its valorization as both an emission reduction technology and a material with practical applications.	Grow end-use markets for biochar by enabling its adoption in material applications while contributing to carbon sequestration targets, with initial projects targeting the use of at least 25,000 tonnes in construction materials by 2035.	Support pilot projects that explore biochar's use in construction material applications (concrete, asphalt, and mortar) to investigate cost reductions and potential for higher mixing rates, for example through an industry fund.

ISSUE	GOAL	ACTION
There is a large gap in material applications for biochar, which are needed to drive a growing market demand instead of relying on carbon markets alone to maximize local emission reduction opportunities that are cost-effective.	Enable annual growth of 6 - 8% for the biochar market in the medium-term.	Explore and mature new end-uses for biochar in BC, such as mining reclamation and as an additive in construction materials, collaborating with industrial partners to accelerate time to market.
POLICY SUPPORT → 2045		
The wood pellet export market represents a source of competition for the local use of biomass to produce biocarbon, while use of biocarbon for local emission reductions may not be as cost-effective.	Biochar should allow to sequester at least 1 MT of CO_2e in BC (close to half a million tonnes of high-quality biochar) by 2035 and 2.7 MT of CO_2e by 2045.	Implement policies to increase the competitiveness of local emission reductions and the local use of biomass for biocarbon outputs compared with international markets. Examples include recognizing biochar as an offset mechanism under the OBPS, advancing LCFS policy targets, and including biochar under investment tax credits for carbon sequestration technologies.

Decarbonizing transport

ISSUE	GOAL	ACTION
PRODUCTION AND END-USE MARKETS → 2035		
Growth of the biofuel market for transportation shows significant opportunity as an end-use market, but technological hurdles still exist.	Secure short-term annual growth of bio-oil upgrading facilities of over 25%.	Collaborate with industry to commercialize improvements in bio-oil upgrading processes, such as new catalysts. This will help secure the transportation sector as a market for biocarbon production facilities.

Decarbonizing heat

ISSUE	GOAL	ACTION
PRODUCTION → 2035		
Industrial uses of syngas and upgraded syngas present an underutilized decarbonization opportunity in the short to medium term.	Facilitate the adoption of biomass-derived syngas into industrial heating processes, targeting a market potential of 5 PJ by 2035.	Prioritize options that offer a short payback period such as biomass gasification for on-site integration with industrial heating applications.
END-USE MARKETS → 2035		
Industrial uses of syngas and upgraded syngas represent a viable decarbonization opportunity in the short-to-medium term.	Reach 5 PJ of syngas consumption in industries by 2035.	Promote industrial use of syngas, particularly in the pulp and paper industry and industrial heating applications.

Required investment

ISSUE	GOAL	ACTION
END-USE MARKETS → 2035		
Biocarbon investment requires long-term markets to provide certainty and reduce financial risk for producers and investors.	Establish stable, long-term markets for biocarbon applications, targeting significant demand by 2035, such as agriculture soil usage (0.4 MT by 2035) and energy usage (>20 PJ by 2035).	Prioritize long-term contracts for biocarbon applications that offer more market certainty, such as agricultural soil amendments, industrial heating, RNG grid injection, and bio-oil upgrading. Track policy changes in RNG blending and injection into the grid, and in the LCFS targets, which impact demand for biogas and biofuels.
PRODUCTION → 2035		
Although volumes vary across scenarios, growth in syngas and raw syngas production is essential to meet net-zero targets, particularly for replacing natural gas with RNG.	Achieve significant growth in syngas production and its upgrading to RNG to replace natural gas and meet net-zero targets, with investments of over $60 MCAD (2022) / yr by 2035.	Invest in biomass gasification with methanation to produce RNG.
PRODUCTION → 2045		
Different technologies produce varying types and quantities of co-products (syngas, bio-oil). While demand for biochar is consistently increasing across all scenarios, the demand for co-products fluctuates depending on assumptions about competing decarbonization options.	Optimize growth in biochar production alongside scalable syngas and bio-oil outputs. Generate about $75 MCAD (2022) in annual investments by 2035, and $190 MCAD (2022) by 2045, to meet biochar and co-product demand in net-zero scenarios, with at least one-third directed toward slow pyrolysis technologies.	Continue orienting investment in slow pyrolysis systems that produce syngas to fuel the process and provide energy for drying biomass residues. Simultaneously, target fast pyrolysis for higher and better-quality bio-oil output. Support the scaling and improvement (new catalysts) of bio-oil upgrading facilities, which will allow for selling of biofuels in the transportation market.
PRODUCTION → 2050		
While slow pyrolysis is currently the most commercialized and advanced biocarbon technology, other technologies could become cost-effective for specific product types or feedstocks with ongoing process improvements.	Commercialize a variety of technologies to meet feedstock requirements and capabilities alongside market demands.	Continue to monitor advancements in emerging technologies such as HTL for processing diverse feedstocks amid increasing feedstock competition, and microwave-assisted and catalytic pyrolysis for producing higher-quality bio-oil and biochar.

Access to reliable feedstock

ISSUE	GOAL	ACTION
RELIABLE FEEDSTOCK SUPPLY → 2035		
Producers need a reliable and low-cost supply of feedstock to enable biocarbon industry growth, but competing demands for biomass from other sectors will make this more challenging.	By 2035, establish a reliable, diversified, and cost-effective supply chain for biocarbon feedstock that will allow: - Double the use of wood processing plant residues or comparable feedstock (from about 1 MT in 2024 to over 2 MT). - A feedstock price range of $45 - 60 CAD / tonne, with the lower-end applicable for the short-term.	Implement financial incentives to make removing harvest residues more economical than burning or abandonment. Also, explore options to restructure stumpage rate calculations for harvest residues. Incentivize the use of urban wood-product waste, woody debris, and RDF for biocarbon production while diverting this feedstock away from landfills.

Biocarbon conclusions

Analysis of study scenarios suggests that BC has significant potential to expand biocarbon production, with projections of 3x by 2035 and 8.5x by 2050. Investing in biocarbon technologies such as slow pyrolysis, fast pyrolysis, and gasification could be a key driver of this growth.

Additionally, doubling sustainable feedstock utilization by 2035 presents a substantial challenge due to competition for reliable, low-cost biomass. Other necessary challenges will be addressing supply chain complexity and economic feasibility, both of which will require robust policy measures across the value-chain.

In both reference and net-zero scenarios, biochar production presents promising avenues to generate negative carbon emissions. While the VCM is currently a popular mechanism to capture this benefit, integrating biochar as a material additive can help ensure attributable emission reductions remain within BC However, the introduction of an offset protocol could enable the VCM to support funding for biochar projects, improving the overall cost-effectiveness of biocarbon production.

Focusing on biochar for carbon sequestration, along with developing bio-oil upgrading and syngas to decarbonize transportation and heating, offers enormous potential. If a NZBC scenario is followed, it is projected that gaseous biocarbon products will be prioritized over bio-coal as a cost-optimal decarbonization solution.

Realizing the potential of biocarbon will require active participation from key stakeholders, (investors, academic institutions, innovators, Indigenous rights holders, and non-profit organizations) to overcome barriers related to social licensing, supply chains, and innovation. Central to this effort is advancing economic reconciliation throughout the biocarbon industry by enabling Indigenous communities to participate in, steward, and lead vital parts of the value chain.

By overcoming key barriers, BC and Canada have a unique opportunity to become global leaders in the emerging biocarbon economy. Leveraging abundant biomass resources can deliver near-term progress towards net-zero targets while unlocking long-term economic growth. While these findings are focused on BC’s context, they offer a scalable model for other jurisdictions with similar resource potential. A robust, exportable biocarbon value chain not only strengthens domestic industries, it sets the stage for international replication and climate leadership on a global scale.

Appendix 1: Detailed market and end-use assessment

APPENDIX 1: DETAILED MARKET AND END-USE ASSESSMENT

Table 8 - Detailed market and end-use assessment

MARKET GROUP	MARKETS	EXPLANATION OF BIOCHAR'S USE IN THIS MARKET	KEY PROPERTIES	OPTIMUM PARTICLE SIZE	MARKET ELIGIBLE FOR CARBON CREDITS	MARKET ACCESS FOR STANDARD WOOD BIOCHAR	COMMENTS FOR MARKETS
Agriculture and soil improvement	Soil amendment	A soil amendment refers to any material added to the soil to improve its physical or chemical properties.	High water retention, high nutrient content, absence of contaminants, granulometry adapted to the soil.	0.2 - 5 mm	Eligible for carbon credits	Accessible	Particularly for growers with very compact, degraded soils. Not interesting for field crops, unless the selling price is very low. Best combined with another amendment when applied to soil. The problem may be the level of certain nutrients that are not balanced for plants, or the expected high pH (to be measured). It can be interesting as a liming agent, but liming capacity needs to be measured.
Agriculture and soil improvement	Micronutrient fertilization	Fertilizers are generally defined as "any material, organic or inorganic, natural or synthetic, which supplies one or more of the chemical elements required for the plant growth." Most fertilizers that are commonly used in agriculture contain the three basic plant nutrients: nitrogen, phosphorus, and potassium.	High sorption capacity, high porosity, high fixed carbon content.	<1 mm	Eligible for carbon credits	Accessible	Biochar contains nutrients, but above all serves as a carrier, a method of delivering nutrients and/or micro-organisms to plants in the form of micro-granules. Fertilizer manufacturers are beginning to use it.
Agriculture and soil improvement	Compost additive	Compost is the result of the natural rotting process that occurs with all organic material. Compost contains valuable nutrients and is rich in humus. Humus is long-lasting in the soil and can be beneficial in providing for improved physical, chemical and biological conditions.	Low contamination tolerance, compatible with almost all raw materials, low total carbon content.	0.5 - 5 mm	Eligible for carbon credits	Accessible	Increases the amount of nutrients in compost. The US Compost Council is interested in biochar (but has not shown as much interest in ash-based products). The low quality of compost makes it difficult to obtain biochar at an attractive price, but the carbon credit only increases interest if the carbon content is higher.
Agriculture and soil improvement	Additive for hydroseeding	Hydroseeding applies soil amendments, fertilizers, soil stabilizers and seeds at the same time with a double objective, soil stabilization and seed germination and plant growth. One of these additives can be biochar.	High sorption capacity for nutrients and water, high carbon content, homogeneous particle size.	<1 mm	Eligible for carbon credits	Accessible	Hydroseeding applies soil improvers, fertilizers, soil stabilizers and seeds at the same time, with the dual aim of soil stabilization, seed germination and plant growth. One of these additives can be biochar.
Agriculture and soil improvement	Soil enhancer for organic production	Enhance the soil's physicochemical properties by the biochar water and nutrients sorption abilities.	In general, high carbon content, low ash content; electrical conductivity mS/m ≤1000; molar H / Corg ≤0.7; low contaminant content.	0.2 - 5 mm	Eligible for carbon credits	Accessible	Regulations applied to biochar used in soil.
Horticulture	Potting soil for ornamentals	Biochar used in smaller scale, often mixed with other ingredients in potting soil for growing ornamentals.	Lightweight, nutrient-rich, water-holding, generally neutral to basic pH, low total acceptable carbon content.	0.7 - 10 mm	Eligible for carbon credits	Accessible	Large companies are beginning to penetrate this market for their potting compounds. Resellers and agglomerators begin operations in the USA and Canada. Acceptance in the USA and Canada.
Horticulture	Soil planting mixes for vegetables and fruits	Biochar used in the soil, improving its nutrients and water-holding capacity for growing high-value crops such as fruits and vegetables.	Best pH and particle size depend on soil pH and particle size, low acceptable carbon content.	0.5 - 5 mm	Eligible for carbon credits	Accessible	Small-scale growers of vegetables, fruits and other high-value crops are often more receptive to new products and practices, especially those looking for more environmentally friendly options.

Appendix 1: Detailed market and end-use assessment

MARKET GROUP	MARKETS	EXPLANATION OF BIOCHAR’S USE IN THIS MARKET	KEY PROPERTIES	OPTIMUM PARTICLE SIZE	MARKET ELIGIBLE FOR CARBON CREDITS	MARKET ACCESS FOR STANDARD WOOD BIOCHAR	COMMENTS FOR MARKETS
Horticulture	Forestry	Activities such as reforestation can significantly increase carbon sequestration in forests. In addition, the application of biochar to seedling or planting or even during growth would greatly increase carbon sequestration.	Light, nutrient-rich, water-holding, neutral to basic pH.	0.5 - 5 mm	Eligible for carbon credits	Accessible	Biochar is a low-volume product that works very well when it comes to increasing carbon content. Accepted in the USA and Canada. You can only pay for cheap biochar.
Horticulture	Landscaping	Biochar used in landscaping to improve plant health, plant growth, and production of flowers. Its role consists of maintaining high porosity, low density of the soil hold water while allowing good drainage and aeration.	Light, nutrient-rich, water-holding, generally neutral to basic pH, low total carbon acceptable.	0.7 - 10 mm	Eligible for carbon credits	Accessible	Large companies begin to penetrate this market for their potting blends. Resellers and agglomerators begin operations in the USA and Canada. Acceptance in the USA and Canada.
Animal husbandry	Silage agent	Silage is an effective method for storing feedstock used for the production of biofuels from energy crops, and is also effective for storing livestock feed, particularly to cover periods of feed shortages. Commercial additives are used to enhance fermentation and aerobic stability while minimizing the growth of undesirable microorganisms. Biochar has shown great potential in improving the storability of materials.	High sorption capacity for nutrients, no contaminants.	<1 mm	Eligible for carbon credits	Accessible	Commercial additives are used to improve fermentation and aerobic stability while minimizing the growth of undesirable micro-organisms. Biochar has shown great potential in improving the storage capacity of materials.
Animal husbandry	Feed additive / supplement	Livestock farmers increasingly use biochar as a regular feed supplement to improve animal health, increase nutrient intake efficiency and thus productivity. It acts as an adsorbent; biochar has been shown to lock up toxins in the digestive tract.	High sorption capacity for nutrients, no contaminants.	<1 mm	Eligible for carbon credits	Accessible	Provides nutrients and balances microflora, promoting growth. Rarely used in the USA and Canada, with a few exceptions, but regularly used in Europe. The CFIA (Canadian Food Inspection Agency) has accepted biochar as a food colorant, but not as an animal growth promoter. Chickens consume it naturally.
Animal husbandry	Litter additive	Biochar will help to remove odor and moisture from the litter, binding ammonia and nitrogen. Used on the litter, it locks in moisture and organic and inorganic nitrogen compounds, and control undesired microbes, controlling infection to feet and cow’s udder.	No contaminants, virgin raw materials, high sorption capacity for liquids and urea, high water retention capacity.	2 - 15 mm	Eligible for carbon credits	Accessible	High carbon biochar is effective at intercepting gases and odors. It reduces foot disease and respiratory problems in livestock, which is more pleasant for farmers. Accepted but little used in the USA. Particularly useful for poultry houses, but market development is slow. Few litter regulations.
Animal husbandry	Manure and slurry treatment	Biochar in slurry improves slurry treatment, favors bacterial activities, reducing nutrient losses to the atmosphere (ammonia).	Few constraints other than high sorption capacity for gases and contaminants, high porosity for micro-organism attachment.	Little importance	Eligible for carbon credits	Accessible	Standard biochar is highly effective at intercepting gases and odors. Helps conserve nitrogen in sludge and manure. Reduces greenhouse gas emissions. Starting to be used in the USA and Europe.
Animal husbandry	Odor control	The high sorption properties of biochar help improve farm hygiene by binding toxic and gases such as ammonia substances and controlling pathogens, limiting the odors from bacteria and gaseous molecules.	Few constraints other than high sorption capacity for gases and contaminants, high porosity for micro-organism attachment.	Little importance	Eligible for carbon credits	Accessible	Standard biochar is highly effective at intercepting gases and odors. Helps conserve nitrogen in sludge and manure. Reduces greenhouse gas emissions. Starting to be used in the USA and Europe.
Animal husbandry	Animal detoxification, infection control	Used to decrease diarrhea. Carbon controls microbial population, favoring good ones, sorbing toxins. Used only when needed.	High sorption capacity for drugs, no contaminants.	Powder - 0.2 mm	Eligible for carbon credits	Accessible	In case of infection or diarrhea, ingestion of biochar (non-active) reduces symptoms and eliminates infections more rapidly, in combination with medication. Used in Europe, but not in North America due to pharmaceutical lobbying. Requires strict quality controls.

Appendix 1: Detailed market and end-use assessment

MARKET GROUP	MARKETS	EXPLANATION OF BIOCHAR'S USE IN THIS MARKET	KEY PROPERTIES	OPTIMUM PARTICLE SIZE	MARKET ELIGIBLE FOR CARBON CREDITS	MARKET ACCESS FOR STANDARD WOOD BIOCHAR	COMMENTS FOR MARKETS
Construction	Additive in asphalt	Biochar can be used as asphalt binders and asphalt mixes. Biochar tends to improve the performance and durability of the materials mostly by influencing mechanical properties.	High compressive, torsional and tensile strength; High surface area 9.7 - 197 m^2 / g Total pore volume 0.016 - 0.18 cm^3 / g Thermal conductivity 0.19 W / (m-K) Water absorption capacity, lower.	0.1 - 1 mm	Eligible for carbon credits	Accessible if it meets specific property requirements	Accepted in Asian countries, it is not yet used in North America or Europe. The industry is not ready, and competition with other additives is strong. Selection is necessary. The additive is used to modify the properties of asphalt. Companies are starting to negotiate with the US government for these types of products.
Construction	Construction panels (drywall, insulation)	Two of biochar's key properties are its low thermal conductivity and its ability to absorb water up to 5 times its weight. These properties mean that biochar is just the right material for insulating buildings and regulating humidity.	Depending on materials.	Variable	Eligible for carbon credits	Accessible if it meets specific property requirements	Does not yet appear to be used in the USA. Post-treatment may be required. Few constraints. Low-cost biochar. Manufacturers are considering it for countertops, worktops, coatings, etc., replacing other fibers, colors, reducing density and modifying other properties.
Construction	Filling for cement/ concrete	Biochar is currently competing with high-performance fillers in the formulation of multifunctional polymer-based composites, inducing high mechanical and electrical properties.	High compressive and torsional strength High surface area combined with other biochar properties such as cation exchange capacity (CEC) or water retention capacity. Ash content 1 - 17%; Volatile matter 1 - 17%; Fixed carbon >65%. Carbon >65%; Particle size 5 - 200 μm; Bulk density - high; Pore volume 0.016 - 0.020 cm^3 / g; Pore size - approx. 2 nm; Surface area: 10 - 197 m^2 / g; Water holding capacity - approx. 4.27%; 2.81 - 9.0 g / g; Thermal conductivity: 0.19 W / (m-K); Electrical conductivity (EC) - 0.16 dS / m.	<5 mm	Eligible for carbon credits	Accessible if it meets specific property requirements	It is very complex to modify the laws governing concrete, which is why the addition of biochar to the concrete structure is not used. Used for "non-load bearing" elements such as pavements, to modify the color, density and other properties of decorative architectural concrete such as benches. In the USA, it has begun to be used in the design of elements, as well as in Europe. Biochar can also be added to cement mortar as a filler. This has more noticeable effects on the mortar's initial strength, whatever the water-cement ratio. The optimum biochar content is around 1 - 2% to improve the hardened density of cement mortar.
Construction	Modifier for cement/ concrete	The addition of biochar offers significantly higher mechanical strength and improved permeability as a carbon-sequestering admixture in concrete constructions. Requires very specific properties for very specific changes in mechanical properties and durability.	High compressive and torsional strength High surface area combined with other biochar properties such as cation exchange capacity (CEC) or water retention capacity. Ash content 1 - 17%; Volatile matter 1 - 17%; Fixed carbon >65%. Carbon >65%; Particle size 5 - 200 μm; Bulk density - high; Pore volume 0.016 - 0.020 cm^3 / g; Pore size - approx. 2 nm; Surface area: 10 - 197 m^2 / g; Water holding capacity - approx. 4.27%; 2.81 - 9.0 g / g; Thermal conductivity: 0.19 W / (m-K); Electrical conductivity (EC) - 0.16 dS / m.	<5 mm	Eligible for carbon credits	Accessible if it meets specific property requirements	Adding biochar to cement mortar as a modifier has significant effects on the mortar's initial strength, whatever the water-cement ratio. The optimum biochar content is around 1 - 2% to improve the hardened density of cement mortar. Biochar performs better in terms of mechanical properties and permeability. Compressive and tensile strength have increased, while water penetration depth and sorptivity have been reduced. The addition of biochar increases the air content of fresh mortar, which is influenced by the porous structure of biochar particles. The biochar acts as a reinforcement to the mortar paste, resulting in higher ductility than control during flexural failure.

MARKET GROUP	MARKETS	EXPLANATION OF BIOCHAR'S USE IN THIS MARKET	KEY PROPERTIES	OPTIMUM PARTICLE SIZE	MARKET ELIGIBLE FOR CARBON CREDITS	MARKET ACCESS FOR STANDARD WOOD BIOCHAR	COMMENTS FOR MARKETS
Construction	Special concrete (e.g. non-load-bearing architectural)	The addition of biochar offers sequestering admixture in concrete in addition to colour and durability in usages where it does not support load such as park bench, pavement, telephone pole, and so on.	High compressive and torsional strength High surface area combined with other biochar properties such as cation exchange capacity (CEC) or water retention capacity. Ash content 1 - 17%; Volatile matter 1 - 17%; Fixed carbon >65%. Carbon >65%; Particle size 5 - 200 μm; Bulk density - high; Pore volume 0.016 - 0.020 cm^3 / g; Pore size - approx. 2 nm; Surface area: 10 - 197 m^2 / g; Water holding capacity - approx. 4.27%; 2.81 - 9.0 g / g; Thermal conductivity: 0.19 W / (m-K); Electrical conductivity (EC) - 0.16 dS / m.	<5 mm	Eligible for carbon credits	Accessible if it meets specific property requirements	Adding biochar to cement mortar as a modifier has significant effects on the mortar's initial strength, whatever the water-cement ratio. The optimum biochar content is around 1 - 2% to improve the hardened density of cement mortar. Biochar performs better in terms of mechanical properties and permeability. Compressive and tensile strength have increased, while water penetration depth and sorptivity have been reduced. The addition of biochar increases the air content of fresh mortar, which is influenced by the porous structure of biochar particles. The biochar acts as a reinforcement to the mortar paste, resulting in higher ductility than control during flexural failure.
Metallurgy	Coke replacement in the blast furnace (BF)	For the replacement of blast furnace coke, optical coal parameters include volatile content <7%, high density, and sizes <20 - 25 mm. With CO_2 emission savings estimated at 3 - 7%, this biochar substitution is already being tested in commercial mini-furnaces and industrial trials in large furnaces. Lump biochar for blast furnace charging requires high strength, a volatile content of 0 - 25%, and sizes in the 30 - 60 mm range.	For the replacement of walnut coke in BF, optical charcoal parameters include VM <7%, high density and sizes <20 - 25mm. Lump charcoal for BF loading requires high strength, 0 - 25% VM, and sizes 30 - 60mm.	Variable	Not eligible for carbon credits	Treatment required	With CO_2 emission savings estimated at 3 - 7%, this substitution by biochar is already being tested in commercial mini-FBs and industrial trials in large FBs. The insufficient strength of biochar may be a problem limiting coke substitution.
Metallurgy	Blast furnace nozzle injection (pulverized coal)	According to several studies, it seems possible to replace pulverized fossil coal with low-ash, high-basicity biochar by reducing blast volume, slag volume and, consequently, to operate with a lower coke rate. In addition, heat losses are reduced, and furnace productivity is increased. Gas volume and calorific value are also reduced. The porosity, particle size and specific surface area of biochar, within a certain range, have no negative impact on coal injection rates.	As BF injectors, biochar's must have a high VM content of 10 - 20%, a low ash content <5% and a low alkali level.	Fine	Not eligible for carbon credits	Treatment required	This substitution can significantly reduce CO_2 emissions, by up to 19 - 25%. Biochar physical parameters such as porosity, particle size distribution and specific surface area within a certain range have no negative effect on coal injection rates. These parameters are currently the subject of theoretical study and combustion tests in mini-FBs and industrial plants.
Metallurgy	Manufacture of coke (coking coal)	In recent years, research has been carried out into the production of coke blends with bio-coal to reduce these emissions.	As BF injectors, biochar's must have a high MV content (10 - 20%), a low ash content (<5%) and a low alkali level.	<1 mm	Not eligible for carbon credits	Treatment required	With net CO_2 emission savings of 1 - 5%, this research is still in the laboratory stage and is on the verge of concrete results. Typical addition rate: 480 - 560 kg / tHM.
Metallurgy	Reducer in ferroalloy Manganese	The ferroalloy industry refers to iron alloys with a high proportion of additional elements, such as aluminum, chromium, manganese or silicon. Biobased reducers have the potential to replace reducers made from fossil materials in metallurgy. Around 10% of biochar has been used for silicon production in European Union countries.	Total carbon: >85 Ash: <12%; Particle size: 5 - 40 mm; Density: 400 - 500 kg / m^3; Surface area: 8 - 650 m^2 / g.	5 - 40 mm	Not eligible for carbon credits	Treatment required	If specific properties are met, testing may be viable.
Metallurgy	Reducer in Ferroalloy Silicon	Biochar could be used in ferroalloys. The desired properties seem achievable. A significant reduction in greenhouse gas (GHG) emissions is conceivable with biochar.	Total carbon: >85 Ash: <12%; Particle size: 5 - 40 mm; Density: 400 - 500 kg / m^3; Surface area: 8 - 650 m^2 / g.	5 - 40 mm	Not eligible for carbon credits	Treatment required	If specific properties are met, testing may be viable.

Appendix 1: Detailed market and end-use assessment

MARKET GROUP	MARKETS	EXPLANATION OF BIOCHAR'S USE IN THIS MARKET	KEY PROPERTIES	OPTIMUM PARTICLE SIZE	MARKET ELIGIBLE FOR CARBON CREDITS	MARKET ACCESS FOR STANDARD WOOD BIOCHAR	COMMENTS FOR MARKETS
Metallurgy	Solid fuel sintering	Biochar can replace coke in varying proportions, depending on its physico-chemical properties. This substitution can reduce CO_2 emissions by 3 to 7%.	For iron ore sintering, replacement coal must have low VM <3%, high density >700kg / m^3, small size <0.3 - 3mm.	<0.3 - 3mm.	Not eligible for carbon credits	Treatment required	It could lead to a net reduction in CO_2 emissions of 5 - 15%. This research is currently being tested on a pilot scale.
Energy	Black pellets for electricity generation	Biochar or black granules with high heating value (18 - 21 MJ / kg) for energy applications, but lower than anthracite.	21 MJ / kg, water-repellent, resistant to 95%.	Pellets	Not eligible for carbon credits	Accessible if it meets the specific properties required	Ready and growing market, particularly in Asia and Europe, with significant exports from the USA and Canada. Little competition at present, with the exception of white granules. Granulation required.
Energy	Additive for biomethanization, anaerobic digestion	Biochar can serve as feedstock (only the volatiles) for anaerobic digestion. Biochar's support formation of a methanogenic microflora, can help produce more methane through its fixed carbon hosting the bacteria and flocks.	High sorption capacity, careful with metals and organic matter Active biochar, specific structural properties (surface area: 87 - 1400 m^2 / g, pore size, pore volume 0.0070 - 0.62 cm^3 / g) High pH and cation exchange capacity High ash concentration - alkalinity 18 - 45 High H_2S sorption capacity 0.167 - 16.0 mmol / g High CO_2 sorption capacity 0.4 - 2.312 mmol / g	Fine to large	Eligible for carbon credits	Treatment required	For this application, biochar is often generated by the user as a co-product. This increases natural gas production. The market is starting to develop.
Energy	Briquettes and charcoal lump for BBQ	Bio-coal in chunk or densified bio-coal, briquettes with high heating value (27 - 31 MJ / kg) for cooking.	28 - 32 MJ / kg, densification of pieces or briquettes with starch, good odor (due to volatile substances), low smoke emission, slow combustion, made from hardwood, briquettes must not be too brittle.	2 - 10 cm	Not eligible for carbon credits	Accessible if it meets specific property requirements	Interesting market if products are sold for semi-residential use. Semi-residential means that the charcoal manufacturer sells directly to retailers. As there is only one intermediary and the package size is very small, the value of this market is high for the producer.
Energy	Energy-dense biochar / bio-coal	Bio-coal with high heating value (22 - 30 MJ / kg) for energy applications.	25 - 30 MJ / kg, compression-resistant, low volatility.	Briquettes, pellets	Not eligible for carbon credits	Accessible if it meets specific property requirements	High energy content (30 kJ / kg), well above that of wood pellets. The market is not yet ready.
Soil and water treatment	Water filtration (residential and commercial)	Biochar and its activated derivatives have the capacity to remove various contaminants, including pathogenic organisms, synthetic and emerging organics, and inorganics such as heavy metals and arsenic, fluoride, phosphate and nitrate through filtration, Biochar have recently attracted attention as a potential heterogeneous catalyst for treating wastewater containing synthetic food dyes because of their cost-effectiveness and eco-friendliness.	Iodine number (mg / g) ≥ 700 - 1000 Methylene blue adsorption capacity, mL / g≥ 100 - 120 Moisture (%) ≤ 5 - 10 Ash content (%) ≤ 2 - 5 Pour density (g / mL) 0.3 - 0.5 Pore Volume cm^3 / g≥ 0.75 - 1	Fine-medium	Eligible for carbon credits	Treatment required	Activated carbon obtained from biochar has various applications and has been studied and evaluated, but there are as yet no specific regulations.

Appendix 1: Detailed market and end-use assessment

MARKET GROUP	MARKETS	EXPLANATION OF BIOCHAR'S USE IN THIS MARKET	KEY PROPERTIES	OPTIMUM PARTICLE SIZE	MARKET ELIGIBLE FOR CARBON CREDITS	MARKET ACCESS FOR STANDARD WOOD BIOCHAR	COMMENTS FOR MARKETS
Soil and water treatment	Flood absorbent	Biochar can be utilized to manage water in flood-prone areas effectively. When spread across the affected terrain, biochar acts as a highly porous and absorbent material. Its innate ability to retain water allows it to capture and store excess floodwater, mitigating flooding impacts and facilitating controlled water distribution.	Particle diameter of 0.6 mm.	Fine, 0.6 - 5 mm	Eligible for carbon credits	Treatment required	Little known to business, no well-known company in the USA or Canada uses it, but the market could easily adopt it. Highly effective. For spills of oily products on water, cannot add contaminants. For a spill on a contaminated industrial site, it's probably fine.
Soil and water treatment	Soil remediation	Soil remediation involves the elimination of contaminants from the soil through a range of chemical, physical and biological means that can be applied to carry it out.	Few constraints other than high sorption capacity and appropriate pH. High carbon content.	0.5 - 5 mm	Eligible for carbon credits	Treatment required	Accepted in Canada and the USA., but very few use it because they're always looking for very low-cost amendments.
Soil and water treatment	Compost toilets	Biochar as a matrix in composting toilets (often using straw, litter and other such agents). The toilets decompose human feces and recover nutrients with agricultural value of the resulting compost.	Low-medium quality biochar (biochar from agricultural wastes can be used). Needs good water sorption, for odor sorption, needs high carbon content. Example of Rice husk Biochar: Total C (mg g − 1) 414.3 Total N (mg g − 1) 5.1 C / N 81.2 Bulk density (mg ml − 1) 96	1 cm	Eligible for carbon credits	Accessible	Biochar is effective in achieving high fecal decomposition, low nitrogen loss and high nutrient input.
Air treatment	Activated carbon filters	Activated carbon is a material with distinguishable properties such as high specific surface area, high porosity and desired surface functionalization. Therefore, activated carbon is used for adsorption, pollutant removal, water treatment, etc.	Iodine number (mg / g) ≥ 700 - 1000 Methylene blue adsorption capacity, mL / g≥ 100 - 120 Moisture (%) ≤ 5 - 10 Ash content (%) ≤ 2 - 5 Pour density (g / mL) 0.3 – 0.5 Pore Volume cm^3 / g≥ 0.75 - 1	Fine-medium	Eligible for carbon credits	Treatment required	Activated carbon obtained from biochar has various applications and has been studied and evaluated, but there are as yet no specific regulations.
Air treatment	Ambient air filters	Biochar air filters can be used in incinerators, kilns, cremation, and smelters, and other dedusting and cleaning systems.	Sorption capacity for contaminants, fine particles, fumes and gases.	<0.2 mm or granulated	Not eligible for carbon credits	Treatment required	For niche markets due to competition. Some trials for cigarette and cannabis filters, post-treatment for industrial use. Not yet used in Canada and the USA. In competition with low-cost materials.
Industry	Additive for foam (cushions, mattresses, etc.)	Biochar can be used as a modifier for mattresses, pillows, cushions as it adsorbs perspiration and odors, shields against electromagnetic radiation (electrosmog), and removes negative ions from the skin. Moreover, it acts as a thermal insulator reflecting heat, thereby enabling comfortable sleep without any heat build-up in summer.	Compression, torsion resistant, long fibers, high fixed carbon.	Powder - 0.2 mm	Not eligible for carbon credits	Accessible	Specific properties, currently marketed mainly by overseas manufacturers, but products can be found here. Little post-treatment.

Appendix 1: Detailed market and end-use assessment

MARKET GROUP	MARKETS	EXPLANATION OF BIOCHAR'S USE IN THIS MARKET	KEY PROPERTIES	OPTIMUM PARTICLE SIZE	MARKET ELIGIBLE FOR CARBON CREDITS	MARKET ACCESS FOR STANDARD WOOD BIOCHAR	COMMENTS FOR MARKETS
Industry	Carbon source for graphite and graphene	Turning biochar into graphene can have many uses, like replacing activated carbon coatings of electrodes used in supercapacitors.	Carbon total: High, 87 - 99%; Water holding capacity: High, 40 - 60%; Ash: Low; Particle size: Fine-medium; Sorption capacity: 0.05 - 0.65 mmol / g; Density: 0.41 - 0.61 g / ml; Porosity: High; Surface area: 2600 m^2 / g; Pore size: 5 - 13 nm; Thermal conductivity: 3,000 - 5,000 W / mK; Electrical conductivity: 400 S / m; Tensile Strength: 100 - 130 GPa Young's Modulus (stiffness): Graphene dosage 2 - 10%: increase of 2 - 91% (28d); Maximum Young's modulus of 1.0 TPa; Flexural strength (MPa): 39 - 137 Mpa Electron mobility: 2,000 - 5,000 cm^2 / Vs; highest 230,000 cm^2 / Vs	Fine-medium	Eligible for carbon credits	Treatment required	This is the carbon structure that offers all the advantages of biochar and provides electrical properties. Carbon content should be around 87 - 99%; posity is high; surface area is much larger; pore size measurement is required. The molar ratio must be less than 0.7 for biochar to be eligible for carbon credit. The duration and end-of-life of the product in which biochar is used greatly influence its eligibility for carbon credits.
Industry	Semiconductors, batteries	Besides the well-known adsorption effects of Biochar, it can also narrow the band gap, facilitate electron transport, suppress the electron-hole charges recombination and reduce the photocorrosion of semiconductors, etc.	Carbon total: High 86 - 96%; Ash: Low ; Particle size: Fine-medium; Density: High; Porosity: High; Surface area and pore size (m^2 / g): 950 - 1500 m^2 / g; Total pore volume: 0.50 - 1.21 cm^3 / g; Average pore size: 3 - 5 nm; Current density: 0.1A / g; Cyclability: capacities retention over 100 cycles with a decay rate per cycle of 0.23%; Discharge capacity: 360 - 1169 mAh / g; (superior to graphite carbon).	Fine-medium	Eligible for carbon credits	Treatment required	Carbon nanospheres as anodes for a Li-ion battery.
Industry	High-tech (carbon nanotubes)	Biochar with high electrical conductivity, specific surface area, and mechanical strength. Due to successfully improving the mechanical and thermal properties of biopolymers, carbon-based materials have been widely used as reinforcing fillers in different applications. Other applications could be as reinforcement in polymeric composites for the manufacture of interior components of automobiles or airplanes, for example, as they are lightweight and fire resistant.	Long fiber, properties highly variable with use, strong carbon structure, high Ctot.	Highly variable	Eligible for carbon credits	Treatment required	Very specific type of carbon, special production and extensive post-conditioning. Several applications are under development.
Industry	Printing (3D and other technologies)	Due to its inert internal structure and highly functionalized surface, biochar offers excellent electron transfer kinetics, reproducibility, and high sensitivity. Therefore, have the potential to be a renewable and biodegradable raw material for 3D printing.	Fiber shape depends on technology, high Ctot, good carbon structure.	<0.4 mm	Eligible for carbon credits	Treatment required	Small volume with specific properties. Price expected to drop considerably over time. Research in progress.
Industry	Specialty paints (cars, aircraft, etc.)	Biochar nanoparticles incorporated into zinc-rich epoxy paint, with the aim of improving zinc powder utilization and the anticorrosion performance.	High Ctot, Cfix, specific carbon structure.	<0.2 mm	Not eligible for carbon credits	Treatment required	Specific markets already exist, notably the automotive industry in North America. Particle size and specific carbon type, post-treatment may be important.

Appendix 1: Detailed market and end-use assessment

MARKET GROUP	MARKETS	EXPLANATION OF BIOCHAR'S USE IN THIS MARKET	KEY PROPERTIES	OPTIMUM PARTICLE SIZE	MARKET ELIGIBLE FOR CARBON CREDITS	MARKET ACCESS FOR STANDARD WOOD BIOCHAR	COMMENTS FOR MARKETS
Industry	Textile additives	In Japan and China bamboo-based biochar's are already being woven into textiles to gain better thermal and breathing properties and to reduce the development of odors through sweat.	Long fibers, high odor absorption.	Long narrow fibers a plus	Not eligible for carbon credits	Treatment required	The more it resembles activated carbon, the more likely it is to be used in highly specialized textiles. Very low volume. Requires extensive post-treatment. Must be tested for odor control.
Industry	Catalyst for chemical reactions	Biochar is widely utilized as support for metals in catalysis, due to its feedstock availability, large surface area (for good metal phase dispersion and stability), low cost, and stability in basic and acidic media.	Carbon >65%; Pore volume: 0.27 - 0.79 cm^3/ g Pore size: <50 nm Contact surface: 350 - 1955 m^2/ g	Fine-medium	Not eligible for carbon credits	Treatment required	Requires high surface area, total pore volume, large pore radius, total acidity and mineral content (i.e. alkali metals such as Na, Ca, K and possibly Fe), all of which must be measured, and high carbon content. The carbon content must be high, the posity high, the surface much larger, and pore size measurement is necessary.
Industry	Additive for plastics	Biochar is a modifier of plastics to increase its resistance to UV, make it lighter and improve mechanical properties.	Low silica and quartz content, medium carbon content.	<0.5 mm	A small part is eligible for carbon credits	Treatment required	Some American companies have supplemented their recipes with specific properties. None are yet on the market. Sieving is important. Tests are needed to determine whether the product has the right properties for the various uses of plastics.
Industry	Explosion (gunpowder, fireworks)	Biochar with high explosion properties. It has always been used as one of the 3 components of the gun powder.	High reactivity, explosiveness, Ctot, low humidity.	Powder - 0.2 mm	Not eligible for carbon credits	Accessible	The market has been protected by a few producers until now, but it is now opening up.
Industry	Carbon fibers	Biochar into the epoxy matrix improved the mechanical and thermal properties of carbon fiber-reinforced composites.	Long fiber, highly variable properties depending on use, high carbon structure, high Ctot.	Highly variable	Eligible for carbon credits	Treatment required	Very specific type of carbon, special production and extensive post-conditioning. Many applications under development.
Industry	Packaging materials	Biochar reinforced polymer composites could be beneficial in the packaging industry.	Long fibers are an asset, as they are water-repellent and have low volatility.	Varied	Not eligible for carbon credits	Treatment required	Little post-treatment in various residential and industrial products. Several research projects, notably for coffee cups. High potential volume for construction packaging, but the market is not yet ready.
Industry	Food preservation (e.g. ethylene capture in sachets)	Biochar absorbs Ethylene which will retard the post ripening of fruits and vegetables prolonging thus their conservation time.	High gas sorption, high sorption capacity and porosity, no contaminants.	0.5 - 5 mm	Eligible for carbon credits	Treatment required	Biochar helps preserve fruit and vegetables by capturing gases, including ethylene. Little competition in this particular field. Less known to potential consumers, rarely used. Little post-treatment.
Health/human care	Cosmetics	Biochar can be used in cosmetics for skin treatment and coloration.	No contaminants, proven clean production, virgin raw materials.	Powder - 0.2 mm	Not eligible for carbon credits	Treatment required	Medium to high processing for specific requirements. Small volume. Many products containing biochar are already on the market in North America.
Health/human care	Activated carbon for pharmaceuticals	Biochar can serve as an agent on which is grafted the medication as carrier.	High sorption capacity, no contaminants.	Fine - 1 mm	Not eligible for carbon credits	Treatment required	Long-established market, small volume, demanding quality control, requires extensive post-processing, must often be activated. Lobbying against its administration as a body pharmaceutical if it is not active. Will not accept contaminated biochar for activation.
Health/human care	Personal care	Biochar used for soaps, masks or other skin applications. Biochar-based adsorbents help remove dead skin cells and pollution particles providing good absorb.	No contaminants, proven clean production, virgin raw material, high Ctot, sorption capacity for certain uses.	<0.5 mm	Not eligible for carbon credits	Treatment required	Any type of clean biochar, the market favors wood biochar. Market consumes a lot of various products in North America. Little post-treatment.

APPENDIX 2: ESMIA MODEL METHODOLOGY

ESMIA modeled two scenarios (using the NATEM[20] model), named reference (REF), and net-zero BC (NZBC); see Table 9 for information on their constraints:

1. Reference scenario (REF): A reference case that represents "business-as-usual" (BAU) activities, plus committed energy policies, which may impact future sector development.
2. Net-zero BC scenario (NZBC): Involves the use of a modelled constraint on GHG emissions, which forces both BC and Canada emissions to be linearly reduced to zero by 2050.

Table 9 - ESMIA model scenario descriptions

SCENARIO CODE	SCENARIO CONSTRAINTS
Reference	Business-as-usual with committed policies • Build limits for biocarbon and biofuels production (14% maximum growth per year) • CCS allowed only after 2035 and a build limit on CCS growth • Biochar price (voluntary carbon market) aligned with market projections
Net-zero BC	Same as Reference with: • Net-zero by 2050 constraint on emissions for BC and for the rest of Canada. • Biocarbon is focused on the decarbonization of industry and carbon sequestration in order to meet net-zero by 2050.

These scenarios were followed on by a range of 'what-if?' conditions, where the model considers impacts to the biocarbon sector until 2050. Specifically, these include:

1. Low build-out: Very limited new facility development is allowed; designed to simulate a lack of support for biocarbon in favour of narrow allowable land-use impacts.
2. High build-out: Rapid growth of biocarbon development within BC; designed to simulate strong support for the development of new and expansion of existing facilities, increasing growth rate from 14% baseline to 20% annual growth.
3. High feedstock quantities: Forest residue quantities are 3x higher than expected.

20 NATEM is developed and operated by ESMIA (www.esmia.ca)

4. Removal of existing Clean Fuel Policies: Separately or together, policies support the development of clean fuels, where gases are removed or no longer supported (LCFS, CFR and GGRR). This would only apply to the BAU scenario.
5. Development of advanced technologies: The intentional development of technologies with lower TRLs and/or different techno-economic parameters.

Within the model, several biocarbon production methods compete with other biofuel production technologies utilizing the same feedstocks. For example, while bio-oil production via pyrolysis and upgrading represents one pathway to produce renewable diesel and gasoline, other pathways such as Fischer-Tropsh, catalytic hydro-processing, and hydrothermal liquefaction represent credible means of production, but face their own constraints. Similarly, biocarbon products will compete with other energy forms for various end-uses.

APPENDIX 3: CARBON INTENSITY AND ENVIRONMENTAL IMPACTS

This lifecycle assessment evaluates the total environmental impacts of biocarbon production under two scenarios for the 2035 timeframe: the reference scenario and the net-zero scenario. The results seen in these two scenarios (as described in the previous sections) are used to select the feedstock, production technology types, and end-uses that are analyzed here from an environmental perspective.

This analysis covers:

- Feedstock types and transportation impacts.
- Positive and negative environmental impacts of production technologies.
- Impacts resulting from end-use of biocarbon.
- A total carbon impact analysis (gCO_2 / MJ) for each facility type deployed in the two scenarios.

Feedstock types

In the two scenarios analyzed, two main feedstocks are utilized: mill residues and CR&D waste. Both sources present distinct environmental advantages and challenges that must be evaluated to ensure the overall sustainability of biocarbon production.

Mill residues are by-products derived from industries such as forestry, pulp and paper production, and agricultural processing. Particularly in regions like BC, which has a vast forestry sector, the management of mill residues is of critical importance due to their abundance and potential as a renewable resource. There is growing interest in using these residues to reduce waste and enhance resource efficiency.

The use of CR&D waste as a feedstock for biocarbon production offers significant environmental benefits, though it is not without its challenges. CR&D waste is one of the largest waste streams in many countries and significant in BC, and its proper management is critical to achieving sustainability goals in the construction and waste sectors.

Table 10 - Environmental impacts of mill residues use as a feedstock

+/-	IMPACT	DETAIL
+	Waste reduction and resource efficiency	Utilizing mill residues helps mitigate waste that would otherwise be discarded in landfills. This practice supports a circular economy by optimizing resource use. By transforming industrial by-products into valuable commodities, industries contribute to a closed-loop system where waste is minimized, and resource efficiency is maximized [56].
-	Air pollution from processing	Despite its advantages, the conversion of mill residues into bioenergy can contribute to air pollution if proper emissions controls are not in place. The combustion of biomass or its processing into biochar can release particulate matter and other harmful pollutants, which pose risks to human health and the environment [57].
-	Soil and water contamination	Poor management of mill residues, particularly during storage and processing, has the potential to contaminate surrounding ecosystems. Leachate from residues can infiltrate soil and water bodies, posing risks to aquatic life and soil quality. For instance, the improper disposal of wood-based residues can lead to nutrient imbalances and harmful effects on soil fertility.
-	Nutrient depletion in ecosystems	While the removal of mill residues offers environmental benefits, extensive removal can also lead to nutrient depletion in ecosystems. Forest ecosystems, in particular, rely on the natural decomposition of organic matter to replenish soil nutrients. Excessive extraction of residues can disrupt this balance, leading to long-term ecological consequences [58].

Table 11 - Environmental impacts of CR&D use as a feedstock

+/-	IMPACT	DETAIL
+	GHG reductions through landfill diversion	One of the primary benefits of recycling and reusing CR&D waste is the reduction in material sent to landfills. This diversion extends the operational life of existing landfill sites and significantly reduces methane emissions and other contamination risks typically associated with landfill use. Methane, a potent greenhouse gas, is a by-product of organic material breakdown in anaerobic landfill conditions, and reducing its generation through landfill diversion is a key strategy in climate change mitigation [58][59][60].
+	Land space savings	Recycling CR&D waste can significantly save land space that would otherwise be occupied by waste in landfills. These savings not only reduce the environmental footprint of waste management but also free up valuable land for other uses, contributing to more efficient land-use planning [59].
-	Energy intensive processing	The recycling of CR&D waste requires extensive sorting and separating to recover usable materials from debris. This process is often energy-intensive, particularly in facilities where advanced mechanical separation methods are used. The energy demands of sorting, crushing, and processing large volumes of mixed materials can partially offset the environmental benefits of recycling.
-	Dust and air quality issues	Processing CR&D waste, especially when crushing or grinding materials like concrete and brick, generates significant amounts of dust and fine particulate matter (PM). Without effective dust control measures, this can negatively impact local air quality and pose health risks to workers and nearby communities.
-	Hazardous materials risks	CR&D waste often contains hazardous substances such as asbestos, lead, and other harmful chemicals. Improper sorting or inadequate handling of hazardous materials can lead to serious environmental contamination and pose health risks to workers. Therefore, strict regulations and safety measures are necessary to prevent environmental and health hazards from hazardous CR&D waste components.

Carbon impacts of transportation

Transportation is a key factor in determining the overall environmental footprint of utilizing feedstocks such as processing mill residues, CR&D waste and any other residues (forestry residues, agricultural waste). Although the reuse of these materials promotes circular economic principles and reduces waste, the carbon impacts from transportation can influence the overall sustainability of these practices.

Carbon emissions from transportation depend largely on factors such as:

- Transport distance: An average distance of 75 km is assumed for this assessment, although some facilities may be co-located with waste/residue streams (e.g., next to a farm).
- Vehicle type and fuel efficiency: Heavy-duty trucks are the primary mode of transport, which significantly influences emissions due to their higher fuel consumption rates.

- Load capacity and frequency: The efficiency of each transportation trip is also determined by load capacity and the number of trips required.

Broadly, transportation emissions may be categorized into four scenarios, where the transport of the final product (e.g., biochar) is considered as well. For both feedstock transport and product distribution, carbon impacts are minimized for when both are co-located with biochar production, an example of which may be in farming, where animal waste or agricultural residues may be used to produce biochar, which is applied to cultivated land. On the other end of the spectrum, a large biocarbon facility may be in an industrial zone, requiring transport of biomass feedstock from forested areas and further requiring transport of biochar to agricultural producers. In an intermediate scenario, either feedstock or end-use markets may be co-located: such as for a gasification plant that requires transport of feedstock but produces syngas for onsite consumption in industrial heating processes.

For future projects, there are a few opportunities to minimize impacts from transportation:

- Optimizing supply chains: To minimize transportation emissions, projects should strive to establish processing plants near abundant and sustainable feedstock sources.
- Balancing market demand: If final products need to be transported to distant markets, emissions may increase, necessitating strategies such as using low-emission vehicles or exploring local markets for product use.
- Infrastructure development: Supporting infrastructure, such as better access to rail or shipping routes, may help reduce the carbon intensity of transportation compared to heavy-duty trucks.

Where infrastructure does not exist and co-location of feedstock or markets may not be possible, mitigation strategies may help to reduce impacts from transportation:

- Optimizing load capacity: Maximizing the truck's carrying capacity reduces the number of trips and thereby lowers overall emissions.
- Transitioning to low-emission vehicles: Utilizing trucks powered by alternative fuels like biodiesel or electric vehicles can significantly reduce emissions.

Production processes

Thermal conversion technologies such as slow pyrolysis and gasification are deployed in both modelling scenarios. These processes not only provide renewable heating sources but also offer a pathway for carbon sequestration and waste management. However, they can inadvertently release various air pollutants into the atmosphere, potentially compromising their environmental benefits [61].

The positive impacts of slow pyrolysis include the generation of biochar for carbon which has sequestration potential, utilizes waste, and consequently enables improved resource utilization. One of the key advantages of slow pyrolysis is its ability to generate co-products that contribute to environmental sustainability in their use as renewable energy sources. The biochar produced during the process can store carbon in soil for extended periods, ranging from hundreds to thousands of years. Finally, slow pyrolysis offers an efficient method for converting waste materials into value-added products. It is particularly effective at processing agricultural waste and forestry residues, thereby reducing the volume of waste directed to landfills. The process is highly versatile in its ability to operate on a variety of feedstocks while requiring minimal land use, making it a sustainable solution for energy and resource management.

The negative impacts of slow pyrolysis include its energy intensity, air particle emissions, and land use (in some cases). Slow pyrolysis is energy-intensive due to the prolonged heating periods, especially when targeting high-quality biochar production. However, the bio-oil and syngas co-products can be used to generate energy, partially offsetting the external energy input. When powered by conventional fuels, pyrolysis can lead to substantial CO_2 emissions. To minimize these impacts, renewable energy sources or waste-derived syngas are increasingly being employed. The biocarbon conversion process can also generate emissions if not effectively managed. These emissions include volatile organic compounds (VOCs), PM, and CH_4, all of which can negatively impact air quality. Pyrolysis systems must be equipped with emission control technologies to mitigate these risks and ensure that the process maintains environmental standards. Finally, the large-scale production of biochar through slow pyrolysis requires substantial amounts of biomass feedstock. This, in turn, could lead to deforestation or competition for land that might otherwise be used for food production.

Gasification produces syngas, a versatile energy carrier that can be used to generate electricity, heat, or even liquid fuels which help in reducing greenhouse gas emissions. The gasification process presents a highly efficient technology for waste-to-energy conversion. Gasification is recognized for its high energy recovery efficiency whereby the syngas produced can be immediately recycled and utilized for energy, reducing the need for external energy inputs. The process enables the conversion of a wide variety of feedstocks and has greater efficiency in terms of energy output per tonne of material processed compared to traditional combustion methods. As with pyrolysis, gasification can facilitate the conversion of diverse waste streams (feedstocks), such as industrial residues, into usable energy. By reducing the volume of waste that ends up in landfills, gasification plays a crucial role in waste management, helping to mitigate the release of methane, a potent greenhouse gas, from the decomposition of waste in landfills. Compared to conventional combustion processes, gasification results in lower emissions of pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and other harmful substances when conditioning units are applied. This makes it a cleaner alternative for energy generation when combined with advanced emission control technologies [62].

While the benefits are significant, the environmental concerns related to gasification must be evaluated as well. The process can produce toxic residues, tar, and ash that contain heavy metals and other contaminants, depending on the feedstock input. If these residues are not carefully handled and disposed of, they can pose serious environmental hazards. Furthermore, gasification systems can involve considerable water consumption, especially for cooling and gas cleanup processes using water scrubbers. This can place additional pressure on water resources, particularly in regions where water availability is limited.

End-uses of biocarbon

The end-uses of biocarbon in the modelled scenarios are diverse. An overview is provided here for two uses of biochar seen in the results: agricultural soil amendment and as an additive in cement and concrete. For bio-oil, the impacts of upgrading are provided and for syngas, which have multiple potential uses, the main trade-offs are given.

Solid biocarbon

BIOCHAR USE IN AGRICULTURE	Improves the soil's physical properties. Adding biochar to soils improves nutrient retention, increases water-holding capacity, and enhances microbial activity. This leads to reduced fertilizer usage and increased crop yields. Biochar can be stable in soil for hundreds to thousands of years, capturing and locking away carbon from the atmosphere, which helps mitigate climate change.	The long-term ecological impacts of biochar on different soil ecosystems are still under study and are uncertain today. Biochar may contain contaminants such as trace metals or polycyclic aromatic hydrocarbons (PAHs) from its production, which could leach into soil or groundwater if not effectively managed. Large-scale biochar production could compete with other biomass applications, potentially leading to land use conflicts or deforestation for biomass cultivation.
BIOCHAR USE IN CEMENT	Biochar addition can replace a portion of clinker in cement, the most energy-intensive component of cement, reducing the energy intensity of production. The cement sector is one of the largest industrial CO_2 emitters: biochar can significantly reduce the carbon emissions associated with cement manufacturing, with proportional impacts that are higher than the fraction of clinker replaced.	Biochar-modified cement may require more water during mixing or curing. This could lead to higher water consumption during the construction process. Depending on the source of biomass feedstock, biochar may contain trace contaminants like heavy metals. These contaminants could leach from the cement or clinker over time, especially in cases where the cement is exposed to water or other environmental elements, potentially harming ecosystems.

Gaseous and liquid biocarbon

BIO-OIL UPGRADING INTO BIOFUELS	Lower lifecycle footprint than traditional diesel or gasoline. Compared to traditional diesel or gasoline, biofuels produce lower levels of sulfur dioxide (SO_2), particulate matter (PM), and carbon monoxide (CO), improving air quality.	Bio-oil requires upgrading (hydrotreating) to meet fuel quality standards, which can be energy-intensive, and emissions will depend on the source of electricity. Similarly, hydrogen is required as an input, which add lifecycle emissions depending on how the hydrogen is produced.
SYNGAS USE	When used onsite combined heat and power (CHP) systems to generate electricity and heat simultaneously to replace fuels like natural gas, supply chain emissions (e.g. methane leakage) are eliminated. Replacing natural gas, oil, or coal with syngas reduces the carbon footprint of high-temperature industrial processes. Utilizing syngas reduces CO_2, SO_2, and NO_x emissions compared to burning coal or oil in lime kilns or other furnaces.	Syngas may not be as energy dense as natural gas or coal, requiring greater volumes to achieve the same heat output, potentially affecting efficiency. Although syngas combustion is cleaner than traditional fossil fuels, it can still emit CH_4, nitrous oxide (N_2O), NOx, and PM. Inadequate gas cleanup systems can exacerbate these emissions, contributing to greenhouse gas effects [62].

Lifecycle assessment: Carbon impacts for 2035

The following table provides an overview of the potential lifecycle impacts of the three technologies (two pyrolysis, one gasification) that are deployed in the modelled scenarios. Note that lifecycle impacts will depend on project-specific factors (e.g. external energy sources, transportation distances), and this analysis is meant to be indicative of the potential factors to consider, which will be project-specific. Two different slow pyrolysis facilities are assessed, based on existing facility data. The gasification technology presented here produces only syngas and is based on techno-economic parameters from literature.

Assumptions:

- The analysis is based on 1 tonne of waste biomass as input.
- Electricity emissions factor for 2035: 0.002 kg CO_2e / kWh (based on projected electricity supply mix in the modelling results).
- 75 km feedstock and biochar transportation distance and truck emission factor of 0.15 kgCO_2e / tonne-km[21].
- Feedstock drying is considered for ARTi pyrolysis, assuming that a moisture reduction of 20% would be required. For other facilities, it is assumed that mills waste and CR&D would not require drying (for mills waste, it may depend on which stage the residues come from and moisture content may vary between 5 - 40% [63]). For other feedstocks such as forest residues, to reduce moisture content by 40%, approximately 900 MJ of energy are required per tonne [62].
- Biochar sequesters 35 - 85% of its carbon content over a 100 - year period (its maximum sequestration potential is assumed to be 2.4 tCO_2e / tonne biochar).

21 Based on truck emission factor from ecoinvent 3.10 Dataset Documentation 'market for transport, freight, lorry 16-32 metric ton, EURO6 - RoW - transport, freight, lorry 16-32 metric ton, EURO6

Table 12 - Lifecycle emission summary for slow pyrolysis and gasification (NZBC)

ASPECT	SLOW PYROLYSIS (GECA DATA, ARTI USA)	SLOW PYROLYSIS (GECA DATA, BIOCARBON INDUSTRIES CAN)	GASIFICATION (MORET ET AL., 2017)
OUTPUT YIELD	Biochar yield: 250 kg Syngas output: 11,350 MJ	Biochar yield: 350 kg Syngas output: 2,800 MJ	Biochar yield: N/A Syngas energy: 12,350 MJ
FEEDSTOCK TRANSPORTATION	11.25 kgCO_2e	11.25 kgCO_2e	11.25 kgCO_2e
FEEDSTOCK DRYING	450 MJ = 0.12 kg CO_2e	-	-
ELECTRICITY USE	18 kWh = 0.007 kg CO_2e	12 kWh = 0.005 kg CO_2e	-
SYNGAS USE	1,135 MJ = 0.31 kg CO_2e	1120 MJ = 0.33 kg CO_2e	-
NET SYNGAS ENERGY OUT	9,763 MJ	1,800 MJ	12,350 MJ
BIOCHAR TRANSPORTATION	2.81 kgCO_2e	3.94 kg CO_2e	-
TOTAL POSITIVE EMISSIONS	14.50 kg CO_2e	15.50 kg CO_2e	11.25 kg CO_2e
NEGATIVE EMISSIONS (BIOCHAR SEQUESTRATION)	80% fixed carbon factor = 480 kg CO_2e	85% fixed carbon factor = 714 kg CO_2e	-
CARBON INTENSITY PER NET SYNGAS OUTPUT	-47.7 gCO_2e / MJ	-416 gCO_2e / MJ	0.91 gCO_2e / MJ

The analysis shows that the factor having the most impact on emissions is the transportation of biomass feedstock. The transportation of biochar to end-use markets has a more limited emission impact since biochar is more energy dense than the feedstock. In the long term, with potential deployment of electric, hydrogen or bio-fueled trucks, these emissions may be reduced. Energy use emissions are minor due to syngas being a renewable fuel and electricity in BC being widely decarbonized. However, if natural gas were to be used for drying feedstock for example, emissions could be much higher, exceeding transportation emissions. Overall, the pyrolysis processes give negative carbon intensities due to the important carbon sequestration potential of biochar.

Considering the deployments seen in the reference and net-zero scenarios in 2035, Table 13 summarizes the total lifecycle carbon impacts of the three facilities. In the reference case, close to 60% of biochar is sold in carbon markets, therefore the associated negative emissions are assumed to leave the province resulting in a large difference in net emission impacts between the two scenarios. Note that existing facilities were not considered as part of the analysis, explaining why total negative emissions for the province (stemming from biochar) are greater (as presented in the previous sections).

Table 13 - Lifecycle emission summary for new biocarbon production (REF and NZBC) in 2035

	REFERENCE			NET-ZERO		
TYPE OF FACILITY	NUMBER OF FACILITIES	TOTAL OUTPUT (PJ)	TOTAL EMISSIONS (KT CO_2E)	NUMBER OF FACILITIES	TOTAL OUTPUT (PJ)	TOTAL EMISSIONS (KT CO_2E)
SLOW PYROLYSIS (ARTI USA)	17	6.5	-159.4	8	3.1	-75.6
SLOW PYROLYSIS (BIOCARBON INDUSTRIES)	24	21.9	-749.6	28s	25.3	-867.1
GASIFICATION (MORET ET. AL)	3	5	4.33	7	12.1	10.56
BIOCHAR EXPORTED (CARBON CREDITS)		7.7	522.7			
TOTAL	44	33.4	-382	43	40.5	-932

APPENDIX 4: REGULATORY SUPPORT AND BARRIERS FOR BIOCARBON IN BC

The regulatory environment in Canada for biochar, bio-oils, and syngas is supportive but there are some barriers that still remain. Regulations related to soil amendment, clean fuels requirements, and natural gas replacement are the key supporting regulations. Whereas the key barriers are related to the exclusion of biocarbon production technologies from investment tax credits for carbon capture, and the lack of biochar specific offset protocols for provincial or federal output-based pricing systems. This section provides an overview of the regulatory support and barriers for biocarbon production at the federal and provincial levels.

Biochar production: Regulatory support and barriers

Federal support for biochar production

Biochar is now allowed as soil amendment without certification required. In Canada, federally, as of 2023, biochar is classified as a Primary Supplement on the List of Materials under the Fertilizers Act that is regulated by the Canadian Food Inspection Agency (CFIA). This means that it does not require registration when used as a soil supplement. Until 2019, biochar for sale, import, or use in Canada required certification through CFIA. This is a former regulatory barrier that has recently changed into a support for biochar production in Canada [64].

Biochar is allowed as a soil amendment under organic production systems. Under the Canadian General Standards Board – CAN/CGSB-32.311-2020 Organic production systems – permitted substances lists, biochar is allowed as a permitted substance for soil amendment in organic crop production. This is dependent on it has being produced through the pyrolysis of forestry by-products which have not been combined with prohibited substances. Recycled biochar from contaminated remediation sites is prohibited [65] from this.

Federal barriers for biochar production

Biochar production equipment is not eligible for the CCUS Investment Tax Credit. The federal government launched a CCUS ITC in 2022 that applies to eligible expenditures for qualified CCUS projects from January 1, 2022, to December 31, 2040. Currently, the CCUS ITC does not consider pyrolysis or gasification projects that produce biochar to be eligible for the CCUS ITC. Under Section 5.1.3 of the Technical Guidance Document, it explicitly states that ineligible property includes: “equipment for the pyrolysis or gasification of hydrocarbon feedstocks to produce hydrogen, fuels, and materials such as biochar or solid carbon...” [66].

Soil carbon sequestration protocol will not address biochar. The federal government is currently working on a soil carbon sequestration protocol, but it will not include biochar.

BC supports for biochar

Biochar allowed as a soil amendment without land application plan. The BC Ministry of Environment and Parks (MEP) has a Code of Practice for Soil Amendments (COPSA) under the Environmental Management Act and Public Health Act that states that if more than 5m^3 of soil amendments will be applied to an application site in a given year, the discharger must file a land application plan. Currently biochar is NOT classified as a soil amendment by the BC MEP. This means that there is no requirement under Section 9 of COPSA for a land application. There are, however, safeguards on the composition of the biochar that can be applied on land. These are outlined in Section 6 of COPSA. They state that the biochar cannot have more than 1% foreign material by dry weight, any sharp foreign matter like glass or metal that could cause injury, and must not exceed specific concentrations of substances (heavy metals) [67].

Biochar Offset Protocol under development. The BC MEP is also currently working on a Biochar Offset Protocol that would be eligible under the OBPS. The protocol would provide an incentive to convert forestry residues/non-merchantable wood/slash piles into biochar. The protocol will have a clear validation plan and annual reporting and paper trail requirements to ensure high-quality carbon removal. The protocol will require "engineered" pyrolysis production for high integrity but will allow for flexibility in production based on market needs (same facility can switch between biochar and bio-oil production). The biochar protocol should be launched for public consultation in Q4 of 2024 or Q1 of 2025. The BC MOE biochar protocol will further detail the safeguards described in COPSA and carbon crediting will be dependent on not exceeding safeguards.

BC barriers for biochar production

Biochar from bioenergy facilities still require land application plans. One potential barrier to biochar innovation and development in BC is that for a company searching for new end uses for biochar that comes from a bioenergy facility, a land application plan with the BC MEP is likely required under COPSA. This is due to the fact that this type of lower grade biochar has historically been considered a waste stream, even though it is chemically and structurally similar to biochar produced from a biochar-specific facility.

Bio-oil production: Regulatory support and barriers

Federal support for bio-oil

Clean Fuel Regulations. The federal Clean Fuel Regulations mandate the reduction of the lifecycle carbon intensity of transportation fuels to decrease by 15% (from 2016 levels) by 2030 with a minimum volume requirement for suppliers of 5% renewable gasoline and 2% renewable diesel in annual fuel pools. Although initially planned to apply to kerosene, jet fuel, and heating fuel, gasoline, and diesel, the federal regulations as implemented apply only to gasoline and diesel.

Biocarbon facilities are capable of converting biomass residues into pyrolysis oil which can be upgraded to renewable gasoline and renewable diesel either onsite via additional processing or at refineries. One way for refineries and fuel importers to comply with the Clean Fuel Regulations and cut the carbon intensity of their products would be by purchasing pyrolysis oil or upgraded pyrolysis oil from biocarbon producers or investing in their own pyrolysis oil production and upgrading.

As regulated parties, oil product producers and importers can create and use/sell credits for reducing the carbon intensity of the gasoline and diesel they produce and sell in Canada. Producers of pyrolysis oil from biocarbon facilities (non-regulated parties/voluntary credit generators) are also able to generate and sell credits for the low carbon fuels they produce on top of revenues from the sale of the fuel itself.

Federal barriers for bio-oil production

Conventional fuels replaceable by bio-oil are not covered under Clean Fuel Regulations. The non-inclusion of jet fuel and heating oil in the Clean Fuel Regulations may be a barrier for biocarbon development as they represent a potentially large market for pyrolysis oil and hydrothermal liquefaction bio-crude.

BC supports bio-oil production

LCFS is more stringent than federal CFR and includes jet fuel. In 2008, BC was the first province to adopt renewable fuel regulations with an LCFS for gasoline and diesel. The LCFS was formally implemented in 2013. The BC government claims that compliance with the LCFS from 2010 to 2021 led to a reduction of more than 15.7 million de tonnes of GHG emissions [68]. As of January 1, 2024, BC has replaced the Greenhouse Gas (Renewable and Low Carbon Fuels Requirements) Act with the Low Carbon Fuels Act (LCFA). The

BC LCFS is the name given to the new LCFA plus its accompanying regulations. The BC LCFS has placed more stringent requirements on gasoline and diesel carbon intensity reductions than the federal Clean Fuel Regulations (CFR) by targeting a 30% reduction by 2030 (relative to 2010 levels). In addition, BC has added a 10% reduction in carbon intensity of jet fuel by 2030 (federal regulations do not have jet fuel requirements). The BC LFCS calls for fuel suppliers to maintain a minimum volume of 5% for renewable gasoline (same as federal) and 4% for renewable diesel (2x federal requirement) in their respective fuel pools each year to 2030 and beyond. For jet fuel the new minimum renewable fuel volume requirements are 1% in 2028, 2% in 2029, and 3% in 2030 and beyond [69].

For suppliers and importers of gasoline, diesel, and jet fuel in BC, the BC LCFS takes precedence over the federal standards due to their greater stringency (while fuel suppliers must comply with both regulations). If a change of government or priorities in BC ever amended or repealed the LCFS, the federal CFR (if still in place) would take precedence.

Similar to the federal regulations, producers and importers of transportation fuels can create and use/sell credits for reducing the carbon intensity of the gasoline, diesel, or jet fuel they produce or sell in BC. Producers of pyrolysis oil from biocarbon facilities (that can be upgraded to renewable gasoline, diesel, or jet fuel) are also able to generate and sell credits for the low carbon fuels they produce on top of the revenues generated from the sale of the fuels.

Syngas production: Regulatory support and barriers

Federal support for syngas production

NRCan's Clean Fuels Fund provides support for syngas production. In March of 2024, Natural Resources Canada announced over $5 MCAD of Clean Fuel Funding going to CHAR Technologies for FEED studies with the goal of repli cating their first-in-Canada high-temperature pyrolysis process that converts waste wood into syngas and then RNG, in Thorold, Ontario. This funding will allow them to replicate this process in four other locations in Canada – one in Ontario, one in Alberta, and two in Quebec [70].

Federal barriers for syngas production

No federal RNG target. There is currently no specific target in place for RNG or syngas replacement of natural gas at federal level.

Appendix 4: Regulatory support and barriers for biocarbon in BC

BC supports for syngas production

Greenhouse Gas Reduction Regulation (GGRR) 15% syngas target, fuel switch offsets. In addition to the BC LCFS, BC also has a GGRR that was updated in 2021 to include a target of 15% RNG supplied by utilities to industrial and residential consumers by 2030 with a cap on acquisition costs of $31 CAD/GJ with a CPI escalation for future years. The 2021 GGRR update also included new prescribed undertakings for syngas that allows for public utilities to purchase and distribute syngas that is derived from the pyrolysis or gasification of biomass (includes wood and wood products, agricultural residues and wastes, biologically derived organic matter from municipal and industrial wastes, black liquor, and kraft pulp fibers) [71].

The Climate Change Accountability Act (formerly The Greenhouse Gas Reduction Targets Act) and the Greenhouse Gas Industrial Reporting and Control Act have led to the validation and generation of offsets for the implementation of a biocarbon-related fuel switch project at the Kruger Products paper mill in New Westminster. In this project the mill reduced its natural gas consumption by switching to a wood gasification system that generates syngas that are then combusted to produce steam. The total project GHG reduction from 2009 to 2019 was calculated to be 15,072 tCO_2e [72].

The Clean or Renewable Resource Regulation under the Clean Energy Act in BC categorizes biogenic waste and waste heat from commercial processes as clean or renewable resources. Both categories can be applied to biocarbon processes, offering support for the clean and renewable status of biocarbon projects.

APPENDIX 5: POLICY MODELLING ASSUMPTIONS

Table 14 - Assumptions used for policy modelling (Federal)

SUBCATEGORY	POLICY ITEM	IMPLEMENTATION NOTES
Federal policy	Federal fuel charge under Greenhouse Gas Pollution Pricing Act	Fuel charge is applied to the combustion of fuel types and end-uses. It is applied to the residential, commercial and transportation sectors - international aviation and marine fuel are exempt. Exemptions - agriculture emissions Exemptions - emissions-intensive trade-exposed industry that are covered by OBPS. Fuel charge increases from $65 CAD/tonne CO_2e in 2023 to $170 CAD/tonne in 2030. After 2030, fuel charge stays at $170 CAD/tonne
Federal policy	Federal output-based performance standard	OBPS is a performance-based emissions trading system for industry. The system uses a set of emissions intensity standards, output based. For every tonne of emissions above the standard, facilities have to either submit a credit or pay the carbon price. The carbon price for emissions in excess of the standard is identical to the price used for the federal fuel standard.
Federal policy	Clean Fuel Regulation	Regulation to reduce the lifecycle carbon intensity of transportation fuel: decrease by 15% (from 2016 levels) in 2030.
Federal policy	Incentives for LDZEVs and zero-emission vehicle infrastructure program	Subsidies for LDZEVs and for charging stations and H_2 refueling stations based on funding amounts available. For the infrastructure program 50% investment cost subsidies with a total budget of $764.9 MCAD from 2023 to 2028 was implemented. For LDZEV, implemented a $5,000 incentive for BEV and FCEV vehicles and a $2,500 incentive for PHEV vehicles from 2022 to 2025 with a cumulative budget of $2.577 BCAD (and annual limits of $788.5 MCAD)
Federal policy	Incentives for MDZEVs and HDZEVs	Subsidies for relevant vehicles based on funding amounts. Subsidy amounts are: $100,000 CAD for BEV and FCEV and $50,000 CAD for PHEV from 2022 to 2026 for the heavy-duty freight segment and intercity buses segment in NATEM. The total budget is $486.7 MCAD with annual limits of $243 MCAD.
Federal policy	Clean Technology Investment Tax Credit	Tax credit of 30% for renewable electricity generation, stationary electricity storage, active solar heating equipment, heat-pumps (Commercial only), CSP, SMRs, non-road ZEV vehicles, charging stations, geothermal heat recovery.
Federal policy	Investment Tax Credit for Clean Hydrogen	Tax credit 40% for a CI of less than 0.75 $kgCO_2e/kgH_2$ (applied for electrolyzers and ATR with CCS) 25% for a CI greater than or equal to 0.75 kg, but less than 2 $kgCO_2e/kgH_2$; (applied for SMR with CCS) 15% for a CI greater than or equal to 2 kg, but less than 4 $kgCO_2e/kgH_2$ (No technologies in the model are in this category)
Federal policy	Investment Tax Credit for CCUS	Tax credit of 37.5% to 60% for DAC and CCUS projects, including: 60% for DAC in 2022 dropping to 30% in 2030. 40% in 2022, 50% in 2030, 25% after 2030 for Biomass gasification with CCS for H_2 production 40% in 2022, 50% in 2030, 25% after 2030 for electricity generating plants with CCS 40% in 2022, 50% in 2030, 25% after 2030 for all other CCS technologies *Pyrolysis for biochar production is not eligible
Federal policy	Investment Tax Credit for Clean Electricity	Tax credit is added for large hydro and nuclear plants. Other technologies are covered by the Clean Technology tax credit.
Federal policy	Federal Methane Goals from 2018 (regulations have not been implemented for more recent goals)	Federal methane regulations (2018) to reduce oil and gas methane emissions from 2012 levels by 45% by 2025.
Federal policy	HFC Regulation (Kigali amendment)	Adopted in 2016, under the HFC phase-down amendment Canada will begin to gradually phase down the consumption of HFCs starting in 2019 to reach 15% of calculated baseline levels by 2036.
Federal policy	Heat pump grants / funding	Oil to Heat Pump Affordability (OHPA) Grant ECCC Home Heating Oil Transition (HHOT) (announced September 2022). Total $250 MCAD funding under HHOT.
Federal policy	Greener Homes Grant	Canada Greener Home Grant (CGHG). We assumed 20% subsidies on all retrofit measures for residential buildings, 1,000 $CAD/kW subsidies for rooftop PV, 500 $CAD/kW of subsidies for heat pumps ($5,000 per heat pump with an average size of 10 kW). Total budget is $2.6 MCAD
Federal policy	GHG emissions standards for vehicles through 2027 (CAFE)	Light-duty vehicles (LDV) GHG emissions standards for the model years 2011 to 2016 (LDV-1) and 2017 to 2026 (LDV-2). Heavy-duty vehicles (HDV) GHG emissions standards for model years 2014 to 2018 (HDV-1) and 2021 to 2027 (HDV-2)

Table 15 - Assumptions used for policy modelling (Provincial)

SUB-CATEGORY	POLICY ITEM	IMPLEMENTATION NOTES
British Columbia policy	Zero-emissions vehicle mandate and incentives	Requires automakers to sell a minimum share of zero or low-emission vehicles in addition to government-funded purchase subsidies and charging network incentives. LDV: 26% in 2026, 90% in 2030, 100% in 2035 HDV and MDV: 10% in 2030 Buses: 94% in 2030 Incentives for zero-emissions with cumulative budget of $35 M 2016CAD per year: BEV, H_2 ($3,000 CAD) PHEV ($1,500 CAD) (for cars < $50,000 CAD and light trucks < $70,000 CAD) BEV and NGA HDV/MDV vehicles: 30% of investment costs.
British Columbia policy	Public charger program	Incentives to increase public chargers (50% of investment cost). Differences in amounts between Indigenous communities and others cannot be modelled.
British Columbia policy	CleanBC Better Homes and Better Buildings programs	Incentives for residential and commercial building efficiency improvements. Incentives of: 15% of investment cost on building efficiency measures 15% to 25% of investment cost on heat pumps.
British Columbia policy	CleanBC Industrial Electrification	Offers discount rates to encourage the use of clean electricity in Industry. Incentives on electricity prices: 80 $CAD/TJ up to 2025 decreasing to 30 $CAD/TJ in 2030 and 0 after 2030.
British Columbia policy	CleanBC Industry Fund	Incentives to low-carbon technologies (CCS, electric, biomass-based and hydrogen-based) in Industry of 30% of investment costs.
British Columbia policy	Renewable Fuel Regulation	A minimum renewable fuel content for gasoline (5% in volume), diesel fuel (4% in volume) and jet fuel (1% in 2028, 2% in 2029, 3% in 2030).
British Columbia policy	Greenhouse Gas Reduction Regulation	A minimum requirement of 15% of industrial, commercial and residential natural gas consumption to come from renewable gas and hydrogen by 2030.
British Columbia policy	Low Carbon Fuel Standard	Requires a decrease in average carbon intensity of transport fossil through several compliance pathways. For diesel and gasoline reduction % are: 16% in 2024 linearly to 30% in 2030. For jet fuel % reduction is: 2% in 2026 linearly to 10% in 2030.

APPENDIX 6: DETAILED MODELLING ASSUMPTIONS

Table 16 - Techno-economic parameters for biocarbon production processes (1 out of 2)

PROCESS NAME	ELECTRICITY INPUT (TJ) (OUTPUT/ ELECTRICITY)	SYNGAS INPUT (TJ) (OUTPUT/ SYNGAS)	BIOCHAR INPUT (TJ) OUTPUT/ BIOCHAR)	BIOCHAR (%)	SYNGAS (%)	BIO-OIL (%)	BIO HEAVY OIL (%)	FIXED CARBON FACTOR (%)	TRL
SLOW PYROLYSIS – SYNGAS	286.24	11.75		40	60			80	9
SLOW PYROLYSIS – BIO-OIL	163.61	10.52		42	14	43		90	8
SLOW PYROLYSIS – BIO-OIL	287.65	16.64		56	9	35		90	8
SLOW PYROLYSIS – SYNGAS	21.07			49	51			35	8
SLOW PYROLYSIS – SYNGAS	7.62	15.67		64	36			35	9
GASIFICATION - SYNGAS	61.71			42	58			35	9
FLEXIBLE PYROLYSIS/ TORREFACTION - SYNGAS	12.03			52	48			35	9
GASIFICATION									
GASIFICATION					100				9
GASIFICATION + CCS					100				6 to 8
GASIFICATION + METHANATION					100				6 to 8
GASIFICATION + METHANATION + CCS					100				5 to 8
ADVANCED TECHNOLOGIES									
SLOW PYROLYSIS – SYNGAS	598.31	4.65		68	32			80	9

MICROWAVE PYROLYSIS – SYNGAS	12.28			56	44			80	5
FAST PYROLYSIS – BIO-OIL		8.72	7.19	39		61		80	6 to 7
SLOW PYROLYSIS – SYNGAS		5.65		65	35			80	7
SLOW PYROLYSIS – BIO HEAVY OIL		5.51		66	18		16	80	7

Table 17 - Techno-economic parameters for biocarbon production processes (2 out of 2). Variable cost excludes input costs such as feedstock (endogenous in NATEM)

PROCESS NAME	EFFICIENCY (%)	INVESTMENT COST (CAD2016/ GJ CAPACITY)	ANNUAL FIXED OPERATING COST (CAD2016/ GJ CAPACITY/ YEAR)	VARIABLE OPERATING COST (CAD2016/ GJ)	LIFETIME (YEARS)	AVAILABILITY FACTOR (%)	REFERENCE
SLOW PYROLYSIS – SYNGAS	98	10.75	4.49		10.00	86	GECA Data - ARTi, USA
SLOW PYROLYSIS – BIO-OIL	93	11.98	10.55		15.00	91	GECA Data - BC Biocarbon, Canada, BC
SLOW PYROLYSIS – BIO-OIL	98	11.86	9.31		15.00	91	GECA Data - Biocarbon Industries, Canada, QC
SLOW PYROLYSIS – SYNGAS	80	150.24	20.76		30.00	86	GECA Data - Bioforcetech, USA, CA
SLOW PYROLYSIS – SYNGAS	87	20.03	11.33		15.00	91	GECA Data - Char Technologies, Canada ON
GASIFICATION – SYNGAS	76	44.24	6.80		15.00	86	GECA Data - Earthcare LLC, USA IN

PROCESS NAME	EFFICIENCY (%)	INVESTMENT COST (CAD2016/ GJ CAPACITY)	ANNUAL FIXED OPERATING COST (CAD2016/ GJ CAPACITY/ YEAR)	VARIABLE OPERATING COST (CAD2016/ GJ)	LIFETIME (YEARS)	AVAILABILITY FACTOR (%)	REFERENCE
FLEXIBLE PYROLYSIS/ TORREFACTION – SYNGAS	91	23.02	21.99		15.00	86	GECA Data - ETIA VOW
GASIFICATION							
GASIFICATION	74	33.61	2.02	-	25	85	Moret et al., 2017 (20MW)
GASIFICATION + CCS	64	43.84	2.63	0.23	25	85	Moret et al., 2017 (20MW) / Global CCS Institute (2021, TRL) (3.)
GASIFICATION + METHANATION	65	38.61	2.32	-	20	96	Panos and Kannan, 2016 / (ABSL, Swindon Plant, 2024, TRL) (4.)
GASIFICATION + METHANATION + CCS	55	51.65	3.09	0.29	20	96	Panos and Kannan, 2016 / (ABSL, Swindon Plant, 2024, TRL) (4.)
ADVANCED TECHNOLOGIES							
SLOW PYROLYSIS – SYNGAS	86	48.13	6.50		30.00	91	Haeldermans (2020)
MICROWAVE PYROLYSIS – SYNGAS	98	48.61	6.56		30.00	91	Haeldermans (2020), Solis & Silviera (2020, TRL) (1.)
FAST PYROLYSIS – BIO-OIL	85	16.36	1.64		30.00	91	Wright, NREL, et al. (2010) (2.)
SLOW PYROLYSIS – SYNGAS	88	12.30	1.58		30.00	91	Wright, NREL, et al. (2010) (2.)
SLOW PYROLYSIS – BIO HEAVY OIL	86	12.62	1.62		30.00	91	Wright, NREL, et al. (2010) (2.)

Glossary

ABBREVIATIONS	DESCRIPTION
A&SI	Agriculture & Soil Improvement
AB	Alberta
BC	British Columbia
BAU	Business As Usual
BCR	Biochar Carbon Removal
BEV	Battery Electric Vehicle
BiCRS	Biomass Carbon Removal and Storage
CAGR	Compound Annual Growth Rate
CCS	Carbon Capture & Storage
CCUS	Carbon Capture & Underground Storage
CDR	Carbon Dioxide Removal
CEC	Cation Exchange Capacity
CFIA	Canadian Food Inspection Agency
CFR	Clean Fuel Regulations
CGHG	Canada Greener Home Grant
CH_4	Methane
CHP	Combined Heat and Power
CI	Carbon Intensity
CICE	British Columbia Center for Innovation and Clean Energy
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CoPSA	Code of Practice for Soil Amendment
CR&D	Construction Renovation & Demolition
DAC	Direct Air Capture
DIF	Drop in Fuels
EBC	European Biochar Certification
ESMIA	Energy Super Modelers & International Analysts
FC	Flash Carbonization
FEED	Front End Engineering Design
FP	Fast Pyrolysis
FPIC	Free Prior and Informed Consent
GGRR	Greenhouse Gas Reduction Regulation
GHG	Greenhouse Gases
H_2	Hydrogen
H_2O	Water
HDV	Heavy Duty Vehicle
HDZEV	High Duty Zero Emission Vehicle
HHV	High Heating Value
HTC	Hydrothermal Carbonization
HTG	Hydrothermal Gasification
HTL	Hydrothermal Liquefaction
IBI	International Biochar Initiative
IP	Intermediate Pyrolysis
IPCC	Intergovernmental Panel on Climate Change
ITC	Investment Tax Credit
LCFA	Low Carbon Fuels Act
LCFS	Low Carbon Fuel Standard
LDV	Light Duty Vehicles
LDZEV	Light Duty Zero Emission Vehicle
MB	Manitoba
MC	Moisture Content
MDV	Medium Duty Vehicle
MoA	Ministry of Agriculture
MoE	Ministry of Environment
MoEP	Ministry of Environment and Parks
MP	Microwave Pyrolysis
MRV	Monitoring, Reporting and Verification
MSW	Municipal Solid Waste
MT	Million Tonnes
NATEM	North American Times Energy Model
NET	Negative Emissions Technology
NO_2	Nitrogen Dioxide
NOx	Nitrogen Dioxides
NRCan	Natural Resources Canada
NS	Nova Scotia
NZBC	Net-zero British Columbia
O&G	Oil and Gas
O_2	Oxygen
OBPS	Output-Based Pricing System
OHPA	Oil to Heat Pump Affordability
ON	Ontario
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
QC	Quebec
RDF	Refuse Derived Fuel
REF	Reference
RNG	Renewable Natural Gas
ROI	Return on Investment
SK	Saskatchewan
SMR	Steam Methane Reforming
SO_2	Sulfur Dioxide
SP	Slow Pyrolysis
TRL	Technology Readiness Level
UNDRIP	United Nations Declaration on the Right of Indigenous Peoples
U.K.	United Kingdom
US	United States
USA	United States of America
VCM	Voluntary CDR Market
VOC	Volatile Organic Compound
WBC	World Biochar Certification

UNITS	DESCRIPTION
μm	Micrometers
A/g	Current Density
B	Billions
bar	Pressure
BL	Billion Litres
CAD	Canadian Dollars
CAD(2022)/yr	Canadian Dollars per year indexed to 2022
cm	Centimeter
cm^2/Vs	Electron Mobility
cm^3/g	Pore volume
DT	Dried Tonnes
g/mL	Pore Density
gCO_2e	Grams of Carbon Dioxide Equivalent
GPa	Tensile Strength
GT	Gigatonnes
ha	Hectare
kg	Kilograms
kg/m^3	Density
$kgCO_2e$	Kilograms of Carbon Dioxide Equivalent
$ktCO_2e$	Kilotonnes of Carbon Dioxide Equivalent
kW	Kilowatts
L	Litres
M	Millions
m^2/g	Surface Area
m^3	Cubic Meters
mAh/g	Discharge Capacity
MDT	Million Dried Tonnes
Mha	Million Hectares
Min	Minute
MJ	Megajoules
MJ/kg	Energy Density
MJ/m^3	Volumetric Energy Density
mL/g	Adsorption Capacity
mm	Millimeter
mmol/g	Sorption Capacity
MPa	Flexural Strength
mS/m	Electrical Conductivity
$MTCO_2e$	Million Tonnes of Carbon Dioxide Equivalent
nm	nanometers
°C	Celsius
PJ	Petajoules
Sec	Second
t	Tonnes
t/yr	Tonnes/yr
TJ	Terajoules
TPa	Youngs Modulus
USD	American Dollars
W/mK	Thermal Conductivity
yr	Year

References

[1] I. P. o. C. Change, “Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,” Intergovernmental Panel on Climate Change, Geneva, 2023.

[2] I. B. Initiative, “Removing Carbon,” 2024. Available: https://biochar-international.org/about-biochar/sustainability-climate-change/.

[3] (carbon)plan, “CDR Verification Framework,” 2024. Available: https://carbonplan.org/research/cdr-verification/docs/pathways/biomaterial-injection. [Accessed 2024].

[4] R. &. O. S. A. Portal, “Upgrading Biomass Pyrolysis Bio-Oil to Renewable Fuels,” 2024. Available: https://rosap.ntl.bts.gov/view/dot/28759. [Accessed 2024].

[5] ScienceDirect, “Fundamentals, kinetics and endothermicity of the biomass pyrolysis reaction,” 2010. Available: https://www.sciencedirect.com/science/article/abs/pii/S0960148109001803?via%3Dihub. [Accessed 2024].

[6] J. S. a. P. G. Manoj Tripathi, “Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review,” Renewable and Sustainable Energy Reviews, vol. 55, pp. 467-481, 2016.

[7] U. J. H. a. I. P. R. De La Cruz Iturbides, “Recent technological innovations on continuous microwave assisted biomass pyrolysis and perspectives for industrial scale applications,” Bioresource Technology Reports, vol. 19, 2022.

[8] M. T. C. G. E. A. Stephen Gent, “Chapter Six - Torrefaction Bioenergy Generation,” Theoretical and Applied Aspects of Biomass Torrefaction, pp. 123-150, 2017.

[9] H2Steel, “Phasing out fossil coal: the bio-coal production in the steel industry,” 2024. Available: https://h2steelproject.eu/phasing-out-fossil-coal-the-bio-coal-production-in-the-steel-industry/. [Accessed 2024].

[10] A. Energy, “FOSSIL FUELS ARE OUT.,” Available: https://airex-energy.com/products/biocoal/. [Accessed 2024].

[11] B. X. Y. D. X. H. S. W. Yunchao Li, “A critical review of the production and advanced utilization of biochar via selective pyrolysis of lignocellulosic biomass,” Bioresource Technology, vol. 312, 2020.

[12] A. R. P. Biller, “Production of biofuels via hydrothermal conversion,” Hydrothermal Processing, pp. 509-547, 2016.

[13] S. D. D. P. M. K. A. K. a. R. G. Ankit Mathanker, “A Review of Hydrothermal Liquefaction of Biomass for Biofuels Production with a Special Focus on the Effect of Process Parameters, Co-Solvents, and Extraction Solvents,” Energies, 2021.

[14] D. A. M.-O. L. N. M.-A. Oscar M. Rodríguez-Narvaez, “Chapter 14 - Functionalized green carbon-based nanomaterial for environmental application,” Sustainable Nanotechnology for Environmental Remediation, pp. 347-382, 2022.

[15] M. M. N. S. W. S. M. Mugoronji, “Techno-economic assessment for bio coal production from brewers spent grain,” South African Journal of Chemical Engineering, vol. 40, pp. 1-9, 2022.

[16] M. T. C. G. E. A. Stephen Gent, “Chapter Six - Torrefaction Bioenergy Generation,” Theoretical and Applied Aspects of Biomass Torrefaction, pp. 123-150, 2017.

[17] V. k. P. K. K. M. Ranjeet Kumar Mishra, “Hydrothermal liquefaction of biomass for bio-crude production: A review on feedstocks, chemical compositions, operating parameters, reaction kinetics, techno-economic study, and life cycle assessment,” Fuel, vol. 316, 2022.

[18] Y. K. R. A. Y. Bulutcem Öcal, “Thermal liquefaction of olive tree pruning waste into bio-oil in water and ethanol with NaOH catalyst,” Journal of the Energy Institute, vol. 113, 2024.

[19] M. A. M. T. M. F. C. J. M. J. U. J. N. N. C. E. B. a. H. L. Jiuling Yu, “Bio-crude oil production and valorization of hydrochar as anode material from hydrothermal liquefaction of algae grown on brackish dairy wastewater,” Fuel Processing Technology, vol. 227, 2022.

[20] D. L.-P. C. P. D. D. C. a. F. C. João C. Martins-Vieira, “Sugar, hydrochar and bio-oil production by sequential hydrothermal processing of corn cob,” The Journal of Supercritical Fluids, vol. 194, 2023.

[21] M. P. M. K. a. A. K. Adetoyese O. Oyedun, “The Upgrading of Bio-Oil via Hydrodeoxygenation,” in Chemical Catalysts for Biomass Upgrading, Wiley Online Library, 2019.

[22] T. C. Programme, “Task 34: Direct Thermochemical Liquefaction,” IEA Bioenergy, Available: https://task34.ieabioenergy.com/bio-crude/. [Accessed 2024].

[23] M. S. M. Y. a. L. B. Tülay Güngören Madenoğlu, “Hydrothermal gasification of biomass model compounds (cellulose and lignin alkali) and model mixtures,” The Journal of Supercritical Fluids, vol. 115, pp. 79-85, 2016.

[24] E. I. E. S. N. D. C. A. K. D. a. J. A. K. Jude A. Okolie, “Modeling and process optimization of hydrothermal gasification for hydrogen production: A comprehensive review,” The Journal of Supercritical Fluids, vol. 173, 2021.

[25] V. S. a. T. J. E. Hannah H. Cho, “Environmental Impact Assessment of Hydrogen Production Technologies,” Encyclopedia of Sustainable Technologies (Second Edition), vol. 3, pp. 302-312, 2024.

[26] S. Safarian, “Performance analysis of sustainable technologies for biochar production: A comprehensive review,” Energy Reports, vol. 9, pp. 4574-4593, 2023.

[27] M. o. F. M. a. Lands, “The State of British Columbia’s Forests: Third Edition,” 2010. Available: https://web.archive.org/web/20130414194446/http:/www.for.gov.bc.ca/hfp/sof/2010/SOF_2010_Web.pdf. [Accessed 2024].

[28] J. G. W. W. Q. L. J. C. a. B. L. Xueyong Ren, “Optimization of Bark Fast Pyrolysis for the Production of Phenol-Rich Bio-Oil,” Bioresources, pp. 6481-6492, 2013.

[29] K. W. H. Z. Ke Yang, “Machine learning prediction of the yield and oxygen content of bio-oil via biomass characteristics and pyrolysis conditions,” Energy, vol. 254, 2022.

[30] G. V. Research, “Biochar Market Size, Share & Trends Analysis Report By Technology (Gasification, Pyrolysis), By Application (Agriculture, Others), By Region (North America, Asia Pacific), And Segment Forecasts, 2024 - 2030,” 2023.

[31] Skyquest, “Torrefied Coal Market Size, Share, and Growth Analysis,” 2025. Available: https://www.skyquestt.com/report/torrefied-coal-market. [Accessed 2025].

[32] A. M. Research, “Pyrolysis Oil Market Size, Share, Competitive Landscape and Trend Analysis Report, by Feedstock, by Process, by End use : Global Opportunity Analysis and Industry Forecast, 2021-2031,” 2023. Available: https://www.alliedmarketresearch.com/pyrolysis-oil-market-A53512. [Accessed 2024].

[33] M. a. Markets, “Biomass Gasification Market by Source (Agricultural, Forest, Animal, Municipal), Gasifier Technology (Fixed-bed, Fluidized-bed,

Entrained Flow), Application (Power, Chemicals, Hydrogen, Transportation, Ethanol, Biochar) - Region - Forecast to 2027,” 2022. Available: https://www.marketsandmarkets.com/Market-Reports/biomass-gasification-market-105152418.html. [Accessed 2024].

[34] P. Nagrale, “Syngas Market Research Report Information,” 2024. Available: https://www.marketresearchfuture.com/reports/syngas-market-7487. [Accessed 2024].

[35] F. B. Insights, “Syngas Market Size, Share & Industry Analysis,” 2024. Available: https://www.fortunebusinessinsights.com/syngas-market-109820. [Accessed 2024].

[36] D. A. Tripathi, “Biochar Research Is On The Rise,” International Biochar Initiative, 2024. Available: https://biochar-international.org/news/biochar-research-is-on-the-rise/. [Accessed 2024].

[37] G. V. Research, “Wood Pellets Market Size, Share & Trends Analysis Report By Application (Heating, Power Generation), By End-use (Residential, Industrial, Commercial), By Region, And Segment Forecasts, 2024 - 2030,” 2023. Available: https://www.grandviewresearch.com/industry-analysis/wood-pellets-market. [Accessed 2024].

[38] C. B. B. G. W. M. a. J. V. Francisco X. Aguilar, “UNECE/FAO Data Brief 2023 Wood pellets and wood fuel,” UNECE and Food and Agriculture Organization of the United Nations, 2023.

[39] E. Voegele, “Report: Canadian wood pellet production, exports down in 2023,” 2024. Available: https://biomassmagazine.com/articles/report-canadian-wood-pellet-production-exports-down-in-2023. [Accessed 2024].

[40] H. W. R. C. X. B. Huimin Yun, “The role of torrefied wood pellets in the bio-economy: A case study from Western Canada,” Biomass and Bioenergy, vol. 163, 2022.

[41] C. S. G. V. B. B. V. M. a. A. K. D. Tumpa R. Sarker, “Techno-economic analysis of torrefied fuel pellet production from agricultural residue via integrated torrefaction and pelletization process,” Heliyon, vol. 9, no. 6, 2023.

[42] I. E. Agency, “CO2 Emissions in 2023: A new record high, but is there light at the end of the tunnel?,” International Energy Agency, 2023.

[43] P.-A. J. R. L. K. L. M. P. S. S. M. D. W. R. L. E. L. Raj K. Shrestha, “Biochar as a negative emission technology: A synthesis of field research on greenhouse gas emissions,” Journal of Envrionmental Quality, vol. 52, no. 4, pp. 769-798, 2023.

[44] P. &. S. Intelligence, “Wood Vinegar Market Revenue Forecast Report: Size, Share, Recent Trends, Strategic Developments, Segmentation Analysis, and Evolving Opportunities, 2024-2030,” Prescient & Strategic Intelligence.

[45] F. B. N. J. C. Y. N. A. a. B. G. Hakim Abdel Aziz Ouattara, “Wood Vinegars: Production Processes, Properties, and Valorization,” Forest Prodicts Journal, vol. 73, no. 3, pp. 239-249, 2023.

[46] G. V. Research, “Syngas Market Size, Share, Growth & Trends Report,” 2023. Available: https://www.grandviewresearch.com/industry-analysis/syngas-market-report. [Accessed 2024].

[47] O. A. B. G. B. R. P. B. a. C. N. Gonçalo Lourinho, "Costs of Gasification Technologies for Energy and Fuel Production: Overview, Analysis, and Numerical Estimation," Recycling and Recovery of Biomass Materials II, 2023.

[48] CDR.fyi, "CDR.fyi," 2024. Available: https://www.cdr.fyi/blog/2023-year-in-review. [Accessed 2024].

[49] I. 2023, "Sixth Assessment Report of the Intergovernmental Panel on Climate Change: Summary for Policymaker In: Climate Change 2023: Synthesis Report," IPCC, Geneva Switzerland, 2023.

[50] G. o. Canada, "Government of Canada," Canada's Carbon Management Strategy, 2024. Available: https://natural-resources.canada.ca/energy-sources/carbon-management/canada-s-carbon-management-strategy. [Accessed 2024].

[51] T. Gill, "Arbios Biotech announces completion of its biomass to bio-oil facility in Prince George.," Arbios, 2024. Available: https://arbiosbiotech.com/arbios-biotech-announces-completion-of-its-biomass-to-bio-oil-facility-in-prince-george/. [Accessed 2024].

[52] M. D. H. C. L. B. V. M. S. D. W. M. Q. U. G. B. G. B. C. T. C. T. C. C. Martin Tampier, "B.C. RENEWABLE AND LOW-CARBON GAS SUPPLY POTENTIAL STUDY," ENVINT, CBER & Associates, 2022.

[53] B. C. P. G. -. M. o. E. a. C. Solutions, "Approved Carbon Intensities - Current," 2024. Available: https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/rlcf012_approved_carbon_intensities_current_21feb2025_v2.pdf. [Accessed 2024].

[54] D. Todd, "Survive and Thrive: Why BC needs a CO2 removal strategy now," Pacific Institute for Climate Solutions, 2022.

[55] R. Letourneau, "Financing Biochar Production Facilitites: Financing in Practice," USBI, 2024.

[56] F. A. M. S. A. W. a. A. T. H. Suhaib A. Bandh, "Waste Management and Circular Economy," Spring Nature, 2024.

[57] G. Z. W.-C. A. a. S. Hadad Elroi, "Enhancing waste resouce efficiency: circular economy for sustainability and energy conversion," Frontiers in Environmental Science, 2023.

[58] K. B.-S. H. V. S. E. C. G. J. V.-K. A. d. V. H. K. H. R. Brian D.Titus, "Sustainable forest biomass: a review of current residue harvesting guidelines," Energy, Sustainability and Society, pp. 1-32, 2021.

[59] M. A. T. Alsheyab, "Recycling of construction and demolition waste and its impact on climate change and sustainable development," International Jounral of Environmental Science and Technology, vol. 19, pp. 2129-2138, 2021.

[60] P. K. R. A. a. V. R. Sri Shalini S., "Biochar from biomass waste as a renewable carbon material for climate change mitigation in reducing greenhouse gas emissions—a review," Biomass Conversion and Biorefinery, vol. 11, pp. 2247-2267, 2020.

[61] S. Li, "Reviewing Air Pollutants Generated during the Pyrolysis of Solid Waste for Biofuel and Biochar Production: Toward Cleaner Production Practices," Sustainability, vol. 16, no. 3, 2024.

[62] M. Z. P. C. J. Y. X. Z. M. Z. M. N. S. E. J. A. a. P. S. F. Vineet Singh Sikarwar, "An overview of advances in biomass gasification," Energy & Environmental Science, no. 10, 2016.

[63] "The potential use of wood residues for energy generation," Available: https://www.fao.org/4/t0269e/t0269e08.htm.

[64] G. o. Canada, "List of Primary Fertilizer and Supplement Materials," Government of Canada, 2023. Available: https://inspection.canada.ca/en/plant-health/fertilizers/regulatory-modernization/list-primary-fertilizer-and-supplement-material#a2. [Accessed 2024].

[65] G. o. Canada, "Canadian General Standards Board Catalogue," Government of Canada, 2022. Available: https://www.tpsgc-pwgsc.gc.ca/ongc-cgsb/programme-program/normes-standards/internet/032-311/032-311-eng.html#s4. [Accessed 2024].

[66] G. o. Canada, "Carbon Capture, Utilization and Storage Investment Tax Credit," Government of Canada, 2024.

[67] B. C. P. Government, "Code of Practice for Soil Amendments," British Columbia Provincial Government, 2021. Available: https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/210_2007#section6. [Accessed 2024].

[68] B. G. P. Government, "New carbon-reduction requirements lower emissions on the road," Energy and Climate Solutions, 2022. Available: https://news.

gov.bc.ca/releases/2022EMLI0066-001925#:~:text=The%20LCFS%20was%20implemented%20in,Columbia%20by%2010%25%20by%202020.. [Accessed 2024].

[69] B. C. P. Government, "Low Carbon Fuel Standard requirements," British Columbia Provincial Government, 2024. Available: https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/renewable-low-carbon-fuels/requirements. [Accessed 2024].

[70] G. o. Canada, "Government of Canada invests $15 Million in Clean Fuels Projects in the Niagara Region and Across Canada," Government of Canada, 2024. Available: https://www.canada.ca/en/natural-resources-canada/news/2024/03/government-of-canada-invests-15-million-in-clean-fuels-projects-in-the-niagara-region-and-across-canada.html. [Accessed 2024].

[71] B. Columbia, "Greenhouse Gas Reduction," 2024. [Online].

Available: https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/102_2012. [Accessed 2024].

[72] B. C. P. Government, "New Westminster Biomass Gasification System Offset Project-Grandfathered under GGIRCA(ID: 104000000011498)," Carbon Registry, 2024. Available: https://carbonregistry.gov.bc.ca/br-reg/public/bc/project.jsp?project_id=104000000011498. [Accessed 2024].

[73] R. C. a. X. B. Huimin Yun, "Environmental and economic assessment of torrefied wood pellets from British Columbia," Energy Conversion and Management, vol. 208, 2020.

[74] USBI, "Generating Carbon Credits from Biochar Production," USBI, 2024.

[75] CDR.fyi, "2024 + Market Outlook Summary Report," 2024. Available: https://www.cdr.fyi/blog/2024-market-outlook-summary-report. [Accessed 2024].

[76] B. Columbia, "Low Carbon Fuel Standard requirements," British Columbia, 2024. Available: https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/renewable-low-carbon-fuels/requirements. [Accessed 2024].

[77] FortisBC, "Renewable Natural Gas," FortisBC, 2024. Available: https://www.fortisbc.com/services/sustainable-energy-options/renewable-natural-gas. [Accessed 2024].

[78] Isometric, "Isometric carbon removal registry," Isometric, 2024. Available: https://registry.isometric.com/. [Accessed 2024].

Biocarbon Rising:

From Concept to Commercialization

ASSESSING OPPORTUNITIES FOR
SCALE, DECARBONIZATION, AND
INDUSTRY LEADERSHIP IN BC

NorthX

NORTHX.CA