Global Biochar C-Sink - Collection of formulas and emission factors

Methodology: Global Biochar C-Sink 3.1

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1. Purpose

In this collection of formulas, emission factor and standard values for the Global Biochar C-Sink. From understanding the pyrolysis process to calculating carbon removals rates, this collection will provide a comprehensive overview of the mathematical formulas that underpin the Global Biochar C-Sink standard.

2. Formulas

The formulas and equations are defined and described in the Global Biochar C-Sink Standard.

2.1. Calculation of Biochar C-Sinks

2.1.1. C-sink potential of biochar, (t CO_2e):

$$[C - Sink\ potential] = [C_{org}\ (\%)] * [dry\ mass_{biochar}(t)] * \frac{44}{12}$$

2.1.2. Decay function of biochar presenting an H/Corg ratio <= 0.4:

$$[C_{remain}(year)] = M_{BC} * C_{cont} * (0.75 + 0.25 * (0.1787 * e^{-0.5337*years} + 0.8237 * e^{-0.00997*years}))$$

2.1.3. Decay function of biochar presenting an H/Corg ratio > 0.4:

$$[C_{remain}(year)] = M_{BC} * C_{cont} * (0.1787 * e^{-0.5337*years} + 0.8237 * e^{-0.00997*years})$$

2.2. Formulas related to feedstock production/growing

In the Global Biochar C-Sink for each described general feedstock classes additional information is provided including calculation examples.

Please see the Global Biochar C-Sink for further information.

$$[Emissions_{feedstock\ growing}(t\ CO_2e)] = [Emissions_{fertilizer}(t\ CO_2e)] + [Emissions_{Pesticide}(t\ CO_2e)]$$

2.2.1. Emissions due to mineral fertilizer usage:

$$[Emissions_{fertilizer}(t\ CO_2e)] = [Amount\ of\ fertilizers\ used\ (kg\ N)] * [1\ t\frac{CO_2e}{100\ kg\ N}]$$

2.2.2. Emissions due to pesticide usage:

$$[Emissions_{Pesticide}(t\ CO_2e)] = [Area\ on\ that\ pesticides\ were\ used\ (ha)] * [0{,}094\ (\frac{t\ CO_2e}{ha})]$$

2.3. Formulas related to feedstock transportation

For the C-sink potential at factory-gate, the Biochar Tool applies the following equation to account for the transport emissions of the feedstock. A factor of 2 is taken into account for empty drives of the lorry to the feedstock supplier or after the transport to the production unit.

2.3.1. Emissions due to feedstock transportation:

$$[Emissions_{transportation\ feedstock}\ (t\ CO_2e)] = \frac{[Amount\ of\ feedstock\ (t\ DM)]}{15t} * [distance\ (km)] * \ 0.2\ \frac{l\ diesel}{km} * \left[2.7\ \frac{kg\ CO_2e}{l\ diesel}\right] * 2$$

If more than one supplier is delivering the feedstock, the weighted average distance has to be taken into account.

2.3.2. Weighted average distance calculation:

$$[Weighted\ distance\ (km)] = \frac{\sum_{i=1}^{n}[Amount\ of\ feedstock_{(Supplier\ i)}\ (t\ DM)] * [distance_{supplier\ i}(km)]}{[Total\ amount\ feedstock\ (t\ DM)]}$$

2.4. Formulas related to preparation of feedstock

The energy and fuel related carbon expenditure due to the preparation of the feedstock has to be accounted for. Preparation of feedstock can include for example the chipping, homogenization or pelletizing of the feedstock.

2.4.1. Emissions due to preparation of feedstock:

$$[Emissions_{preparation\ feedstock}\ (t\ CO_2e\ ] = [Emissions_{fossil\ fuel\ consumption\ preparation}\ (t\ CO_2e)] + [Emissions_{electricity\ usage\ preparation}\ (t\ CO_2e)]$$

2.4.2. Emissions due to fossil fuel consumption for preparation of feedstock:

$$[Emissions_{fossil\ fuel\ consumption\ preparation\ feedstock}\ (t\ CO_2e)\ ] = [diesel\ consumption_{preparation}\ \ (l)] * [2.7\ \frac{kg\ CO_2e}{l\ diesel}]$$

2.4.3. Emissions due to electricity consumption preparation of feedstock:

$$[Emissions_{electricity\ usage\ reparation\ feedstock}\ (t\ CO_2e)] = [electricity\ consumption_{preparation}\ (kWh)] *\ ] + [factor_{electrcitiy}(\frac{g\ CO_2e}{kWh})]$$

The conversion of electricity consumption into CO_2e ($factor_{electricity}$) is based on the specific information provided by the contractual energy provider or the average CO_2e value of the regional electricity mix used. In the case that the energy provider cannot provide a reliable footprint assessment, average literature values are provided in chapter 3.

If the pyrolysis plant itself generates at least as much electricity on an annual average as is consumed in the production facility and the entire production facility offsets its emission with biochar C-sinks, a CO_2e of zero may be assumed for electricity consumption.

2.5. Formulas related to emissions for drying of feedstock

The energy and fuel related carbon expenditure due to the drying of the feedstock has to be accounted for.

2.5.1. Emissions due to drying of feedstock:

$$[Emissions_{drying\ feedstock}\ (t\ CO_2e\ ] = [Emissions_{fossil\ fuel\ consumption\ drying}\ (t\ CO_2e)] + [Emissions_{electricity\ usage\ drying}\ (t\ CO_2e)]$$

2.5.2. Emissions due to fossil fuel consumption for drying of feedstock:

$$[Emissions_{fossil\ fuel\ consumption\ drying}\ (t\ CO_2e)\ ] = [diesel\ consumption_{drying}\ (l)] * [2.7\ \frac{kg\ CO_2e}{l\ diesel}]$$

2.5.3. Emissions due to electricity consumption drying of feedstock:

$$[Emissions_{electricity\ usage\ reparation\ feedstock}\ (t\ CO_2e)] = [electricity\ consumption_{drying}\ (kWh)] *\ ] + [factor_{electrcitiy}(\frac{g\ CO_2e}{kWh})]$$

The conversion of electricity consumption into CO_2e ($factor_{electrcitiy}$) is based on the specific information provided by the contractual energy provider or the average CO_2e value of the regional electricity mix used. In the case that the energy provider cannot provide a reliable footprint assessment, average literature values are provided in chapter 3.

If the pyrolysis plant itself generates at least as much electricity on an annual average as is consumed in the production facility and the entire production facility offsets its emission with biochar C-sinks, a CO_2e of zero may be assumed for electricity consumption.

2.6. Formulas related to storage of feedstock

If moist feedstocks are stored for too long in too large piles, uncontrolled self-heating occurs. In this process, the feedstock is microbially degraded, similar to composting, which results in the loss of carbon as CO_2. Depending on the feedstock and storage conditions, emissions of CH_4 may also occur.

Storage emissions can be effectively avoided. Although this involves additional effort and possibly also costs, the avoidance of emission losses has the beneficial side effect of losing less of the feedstock's energy content. In the Global Biochar C-Sink measures are recommended for feedstock storage and, if implemented correctly, would avoid any storage emissions to be added to the emission portfolio of the batch and production unit.

If none of these recommendations can be implemented, it must be assumed that substantial methane emissions occur, that they are not covered by the margin of safety, and therefore must be calculated.

For the storage period, not only the storage on the premises of the pyrolysis plant is considered, but the entire storage period of the feedstock, whether at the harvest site or the site of any feedstock processor or trader.

The absolute global warming potential (AGWP) of methane caused by feedstock storage have to be compensated by temporary C-sinks (C-sink_20).

2.6.1. Methane emissions due to storage of moist wood chips and sawdust (above 20% moisture content):

$$[Emissions\ Wood\ storage\ (t\ CH_4)] = [m_{feedstock\ DM}(t)] * [C_{content\ feedstock}] * [\#days_{storage} - 30\ ] * [0.13\ (\%)] * [\frac{16\ kg * mol^{-1}}{12\ kg\ mol^{-1}}]$$

2.6.2. Methane emissions due to storage of non-woody feedstock (above 20% moisture content):

$$[Emissions\ non\ Wood\ storage\ (t\ CH_4)] = [m_{feedstock\ DM}(t)] * [C_{content\ feedstock}] * [\#days_{storage} - 30\ ] * [0.25\ (\%)] * [\frac{16\ kg * mol^{-1}}{12\ kg\ mol^{-1}}]$$

2.7. Formulas related to pyrolysis

The energy and fuel-related carbon expenditure for the entire process chain, from the provision of feedstock to the packaging of the biochar, is calculated in CO2e and included in the emission portfolio of the batch and the respective production unit (i.e., the pyrolysis unit that is used to produce the batch).

2.7.1. Emissions due to electricity consumption pyrolysis:

$$[Emissions_{electricity\ usage\ pyrolysis}\ (t\ CO_2e)] = [electricity\ consumption_{pyrolysis}\ (kWh)] *] + [factor_{electrcitiy}(\frac{g\ CO_2e}{kWh})]$$

2.7.2. Emissions due to external fuel for reactor heating:

$$[Emissions_{fossil\ fuel\ reactor\ heating}\ (t\ CO_2e)\ ] = [diesel\ consumption_{reactor\ heating}\ (l)] * [2.7\ \frac{kg\ CO_2e}{l\ diesel}]$$

OR

$$[Emissions_{fossil\ fuel\ reactor\ heating}\ (t\ CO_2e)\ ] = [LPG\ consumption_{reactor\ heating}\ (l)] * [3\ \frac{t\ CO_2e}{t\ LPG}]$$

2.7.3. Emissions due to carrier gas:

Carrier gases are not yet used when it comes to pyrolysis. The equation and emission factor or standard values will be provided when needed.

2.7.4. Emissions due to methane emissions of pyrolysis unit:

Measuring methane emissions below 5 ppm is technically complex. Continuous measurement over an entire production year is not possible with currently available technology. Therefore, either at least two CH_4-emission tests per pyrolysis unit with the same feedstock representing the typical operation of the unit are required, or the pyrolysis unit must have a type certification according to EBC or WBC.

For CH_4 emission tests, a detailed measurement strategy with precise details of the measurement technology, measurement intervals, and measurement accuracy must be submitted in advance to Carbon Standards for review. Once the procedures are accepted, the methane emissions factor of the pyrolysis unit is calculated as the mean of the two measurements plus one standard deviation as the margin of security.

$$[Emissions_{methane\ pyrolysis}\ (t\ CH_4)\ ] = [amount\ of\ feedstock\ (t\ DM)] * [methane\_output\ \frac{t\ CH\_4}{t\ feedstock\ (DM)}]$$

$$\left[Methane\_output\ (\frac{t\ CH_4}{t\ feedstock\ (DM)})\ \right] = \left[methane\ content_{exhaust\ gas,measured}\right] * [gas\ volume\ flow_{measured}\left(\frac{m^3}{h}\right)] * \frac{[operating\ hours_{measured}\ (h)]}{[amount\ feedstock_{measured}(t\ DM)]}$$

2.8. Margin of Safety

For Scope 3 emissions of involved organizations, only the emissions from feedstock production and its transport are directly quantified. Other indirect emissions from Scope 3 are not recorded individually due to their comparatively low volume but are instead included in the calculation with a flat margin of safety to account for the whole value chain. This margin of safety covers the indirect emissions not quantified in the system and unavoidable imprecisions in measuring and analyzing the produced biochar.

Please see the Global Biochar C-Sink for further information.

$$[Margin\ of\ Safety] = [produced\ biochar\ (t, DM)] * [0.02\ (t\ CO_2e)]$$

2.9. Formulas related to Reduction of Fossil Carbon Emissions

Certified biochar producers must present a plan outlining how to reduce fossil GHG emissions of biochar production as specified below to less than 100 kg CO_2e per ton of biochar-carbon in 2030 and to less than 20 kg CO_2e per ton of biochar-carbon in 2035.

The following fossil carbon emissions must be included: feedstock production, harvest, transport, preparation such as chipping or pelletizing, drying, pyrolysis, and packaging. Methane emissions from storing and pyrolysis should equally be avoided but are not included in the fossil carbon emission reduction plan because of their biogenic origin. Fossil carbon emissions from biochar transportation and external processing do not fall under the responsibility of the biochar producer and will be part of the control of biochar traders, biochar product manufacturers, and users.

$$[Biochar\ GHG\ balance\ (\frac{t\ CO_2e}{t\ biochar_{carbon}})] = \frac{[Emissions\ at\ factory\ gate\ (t\ CO_2e)] - [non\ fossil\ CH_4 emissions\ (t\ CO_2e)]}{[mass\ of\ biochar\ per\ batch\ (t\ DM)] * [C_{content}\ of\ biochar\ (\%)]}$$

2.10. Pro Rata calculation of GHG Footprint

To be eligible to use the pro-rata GHG calculation, the producer has to prove that the non-biochar products are regularly traded and generate substantial income or measurable add value. The income or added value for all non-biochar products must not be inferior to 30% of the income generated with biochar.

The input energy (E_{input}) is calculated by multiplying the analyzed lower heating value (LHV) of the feedstock feedstock ($LHV_{feedstock}$) with the mass of the feedstock on a dry matter base ($m_{feedstock\ (DM)}$).

The output energy of the non-biochar products ($E_{non\ biochar\ output}$) is calculated by multiplying the LHV of the marketable non-biochar solid (e.g., charcoal), liquid, and gaseous products with the respective mass of the products on a dry matter base and adding the produced, measured electric energy ($E_{electric}$) and thermic energy ($E_{thermic}$). A pyrolysis product is considered as marketed when it is sold to or used in processes not directly linked to the pyrolysis/gasification facility. For example, hydrogen is considered a marketable product when hydrogen is produced, stored in a tank, and sold to another company or used, e.g., in a methanol synthesis at the production site. If the hydrogen is combusted in the combustion chamber of the pyrolysis unit or in a directly linked generator for electricity production, the hydrogen is not considered a marketable product. The use of thermic energy to dry the pyrolysis feedstock is considered part of the biochar production and cannot be accounted for the pro-rata GHG allocation.

$$[GHG\ emission\ biochar\ (t\ CO_2e)] = [Production\ emissions\ (t\ CO_2e)] * \frac{E_{biochar}}{E_{non\ Biochar\ Output} + E_{biochar}}$$

With:

$$[E_{biochar}\ (MJ)] = \left[LHV_{biochar}\left(\frac{MJ}{kg}\right)\right] * [m_{biochar\ (DM)}(kg)]$$

$$\begin{aligned}[E_{non\ biochar\ output}\ (MJ)] &= \left[LHV_{non\ biochar\ solid}\left(\frac{MJ}{kg}\right)\right] * [m_{non\ biochar\ solid\ (DM)}(kg)] + \left[LHV_{liquid}\left(\frac{MJ}{l}\right)\right] * [m_{liquid}(l)] \\ &+ [LHV_{gas}\left(\frac{MJ}{m^3}\right)] * [m_{gas}(m^3)] + [E_{electric}\ (MJ)] + [E_{thermic}(MJ)]\end{aligned}$$

$$[E_{input}\ (MJ)] = \left[LHV_{feedstock}\left(\frac{MJ}{kg}\right)\right] * [m_{feedstock\ (DM)}(kg)]$$

2.11. Formulas related to the carbon efficiency

Carbon efficiency refers to the ratio of carbon transformed into a storable form (i.e., amount of carbon in a batch of biochar) to the input of carbon (i.e., amount of carbon in the feedstock used to produce the biochar).

The carbon efficiency of a pyrolysis facility is a measure of the part of feedstock-carbon that is preserved by a technical transformation process as a potential C-sink. It is assessed at the factory gate of the pyrolysis facility independent of the further storage and use of the carbon products.

$$[Carbon\ Efficiency\ (\%)] = \frac{[Pyrogenic\ carbon\ (t\ C)]}{[Feedstock\ (t\ DM)] * [C_{content}\ of\ feedstock\ (\%)]}$$

With:

$$\begin{aligned}[Pyrogenic\ carbon\ (t\ C)] &= [\ Biochar\ (t\ DM)] * \ [C_{content}\ Biochar\ (\%)] + \ [\ Pyrolysis\ oil(t)] \\ &* \ [C_{content}\ Pyrolysis\ oil\ (\%)] + \ [\ Purified\ CO_2\ (t)] * \ [C_{content}\ Purified\ CO_2\ (\%)]\end{aligned}$$

2.12. Formulas related to the energy efficiency

It is increasingly important from a climate perspective to extract maximum energy from feedstock. Therefore, a minimum threshold of 60% energy efficiency must be met for biochar production to meet the Global Biochar C-Sink standard. Energy efficiency includes beneficial products (e.g. biochar) plus thermal or electric energy, pyrolysis oil, CO_2, hydrogen, etc. From the energy perspective, using these pyrolysis derivatives even for non-sequestering activities such as fossil fuel displacement, steel production or other short cycling carbon uses is considered as a meaningful energy use. Energy can be used within the biochar production plant (e.g. for drying feedstock) or externally (e.g. district heating system).

For every batch of a certified pyrolysis unit, at least 60% of the sum of the energy contained in the feedstock and all energy expenditures of the process must be used.

For more details please refer to the Global Biochar C-Sink standard.

$$E_{eff} = \frac{E_{solid} + E_{pyrooil} + E_{fuelproducts} + E_{thermal} + E_{drying} + E_{electric} + E_{co2pur}}{E_{feedstock} + E_{expenditures}}$$

In most cases of today's pyrolysis facilities, some summands are zero, the formula then simplifies to:

$$E_{eff} = \frac{E_{solid} + E_{thermal} + E_{drying} + E_{electric}}{E_{feedstock} + E_{expenditures}}$$

With:

$[E_{feedstock}\ (kWh)] = [LHV_{feedstock} (\frac{kWh}{t\ DM})] * [M_{feedstock}\ (t\ DM)]$	If the feedstock is clearly defined, the LHV can be taken from the literature. Mixed and not clearly defined feedstock and feedstock known for its high energy content variability (e.g., sieving residues from composting) must be analyzed in a laboratory endorsed by Carbon Standards.
$[E_{solid}\ (kWh)] = [LHV_{biochar}\ (\frac{kWh}{tDM})] * [M_{biochar}\ (t\ DM)]$	The LHV of the biochar and charcoal must be analyzed from the EBC/WBC certification sample.
$[E_{thermal}\ (kWh)] = 810\frac{\mathrm{kWh}}{\mathrm{t}} * [M_{water}\ (t)]$ $[M_{water}(t)] = [Water\ content\ of\ biomass\ at\ delivery\ (\%)] * [Mass\ of\ biomass\ at\ delivery\ (t)] - [Water\ content\ of\ biomass\ after\ drying\ (\%)] * [Mass\ of\ biomass\ after\ drying\ (t)]$	If thermal energy is supplied to district heating or industry, the actual amount used must be metered ($E_{thermal}$)
$[E_{pyrooil}(kWh)] = [LHV_{pyrooil}\ (\frac{kWh}{t}) * [M_{pyrooil}\ (t)]$	If pyro-oil is separated for storage or use, its LHV is quantified and multiplied by the total amount of pyro-oil co-produced with the biochar batch ($E_{pyrooil}$). The LHV of the pyro-oil must be analyzed in a laboratory endorsed by Carbon Standards. If different fractions of the pyro-oil are produced, the LHV of each fraction has to be analyzed.

$$[E_{CO_2pur}(kWh)] = 1000\frac{\text{kWh}}{t_{CO2}} * [M_{CO_2}\ (t)]$$	If the pyrolysis gas is used to produce hydrogen, methanol, or other marketable fuels or chemicals, their energy content is to be provided as $E_{fuel\ products}$. If CO_2 is separated after oxidation of the pyro-gas, this can be accounted for with a maximum of 1000 kWh/t CO_2 which provides the parameter (E_{CO_2pur}).
$$[E_{fuel\ products}(kWh)] = \sum_{n=1}^{x}[LHV_{fuel\ product\ x}\ (\frac{kWh}{t}) * [M_{fuel\ product\ x}\ (t)]$$	
$$[E_{expenditures}\ (kWh)] = [E_{feedstock\ transportation}\ (kWh)] + [E_{feedstock\ preparation}\ (kWh)] + [E_{electricity\ consumption\ batch}\ (kWh)] + [E_{reactor\ heating}(kWh)\ ]$$ $$[E_{feedstock\ transportation}(kWh)] = [LHV_{Diesel}\ (\frac{kWh}{t}) * [M_{Diesel}\ (t)]$$ $$[E_{feedstock\ preparation}(kWh)] = [LHV_{Diesel}\ \left(\frac{kWh}{t}\right) * [M_{Diesel}\ (t)] + \ electricity\ consumption_{preparation}\ (kWh)\ electricity\ consumption_{drying}\ (kWh)$$ $$[E_{reactor\ heating}(kWh)] = [LHV_{fuel}\ (\frac{kWh}{t}) * [M_{fuel}\ (t)]$$	

2.13. Formulas related to absolute global warming of methane emissions

The Absolute Global Warming Potential of the methane emissions are calculated based on:

$$AGWP\_CH4(100) = \sum_{t=0}^{99}(IRF\left(CO_{2,a}(t)\right) * \ [CO_2e\ of\ CH_4\ emissions\ per\ tonne\ of\ biochar]\ )$$

To calculate the *Absolute Global Warming Potential (AGWP)* over 100 years we are using Jeltsch-Thömmes & Joos (2019)[1] to calculate the decay of the CO_2. Greenhouse gases decay in the atmosphere. The quantities of CO_2 still present in the atmosphere each year are added up over the 100 years, resulting in the absolute global warming potential (AGWP) over 100 years.

The decay is described by the equation:

$$\left[IRF(CO_{2,a}(t))\right] = a_0 + \sum_{i=1}^{5} a_i * \exp\left(\frac{-t}{\tau_i}\right) for\ t \geq 0$$

With the values

i	ai	ti
0	0.008	

[1] Jeltsch-Thömmes, A., Joos, F., 2019. The response to pulse-like perturbations in atmospheric carbon and carbon isotopes 1–36.

1	0.044	68521
2	0.112	5312
3	0.224	362
4	0.31	47
5	0.297	6

The resulting methane emissions of the produced biochar are calculated as below, with the GWP100 (CH_4) value of 25 CO_2e.

$$[CO_2e\ of\ CH_4\ emissions\ per\ tonne\ of\ biochar] = [Total\ methane\ emissions] * [GWP100_{CH4}]$$

2.14. Formulas related to absolute global cooling of SPC fraction

Carbon Standards is offering an online calculator for the calculation of the AGCP of the SPC fraction.

The Absolut Global Cooling Potential (AGCP) of the SPC for the first 20 years is calculated as follow:

$$[AGCP(20)] = [C - Sink\_20] = \sum_{t=0}^{20} (C_{remain}(t, SPC) * \ IRF(CO_{2,a}(t)))$$

With:

C_{remain} (t, SPC) as the adjusted equation 2 of Global Artisan C-Sink Standard for the SPC fraction of the biochar (25%)

$$[C_{remain}(t, SPC)] = \frac{M_{BC} * C_{Content}}{1000} * (45 * \ e^{-0.5232*t} + 205 * \ e^{-\ 0.009966*t})$$

3. Emission factors

Parameter	Unit	Factor	Source
GWP100 N_2O	t CO_2e/t N_2O	298	IPCC 2022, (GBCS)
GWP20 CH_4	t CO_2e/t CH_4	25	IPCC 2022, (GBCS)
Mineral nitrogen fertiliser	t CO_2e/ 100 kg N	1	Zhang et al., 2013, (GBCS)
Pesticides	kg CO_2e/ ha	94	Audsley et al., 2009, (GBCS)
Diesel consumption	t CO_2e/ton diesel	3.2	Juhrich, 2016, (GBCS)
Diesel consumption	kg CO_2e/liter diesel	2.7	Juhrich, 2016, (GBCS)
LPG consumption	t CO_2e/ton LPG	3	GBCS
Carbon content of wood	%	48	GBCS
Carbon content of non-woody feedstock	%	50	GBCS
Emission factor solar PV power	g CO_2e/kWh	48	IPCC 2018
Emission factor wind power	g CO_2e/kWh	12	IPCC 2018
Emission factor hydro power	g CO_2e/kWh	24	IPCC 2018
Emission factor nuclear power	g CO_2e/kWh	12	IPCC 2018
Emission factor coal power	g CO_2e/kWh	820	IPCC 2018
Thermal energy used for feedstock drying	kWh / t evaporated water	810	GBCS
$\boldsymbol{LHV_{Diesel}}$	kWh / kg	11.8	GBCS
$\boldsymbol{LHV_{LPG}}$	kWh / kg	13	GBCS

4. Annexes

4.1 Literature

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