Actions required to secure the large-scale deployment of the leading CDR approaches to meet EU climate targets

C-SINK– FACTSHEET LECTURE 4 DELIVERED BY ICAMCYL & UED

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T): BIOCHAR (BC)

INTRODUCTION

The urgency to address climate change was highlighted in the Paris Agreement in 2015 (United Nations, 2015), followed by a detailed assessment by the IPCC (IPCC, 2018b) based on scientific, technical, and socio-economic data available in the literature on global warming of 1.5°C and the comparison between global warming of 1.5°C and 2°C above pre-industrial levels. Subsequently, the European Commission (EC) accepted that human activities (both industrial and domestic) have caused around 1°C of global warming to date, resulting in abrupt climate changes, and acknowledged that most countries, especially the highly industrialized ones, must take drastic measures to avoid disastrous impacts on public health and safety. The EC (European Commission, 2018a-773) additionally, it was agreed that CO_2 capture will be required in significant quantities through land solutions and other technological solutions such as ocean alkalinisation, biochar (BC), direct capture of CO_2 in the air, bioenergy with CO_2 capture and storage (BECCS), etc., to achieve net zero greenhouse gas (GHG) emissions by the end of the century.

The C-SINK project, funded by Horizon Europe, aims to lay the foundations for a standardized, transparent European CDR market with trustworthy accounting methodologies based on robust Monitoring, Reporting, and Verification (MRV) pre-standards and policy strategies.

WHAT IS CARBON DIOXIDE REMOVAL (CDR)?

CDR refers to activities that remove CO_2 from the atmosphere and store it permanently (IPCC, 2018a). Available CDR technologies can be grouped into nature-based and technology-based removals (Meyer-Ohlendorf, 2020), in which nature-based methods enhance biological sinks of CO_2 (e.g., afforestation (AF) and reforestation (RF), soil carbon sequestration (SCS). Technology-based removals employ chemical engineering to achieve long-term removal and storage. Current techniques include Biomass Energy with Carbon Capture, Enhanced Weathering, improved soil quality, or biochar (Ornelas et al., 2023).

WHAT IS BIOCHAR?

Biochar is the solid residue of biomass pyrolysis, i.e., a pyrogenic carbonaceous material resulting from the thermochemical conversion of biomass at elevated temperatures between 400-1200 °C in an oxygen-free or oxygen-limited atmosphere[1].

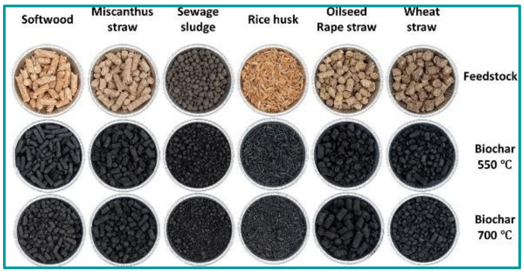

Figure 1. Feedstock types in the biochar process. UKBRC (2018). *Standard Biochars*. Retrieved [2025], from https://www.biochar.ac.uk/standard_materials.php

DEFINING CO_2 REMOVAL FROM A BC STANDPOINT

The carbon sequestration potential of biochar is based on stopping the release

[1] https://era.ed.ac.uk/handle/1842/39193

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of CO_2 from natural biomass decomposition through carbon stabilisation in the form of solid biochar. Organic carbon concentrated in biochar represents the removed CO_2 after deducting production emissions. The recalcitrance or degradation of the organic carbon content of biochar determines the CDR potential.

BIOCHAR PRODUCTION/ROUTES

According to C-SINK experts, biochar production is currently focused on three main routes with different target products. Slow pyrolysis is aimed at maximizing biochar production, while biomass gasification maximizes energy production with biochar as a potential co-product. Biomass intermediate pyrolysis polygeneration (BIPP) optimizes for biochar, fuel, and electricity production. All 3 approaches show promising industrial potential under different circumstances and should be included as base scenarios. Within these 3 approaches, a wide array of different combinations exists, which are mainly based on different mass flows (based on differences in feedstocks, processing conditions, or energy recovery).

Despite the different scenarios for biochar production, once the biochar is produced, its application adds additional – but separated - scenarios as the application of biochar can be as a soil amendment with ensured carbon sequestration, or as a material input in other products, which might not count as a carbon sequestration route.

DEFINITION OF EACH PROCESS-STEP

1. Biomass harvest and transport to the pyrolysis plant: Ideally, this involves waste biomass streams consisting of industrial residues such as sawdust or agricultural residues (i.e., straw, chippings, manure). See Figure 2.

2. Processing: Processing requirements for biomass depend on individual reactor configurations for the pyrolysis technology used and the utilized feedstock type, form, and condition. Generally, this involves size reduction (chipping, cutting, milling), densification (pelletizing), and/or drying to a moisture content suitable for the utilized reactor technology.

3. Pyrolysis: The actual pyrolysis reactor heats the biomass to the target temperature of the technology and breaks the material down into three product fractions (biochar, bio-oil, and pyrogas). The fraction between these portions is not independent of the employed technology type and economic considerations. For example, gasification is a biochar production process in which the main target product is a combustible gas utilized as an energy carrier, in contrast to slow pyrolysis routes in which biochar is the main product.

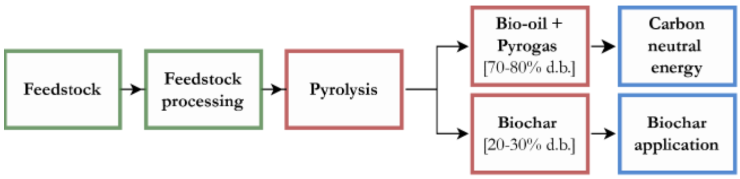

Figure 2. Simplified process diagram for slow pyrolysis systems with energy utilisation of co-products (green – biomass sourcing phase; red – biomass conversion phase; blue – application phase). Source: Wurzer, C. & Masek, O. (2024).

4. Pyrolysis by-products:

- Syngas: the product gas produced from the decomposition of biomass can be utilized as an energy source to heat the reactor, as a stand-alone product, or as an input material to produce electricity.
- Pyro-oil: the liquid fraction of biomass decomposition can be utilized as an energy carrier or directly combusted to provide heat.
- Biochar

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5. Biochar processing: Biochar processing involves cooling the product at the outlet of the reactor to ambient, size reduction or densification procedures (i.e., grinding, milling, palletization), or mixing with additional materials to produce bespoke products (i.e., compost, nutrients, fertilizers).

6. Soil application: The main application of biochar is within agricultural soils and requires spreading on land. Alternative application routes can be found as a substitute material in material production, such as concrete or plastics.

WHAT IS THE CURRENT STATE OF THE TECHNOLOGY?

Biochar production and utilisation are already in industrial operation worldwide, with over 170 operational plants within Europe alone. This highlights the maturity of biochar technology to date, with several turn-key technology providers available. Biochar's carbon sequestration potential was estimated in a recent study by Lefebvre et al. (2024) at 6.9 Mt CO_2e year−1, representing ~ 6.2% of current emissions in the covered 155 countries. European biomass availability is also significant, with approximately 452 Mt of biomass available annually, representing around 121 Mt of biochar or 245 Mt of CO_2e year-1.

PERMANENCE

The most common timeframe utilised to model CO_2-removal through biochar technology is 100 years (Woolf et al., 2021) and (Chiquier et al., 2022). Regarding the biochar time factor in removing, direct CDR effects of biochar are immediate at the point of production (if not burned subsequently). Indirect effects, such as increasing soil organic stocks beyond biochar carbon might take effect over longer periods.

According to (Schmidt et al., 2022) biochars generally consist of two pools– semi-persistent (SPC) and persistent carbon (See Figure 3). The higher the production temperature- the more

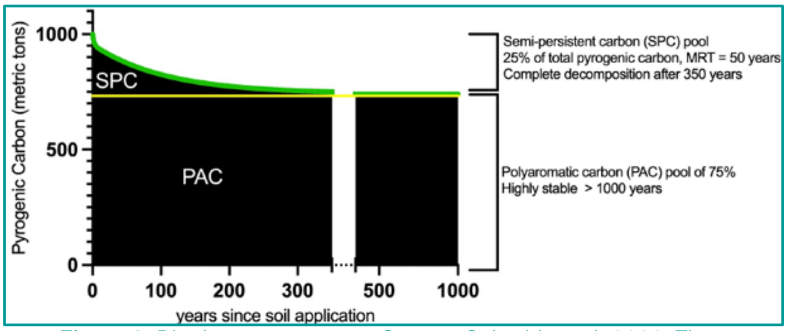

Figure 3. Biochar permanence. Source: Schmidt et al. 2022. The permanence of soil-applied biochar. The Biochar Journal.

persistent the carbon. Polyaromatic carbon will be stable on geological timescales and was shown to comprise the majority of high-temperature biochars, which are the common output of current industrial reactors within the European Union (Sanei et al., 2024).

Due to the dramatically enhanced carbon stability of biochar, biomass carbon is moved from the short-lived biosphere into geosphere timeframes, representing a shift in carbon residence times beyond timeframes relevant for human intervention to tackle climate change (centuries to millennia)(Chiaramonti et al., 2025).

REVERSAL RISK

Biochar presents a comparably low risk of unexpected leakage according to the latest research demonstrating biochar's permanence (Chiaramonti et al., 2024) (Sanei et al., 2024). While biochar carbon consists of a labile and a stable fraction, stable biochar carbon is likely sequestered for geological timescales if produced in modern reactors. The labile fraction degrades more rapidly (i.e., within a century), but represents minor parts of biochar carbon. Reversal risks can be present if production temperatures are insufficient for carbon

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stabilisation within biochar, but are omitted in industrial reactors. Besides carbon degradation, the combustibility of biochar is an additional risk; however, after soil application, the risk of reversal through wildfires is minimal due to incorporation within the soil matrix.

COSTS, TRL, AND TYPICAL SCALE

Generalized biochar cost estimations are unreliable due to the many possible combinations of feedstock, production technology, and application (Campion et al., 2023). Key cost factors vary widely, influenced by location, scale of operation, whether waste or virgin materials are used, and the specific final product (e.g., agricultural char versus energy co-products). Table 1 shows biochar price estimation from academic literature in USD per ton from academic literature and voluntary carbon credit marketplaces.

The European Biochar Industry (EBI)[2] classifies biochar production plants into small (100-199t), medium (200-499t), large (500-1999t), very large (2kt-5kt), and industrial (>5kt) production volume per year. Calculating the CO_2 removal potential requires the application of an average CO_2 removal multiplicator of 2-2.6.

Table 1. Biochar price estimation. Source: Wurzer, C. & Masek, O. (2024).

Biochar cost estimation [USD per ton of biochar]				
Reference	**Region**	**Min**	**Max**	**Mean**
Nematian et al. (2021)	North America	450	1850	
Stefan Jirka and Tomlinson (2015)	North America			1500
Alhashimi and Aktas (2017)	North America	800	1780	
Bergman et al. (2022)	North America	530	1050	
Ahmed et al. (2016)	North America	500	600	
Sessions et al. (2019)	North America	500	600	
Nematian et al. (2021)	North America	571	1455	
Kim et al. (2015)	North America			330
Sorensen and Lamb (2018)	North America			290
Struhs et al. (2020)	North America			240
Dutta and Raghavan (2014)	North America	40	50	
Liu et al. (2022)	China	790	930	
Xiao et al. (2020)	China			20
Shackley et al. (2011)	UK	150	600	
Latawiec et al. (2021)	Poland			85
Ahmed et al. (2016)	Spain			75
Robb and Dargusch (2018)	Australia			265
Wrobel-Tobiszewska et al. (2015)	Australia			1000
Dickinson et al. (2015)	Sub-Saharan Africa	100	165	
Ahmed et al. (2016)	Sub-Saharan Africa			100

BIOCHAR PRODUCERS WITHIN THE C-SINK CONSORTIUM

Figure 4. Ibero Massa Florestal, S.A (IMFLORESTAL). It is located in Oliveira de Azeméis, Portugal. Capacity: 5000 tons/year.

IMFLORESTAL is a pioneering company in producing and commercializing biocharcoal for domestic and agricultural use. It uses an innovative green technology of its own development for transforming agricultural and forest biomass through slow pyrolysis. With a current production of biochar derived from woody invasive species of 1000 tons/year.

Figure 5. Pyrogenesys in Birmingham, UK.

The innovative technology provided by the company converts waste grain and hops from brewing and dried distillers' grains (DDGS) from the whisky industry into heat to supply to the brewery, as well as into bio-oil and glucose. The approach will improve energy efficiency and contribute to decarbonization by reducing dependency on fossil fuel-derived process heat (natural gas) and developing potential uses for coproduct streams.

NEGATIVE EFFECTS

❖ Priming effect: Biochar has the potential to either increase or decrease soil carbon mineralisation (positive or negative priming). This effect is typically

[2] https://www.biochar-industry.com/

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short-lived due to initial disturbance of soil microbiology (Wang et al. 2016).

❖ Particulate and greenhouse gas emissions from biochar production; biodiversity and carbon stock loss if from unsustainable biomass harvest (Smith et al., 2023).

❖ Biochar production can affect land-use conflicts as it requires biomass feedstocks and can either in or exclude the local population depending on the intervention's design (Honegger et al., 2021).

Biochar might change the albedo effect of surfaces (Wurzer, C. & Masek, O., 2024).

CO-EFFECTS

❖ Better crop yields (Smith et al., 2023).

❖ Biochar use in agricultural practices can enhance agricultural resilience (Honegger et al., 2021).

❖ Combining with mining residues shows positive results for the reduction of metal (Smet et al., 2021) (Fabbri et al., 2021).

❖ Substitution of fossil materials or materials with a high carbon footprint [cement, sand].

❖ As a soil amendment, biochar (Wallace et al., 2012) (Geden & Schenuit, 2020) (Fabbri et al., 2021) (Ruiz et al., 2023) can contribute to 1) add nutrients and improve the uptake of applied fertilizers; 2) increase the properties of sandy soils through water retention improvements; and 3) increases microbial activity, enhancing agronomic yield.

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