

# TECHNICAL ASSESSMENT FOR BIOCHAR

SECTOR: ENGINEERED SINKS

AGENCY LEVEL: FULL SPECTRUM

KEYWORDS: BIOCHAR, CARBON DIOXIDE REMOVAL,  
NEGATIVE EMISSIONS, BIOMASS, PYROLYSIS

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\*Note: For some of the technical reports, the result section is not yet updated. Kindly refer to  
the model for the latest results.

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## ACRONYMS AND SYMBOLS USED

- BECCS – bio-energy with carbon capture and storage
- BiCRS – biomass carbon removal and storage
- CDR – carbon dioxide removal
- CO<sub>2</sub>e – carbon dioxide equivalent
- t – tonne or metric ton
- Mt – million metric tons
- Gt – billion metric tons

## EXECUTIVE SUMMARY

Biochar has been a topic of much recent research and commercial attention. The potential uses of this charcoal-like product seem to be expanding rapidly. And the feedstocks that can be converted to biochar are similarly diverse. In the context of drawdown and climate change biochar's most meaningful attribute is durable carbon sequestration, which could be significant in global efforts to mitigate greenhouse gas emissions and even remove them from the atmosphere.

Global estimates in the literature of biochar's annual emission reduction potential are at gigatonne scale. These figures usually account for abundant feedstock and additional co-benefits expected to arise from biochar production or use, such as increased crop yields and displaced fossil fuels and fertilizers. Compared to the technical potential, current adoption of biochar is low. Hurdles to wider commercial adoption remain. They include high costs and lack of product standardization.

We take a conservative modeling approach, focusing on the stored carbon benefits of biochar and selectively allocating feedstocks in a way that minimizes ecological tradeoffs and balances biomass among other climate solutions that are expected to need it. The feedstocks considered are calculated in Project Drawdown's integrated biomass model and range from traditional sources such as crop residues to emerging sources such as macroalgae and agroforestry residues. In our most ambitious case, we model biochar production increasing from its current low level to approximately 150 million tonnes of annual production in 2050, with a corresponding cumulative emissions reduction of 4.73 gigatonnes of carbon dioxide equivalent from 2020-2050. In all cases, marginal abatement costs are found to be approximately \$190 per tonne carbon dioxide equivalent, placing biochar between soil carbon sequestration and comparable to bio-energy with carbon capture and sequestration for this indicator.

We find that feedstock limitations will only likely impose constraints on biochar production growth in the long-term, while for the time being capital scale-out is a much more pressing limitation for industry growth. Widening our model scope to consider co-products and co-benefits of biochar production and use would likely result in reduced costs and expanded emissions reductions potentials. The heterogeneity of biochar products and the varied scale of production facilities limited our modeling approach in the current version, but they may be strong advantages to biochar adoption in practice. We are optimistic that our next model updates will incorporate these details and new data on global progress of the industry.

# 1. LITERATURE REVIEW

## 1.1. STATE OF BIOCHAR PRODUCTION

Biochar is a solid, carbon-rich product that is similar to charcoal. It is most commonly produced by pyrolysis, wherein biomass or other feedstocks are thermally decomposed in a low-oxygen environment. Along with biochar pyrolysis produces gases and liquids, with the yields of all three products approximately evenly split, depending on the process parameters (K. G. Roberts et al., 2010). A significant portion of the carbon in biochar is typically stable and resistant to degradation (Wang et al., 2016). The resulting difference in decomposition between biochar and non-charred biogenic feedstock can therefore result in net carbon sequestration on time-scales long enough to be significant for climate change mitigation. The gases and liquids co-produced with biochar can be used on- or off-site as fuels.

Biochar has found use in many applications. It is most prominently produced for use as a soil amendment. While biochar is a recently developed term, the use of charcoal as a soil amendment has been in place for a very long time, and some portion of the carbon in many soils was produced in natural fire events and has similar properties (Lehmann & Joseph, 2015). Biochar differs from charcoal, though, in that it is generally considered to be a material that is produced with the intention of being used as a soil amendment, or more recently, as other products.

Additional applications for biochar are emerging. Given that biochar can be generated from pyrolysis of low-quality feedstocks, this process may find wider use as a waste disposal solution for municipal sewage sludge, forest residues, or other wastes (Agrafioti et al., 2013; Campbell et al., 2018; Keske et al., 2020; Sessions et al., 2019). The biochar product can in turn abate odors and stabilize environmental pollutants when applied back to wastes such as sewage sludge and manure (Gunarathne et al., 2019). Biochar further has been used as a livestock feed supplement with the potential for reduced methane emissions and increased soil nutrient retention from manuring (Joseph et al., 2015; Schmidt et al., 2019).

In the context of drawdown and climate change, the most meaningful attribute of biochar production is carbon sequestration. The recalcitrant carbon portion of biochar carbon can remain intact for somewhere on the order of decades or centuries (Woolf et al., 2018), whereas untreated biomass decomposes more rapidly and re-emits its photosynthetically-captured carbon. This difference in carbon fates gives rise to sequestration with sufficient durability to be significant in current efforts to limit global warming. In addition to this sequestration effect, biochar production may further indirectly reduce emissions. Biochar pyrolysis can displace fossil fuel use and fertilizer consumption (K. G. Roberts et al., 2010). When

incorporated in soils there are also potential improvements to native soil carbon retention (Blanco-Canqui et al., 2020), water retention, crop yields, and other attributes; however, these effects are application-specific (Woolf et al., 2018) and significant knowledge gaps remain (Amonette et al., 2021).

Biochar production at the global level has been analyzed alongside other processes as a means of carbon dioxide removal (CDR)(Bossio et al., 2020; Fawzy et al., 2021; Paustian et al., 2016; Smith, 2016). A recent comprehensive review of CDR methods identified global estimates of biochar mitigation potential ranging from 0.6 to 11.9 Gt CO<sub>2</sub> per year; however, the review authors' own assessment is a narrower and lower range of 0.3 to 2 Gt CO<sub>2</sub> per year by 2050 (Fuss et al., 2018). The disparity in estimates is largely due to varying assumptions about the amount of feedstock that will be available for biochar conversion. If future negative emissions are to eventually be realized at large scale, it is likely that biochar will be in a portfolio of various CDR measures, including both natural and engineered solutions (Minx et al., 2018; Rickels et al., 2019). It is difficult to predict what role biochar production will play in this future; it may benefit early on from being a relatively mature technology, and may simultaneously experience natural constraints from competition with other solutions such as bio-energy with carbon capture and storage (BECCS) and afforestation and reforestation, which also require land, water, and nutrient inputs.

A potentially advantageous feature of biochar production is the wide range of potential production scales and co-products. Biochar lies on a spectrum of related bioenergy and carbon sequestration solutions and process variation can shift production closer to either end. This suggests that biochar with energy co-production may serve an important transition role in the development of larger-scale CDR methods such as BECCS (Woolf et al., 2014, 2016; Yang et al., 2021). Biochar can also be implemented at scales ranging from individual to industrial (Timmons et al., 2017) and can be stationary or mobile and capable of operating at remote sites at the source of feedstock (Puettmann et al., 2020). This flexibility may favor early adoption of biochar and support CDR governance as a whole, by allowing for greater inclusion and a gradual build-up of these new technologies (Bellamy & Geden, 2019).

## **1.2. ADOPTION PATH**

### **1.2.1 Current Adoption**

Compared to estimates of the global technical potential of biochar production, current adoption is very limited. Though research on the topic has grown significantly and new end uses and feedstocks have been identified, there is a lack of current data on the industry production and organization at global level. The most comprehensive dataset available was produced through industry surveys in 2013-2015, during which time biochar sales are reported to have increased from 827 to 85,000 tonnes per year (International Biochar



Initiative, 2013, 2014, 2015). Since then, there are few data sources to inform on the development of this industry, though we are anecdotally aware of continued experimentation and commercialization. A recent source suggests that production in 2020 may be around 375,000-575,000 tonnes annually, with the majority in China (ANZBIG, 2020).

### **1.2.2 Trends to Accelerate Adoption**

Much recent research interest has been directed to biochar as a means of CDR (Griscom et al., 2017; Minx et al., 2018; Paustian et al., 2016; Smith, 2016; Woolf et al., 2018). This has been solidified by voluntary movements (for example, the 4-per-1000 Initiative for soil carbon) and governmental research and strategies on negative emissions (Baker et al., 2020; Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration et al., 2019; McMullin et al., 2020; UK Committee on Climate Change, 2019).

Though Project Drawdown does not explicitly model the effect of carbon pricing, it seems likely that compliance or voluntary methods of pricing carbon would further incentivize biochar production. Voluntary biochar carbon credits are already being transacted amidst corporate recognition that meeting net-zero climate goals will in many cases require measurable emissions removals. Microsoft Corporation's recent procurement of carbon removals credits, including from biochar production, is a noteworthy example (Willmott & Joppa, 2021). Global compliance carbon pricing is also increasing (World Bank, 2020) and may eventually provide support to sequestration activities like biochar production, with ongoing discussion about how to facilitate such a transition in existing markets (Rickels et al., 2020).

### **1.2.3 Barriers to Adoption**

Hurdles to widespread biochar adoption remain. While the research community addresses technical and scientific priorities, efforts are also underway to elucidate regulatory, cultural, and social adoption factors (Amonette et al., 2021). Agricultural stakeholders have expressed limited awareness amidst lack of information and product availability (Latawiec et al., 2017). A key challenge is the heterogeneity of products under the heading *biochar*, though voluntary standards and regulations are emerging to define product criteria for greater consistency (Meyer et al., 2017; Verde & Chiaramonti, 2021). Biochar product price also plays a role. We identified a current product price range of about \$500-\$1700 per tonne of wholesale biochar, which is likely too high to be competitive with conventional agricultural inputs or the other products that bulk biochar may substitute. This high price may for now induce increased interest in production while limiting widespread adoption of biochar product use at scale.

#### **1.2.4 Adoption Potential**

The current adoption of biochar can be contextualized by comparing it with the amount of feedstock available for conversion and the total addressable markets for product use. Feedstock availability will, in the long term, likely provide an upper constraint to global biochar production and other similar CDR methods. Though previous studies have identified large potential feedstock availability (Woolf et al., 2010), these feedstocks are expected to come under increasing pressure as the world balances the needs for feeding people, restoring ecosystems, and generating bio-energy and other bio-products (Toensmeier & Garrity, 2020). Even when considering wastes as feedstock (Langholtz et al., 2016), challenges remain at scale, such as separating waste streams and developing the infrastructure to transport or co-locate them with conversion facilities and end uses.

Biochar can additionally be considered in the context of a projected global demand for CDR which may be on the order of five Gt CO<sub>2</sub>e per year in 2050 (Minx et al., 2018). Current biochar production, according to the last available global estimate, would contribute less than 0.01% to this figure, though this is not surprising, considering that many other CDR methods are at a similar low level of adoption. Given that a prominent use of biochar is as an agricultural input or soil amendment, we can also compare biochar production to the fertilizer industry – current biochar production represents less than 0.05% of current global fertilizer consumption in a mass comparison (FAO, 2017).

### **1.3 ADVANTAGES AND DISADVANTAGES OF BIOCHAR PRODUCTION**

#### **1.3.1 Similar Solutions**

Biochar production is related to several other climate solutions. Carbon dioxide removal methods can be broadly classified according to their sequestration process as natural, engineered, or hybrid (Figure 1). Hybrid methods combine natural carbon capture with engineered feedstock conversion or carbon storage methods. Two relevant sub-classes of hybrid CDR methods are BECCS (bioenergy with capture and storage) and BiCRS (biomass carbon removal and storage). The term BiCRS has been recently proposed as a distinction to BECCS, with the former placing greater emphasis on the carbon removal value of biomass rather than its energy value (Sandalow et al., 2021). In practice these sub-classes contain many methods in common. Biochar can be classified under BiCRS due to direct carbon sequestration capability. It can also be classified under BECCS, in cases where energy co-products are generated, or, viewed from a different angle, when biochar is the by-product of a bioenergy production process. Finally, biochar can be generated directly for other end uses falling outside BECCS or BiCRS classification, with carbon storage arising as a co-benefit.

Among the researched CDR methods, biochar is most closely related to soil carbon sequestration, which is typically classified as a natural CDR method. The two solutions may work in parallel, for example, by incorporating biochar into soil for carbon sequestration both in the biochar fraction and through increased in-situ soil carbon retention (Blanco-Canqui et al., 2020). See Project Drawdown’s previously modeled solutions for additional practices and technologies that can lead to natural CDR. Other engineered and hybrid CDR solutions will be examined in a forthcoming Project Drawdown publication.

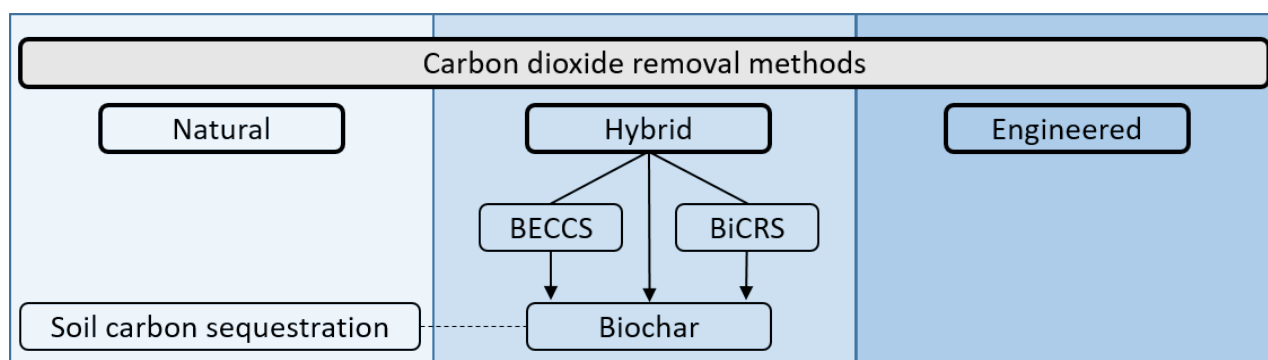


Figure 1: Biochar and related solutions within a taxonomy of carbon dioxide removal methods

### 1.3.2 Arguments for Adoption

As with many climate solutions, especially those that convert biomass feedstocks, biochar production comes with tradeoffs. We frame arguments for biochar adoption in two ways: a tradeoffs comparison with similar solutions (Table 1), and a side-by-side comparison of additional benefits and burdens (Table 2).

Table 1: Comparative analysis of biochar and similar solutions

	Biochar	BECCS	Soil carbon sequestration
Carbon sequestration permanence	Durable	Permanent	Reversible
Technology readiness	High	Medium	High
Implementation unit scale	Individual to industrial	Industrial	Individual to industrial
Ecological risks	Medium	High	Low

In a comparison with BECCS and soil carbon sequestration biochar takes the middle position in many categories of potential arguments for adoption. Biochar benefits from being a relatively mature technology and achieving reasonably durable carbon sequestration. We place biochar between soil carbon sequestration and BECCS in evaluation of ecological risks: deployment of BECCS at the scale envisioned by some global models would imply significant impacts for land use, biodiversity conservation, water consumption, and other natural values (Fajardy & Mac Dowell, 2017; Rueda et al., 2021; Smith et al., 2019; Stenzel et al.,

2021). To a great extent, these risks also apply to deployment of biochar at scale, but biochar benefits from being able to utilize additional waste feedstocks and being scalable to the resource availability. This attribute also means that biochar can be favorably implemented across the full spectrum of agency levels, from individual to industrial. Soil carbon sequestration likely carries fewer ecological burdens than the other methods compared, and requires the least infrastructure, but carbon storage is transient and reversible with changes in land use. All CDR methods face numerous tradeoffs and as a whole raise additional questions of societal acceptance and moral hazard (Minx et al., 2018).

### 1.3.3 Additional Benefits and Burdens

In addition to its carbon sequestration potential in the context of CDR, we consider below other factors that may be benefits or burdens in the adoption of biochar production.

*Table 2: Comparison of benefits and burdens in biochar adoption*

Benefits of adoption	Burdens or drawbacks of adoption
<ul style="list-style-type: none"> <li>• Technology readiness is relatively high. Individual components and processes should be technically scale-able.</li> <li>• Can be implemented at many scales, ranging from individual to industrial.</li> <li>• Can utilize waste feedstocks to minimize land-use change or detrimental ecological effects; may act synergistically as a waste treatment or disposal solution.</li> <li>• May confer co-benefits in end use of biochar, for example, increased crop yield, increased soil carbon retention.</li> </ul>	<ul style="list-style-type: none"> <li>• Feedstock limitations likely to provide upper constraint to deployment.</li> <li>• Large-scale deployment may divert feedstock from other climate-aligned purposes.</li> <li>• In case of massive deployment, feedstock demand could lead to ecological damage from land-use change, water consumption, and other impacts.</li> <li>• Lack of product standardization may impede acceptance and enable obfuscation of climate impacts.</li> <li>• Co-benefits of biochar end use are site-specific and may in some cases even be detrimental.</li> <li>• Field application may cause increased global warming effect due to reduced albedo.</li> </ul>

## 2 METHODOLOGY

### 2.1 INTRODUCTION

Project Drawdown’s solution spreadsheet models follow an internally consistent framework with common assumptions and procedures. Key inputs are harmonized in a meta-analysis of best-available literature and combined with custom model scenarios for adoption of the specific technology or practice over time. Adoption scenarios are rooted in actual values to date. In the case of biochar, a key input is the amount of feedstock available for conversion. In our analysis this is governed by Project Drawdown’s global integrated biomass model, which allocates various feedstock streams to an array of bio-based solutions over

time. We assume that real-world biochar production will be implemented across a spectrum of facility scales and perhaps with multiple technology process types; for the sake of global estimates our model biochar production plant is a pyrolysis facility that is energy-neutral and optimized to yield biochar. While the end use of biochar may confer additional climate benefits, we foresee numerous potential uses with varying impacts that are difficult to model consistently. We therefore focus our analysis on the direct net sequestration in the recalcitrant carbon content of the biochar product.

## **2.2 DATA SOURCES**

To harmonize life-cycle assessment data for biochar production, we developed a process calculation with inputs informed by best-available literature. To assess the global potential of biochar production, we needed figures on the maximum sustainable amount of feedstock that could be dedicated to biochar production. For internal harmonization and to avoid double-counting of biomass allocation, we relied on Project Drawdown's own global integrated biomass model. Financial impacts were estimated using facility data, both real and modeled, reported in the scientific literature (Campbell et al., 2018; Sessions et al., 2019; Timmons et al., 2017, and others). We inform our adoption scenarios with data from an industry non-governmental organization, which provided the most comprehensive data available (International Biochar Initiative, 2013, 2014, 2015). Climate impacts were calculated in process model combining inputs from previous studies (Roberts et al., 2010; Wang et al., 2016, and others) and a database of biochar properties (UC Davis, 2021).

Where data availability permitted, multiple sources were used for model inputs by combining in a meta-analysis. Bounds to input ranges were established as one standard deviation above and below the mean. Specific inputs and sources are addressed in greater detail in the following sections.

## **2.3 TOTAL ADDRESSABLE MARKET**

In Project Drawdown's methodology, technologies or practices are assumed to be bounded by a total addressable market (TAM) that they may fulfill. In land-based solutions this figure is expressed as total land area, whereas in technology-based solutions this figure is expressed as an amount of functional units produced and consumed. Biochar is a hybrid solution and we therefore define its TAM in terms of the feedstock that may be allocated for conversion. Though the addressable markets for biochar could alternatively be viewed in terms of demand for soil amendments, waste treatment, or CDR, selecting feedstock availability as the TAM facilitates integration with Project Drawdown's own integrated biomass model. This model calculates future biomass availability annually across various streams of biomass type

and allocates these feedstocks to the solutions that need them (see 2.7). Within the integrated biomass model we allocate feedstock to biochar only after demand by all other bio-based solutions has been satisfied.

Our modeled TAM, which serves our theoretical upper limit to biochar adoption, ranges from 215 million metric tons (Mt) of biomass in 2020 to 1.0 billion metric tons (Gt) in 2050. These figures can be expressed in terms of potential biochar production using our modeled yield of 0.298 t biochar per t feedstock to arrive at 64.0 Mt and 298 Mt biochar potential in 2020 and 2050, respectively.

## 2.4 ADOPTION SCENARIOS

Adoption scenarios are expressed as tonnes biochar produced for every year over the model period of 2020-2050. These scenarios are rooted in adoption to date and bound, where applicable, by feedstock availability. Data on current biochar production are scarce: we used the industry surveys from the International Biochar Initiative (2013-2015) as initial values for most scenarios and in some cases assume a higher starting value in 2020 based on an alternative source (ANZBIG, 2020) Table 3. We then fit trends of adoption pathways. Two different types of adoption scenarios were developed: a reference (REF) scenario and a set of Project Drawdown Scenarios (PDS) with varying levels of adoption ambition (Table 3). The model results show the comparison of one PDS to the REF, and therefore focus on the change relative to a baseline. Custom scenarios are combined into three overarching scenarios (PDS1, 2, 3) to represent plausible, central, and optimized estimates, respectively.

*Table 3: Custom adoption scenarios*

Scenario	Description	Explanation
1	Linear trend growth	Growth at linear trend based on production data from 2013-2015. Production increases by approximately 42,000 t per year. Represents most conservative adoption case or low growth.
2	Cumulative annual growth at 5%	An alternative to scenario 1, representing consistent low growth starting from industry production values in 2013-2015.
3	Cumulative annual growth at 5%, starting from 500,000 in 2020	Same as above, but assuming 2020 production to be a higher level of 500,000 tonnes of biochar per year.
4	Second-order polynomial trend growth	Mid-level growth, based on a second-order polynomial fit of production data from 2013-2015.

5	Cumulative annual growth of 20%	Rapid sustained growth, meant to represent upper bound of realistic options.
6	Cumulative annual growth of 20%, starting from 500,000	Same as above, but assuming 2020 production to be a higher level of 500,000 tonnes of biochar per year
7	Linear growth to 50% of TAM in 2050	A theoretical optimum case that may represented early targeted support to biochar industry growth and converting 50% of all allocated feedstock in 2050.

#### 2.4.1 Reference Case

The reference case refers to a baseline scenario in which annual biochar production remains at reported 2015 levels of 85,000 t of biochar per year.

#### 2.4.2 Project Drawdown Scenarios

Seven PDS scenarios were developed to span the range of possible adoption fates (Table 3).

The seven PDS above were then combined into three representative scenarios, which are the basis of further analysis:

**PDS1** – Average of all custom PDS.

**PDS2** – High of all custom PDS, expressed as one standard deviation above average.

**PDS3** – A theoretical optimum scenario based on scenario 7 in Table 3. **Table 3**

## 2.5 INPUTS

### 2.5.1 Climate Inputs

#### Direct emissions

*The model pyrolysis facility is assumed to be energy-neutral, with all on-site energy provided by the exothermic reaction of feedstock. Direct feedstock combustion emissions are accounted as zero because we consider only biogenic feedstocks. We examined the potential need for natural gas input during startup of the pyrolysis system, as has been previously modeled by others (Roberts et al., 2010), but excluded this from analysis as it accounted for less than 0.5% of net process global warming potential. We combined key model inputs (Table 4) in a process flow model*

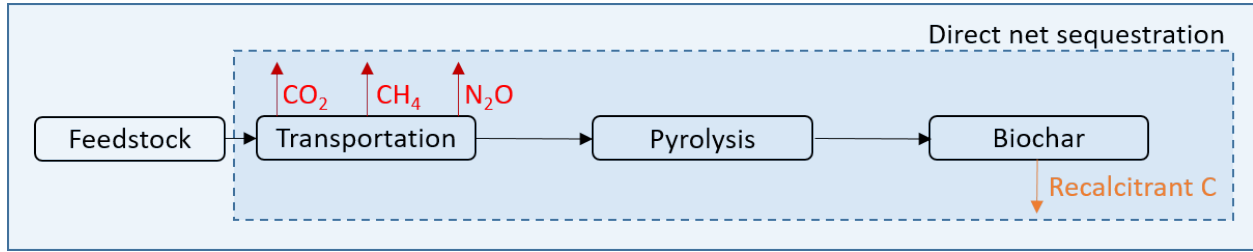


Figure 2) to calculate direct net emissions (Table 5).

Though we expect biochar facilities in many cases to be co-located with feedstock sources, for conservatism we model the emissions associated with feedstock transportation using the Argonne National Laboratory GREET model with default values for transportation of forest residues and corn stover by medium heavy-duty diesel truck as a proxy for all feedstock transportation. Our methods align closely with other another study (Yang et al., 2021).

Table 4: Key model climate inputs.

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources
Biochar yield	$t \text{ biochar} / t \text{ feedstock}$	0.25 - 0.36	0.298	10	(Campbell et al., 2018; K. G. Roberts et al., 2010; Sessions et al., 2019; Timmons et al., 2017)
Biochar carbon content	%	1.4 - 97.4%	64.0%	1031	(UC Davis, 2021)
Biochar recalcitrant fraction of carbon	%	80-97%	88.5%	2	(K. G. Roberts et al., 2010; Wang et al., 2016)
Feedstock transportation emissions	$t \text{ CO}_2e / t \text{ biochar}$	0.042 - 0.12	0.082	2	(Argonne National Laboratory, 2020)



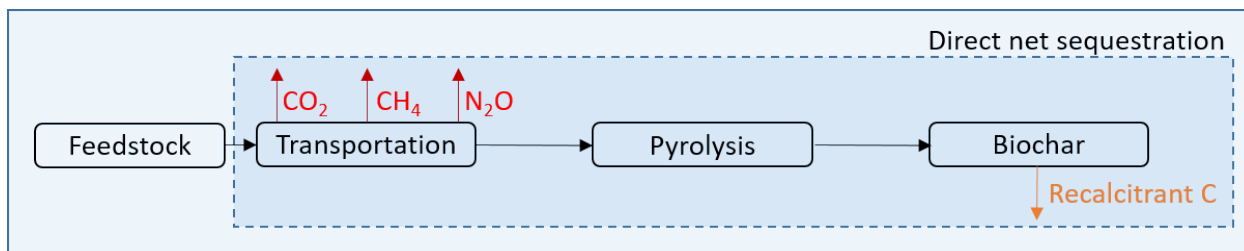


Figure 2: Modeled process flow for emissions calculations.

Direct emissions are calculated as the sum of carbon sequestration and feedstock transport emissions. Carbon sequestration is calculated as the recalcitrant carbon fraction of the biochar product. In total, net direct emissions are  $-2.00 \text{ t CO}_2\text{e} / \text{t biochar}$ , with the negative sign indicating sequestration or negative emissions.

Table 5: Net direct emissions.

Process	Global warming potential intensity ( $\text{tCO}_2\text{e} / \text{t biochar}$ )
Sequestration from recalcitrant carbon in biochar	-2.08
Feedstock transport	0.082
<b>Total net direct emissions</b>	<b>-2.00</b>

## 2.5.2 Financial Inputs

Key financial values from the literature were collected and harmonized for model inputs. All dollar values are expressed in 2014 USD for consistency. Feedstock costs, where explicitly reported in the literature, were omitted from operating costs. All operating costs are categorized as variable operating costs because not all sources used made a distinction to fixed operating costs.

Table 6: Financial inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs	$\text{US\$2014} / \text{t biochar-yr capacity}$	568 – 3698	1688	8	(Campbell et al., 2018; Sessions et al., 2019;

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
					Timmons et al., 2017)
Operating costs	<i>US\$2014 / t biochar</i>	19 – 506	224	19	(Campbell et al., 2018; Sessions et al., 2019; Shackley et al., 2015; Timmons et al., 2017)

### 2.5.3 Technical Inputs

The facility lifespan was modeled at 20 years, based on Project Drawdown assumptions and additional sources (Campbell et al., 2018; Timmons et al., 2017). Cost data were normalized to capacity factor, which was modeled to range from 75% (Campbell et al., 2018; Sessions et al., 2019) to 90% (Timmons et al., 2017).

## 2.6 ASSUMPTIONS

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology are available at [www.drawdown.org](http://www.drawdown.org). Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

**Assumption 1:** Feedstocks sustainably sourced and available at no cost. All feedstock allocated to biochar is a surplus after allocation to other solutions. We therefore do not allocate any land-use change effects to biochar production. It is important to note that our crop residue feedstock streams represent available residues after accounting for leaving a portion in the field, so as not to affect local soil carbon stocks. We model feedstocks as cost-neutral because in some cases feedstock conversion to biochar may come as a credit (Timmons et al., 2017) or already be available at the facility gate (Baker et al., 2020).

**Assumption 2:** Biochar facilities utilize pyrolysis, are optimized for the yield of biochar, and completely combust any co-products. Though we expect some future biochar facilities to also produce usable

energy or co-products, we do not expect this to be universal. Though they may have an important role to play, in our analysis such facilities have a significantly lower biochar yield (Timmons et al., 2017; Woolf et al., 2014) and we do not consider them here.

**Assumption 3:** Carbon sequestration is measured as the recalcitrant carbon portion of the biochar product, which is assumed to be stored in soil near the production facility. The literature presents a vast range of systems boundaries and life-cycle global warming potentials associated with biochar production and use. To harmonize these for our own estimates we do not consider emissions reductions or sequestration that may arise from expanding our system to consider the various end uses of biochar. These effects are site-specific (Woolf et al., 2018). Field application can lead to either an increase or decrease in local non-CO<sub>2</sub> emissions, and we therefore assume there is no net effect from these gases, as has been modeled by others (Smith, 2016). Given the various potential end uses of biochar we do not model product transport, instead assuming that the biochar is stored in soil near the production facility, as has been previously modeled by others (Baker et al., 2020).

## 2.7 INTEGRATION

All Project Drawdown solutions are integrated for consistent accounting. This is essential for supporting our bottom-up process modeling. In the case of biochar, integration with other solutions is provided by using Project Drawdown's integrated biomass model. This ensures avoidance of double-counting of input feedstock and resulting emissions results. The issue of non-additive global potentials for similar solutions reliant on the same feedstock is therefore avoided.

Drawdown's Biomass model begins with projected global biomass demand through 2060, based on FAO historical data and other sources, in categories including sawnwood, other woody biomass, and herbaceous biomass (which includes crop residues). It determines the impact of demand reduction solutions including *clean cookstoves* and *recycled paper*, resulting in an adjusted demand projection through 2060. Biomass supply reductions are modeled as well, which result from protection of forests, reducing biomass availability. Biomass supply increases are modeled through the increased adoption of solutions including *afforestation*, *bamboo*, *perennial biomass* and agroforestry solutions like *tree intercropping*, *silvopasture*, and *multistrata agroforestry*. Biomass availability from crop residues, *seaweed farming*, and dedicated biomass crops planted on cropland freed up by *sustainable intensification* is also modeled.

Surplus biomass is allocated to climate solutions that require biomass as feedstock. These include *biochar*, *biomass electricity*, *bioplastic*, *2<sup>nd</sup> generation biofuels*, *building with wood*, *insulation*, *small-scale biogas*, and *district heating*. This biomass feedstock allocation was a constraint to the adoption of this solution.

## 3 RESULTS

### 3.2 ADOPTION

Below are shown the world adoption of biochar in some key years of analysis in functional units and percent for the three Project Drawdown scenarios.

Table 7: Modeled world adoption of biochar

Solution	Units	Base Year (2014)	World Adoption by 2050		
			PDS1	PDS2	PDS3
Biochar	<i>Mt biochar</i>	7500	63.0	118	148
	<i>% of TAM</i>	0.000012%	21.2%	40.0%	50.0%

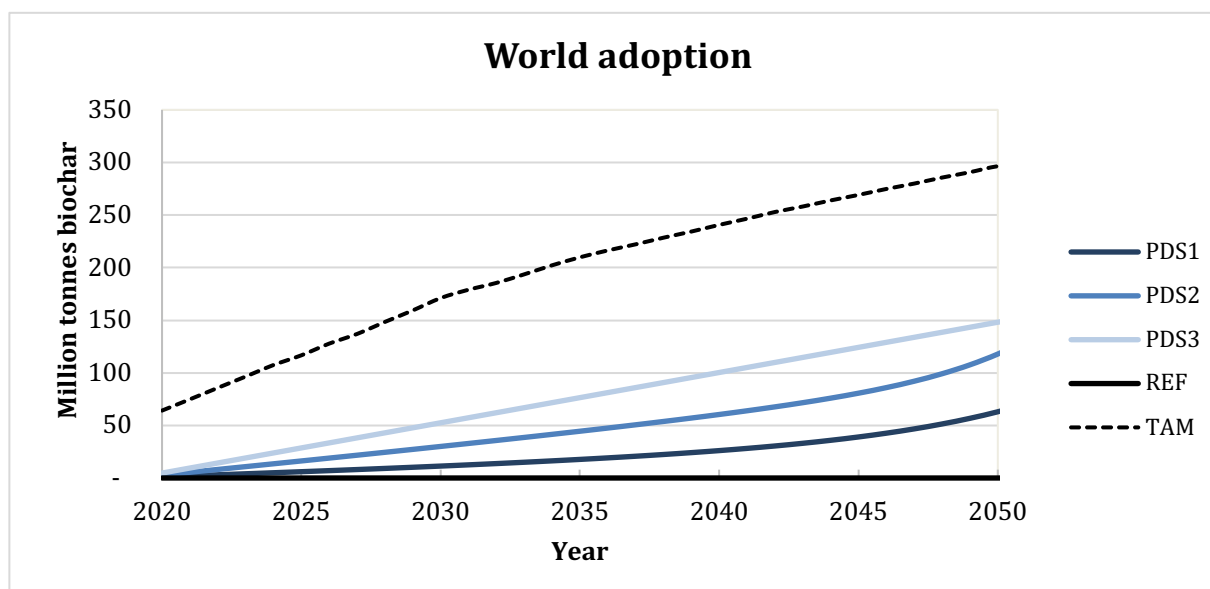


Figure 3: World adoption of biochar 2015-2060

### 3.3 CLIMATE IMPACTS

Below are the emissions results of the analysis for each scenario which include total emissions reduction, atmospheric concentration changes, and sequestration where relevant. For a detailed explanation of each result, please see the glossary (Section 6).

Table 8: Key emissions results.

Scenario	Max Annual Emissions Reduction (Gt CO <sub>2</sub> e / yr)	Emissions Reduction in 2050 (Gt CO <sub>2</sub> e / yr)	Total Sequestration 2020-2050 (Gt CO <sub>2</sub> e)
<b>PDS1</b>	0.13	0.13	1.36
<b>PDS2</b>	0.24	0.24	3.00
<b>PDS3</b>	0.30	0.30	4.73

Table 9: Impacts on atmospheric concentrations of CO<sub>2</sub>-e

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO <sub>2</sub> -e (2050)	PPM CO <sub>2</sub> -e change from 2049-2050
<b>PDS1</b>	0.13	0.01
<b>PDS2</b>	0.26	0.02
<b>PDS3</b>	0.40	0.02

### 3.4 FINANCIAL IMPACTS

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary.

Table 10: Financial results

Scenario	Cumulative First Cost	Marginal First Cost	Average Abatement Cost
	2020-2050 Billion USD	2020-2050 Billion USD	2020-2050 \$/tCO <sub>2</sub> e
<b>PDS1</b>	123.54	123.83	202.74
<b>PDS2</b>	245.22	244.94	193.52
<b>PDS3</b>	330.90	330.62	182.26

## 4 DISCUSSION

Current biochar production is minimal when compared to the amount of potential feedstock available for conversion (Figure 3). Our results also indicate a future biochar production that is lower than most other estimates in the literature (Table 11) and aligns closely with the lower bound of experts' estimate in a recent review (Fuss et al., 2018). Given that Project Drawdown allocates a fraction of globally available biomass to biochar, it may seem that this would be the main constraint to biochar adoption. However, our modeled scenarios do not approach this feedstock limit within the analysis time horizon to mid-century, with the theoretical optimum case (PDS3) only reaching 50% of this limit in 2050. This indicates that biochar growth will likely only be feedstock constrained in the long-term, while in the near-term capital scale-out is a far more limiting factor.

*Table 11: Benchmark comparison with selected relevant studies*

Study	Global annual biochar emissions reduction potential (Gt CO <sub>2</sub> e / year)
Project Drawdown – this study	0.13-0.3
Bossio et al., 2020	1.1
Fuss et al., 2018 – authors' estimate based on review	0.3-2.0
Smith, 2016	0.7 (realistic) – 1.3 (maximum)
Woolf et al., 2010	1.8 (maximum)

This notion can be further reinforced by comparing annual growth rates in our modeled scenarios with other research and analog industries. Our custom scenarios considering cumulative annual growth are bound by a 20% per year upper limit, in line with recent research on another CDR technology suggesting that sustained industry growth above this level for multiple decades is unrealistic (Hanna et al., 2021). Our theoretical optimum case considers linear growth, with an initial resulting cumulative annual growth rate above 20% for the first four years, which may simulate targeted support for global industry development. Our modeled central case (PDS2) considers an initial period of rapid relative growth but sustained growth is around 10% per year or less. For comparison, the compound annual growth rate observed in global fertilizer production during a period of significant growth (1961-1988) was approximately 7% (FAO,

2020b). The same was observed for the adoption of composting in the United States from 1990-2018 (US EPA, 2018). Comparison with these analogs suggests that our modeled low-growth scenario is plausibly consistent with real-world industries and practices, and that our central and optimum cases are optimistic.

We can further contextualize our modeled growth scenarios with the biochar industry's aspirational goal of global production of one billion tonnes in 2050 – this implies a compound annual growth rate of 29% for three decades assuming a start from 500,000 tonnes in 2020. Such sustained high growth seems unlikely based on our modeling and other research (Hanna et al., 2021). We also expect that in the long run if this billion-tonne goal is approached biochar production will likely face competition for feedstock, especially if numerous bio-based solutions are to increase in parallel (Rickels et al., 2019; Toensmeier & Garrity, 2020).

A benefit of modeling a limited selection of feedstock is that our results will be additive to other solutions that are also expected to rely on feedstock, which is sometimes overlooked when solutions are assessed in isolation, leading to unrealistic projections and double counting of climate benefits. From this integrated standpoint we also acknowledge that current waste streams could be reduced in the future through circular economy structures that incentivize re-use and minimize waste. Though this would reduce feedstock availability for solutions like biochar, it would achieve climate benefits farther upstream.

The relatively high technology maturity of pyrolysis for biochar production may be advantageous to its further deployment, but our analysis suggests that this does not occur cheaply. Our calculated marginal abatement costs of approximately \$190/tCO<sub>2</sub>e are generally higher than most reported in the biochar literature, where a central range may be considered \$30-\$120/tCO<sub>2</sub>e (Fuss et al., 2018). To compare with similar climate solutions, our estimate for biochar marginal abatement cost is comparable to BECCS, where a central range may be \$100-\$200/t CO<sub>2</sub>e, and higher than soil carbon sequestration, in the range of \$10-\$100/t CO<sub>2</sub>e (Fuss et al., 2018). A lower marginal abatement cost estimate could be modeled by considering lower first costs, lower operating costs, and expanded life-cycle emissions reductions.

Product revenues could play an additional role in reducing the biochar marginal abatement cost. We identified a wide range of prices in the literature. Though biochar producers likely expect a significant product revenue, it is not clear what this market would look like in terms of end use, product transport, and price under a massive deployment for CDR purposes. Including this in our model could reduce operating costs and in turn marginal abatement costs, but we do not currently consider this effect. Our approach is consistent with another CDR modeling effort that includes biochar but does not examine associated product revenues (Baker et al., 2020).

## 4.2 LIMITATIONS

Project Drawdown’s models are updated periodically as new data and methods become available. The bottom-up nature of the methodology for arriving at global estimates inherently includes uncertainty, assumptions, and simplifications. In addition to those discussed above, we elaborate here on modeling limitations and suggest areas for further development.

Our literature review identified several estimates of the durability of recalcitrant carbon in biochar, and what fraction of the biochar product it represents. We assume for simplification that the recalcitrant fraction is fixed and durability is consistent across end uses, but this is likely to vary in practice. It seems that more precise estimates may be obtained by examining elemental ratios within the biochar product (Woolf et al., 2018), though this would require greater characterization and standardization of products termed *biochar*. Determining the variation in carbon fate among end uses will require additional longer-term studies. This is also the case for modeling the climate co-benefits of biochar application, which are for the current time too heterogeneous to model globally.

We model facilities that are optimized for the yield of biochar; however, a variety of co-products, including energy, can be produced in conjunction with biochar. Such a biorefinery approach has existed for decades, especially within the biofuels arena, and we expect that it will apply to some combination of biochar facilities in the future and may serve as an important transition to developing CDR technologies such as BECCS (Woolf et al., 2016; Yang et al., 2021). Modeling this will require additional data, namely product yields, their impacts, and their intended uses.

The ability of biochar to store carbon for long periods may emerge as its most valuable attribute. Both voluntary and compliance carbon markets are likely to recognize this value and potentially attract increased focus to biochar production as a CDR method. Though Project Drawdown’s solution models do not explicitly examine the effect of a carbon price, we expect biochar production could benefit from one.

New biochar feedstock categories are emerging. The expansion of sustainably-sourced biogenic feedstocks is expected to increase biochar emissions reductions potential and cost savings at scale. In an update to this model compared to our previous version, we modeled the emergence of macroalgae as a potential future source of biogenic feedstock for biochar and other solutions. Use of macroalgae in biochar production has been previously examined and may have the additional benefit of reducing land use competition with other feedstock-based solutions (Bird et al., 2011; D. A. Roberts et al., 2015; Smith et al., 2019; Yang et al., 2021).

Other Prominent examples of emerging feedstocks are biosolids and construction and demolition wastes. These are expected to be available at significant scale – about 8 million and 15 million tons, respectively



could at present be annually available for conversion in the USA (Langholtz et al., 2016). However, these feedstocks face similar challenges of transport, aggregation, and separation from their parent streams. We also acknowledge emerging approaches to restore degraded lands and produce a combination of crops and woody biomass at the community level. Synergistic combinations of coppiced fertilizer shrubs and food crops, among other forms of agroforestry, have potential for biochar production and other bio-based climate solutions (IRENA, 2017; Toensmeier & Garrity, 2020).

Our current review likely does not capture small-scale developments that may be taking place and advancing the biochar industry. From a modeling perspective the spectrum of implementation scales presents challenges, though from an implementation perspective this may be an advantageous attribute of biochar production. Industry data on production across all scales would enable modeling efforts to better capture such developments. It is also apparent that both technological scale-up and scale-out processes may come with cost reductions from learning. We have not modeled these yet as we found no significant differences in financial inputs between this updated model and our previous version. There is currently an apparent paradox in development where the technological sub-processes are relatively mature, implying low potential for further learning, but deployment to date has been limited, implying that scale-out could in fact bring cost reductions.

## 5 REFERENCES

- Amonette, J. E., Blanco-Canqui, H., Hassebrook, C., Laird, D. A., Lal, R., Lehmann, J., & Page-Dumroese, D. (2021). Integrated biochar research: A roadmap. *Journal of Soil and Water Conservation*, 6.
- ANZBIG. (2020). *National Bioenergy Roadmap Submission—The Significant Role for Biochar in Australia*. Australia New Zealand Biochar Initiative, inc. [https://anzbig.org/wp-content/uploads/2020/07/Part-2-ANZBI-Submission\\_National-Bioenergy-Roadmap\\_June-2020.pdf](https://anzbig.org/wp-content/uploads/2020/07/Part-2-ANZBI-Submission_National-Bioenergy-Roadmap_June-2020.pdf)
- Argonne National Laboratory. (2020). *GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technology) Model*. Argonne National Laboratory. <https://greet.es.anl.gov/>
- Baker, S. E., Stolaroff, J. K., Peridas, G., Pang, S. H., Goldstein, H. M., Lucci, F. R., Li, W., Slessarev, E. W., Pett-Ridge, J., Ryerson, F. J., Wagoner, J. L., Kirkendall, W., Aines, R. D., Sanchez, D. L., Cabiyo, B., Baker, J., McCoy, S., Uden, S., Runnenbaum, R., ... McCormick, C. (2020). *Getting to Neutral: Options for negative carbon emissions in California*. Lawrence Livermore National Laboratory. LLNL-TR-796100
- Bellamy, R., & Geden, O. (2019). Govern CO<sub>2</sub> removal from the ground up. *Nature Geoscience*, 12(11), 874–876. <https://doi.org/10.1038/s41561-019-0475-7>

- Bird, M. I., Wurster, C. M., de Paula Silva, P. H., Bass, A. M., & de Nys, R. (2011). Algal biochar – production and properties. *Bioresource Technology*, 102(2), 1886–1891. <https://doi.org/10.1016/j.biortech.2010.07.106>
- Blanco-Canqui, H., Laird, D. A., Heaton, E. A., Rathke, S., & Acharya, B. S. (2020). Soil carbon increased by twice the amount of biochar carbon applied after 6 years: Field evidence of negative priming. *GCB Bioenergy*, 12(4), 240–251. <https://doi.org/10.1111/gcbb.12665>
- Bossio, D. A., Cook-Patton, S. C., Ellis, P. W., Fargione, J., Sanderman, J., Smith, P., Wood, S., Zomer, R. J., von Unger, M., Emmer, I. M., & Griscom, B. W. (2020). The role of soil carbon in natural climate solutions. *Nature Sustainability*, 3(5), 391–398. <https://doi.org/10.1038/s41893-020-0491-z>
- Campbell, R. M., Anderson, N. M., Daugaard, D. E., & Naughton, H. T. (2018). Financial viability of biofuel and biochar production from forest biomass in the face of market price volatility and uncertainty. *Applied Energy*, 230, 330–343. <https://doi.org/10.1016/j.apenergy.2018.08.085>
- Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration, Board on Atmospheric Sciences and Climate, Board on Energy and Environmental Systems, Board on Agriculture and Natural Resources, Board on Earth Sciences and Resources, Board on Chemical Sciences and Technology, Ocean Studies Board, Division on Earth and Life Studies, & National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. National Academies Press. <https://doi.org/10.17226/25259>
- Fajardy, M., & Mac Dowell, N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? *Energy & Environmental Science*, 10(6), 1389–1426. <https://doi.org/10.1039/C7EE00465F>
- FAO. (2017). *World fertilizer trends and outlook to 2020*. Food and Agriculture Organization of the United Nations. <http://www.fao.org/3/i6895e/i6895e.pdf>
- FAO. (2020). *Fertilizers archive (Data set RA)*. Food and Agriculture Organization of the United Nations. <http://www.fao.org/faostat/en/#data/RA>
- Fawzy, S., Osman, A. I., Yang, H., Doran, J., & Rooney, D. W. (2021). Industrial biochar systems for atmospheric carbon removal: A review. *Environmental Chemistry Letters*. <https://doi.org/10.1007/s10311-021-01210-1>
- Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., del Mar Zamora Dominguez, M., & Minx, J. C. (2018). Negative emissions—Part 2: Costs,

potentials and side effects. *Environmental Research Letters*, 13(6), 063002. <https://doi.org/10.1088/1748-9326/aabf9f>

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., & Smith, P. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, 114(44), 11645–11650.

Hanna, R., Abdulla, A., Xu, Y., & Victor, D. G. (2021). Emergency deployment of direct air capture as a response to the climate crisis. *Nature Communications*, 12(368), 13.

International Biochar Initiative. (2013). *State of the Biochar Industry 2013*. International Biochar Initiative. <https://biochar-international.org/state-of-the-biochar-industry-2013/>

International Biochar Initiative. (2014). *State of the Biochar Industry 2014*. International Biochar Initiative. <https://biochar-international.org/state-of-the-biochar-industry-2014/>

International Biochar Initiative. (2015). *State of the Biochar Industry 2015*. International Biochar Initiative. <https://biochar-international.org/state-of-the-biochar-industry-2015/>

Langholtz, M. H., Stokes, B. J., & Eaton, L. M. (2016). *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy* (DOE/EE-1440, ORNL/TM-2016/160, 1271651; p. DOE/EE-1440, ORNL/TM-2016/160, 1271651). <https://doi.org/10.2172/1271651>

Latawiec, A., Królczyk, J., Kuboń, M., Szwedziak, K., Drosik, A., Polańczyk, E., Grotkiewicz, K., & Strassburg, B. (2017). Willingness to Adopt Biochar in Agriculture: The Producer's Perspective. *Sustainability*, 9(4), 655. <https://doi.org/10.3390/su9040655>

Lehmann, J., & Joseph, S. (2015). *Biochar for Environmental Management: Science, Technology, and Implementation* (Second). Routledge.

McMullin, B., Jones, M., Price, P., McGeever, A., & Rice, P. (2020). *IE-NETs: Investigating the Potential for Negative Emissions Technologies (NETs) in Ireland (Report 354)*. Ireland EPA. [https://www.epa.ie/pubs/reports/research/climate/Research\\_Report\\_354.pdf](https://www.epa.ie/pubs/reports/research/climate/Research_Report_354.pdf)

Meyer, S., Genesio, L., Vogel, I., Schmidt, H.-P., Soja, G., Someus, E., Shackley, S., Verheijen, F. G. A., & Glaser, B. (2017). Biochar Standardization and Legislation Harmonization. *Journal of Environmental Engineering and Landscape Management*, 25(2), 175–191. <https://doi.org/10.3846/16486897.2016.1254640>

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente Vicente, J. L., Wilcox, J., & del Mar Zamora Dominguez, M. (2018). Negative emissions—Part 1:

- Research landscape and synthesis. *Environmental Research Letters*, 13(6), 063001. <https://doi.org/10.1088/1748-9326/aabf9b>
- Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, 532(7597), 49–57. <https://doi.org/10.1038/nature17174>
- Puettmann, M., Sahoo, K., Wilson, K., & Oneil, E. (2020). Life cycle assessment of biochar produced from forest residues using portable systems. *Journal of Cleaner Production*, 250, 119564. <https://doi.org/10.1016/j.jclepro.2019.119564>
- Rickels, W., Merk, C., Reith, F., Keller, D. P., & Oschlies, A. (2019). (Mis)conceptions about modeling of negative emissions technologies. *Environmental Research Letters*, 14(10), 104004. <https://doi.org/10.1088/1748-9326/ab3ab4>
- Rickels, W., Proelss, A., Geden, O., Burhenne, J., & Fridahl, M. (2020). *Kiel Working Paper 2164: The Future of (Negative) Emissions Trading in the European Union*. Kiel Institute for the World Economy. [https://www.ifw-kiel.de/fileadmin/Dateiverwaltung/IfW-Publications/Wilfried\\_Rickels/The\\_Future\\_of\\_Negative\\_Emissions\\_Trading\\_in\\_the\\_European\\_Union/KWP\\_2164.pdf](https://www.ifw-kiel.de/fileadmin/Dateiverwaltung/IfW-Publications/Wilfried_Rickels/The_Future_of_Negative_Emissions_Trading_in_the_European_Union/KWP_2164.pdf)
- Roberts, D. A., Paul, N. A., Dworjanyn, S. A., Bird, M. I., & de Nys, R. (2015). Biochar from commercially cultivated seaweed for soil amelioration. *Scientific Reports*, 5(1), 9665. <https://doi.org/10.1038/srep09665>
- Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential. *Environmental Science & Technology*, 44(2), 827–833. <https://doi.org/10.1021/es902266r>
- Rueda, O., Mogollón, J. M., Tukker, A., & Scherer, L. (2021). Negative-emissions technology portfolios to meet the 1.5 °C target. *Global Environmental Change*, 102238. <https://doi.org/10.1016/j.gloenvcha.2021.102238>
- Sandalow, D., Aines, R., Friedmann, J., McCormick, C., & Sanchez, D. L. (2021). *Biomass Carbon Removal and Storage (BiCRS) Roadmap*. Innovation for Cool Earth Forum. <https://www.icef-forum.org/pdf/2020/roadmap/roadmap.pdf?0128>
- Sessions, J., Smith, D., Trippe, K. M., Fried, J. S., Bailey, J. D., Petitmermet, J. H., Hollamon, W., Phillips, C. L., & Campbell, J. D. (2019). Can biochar link forest restoration with commercial agriculture? *Biomass and Bioenergy*, 123, 175–185. <https://doi.org/10.1016/j.biombioe.2019.02.015>

- Shackley, S., Clare, A., Joseph, S., McCarl, B. A., & Schmidt, H.-P. (2015). Economic evaluation of biochar systems: Current evidence and challenges. In *Biochar for Environmental Management: Science, Technology and Implementation*. Routledge.
- Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, 22(3), 1315–1324. <https://doi.org/10.1111/gcb.13178>
- Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., Griscom, B., Hagemann, N., Kammann, C., Kraxner, F., Minx, J. C., Popp, A., Renforth, P., Vicente Vicente, J. L., & Keesstra, S. (2019). Land-Management Options for Greenhouse Gas Removal and Their Impacts on Ecosystem Services and the Sustainable Development Goals. *Annual Review of Environment and Resources*, 44(1), 255–286. <https://doi.org/10.1146/annurev-environ-101718-033129>
- Stenzel, F., Greve, P., Lucht, W., Tramberend, S., Wada, Y., & Gerten, D. (2021). Irrigation of biomass plantations may globally increase water stress more than climate change. *Nature Communications*, 12(1), 1512. <https://doi.org/10.1038/s41467-021-21640-3>
- Timmons, D., Lema-Driscoll, A., & Uddin, G. (2017). *The Economics of Biochar Carbon Sequestration in Massachusetts*. UMass Clean Energy Extension. [https://ag.umass.edu/sites/ag.umass.edu/files/reports/timmons\\_-\\_biochar\\_report\\_10-16-17.pdf](https://ag.umass.edu/sites/ag.umass.edu/files/reports/timmons_-_biochar_report_10-16-17.pdf)
- Toensmeier, E., & Garrity, D. (2020). *How Climate Change Strategies That Use Biomass Can Be More Realistic*. Scientific American. <https://doi.org/10.1038/scientificamerican0820-64>
- UC Davis. (2021). *UC Davis Biochar Database*. University of California Davis. <http://biochar.ucdavis.edu/>
- UK Committee on Climate Change. (2019). *Net Zero: The UK's contribution to stopping global warming*. <https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf>
- US EPA. (2018). *National Overview: Facts and Figures on Materials, Wastes and Recycling*. United States Environmental Protection Agency. <https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials#composting>
- Verde, S. F., & Chiaramonti, D. (2021). The Biochar System in the EU: the Pieces are Falling Into Place, but Key Policy Questions Remain. *European University Institute Florence School of Regulation - Climate*, 2021/08, 10.
- Wang, J., Xiong, Z., & Kuzyakov, Y. (2016). Biochar stability in soil: Meta-analysis of decomposition and priming effects. *GCB Bioenergy*, 8(3), 512–523. <https://doi.org/10.1111/gcbb.12266>

- Willmott, E., & Joppa, L. (2021). *Microsoft Carbon Removal—Lessons From an Early Corporate Purchase*. Microsoft Corporation. <https://query.prod.cms.rt.microsoft.com/cms/api/am/binary/RE4MDIc>
- Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, 1(1), 56. <https://doi.org/10.1038/ncomms1053>
- Woolf, D., Lehmann, J., Cowie, A., Cayuela, M. L., Whitman, T., & Sohi, S. (2018). Biochar for Climate Change Mitigation. In R. Lal & B. A. Stewart (Eds.), *Soil and Climate* (1st ed., pp. 219–248). CRC Press. <https://doi.org/10.1201/b21225-8>
- Woolf, D., Lehmann, J., Fisher, E. M., & Angenent, L. T. (2014). Biofuels from Pyrolysis in Perspective: Trade-offs between Energy Yields and Soil-Carbon Additions. *Environmental Science & Technology*, 48(11), 6492–6499. <https://doi.org/10.1021/es500474q>
- Woolf, D., Lehmann, J., & Lee, D. R. (2016). Optimal bioenergy power generation for climate change mitigation with or without carbon sequestration. *Nature Communications*, 7(1), 13160. <https://doi.org/10.1038/ncomms13160>
- World Bank. (2020). *State and Trends of Carbon Pricing 2020*. <https://openknowledge.worldbank.org/handle/10986/33809>
- Yang, Q., Zhou, H., Bartocci, P., Fantozzi, F., Mašek, O., Agblevor, F. A., Wei, Z., Yang, H., Chen, H., Lu, X., Chen, G., Zheng, C., Nielsen, C. P., & McElroy, M. B. (2021). Prospective contributions of biomass pyrolysis to China's 2050 carbon reduction and renewable energy goals. *Nature Communications*, 12(1), 1698. <https://doi.org/10.1038/s41467-021-21868-z>

## 6 GLOSSARY

**Adoption Scenario** – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate high growth of the solution.

**Approximate PPM Equivalent** – the reduction in atmospheric concentration of CO<sub>2</sub> (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

**Average Abatement Cost** – the ratio of the present value of the solution (**Net Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario**, and is used to build the characteristic “*Marginal Abatement Cost*” curves when Average Abatement Cost values for each solution are ordered and graphed.

**Average Annual Use** – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, total number of passenger-km driven by a hybrid vehicle in a year depends on country and typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

**Cumulative First Cost** – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Direct Emissions** – emissions caused by the operation of the solution, which are typically caused over the lifetime of the solution. They should be entered into the model normalized per functional unit.

**Discount Rate**- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

**Emissions Factor**– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO<sub>2</sub>e/kWh.

**First Cost**- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014\$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.



**Functional Unit** – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high speed rail provides billions of passenger-km of mobility.

**Grid Emissions** – emissions caused by use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner, and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

**Implementation Unit** – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV's in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

**Indirect Emissions** – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

**Learning Rate/Learning Curve** - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a *good* drops by 2% every time total production doubles.

**Lifetime Capacity** – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**, and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

**Lifetime Operating Savings** – the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.



**Lifetime Cashflow NPV**—the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

**Marginal First Cost** – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Net Annual Functional Units (NAFU)** – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

**Net Annual Implementation Units (NAIU)** – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU)**. This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

**Net Operating Savings** – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

**Operating Costs** – the average cost to ensure operation of an activity (conventional or solution) which is measured in 2014\$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

**Payback Period** – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

**PDS/ Project Drawdown Scenario** – this is the high growth scenario for adoption of the solution

**PPB/ Parts per Billion** – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

**PPM/ Parts per Million** – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

**REF/ Reference Scenario** – this is the low growth scenario for adoption of the solution against which all **PDS scenarios** are compared.

**Regrets solution** has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

**Replacement Time**- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

**TAM/ Total Addressable Market** – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

**Total Emissions Reduction** – the sum of grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as “emissions avoided” as they may have occurred in the REF Scenario, but not in the PDS Scenario.

**Transition solutions** are considered till better technologies and less impactful are more cost effective and mature.

**TWh/ Terawatt-hour** – A unit of energy equal to 1 billion kilowatt-hours