Bioenergy with or without carbon dioxide removal: influence of functional unit choice and parameter variability

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Abstract

PURPOSE. Bioenergy with carbon dioxide removal (CDR) is increasingly presented as an efficient way to mitigate climate change. This study set out to determine under which circumstances and methodological choices CDR bioenergy systems are preferable over a reference bioenergy system from a climate change mitigation perspective. In addition, the CDR systems investigated were compared to each other.

METHODS. Three systems were modelled: two CDR systems (Biochar and Bioenergy with carbon capture and storage (BECCS)), with a combined heat and power (CHP) system as reference. A parametrised life cycle inventory model was developed and computed for all systems and four different functional units (FUs), resulting in distributions of climate impacts. Contribution analysis was performed, as well as a pairwise comparison of all scenarios to establish their ranking. First-order Sobol indices were computed to assess the contribution of each parameter to the variance. Whenever ranking of scenarios was largely dependent on parameter values, decision tree analysis was applied.

RESULTS AND DISCUSSION. The CDR systems had a lower climate impact than CHP for most computations, across all FUs. However, when comparing the two CDR systems, the preferable system changed with FU; for heat or carbon sequestration as FU the Biochar system was preferable in general, while for electricity or biomass use as FU, the BECCS system had the lowest climate impact for most computations. For most system configurations, the contribution from energy substitutions were large and contributed to most of the variance in results. Furthermore, the ranking of systems depended on the reference activities of the background energy system.

CONCLUSIONS. The results of this study indicate that the Biochar and BECCS systems are in general preferable over the reference CHP system from a climate mitigation perspective, particularly when the reference energy systems have a relatively low climate impact. However, FU and parameters affect the ranking of these three systems.

RECOMMENDATIONS. When conducting a comparative LCA study for multifunctional systems, the LCA practitioner should be aware that choice of FU and specific system configurations, including reference activities, could potentially affect the climate impacts of the system, which in turn potentially affects the ranking among systems and conclusions communicated to decision makers. Conducting LCA for several FUs, with parametrised LCI, and contribution analysis, allows for a deeper analysis than traditional sensitivity analyses.

Keywords

Climate change, environmental assessment, carbon capture and storage, biochar, negative emission technologies, functional unit, system expansion, substitution.

1 Introduction

To reach the climate goals stated in the Paris Agreement, humanity must succeed in reducing greenhouse gas emissions. In addition, it is likely that carbon dioxide removal (CDR) technologies will be needed to reach net zero emissions and to compensate for a possible overshoot of the carbon budget (IPCC, 2021). Over the course of the 21st century, estimates of required carbon dioxide (CO_2) removal from the atmosphere range from 150 to 1200 $GtCO_2$ depending on the chosen development pathways (Minx, 2018) (the total annual anthropogenic carbon dioxide emissions of 2019 were at approximately 42.2 $GtCO_2$ (Friedlingstein et al, 2020)).

Biochar and bioenergy with carbon capture and storage (BECCS) are two CDR technologies that rely on the ability of biomass to capture carbon dioxide from the atmosphere via photosynthesis. Biochar is the carbon rich solid produced from biomass pyrolysis, a thermal degradation process in partial or total absence of oxygen (Woolf et al, 2010). Biochar produced in adequate conditions can remain stable in soils on centennial time scales, thereby providing long-term carbon sequestration (Spokas, 2010; Woolf et al, 2021). Biochar is also a material product with an economic value in various sectors (Oni et al, 2019; Sakhiya et al, 2020). Moreover, electricity and heat can be obtained from the combustion of the gases and tars co-produced during pyrolysis. BECCS is the process of burning biomass for bioenergy generation, combined with capturing the CO_2 from the flue gases and transporting it to a permanent geological storage (Kemper, 2015). Similar to a combined heat and power (CHP) bioenergy plant, electricity and heat can be produced from the BECCS process, but the carbon capture and storage (CCS) process consumes some of the electricity produced (Gustafsson et al, 2021; Levihn et al, 2019).

CDR research acknowledges the importance of carbon accounting, and often refers to the use of life cycle assessment (LCA) to guarantee that supply-chain emissions do not outweigh the amount of CO_2 captured (Tanzer and Ramirez, 2019; Brander et al, 2021). CDR research also reckons that only system-wide change in greenhouse gas emissions and sinks actually leads to climate change mitigation (Tanzer and Ramirez, 2019; Brander et al, 2021). However, determining supply-chain emissions and system-wide emission change requires delimitation of system boundaries in LCA, which is not always straightforward for multi-functional bio-based systems like biochar and BECCS. Multi-functional systems deliver several products that share the supply-chain burdens and benefits. The environmental impacts of each product cannot always be separated from one another, and results depend on the choice of functional unit (FU) (Ahlgren et al, 2015). Bio-based systems rely on biogenic resources, thus involving the short cycle of carbon and various stocks of biogenic matter. Changes in these stocks are relative to the choice of a reference biomass or land use, and often have large contributions to the climate impact (Cherubini and Strømman, 2011; Koponen et al, 2018).

LCA can be used to compare the environmental performance of several CDR technologies and to inform decision-making. However, results from comparative LCA studies are affected by methodological choices. These differences are prominent for LCAs of bioenergy systems and comparing results across multiple studies is therefore difficult (Cherubini and Strømman, 2011). Likewise, Terlouw et al (2021) recommend that LCA results of CDR technologies must not be compared without further harmonization due to lack of consistency in methodological choices. When reviewing the biochar LCA literature, Terlouw et al (2021) found that the calculated climate impacts from the studies were not comparable, partly due to use of different FUs. These inconsistencies in methodological choices indicate that there is reason to examine to what extent different FUs lead to different conclusions for an otherwise identical LCA. In addition, the LCA results of bioenergy systems and CDR systems can differ, depending on choice of reference activity when performing substitutions (Koponen et al, 2018; Terlouw et al, 2021). Matuštík et al (2020) found that results from LCAs of biochar systems are difficult to compare, partly due to methodological inconsistencies, but also because of contextual differences. Therefore, parameters can be defined when modelling the system studied, allowing for parametric uncertainty and variability to be taken into account.

Taking all these methodological aspects (choice of FU, multifunctionality and parametric uncertainty and variability) into account, the results and process of a comparative LCA can be complex, and hinder decision-making. Therefore, this study aims to examine under which circumstances it is beneficial for climate change mitigation to implement CDR in bioenergy systems. Additionally, this study also sets out to compare the climate impacts of Biochar and BECCS systems in relation to each other. These comparisons are to be made by conducting an LCA with respect to different methodological choices, such as parametric uncertainty and variability as well as choice of FU.

2 Methods

2.1 Goal and scope definition

Studied systems & products

Three systems have been modelled and their climate impacts have been calculated in an LCA. The three systems are named CHP, Biochar and BECCS (Figure 1). The CHP system is based on a bioenergy plant without CCS that produces heat and power. The Biochar system includes pyrolysis instead of combustion, and the system produces heat, power and biochar. The BECCS system entails a bioenergy plant, which is similar to the CHP scenario, with CCS technology separating CO_2 from the flue gas. The systems are multifunctional and deliver the following functions: electricity production, heat production, biomass use, carbon sequestration (Biochar and BECCS only) and biochar usage (Biochar system only). In order to account for this multifunctionality, the substitution method was applied (see section 2.2).

The biomass feedstock for all systems is woodchips from logging residues (tops and branches) assumed to be produced in proximity of the power plant. The residues are assumed to be forwarded to a roadside storage, where they are stored for 8 months and subsequently chipped. The woodchips are transported by lorry to the power plant and the ashes after combustion are assumed to be returned to the forest. All biochar produced from the Biochar system is assumed to be used in soil. The CO_2 captured from the BECCS system is shipped to an intermediate storage and subsequently transported through a pipeline and injected into a permanent geological storage. More details and data can be found in the supplementary material.

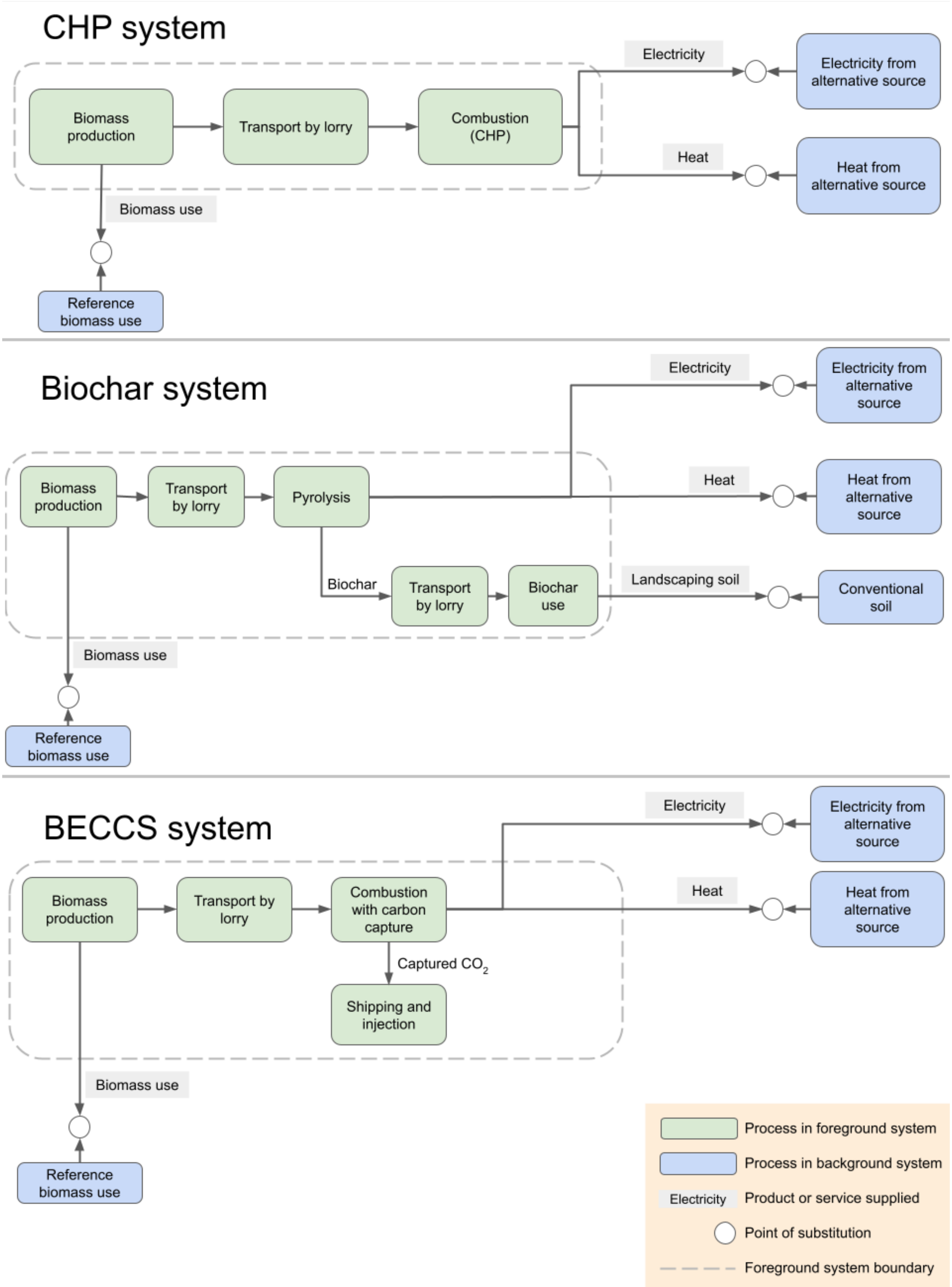

Figure 1. Flowcharts of the three systems: CHP, Biochar and BECCS.

Goal, impact categories, database and software

The goal of the LCA was to determine if bioenergy systems with implemented CDR technologies yield lower climate impacts than bioenergy system without CDR. Additionally, the LCA aimed to determine which of the analysed CDR technologies has the lowest climate impact. Climate change was the only impact category used to evaluate the systems, characterised by global warming potential with a time horizon of 100 years (GWP_{100}). The greenhouse gas emissions modelled are carbon dioxide (CO_2), nitrous oxide (N_2O; GWP_{100} = 265), and methane (CH_4; GWP_{100} = 29.7). The Ecoinvent database, version 3.6 cut-off system-model (Wernet et al, 2016), was used. The model was developed and implemented using the python framework for LCA, brightway2 (Mutel, 2017), its graphical user interface, the activity-browser (Steubing et al, 2020), and the algebraic extension, lca_algebraic (Jolivet et al, 2021). In addition, several python scripts were developed to automate the comparative LCA of several systems with multiple FUs, multiple choices of reference activities and defined parameters.

Functional units

The functional unit, the reference flow on which the results of an LCA are based, is usually chosen based on the aim of the study (Ahlgren et al. 2015). Traditionally, only one FU is chosen. In this study, we took an interest in all FUs that could lead to different results. The number of FUs could however be limited based on reasoning presented in the supplementary material; in short, it was found that the number of FUs relevant to compare is limited to the number of functions delivered by all of the studied systems. When analysing all three systems, the defined FUs for the case study are the single products which are delivered by all systems, namely heat, electricity or biomass use. Furthermore, carbon dioxide sequestration was defined as a FU for analysing only the CDR systems (Table 1). According to Terlouw et al (2021), the recommended FU for comparing CDR systems is impact per tonne of CO_2-removal, where CO_2-removal is sequestration only, excluding any avoided burdens. In the case where only CDR systems are evaluated against one another, it could be argued that CO_2-removal is the most relevant FU for comparison, since carbon sequestration is (probably) the primary reason for implementing these systems.

Table 1. Functional units selected for case study and the corresponding potential interpretations of the results.

Function	Input/output	Amount	Interpretation
Biomass used	Input	1 tonne	How to use biomass resources in a climate efficient way
Electricity generated	Output	1 MWh	How to produce electricity with the least climate impact
Heat produced	Output	1 GJ	How to produce heat with the least climate impact
Carbon dioxide sequestered	Output	1 kg	How to sequester carbon dioxide with the least climate impact

Limitations and cut-offs

Some limitations and generalisations have been applied to the model: parts of the systems that have been excluded are for example biochar effects on soil, pre-treatment of biomass before combustion and production of necessary infrastructure.

2.2 Parametrisation of life cycle inventories

In order to account for uncertain or ambiguous data, parameters were defined for some data entries in the LCI, which allows for multiple possible values of the same exchange to be considered in the results and analysis (Table 2). All parameter values are based on literature sources, with the exception of transport distances, which are all simply modelled based on assumptions. The purpose of the LCI was to portray a general scenario, it was not specified to represent a distinct, local case. However, the data selection is based on Swedish/Nordic case studies. More details and data can be found in the supplementary material.

Thermochemical conversion

Electricity and heat output from the CHP system were calculated as shown in Equation 1 and Equation 2, respectively:

$E = LHV \times \eta$ [GJ tonne^{-1} biomass] Equation 1

$H = LHV \times \theta$ [GJ tonne^{-1} biomass] Equation 2

where E is electricity produced, H is heat produced, LHV is the lower heating value of the woodchips, η is the power efficiency of the combustion process and θ is the thermal efficiency.

The electricity and heat produced from the biochar system are calculated as shown in Equation 3 and Equation 4, respectively (Azzi et al, 2019).

$E = r \times 234.95 \times e^{-6.56\beta} \times \beta$ [GJ tonne^{-1} biomass] Equation 3

$H = (1 - r) \times 234.95 \times e^{-6.56\beta} \times \beta$ [GJ tonne^{-1} biomass] Equation 4

Here, r is the ratio of electricity from the total energy output and β is the biochar yield in weight percentage compared to weight of biomass (Azzi et al, 2019).

The outputs of electricity and heat from the BECCS system are calculated as shown in Equation 5 and Equation 6, respectively.

$LHV \times \eta \times \eta_{CCS}$ [GJ tonne^{-1} biomass] Equation 5

$LHV \times \theta \times \theta_{CCS}$ [GJ tonne^{-1} biomass] Equation 6

The production of electricity and heat are calculated similarly to the outputs from the CHP system and use the same parameters but are further multiplied by $\eta_{CCS}$and θ_{CCS}, respectively, where η_{CCS} is the relative electricity efficiency of the BECCS system compared to the CHP system and θ_{CCS} is the corresponding value for heat efficiency in the BECCS system. All values for θ_{CCS} are greater than 1, meaning that the CCS process actually allows for the system to produce more heat than the CHP system (Gustafsson et al, 2021).

Table 2. Definitions of parameters used in the case study. For parameters defined with normal uncertainty distribution, μ is the mean value and σ is the standard deviation.

Name, symbol	System	Definition	Uncertainty distribution	Parameter range	Unit	Source
Biochar decay, D	Biochar	Decay of biochar over 100 years after being applied to soil, measured in mass percentage.	Uniform	Min = 0.10 Max = 0.50	Fraction of decay over 100 years	Azzi et al (2019)
Biochar yield, β	Biochar	Yield of biochar from pyrolysis process, measured in mass percentage compared to biomass.	Uniform	Min = 0.21 Max = 0.36	kg biochar kg^{-1} biomass	Azzi et al (2019)
Carbon capture percentage, C	BECCS	Ratio of CO_2 captured from the CO_2 emissions of the combustion process.	Uniform	Min = 0.70 Max = 0.90	-	Gustafsson et al (2021)*
CCS electricity efficiency, η_{CCS}	BECCS	Ratio of electricity produced by the BECCS plant, compared to electricity production from CHP plant. See Equation 5 in Section 2.2.	Uniform	Min = 0.3273 Max = 0.4546	-	Gustafsson et al (2021)
CCS heat efficiency, θ_{CCS}	BECCS	Ratio of heat produced by the BECCS plant, compared to heat production from CHP plant. See Equation 6 in Section 2.2.	Uniform	Min = 1.2162 Max = 1.2534	-	Gustafsson et al (2021)
CO_2 long-term storage leakage, L_2	BECCS	Fraction of CO_2 leaking from long-term storage.	Normal	μ = 0.0050 σ = 0.0010	-	Erlandsson and Tannoury (2020)
CO_2 pipeline leakage, L_1	BECCS	Fraction of CO_2 leaking from pipeline transport.	Normal	μ = 0.00032 σ = 0.000050	-	Erlandsson and Tannoury (2020)

Electricity for CO_2 discharge from ship	BECCS		Uniform	Min = 0.10 Max = 0.13	kWh $tonne^{-1}$ CO_2	Erlandsson and Tannoury (2020)
Electricity for CO_2 liquefaction	BECCS		Uniform	Min = 110 Max = 140	kWh $tonne^{-1}$ CO_2	Erlandsson and Tannoury (2020)
Electricity for CO_2 loading to ship	BECCS		Uniform	Min = 0.099 Max = 0.12	kWh $tonne^{-1}$ CO_2	Erlandsson and Tannoury (2020)
Electricity for CO_2 storage 1	BECCS	Storage of CO_2 at power plant.	Uniform	Min = 0.0 Max = 15	kWh $tonne^{-1}$ CO_2	Erlandsson and Tannoury (2020)
Electricity for CO_2 storage 2	BECCS	Storage of CO_2 at intermediary storage.	Uniform	Min = 8.0 Max = 15	kWh $tonne^{-1}$ CO_2	Erlandsson and Tannoury (2020)
LHV woodchips (dry weight), LHV	All		Uniform	Min = 17 Max = 19	GJ $tonne^{-1}$	Azzi et al (2019)**
Power efficiency, η	CHP and BECCS	Share of electricity recovered from the combustion of the CHP plant, expressed as ratio of the LHV value. See Equation 1 in section 2.2. The electricity from the BECCS plant is further multiplied by η_{CCS}.	Normal	μ = 0.33 σ = 0.033	-	Azzi et al (2019)
Pyrolysis power-to-heat ratio, R	Biochar	The ratio of electricity of the total energy produced from the biochar plant (the rest is heat).	Uniform	Min = 0.20 Max = 0.40	-	Azzi et al (2019)

Thermal efficiency, θ	CHP and BECCS	Share of heat recovered from the combustion of the CHP plant, expressed as ratio of the LHV value. See Equation 2 in section 2.2. The electricity from the BECCS plant is further multiplied by θ_{CCS}.	Normal	μ = 0.70 σ = 0.070	-	Azzi et al (2019)
Transport distance biochar	Biochar	Transport of biochar from power plant to manufacturer of landscaping soil.	Normal	μ = 250 σ = 75	km	-
Transport distance biomass	All		Normal	μ = 500 σ = 100	km	-
Transport distance carbon dioxide	BECCS		Normal	μ = 1800 σ = 180	km	-
Transport distance soil	Biochar	Transport of landscaping soil from manufacturer to location of usage	Normal	μ = 100 σ = 10	km	-

* maximum value from source, minimum value based on assumption.

** source gave one value, range assumed based on this value.

Carbon dioxide sequestration

The amount of carbon sequestered in the Biochar system is calculated as shown in Equation 7.

$C_S = \beta \times C_{BC} \times \frac{44}{12} \times (1 - D)$ [kg CO_2 kg biomass^{-1}] Equation 7

Where C_S is the amount of carbon sequestered, β is the biochar yield, C_{BC} is the percentage of carbon in the biochar and D is the fraction of biochar decaying over 100 years. The carbon sequestration in the BECCS system is calculated as shown in Equation 8.

$C_S = C_B \times \frac{44}{12} \times C \times (1 - L_1) \times (1 - L_2)$ [kg CO_2 kg biomass^{-1}] Equation 8

where C_B is the carbon content in the biomass, C is the percentage of carbon captured from the CCS process, L_1 is the leakage from the pipeline and L_2 is the leakage from long term storage.

Reference activities

In order to account for multi-functionality, the substitution method was applied (substitution is defined as described by Heijungs et al, 2021). In order to perform this allocation, a reference system was defined consisting of reference activities. Each function delivered from the foreground system has at least one corresponding reference activity that fulfils the same function (Table 3). The emissions of the reference activities are seen as so-called avoided burdens and are subtracted from the total system impact when allocating. The reference activity of the biomass use product is leaving the biomass in the forest for continued carbon sequestration, as an alternative to harvesting the biomass. Several alternative reference activities were chosen for the electricity and heat products and the choices was defined as discrete parameters in the LCI with equal probability. These were, for electricity, production from natural gas, wind power and coal, and for heat, production from natural gas, oil and wood chips combustion. The electricity consumed by each system is modelled as the same entry in the Ecoinvent database as the reference activity for electricity production. The biochar from the pyrolysis plant is assumed to be used as a component in landscaping soil; therefore, the corresponding reference activity is the same amount of conventional landscaping soil.

2.3 Analysis of results

Climate impacts of both stand-alone systems and pairwise comparisons of systems were calculated, allowing them to be ranked according to performance. Rather than calculating impacts for a single set of parameters, global sensitivity analysis was used to generate distribution of impacts, with 460 000 iterations. These distributions were then interpreted using contribution analysis, Sobol indices, and decision trees. The analyses were conducted for each system (CHP, Biochar and BECCS) and FU (heat, electricity, biomass use and carbon sequestration), i.e. a total of eleven different scenarios to analyse and compare.

Table 3. The reference activities defined for every function delivered by the three systems studied. The reference activity for biomass use has a negative impact since carbon is being sequestered, in contrast to emitted carbon dioxide, which is the case of all other reference activities.

Function	Reference activity	Impact of reference activity	Source
Biomass use	Biomass decay in forest (no harvesting)	-89.1 kg CO_2-eq $tonne^{-1}$	Hammar et al (2019)
Electricity generated	Electricity from wind power	0.015 kg CO_2-eq kWh^{-1}	Ecoinvent
	Electricity from natural gas	0.750 kg CO_2-eq kWh^{-1}	Ecoinvent
	Electricity from coal	1.10 kg CO_2-eq kWh^{-1}	Ecoinvent
Heat produced	Heat from woodchips	0.011 kg CO_2-eq MJ^{-1}	Ecoinvent
	Heat from natural gas	0.070 kg CO_2-eq MJ^{-1}	Ecoinvent
	Heat from oil	0.093 kg CO_2-eq MJ^{-1}	Ecoinvent
Landscaping soil	Conventional landscaping soil	84 kg CO_2-eq $(m^3)^{-1}$	Azzi et al (2022)

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Contribution analysis

In order to identify which parts of the life cycle contributes to a relatively high share of the total impact, i.e. hot-spots, a contribution analysis was performed across the distribution of impacts. Here, the total impact was divided into the following groups: carbon sequestration (only for CDR systems), supply chain emissions (all impacts which are not part of the other groups), avoided burdens due to substitutions for heat and electricity production (one group for each), avoided burdens due to biochar use (only for Biochar system) and additional impacts due to the reference biomass use (see Table 3). Separating the avoided burdens due to substitutions and permanent carbon sequestration allows for a distinction between avoided emissions and actual negative emissions, as recommended by Terlouw et al (2021).

Pairwise comparison

When conducting a comparative LCA, it is of specific interest to calculate the differences of impacts when comparing two systems. These differences were calculated for each computation of impacts, i.e. with the same parameter values for both systems, and for each FU the systems have in common. Based on these differences, the number of computations for which each system had a lower impact, and was therefore preferable from a climate mitigation perspective, was calculated.

Sobol indices

Sobol indices are suitable to use for sensitivity analysis of complex environmental models with high number of parameters (Nossent et al, 2011) in order to determine the variance contribution for the parameters. If Y is the output of a system which depends on several parameters, then the Sobol index of the first order for parameter i, S_i, is defined according to Equation 9:

$$S_i = \frac{V_i}{V(Y)} \qquad \text{Equation 9}$$

where V_i is the variance in Y due to uncertainty for i, and $V(Y)$ is the variation of the output Y (Nossent et al, 2011). The sum of all Sobol indices is 1, taking into account the total variability and all indices of all orders (Sobol 2001).

In this framework, Sobol indices can be computed for the parameters in order to determine the contribution to the variance of the result for single parameters as well as interactions of multiple parameters. This is especially useful for parameters which are defined according to a continuous uncertainty distribution since the number of combinations to analyse is infinite. Sobol indices can be computed for the choice of reference activities as well (if they have been defined as parameters, as described before). Sobol indices were calculated for all single scenarios, but also for the algebraic expressions of the differences in impacts from the pairwise comparisons. Only Sobol indices of the first order were calculated. i.e. only the contributions of single parameters were taken into account and interactions of multiple parameters were excluded (Sobol, 2001). Sobol indices of higher order were not deemed relevant as all sums of Sobol indices of the first order were close to 1 (between 0.84-0.99; see Table 4 and Table 5), meaning that the majority of the variance could be attributed to single parameters.

Decision trees

Lastly, based on the results from the pairwise comparison, decision trees were generated for comparisons where the results were ambiguous, i.e. when it is unclear which system is (generally) preferable. Decision trees are used to classify data according to known attributes and predefined classes (Quinlan, 1993). Generated decision trees are visualised as top-down flowcharts, where each so-called *decision node* represents a test for a given attribute on the data, dividing the data into several branches. Decision trees in this study were generated in order to identify the parameter values which are most influential when calculating the difference between two systems. In other words, to identify the system configurations where one system is preferable over the other. In order to generate the decision trees, the Scikit-learn Python module was used (Pedregosa et al, 2011).

3 Results

3.1 Stand-alone climate impact distributions and contribution analysis

The total impacts of the CDR systems were always negative, i.e. the avoided emissions and carbon sequestrations outweighed the positive emissions from the systems (Figure 2). The CHP system had net positive emissions in some cases where the electricity reference activity was wind power, or when the heat reference activity was wood chips, i.e. when the energy reference activity/activities had a relatively low climate impact. Otherwise, the total impact of the CHP system was negative, meaning that the avoided emissions were larger than the positive emissions. For both CDR systems, carbon sequestration contributed significantly to the total impact, especially for the BECCS system, where the relative contribution from carbon sequestration varied across the distribution and was the biggest contributor when the impact was relatively high. For the Biochar system, the reference activity for biochar usage was a significant contributor across the entire distribution (Figure 2b, 2e, 2h, 2j). The substitutions for electricity and heat were in general dominant contributors to the total impact, and their contribution increased drastically with a lower impact, meaning that the avoided burdens were the main reasons for the low, negative impacts. The contribution of other sources of emissions, such as supply chain impact, and substitution for biomass use, were more constant (relative to each other), regardless of their variance.

For all distributions, a high total impact was always coupled with an energy system with a low climate impact (wind power and/or woodchips) and the lowest total impact occurred in an energy setting with a high climate impact (oil and/or coal). This is expected since a high impact energy reference system results in a larger impact being subtracted from the total impact of the foreground system.

The Sobol indices for each system and FU (Table 4) indicated that much of the variance in the distributions is due to the differences in impacts for the multiple energy reference activities. In fact, for nine out of eleven scenarios most of the variance in results could be attributed to these parameters. These nine scenarios include all three CHP scenarios. For the Biochar system, the parameters biochar decay, biochar yield and power-to-heat ratio also had high contribution to variance. The parameters which had high contribution to variance for the BECCS system were the electricity percentage for CCS and the percentage of carbon captured. Some parameters did not significantly affect the variance of the results of any system or FU, for example the transport distances.

3.2 Pairwise comparisons of climate impact

When the systems were compared pairwise for every FU it became clear that the preferred system depended on the FU (Figure 3). When the CDR systems were compared to the reference system (CHP), the CDR systems were preferable for the majority of cases. However, the CHP scenario scored somewhat better when compared to the BECCS system with heat as FU (preferable in 25.9% of all cases) and compared to the Biochar system with biomass as FU (preferable in 39.7% of all cases). For all other FUs and pairwise comparisons involving the CHP system, it was preferable in less than 1% of all cases. In fact, when compared to the BECCS system with electricity as FU, CHP was the least preferable system for all computed scenarios.

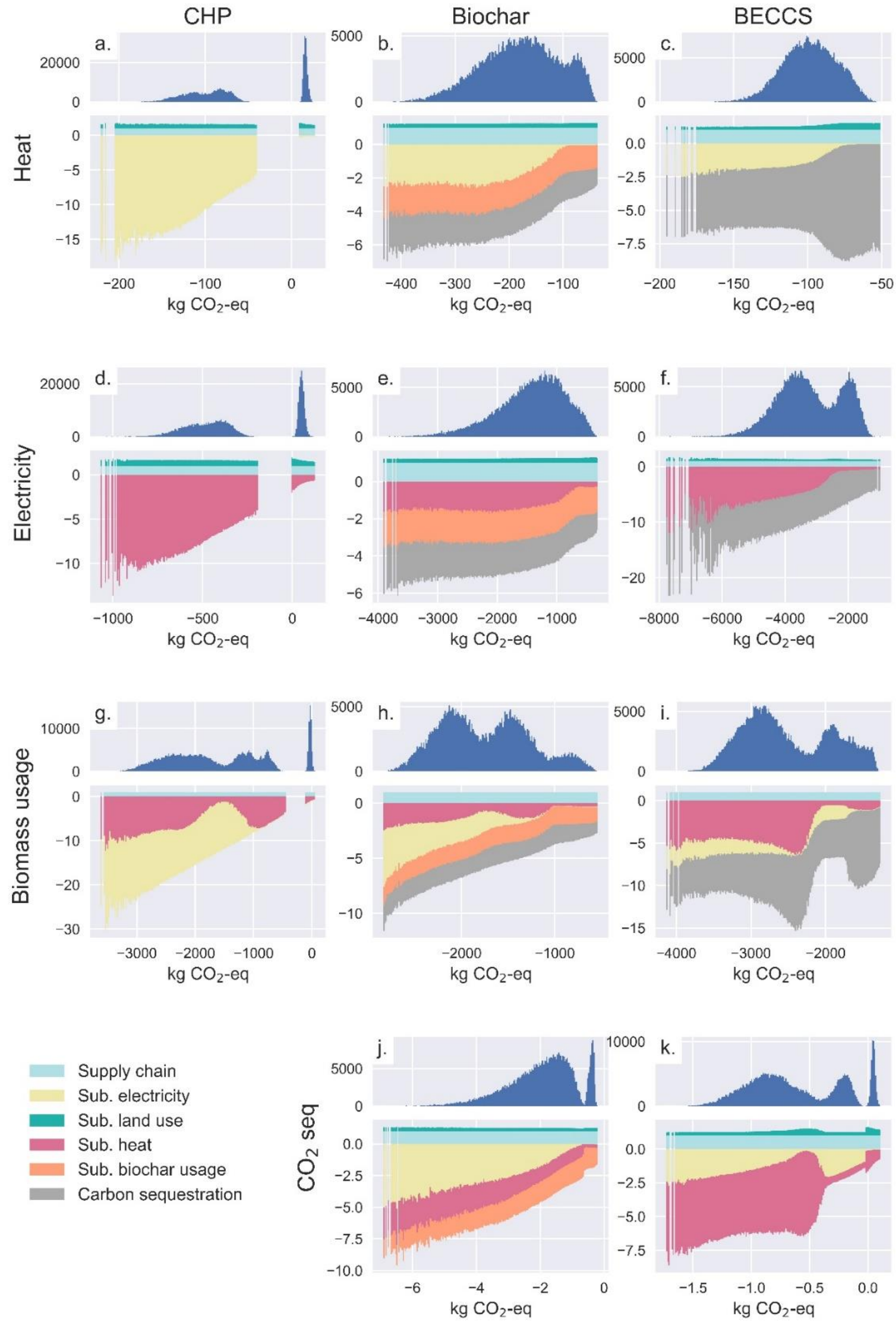

Figure 2. Contribution analysis. For each scenario a-k (every system and applicable functional unit (FU)) the distribution of climate impacts is shown in the upper half, and the relative contribution to the total impact for each category of emissions in the lower half. The contributions are normalised to the supply chain emissions with supply chain emissions = 1. The x-axis shows the climate impact, expressed in kg CO_2-eq, and is the same scale for the upper and lower part of each graph. The specific system configurations corresponding to each graph are as follows: a) CHP, heat as FU, b) BC, heat as FU, c) – BECCS, heat as FU, d) – CHP, electricity as FU, e) BC, electricity as FU, f) BECCS, electricity as FU, g) CHP, biomass usage as FU, h) BC, biomass usage as FU, i) BECCS, biomass usage as FU, j) BC, carbon sequestration as FU, k) BECCS, carbon sequestration as FU.

Comparing the CDR systems to each other, the preferable system shifted with the choice of FU (Figure 3). The BECCS system was preferable over the Biochar system with electricity generation or biomass usage as FU (preferable for 98.7% and 97% of all scenarios, respectively), while the Biochar system was preferable when the FU was heat generated or carbon sequestered (performs better for 89% and 99.7% of all scenarios, respectively).

For the Sobol indices calculated for the differences in results (Table 5), the choice of background energy system again significantly affected the results, though it seemed in general somewhat less than for single systems. The differences in impacts involving the biochar system also had relatively high contribution to variance from the parameters biochar decay, biochar yield and power-to-heat ratio.

For the cases of pairwise comparison where it was ambiguous which system performed better, the sensitive parameters were identified with decision tree analysis. In the case where the Biochar system and CHP were compared with biomass as FU (Figure 3g), the Biochar system was preferable for 99.8% of all cases if the reference electricity supply was wind power (Figure S2). When comparing BECCS to the CHP system with heat as FU (Figure 3b), BECCS was preferable for most cases (99.3%) if the reference electricity supply was wind power or natural gas (Figure S3). Lastly, comparing BECCS to the Biochar system with heat as FU (Figure 3c), the Biochar system was preferable for 99.1% of all cases when the reference electricity supply was natural gas or coal (Figure S4).

Table 4. Sobol indices of the first order for the calculated impacts of each system and each functional unit (FU). These Sobol indices express the contribution of a single parameter to the total variance of the result. The three highest values of Sobol indices are marked in bold, in each column. If the parameter was not present in the algebraic expression of the impact, the corresponding Sobol index is marked with '-'. Parameters which had the value of zero as Sobol index for all scenarios are not represented in the table.

FU	**Heat**			**Electricity**			**Biomass use**			**CO_2 seq.**	
System	CHP	Biochar	BECCS	CHP	Biochar	BECCS	CHP	Biochar	BECCS	Biochar	BECCS
Parameter name											
Biochar decay, D	-	0.04	-	-	0.05	-	-	**0.04**	-	0.10	-
Biochar yield, β	-	**0.23**	-	-	**0.28**	-	-	0.00	-	**0.16**	-
Carbon capture percentage, C	-	-	**0.12**	-	-	0.02	-	-	**0.03**	-	**0.02**
CCS electricity efficiency, η_{CCS}	-	-	0.02	-	-	**0.09**	-	-	0.00	-	0.00
Electricity source	**0.95**	**0.54**	**0.49**	0.00	0.00	0.02	**0.71**	**0.62**	**0.11**	**0.44**	**0.11**
Heat source	-	-	-	**0.94**	**0.29**	**0.71**	**0.26**	**0.27**	**0.81**	**0.19**	**0.81**
LHV woodchips, LHV	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Power efficiency, η	**0.02**	-	0.02	**0.02**	-	**0.11**	**0.01**	-	0.00	-	0.00
Pyrolysis power-to-heat ratio, R	-	**0.16**	-	-	**0.34**	-	-	0.02	-	0.01	-
Thermal efficiency, θ	**0.01**	-	**0.30**	**0.03**	-	0.02	**0.01**	-	0.02	-	**0.02**
Sum	0.98	0.97	0.97	0.99	0.96	0.97	0.99	0.95	0.97	0.90	0.96

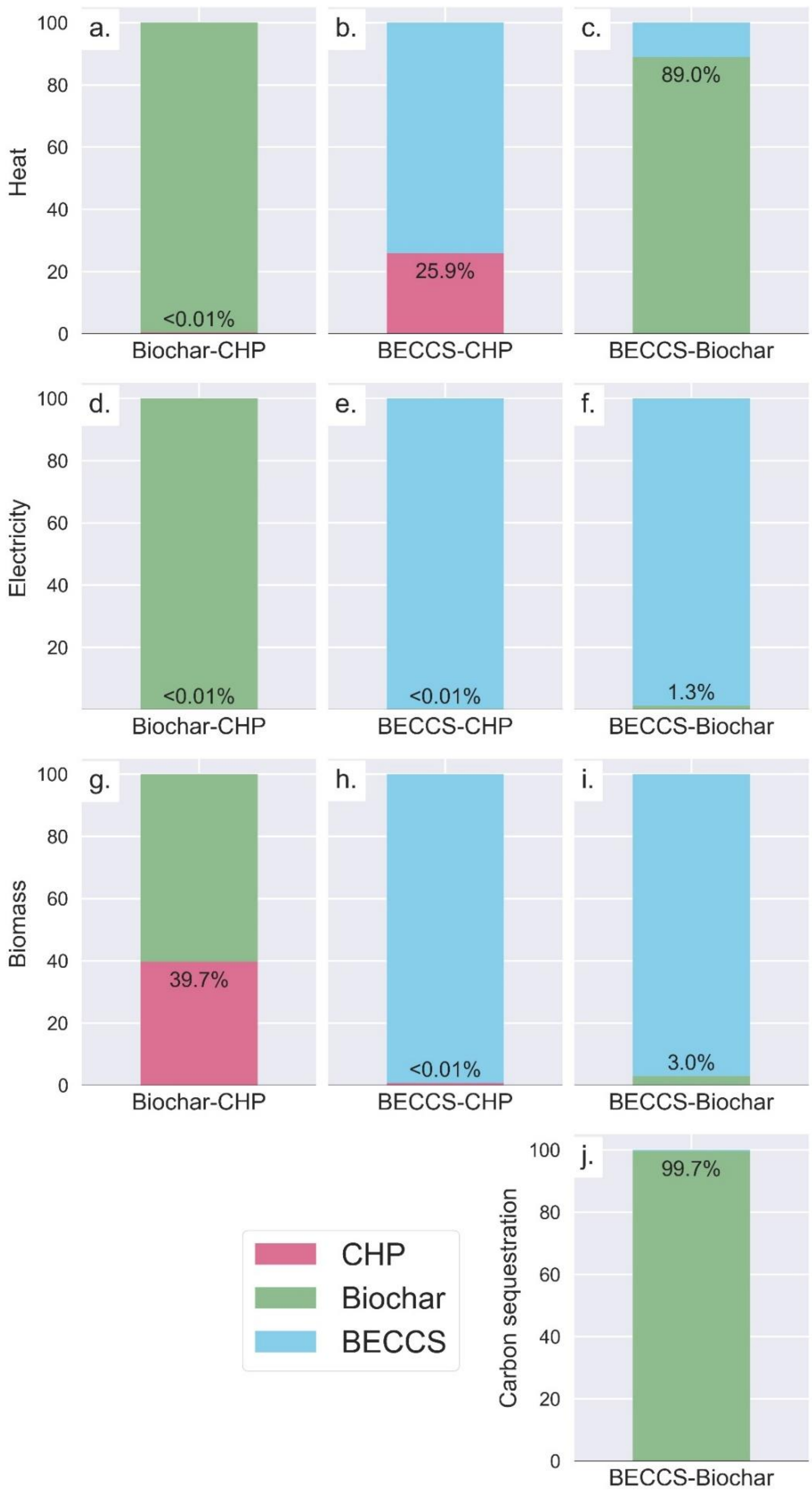

Figure 3. Pairwise comparisons of systems and scenarios, showing the share of computations for which each system (BECCS, biochar or CHP) has a lower climate impact than the other, for each functional unit (heat, electricity, biomass or carbon sequestration).

Table 5. Sobol indices of the first order for the calculated differences in impacts for each pair of systems and each functional unit (FU). The three highest values of Sobol indices are marked in bold, for each case. If the parameter was not present in the algebraic expression of the impact, the corresponding Sobol index is marked with '-'. Parameters with zero as Sobol index for all differences are not represented in the table.

FU	**Heat**			**Electricity**			**Biomass use**			**CO_2 seq.**
Systems compared	Biochar vs CHP	BECCS vs CHP	BECCS vs Biochar	Biochar vs CHP	BECCS vs CHP	BECCS vs Biochar	Biochar vs CHP	BECCS vs CHP	BECCS vs Biochar	BECCS vs Biochar
Parameter name										
Biochar decay, D	**0.07**	-	0.05	**0.06**	-	0.02	**0.05**	-	**0.06**	**0.15**
Biochar yield, β	**0.45**	-	**0.28**	**0.38**	-	0.11	0.00	-	0.00	**0.24**
Carbon capture percentage, C	-	**0.02**	0.01	-	0.04	0.03	-	**0.03**	**0.06**	0.00
CCS electricity efficiency, η_{CCS}	-	0.00	0.00	-	**0.16**	0.12	-	0.00	0.01	0.00
Electricity source	0.01	**0.93**	**0.38**	0.00	0.03	0.02	**0.58**	**0.90**	**0.19**	**0.42**
Heat source	-	-	-	0.01	**0.57**	**0.36**	**0.17**	**0.03**	**0.50**	0.01
LHV woodchips, LHV	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.01	0.00
Power efficiency, η	0.02	**0.01**	0.00	0.00	**0.15**	**0.13**	**0.06**	**0.01**	0.01	0.00
Pyrolysis power-to-heat ratio, R	**0.31**	-	**0.20**	**0.47**	-	**0.14**	0.02	-	0.03	0.02
Thermal efficiency, θ	0.02	**0.01**	0.02	0.01	0.02	0.03	0.03	0.00	0.05	0.01
Sum	0.88	0.97	0.94	0.93	0.98	0.96	0.93	0.97	0.92	0.85

4 Discussion

4.1 Interpretation of results

In general, both CDR systems have a lower climate impact than the CHP system, since the clear majority of computations of pairwise comparisons were in favour of the CDR systems. However, there were also system configurations where the CHP system scored better. These were primarily settings when the background energy system had high climate impact due to combustion of fossil fuels, so the climate benefit of the higher fossil fuel replacement caused by the higher energy efficiency of the CHP outweighed the climate benefits of CDR.

Biomass as FU may be used in order to assess how biomass resources are most efficiently used for climate change mitigation (Ahlgren et al, 2015). Assessing the most efficient use of biomass is of clear interest as the demand of biomass will increase in a future transition from fossil fuels to biofuels (Berndes et al, 2016). This is especially important in contexts where biomass or land are limited resources. BECCS was preferable to both Biochar and CHP with biomass as FU (Figure 3), indicating that it is a more climate-efficient use of biomass.

With electricity or heat as FU, the results of an LCA can be used to identify a system which provide electricity and heat, respectively, with a relatively low climate impact. Electricity with low climate impact is of importance when planning the national electricity supply, which is of particular interest for energy prospects that include both a growing demand for electricity and a simultaneous phase-out of fossil fuels (Luderer et al, 2022). Producing heat with low climate impact is relevant when the aim of the plant is to supply heat, e.g. for industrial or district heat systems. This is a critical question especially for countries situated in colder climates, with a large demand for heat.

Using carbon sequestration as FU can be relevant when CDR is in focus and to make sure that the accomplished negative emissions are not outweighed by supply chain emissions (i.e. the total net emissions are negative). Terlouw et al (2021) finds carbon sequestration as an appropriate FU when comparing different CDR systems to each other. Choosing between and comparing different CDR systems are relevant questions when designing future climate pathways including CDR techniques to reach climate goals (Fuss et al, 2018).

The ranking between the CDR systems depended on the FU. This means that when deciding which CDR system to implement, the better choice will be different depending on which indicator is of most interest. In our analysis, Biochar was preferable to BECCS when CDR was a FU (Figure 3), indicating that the supply chain and side-effects of Biochar have more climate benefits than those of BECCS. Furthermore, Biochar always yielded negative climate impacts and BECCS impacts were negative or close to zero, showing that most configurations of both of these CDR technologies have overall beneficial climate effects, considering their total lifecycle impact.

The results allow for a general conclusion to be drawn regarding whether the CHP or the CDR systems in question are preferable, since both CDR systems were preferable in most systems constellations (though not all) across all FUs. However, when attempting to compare the CDR systems, the preferable system varies depending on FU, making it difficult to rank them according to climate impact. It seems, as illustrated in the review by Terlouw et al (2021), that most LCAs applied to Biochar and BECCS systems only consider one FU. This study has shown that an analysis based on one FU is not sufficient when considering the climate impact of these systems when the purpose is to make a general comparison.

4.2 Limitations

In this study, we only analysed systems with biomass with low climate impact, assuming that such bioenergy systems are the primary interest from a policy perspective. Feedstock with other climate impact may affect the (relative) performance of the systems. The BECCS system studied was a CHP system, producing both electricity and heat, as that is of most relevance from a Nordic perspective. The results are not directly applicable to bioenergy systems that produces electricity only, where heat is not considered a valuable product. Some parts of the LCI were omitted from this study, e.g. infrastructure. Side-effects such as albedo effects and indirect land use were also not considered, though they could potentially affect the result (Terlouw et al, 2021).

The analysis presented in this paper is limited to the ranges of parameters set by the authors. Other approaches and parameter definitions would lead to differences in distributions, rankings and decision tree classification rules. With a broader parameter range, several potential scenarios could be considered, but they may not be very relevant or realistic. Based on this trade-off, two different rationales can be distinguished, according to which the parameters may be defined. In Rationale 1, each parameter is given its maximum theoretical range, e.g. for biochar stability the parameter range defined would be 0 – 100%. This means that all possible scenarios are considered, even though they may be considered unreasonable. However, when defining parameters which do not have a clear maximum or minimum, such as transport distances, there is still a need to set a subjective, reasonable limit. In Rationale 2, each parameter is given a likely range in a given context, e.g. for biochar stability of a biochar with fairly good stability, the parameter range could be constrained (to e.g. 60-90%). The range can be defined by e.g. conferring with literature and defining a marginal of uncertainty. Using Rationale 1 will probably result in many calculated results being outside the scope of what is deemed realistic, but will allow to identify extreme cases and more general conclusions. Rationale 2 may result in a distribution which does not include all possible results, but is more context specific. For this study, Rationale 2 was chosen, with the implications that there may be cases of relevance for individual assessments that fall outside of the parameter ranges defined in this study and are thus not part of the analysis.

The LCA in this study only calculated the climate impacts, though naturally there are many other impact categories which are of interest when assessing the environmental performance of a system. To include additional impact categories or even decision-making tools could also clarify which system is preferable in general, though subsequently this would entail an assessment of several criteria instead of just one. This study focused on the climate impact since it is a crucial impact category for energy systems and CDR technologies.

For bioenergy systems, it is of particular interest to look into how much biomass is used, since biomass is in competition with other forms of land-use, for example agriculture. In this study, for all FUs that were not biomass use, the systems were penalised by a higher use of biomass since the reference activity was carbon sequestration from biomass decay in forests (see Table 3), which has a negative impact, meaning that using biomass resulted in a higher total climate impact. Even if there is a net negative impact from a system with biomass as FU, i.e. a climate benefit for each tonne biomass consumed, biomass is still a limited resource and therefore there are constraints on the amount of biomass which can be used. In other words, there are sustainable and non-sustainable ways to produce and harvest biomass, depending on the type and amounts of biomass being extracted. This resource limitation is not reflected in an LCA, a tool which assumes linear relationships between resource use and environmental impact, and does not take into account e.g. the concept of tipping points (cf Rockström et al, 2009).

Harvesting biomass is thus subject to several sustainability issues, including and beyond climate impact. Therefore, an interesting indicator to look into is the amount of biomass used for each unit of product, e.g. kg of biomass per kWh of electricity. The BECCS system will produce more heat but less electricity than the CHP system per kg biomass (as can be seen in Equations 1, 2, 5, and 6, and the fact that the parameter η_{CCS} is always lower than 1, and parameter θ_{CCS} is always higher than 1). Hence, in a local scenario where biomass is a limited resource, either BECCS or CHP will be the most suitable systems to implement, depending on whether the product of particular interest is heat or electricity. The amount of biomass required for producing electricity will vary with the parameters defined. Still, when the mean and median values for the amount of biomass required for producing 1 MWh of electricity are compared for all three systems (Table S3), BECCS requires the highest amount of biomass and CHP the lowest (less than half of the BECCS system). For production of 1 GJ of heat, Biochar requires the highest amount of biomass and BECCS the lowest (about half of the Biochar system). Lastly, for 1 kg of sequestration of carbon, the Biochar system requires about three times the amount of biomass when compared to the BECCS system.

5 Conclusions

In a large majority of analysed scenarios, the CDR systems were preferable over the reference CHP system, but the preferable CDR system depended on the choice of FU. The Biochar system was preferable for heat and carbon sequestration as FUs, while the BECCS system was preferable for FUs electricity and biomass use. This finding indicates that when conducting a comparative LCA for multifunctional systems, the choice of FU is important and must be chosen to suit the purpose of the LCA. In the case of bioenergy with CDR, the choice of FU is related to the views on the use of limited biomass resources, the role of bioenergy in the energy system and the role of CDR in climate change mitigation.

Due to the multifunctionality of systems, the substitution method was used to take into account and give credit for all products delivered by the systems. The parameters which contributed the most to variance, both for single systems and pairwise comparisons of scenarios, were the parameters for heat and electricity reference activities. This is because there is a large difference in climate impact between the alternative background energy supplies that were modelled. Decision tree analysis showed that the CDR systems performed better than the CHP system particularly in an energy setting with low climate impact electricity supply. Parametrisation of the systems allowed for a more generalised analysis than conventional LCA practice, although parameter ranges should be clearly motivated. In addition, presenting climate impact results with contributions (e.g. carbon storage, supply-chain emissions, substitutions) rather than just a net score is important to understand the composition of the climate change impact of multifunctional CDR systems.

Data availability statement

Additional data is given upon request. The code and supplementary material is available online at github.com/SLU-biochar/Bioenergy-CDR-LCA.

Conflict of interest

Author Elias Azzi is currently hired as a consultant for Puro.earth.

References

Ahlgren, S., Björklund, A., Ekman, A., Karlsson, H., Berlin, J., Börjesson, P., Ekvall, T., Finnveden, G., Janssen, M., and Strid, I. 2015. Review of methodological choices in LCA of biorefinery systems - key issues and recommendations. *Biofuels Bioprod. Biorefin.*, *9*, 606–619. https://doi.org/10.1002/bbb.1563

Azzi, E.S., Karltun, E., and Sundberg, C. 2019. Prospective life cycle assessment of large-scale biochar production and use for negative emissions in Stockholm. *Environ. Sci. Technol.*, 53(14), 8466–8476. https://doi.org/10.1021/acs.est.9b01615

Azzi, E.S., Karltun, E., and Sundberg, C. 2022. Life cycle assessment of urban uses of biochar and case study in Uppsala, Sweden. *Biochar*, 4(18). https://doi.org/10.1007/s42773-022-00144-3

Berndes, G., Abt, B., Asikainen, A., Cowie, A., Dale, V., Egnell, G., Lindner, M., Marelli, L., Paré, D., Pingoud, K., and Yeh, S. 2016. Forest biomass, carbon neutrality and climate change mitigation. *Sci. Policy*, 3. European Forest Institute. https://doi.org/10.36333/fs03

Brander, M., Ascui, F., Scott, V., and Tett, S. 2021. Carbon accounting for negative emissions technologies. *Clim. Policy*, 21(5), 699-717. https://doi.org/10.1080/14693062.2021.1878009

Cherubini, F. and Strømman, A. H. 2011. Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresour. Technol.*, 102(2), 437–451. https://doi.org/10.1016/j.biortech.2010.08.010

Erlandsson, J., and Tannoury, F. 2020. *Climate Footprint of Transportation and Storage of Carbon Dioxide (CO_2).*

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S., Aragão, L. E. O. C., Arneth, A., Arora, V., Bates, N. R., Becker, M., Benoit-Cattin, A., Bittig, H.C., Bopp, L., Bultan, S., Chandra, N., Chevallier, F., Chini, L.P., Evans, W., Florentie, L., Forster, P.M., Gasser, T., Gehlen, M., Gilfillan, D., Gkritzalis, T., Gregor, L., Gruber, N., Harris, I., Hartung, K., Haverd, V., Houghton, R.A., Ilyina, T., Jain, A.K., Joetzjer, E., Kadono, K., Kato, E., Kitidis, V., Korsbakken, J.I., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Liu, Z., Lombardozzi, D., Marland, G., Metzl, N., Munro, D.R., Nabel, J.E.M.S., Nakaoka, S.I., Niwa, Y., O'Brien, K., Ono, T., Palmer, P.I., Pierrot, D., Poulter, B., Resplandy, L., Robertson, E., Rödenbeck, C., Schwinger, J., Séférian, R., Skjelvan, I., Smith, A.J.P., Sutton, A.J., Tanhua, T., Tans, P.P., Tian, H., Tilbrook, B., Van De Werf, G., Vuichard, N., Walker, A.P., Wanninkhof, R., Watson, A.J., Willis, D., Wiltshire, A.J., Yuan, W., Yue, X., and Zaehle, S. 2020. Global Carbon Budget 2020. *Earth Syst. Sci. Data*, 12(4), 3269–3340. https://doi.org/10.5194/essd-12-3269-2020

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. V., Wilcox, J., Del Mar Zamora Dominguez, M., and Minx, J. C. 2018. Negative emissions - Part 2: Costs, potentials and side effects. *Environ. Res. Lett.*, 13(6). https://doi.org/10.1088/1748-9326/aabf9f

Gustafsson, K., Sadegh-Vaziri, R., Grönkvist, S., Levihn, F., and Sundberg, C. 2021. BECCS with combined heat and power: assessing the energy penalty. *Int. J. Greenh. Gas Control*, 110, 103434. https://doi.org/10.1016/j.ijggc.2021.103434

Hammar, T., Stendahl, J., Sundberg, C., Holmström, H., and Hansson, P. A. 2019. Climate impact and energy efficiency of woody bioenergy systems from a landscape perspective. *Biomass Bioenergy*, 120, 189–199. https://doi.org/10.1016/j.biombioe.2018.11.026

Heijungs, R., Allacker, K., Benetto, E., Brandão, M., Guinée, J., Schaubroeck, S., Schaubroeck, T., and Zamagni, A. 2021. System Expansion and Substitution in LCA: A Lost Opportunity of ISO 14044 Amendment 2. *Front. Sustain*. 2:692055. https://doi.org/10.3389/frsus.2021.692055

IPCC. 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Jolivet, R., Clavreul, J., Brière, R. Besseau, R., Prieur Vernat, A., Sauze, M., Blanc, I., Douziech, M., and Pérez-López, P. 2021. lca_algebraic: a library bringing symbolic calculus to LCA for comprehensive sensitivity analysis. *Int J Life Cycle Assess*, 26, 2457–2471. https://doi.org/10.1007/s11367-021-01993-z

Kemper, J. 2015. Biomass and carbon dioxide capture and storage: A review. *Int. J. Greenh. Gas Control*, 40, 401-430. https://doi.org/10.1016/j.ijggc.2015.06.012

Koponen, K., Soimakallio, S., Kline, K.L., Cowie, A., Brandão, M. 2018. Quantifying the climate effects of bioenergy – Choice of reference system. *Renew. Sustain. Energy Rev.*, 81(2), 2271-2280. https://doi.org/10.1016/j.rser.2017.05.292

Levihn, F., Linde, L., Gustafsson, K., and Dahlen E. 2019. Introducing BECCS through HPC to the research agenda: The case of combined heat and power in Stockholm. *Energy Rep.*, 5, 1381-1389. https://doi.org/10.1016/j.egyr.2019.09.018

Luderer, G., Madeddu, S., Merfort, L. Ueckerdt, F., Pehl, M., Pietzcker, R., Rottoli, M., Schreyer, F., Bauer, N., Baumstark, L., Bertram, C., Dirnaichner, A., Humpenöder, F., Levesque, A., Popp, A., Rodrigues, R., Strefler, J., and Kriegler, E. 2022. Impact of declining renewable energy costs on electrification in low-emission scenarios. *Nat. Energy*, 7, 32–42. https://doi.org/10.1038/s41560-021-00937-z

Matuštík, J., Hnátková, T., and Kočí, V. 2020. Life cycle assessment of biochar-to-soil systems: A review. *J. Clean. Prod.*, 259, 120998. https://doi.org/10.1016/j.jclepro.2020.120998

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., and Del Mar Zamora Dominguez, M. 2018. Negative emissions - Part 1: Research landscape and synthesis. *Environ. Res. Lett.*, 13(6). https://doi.org/10.1088/1748-9326/aabf9b

Mutel, C. 2017. Brightway: An open source framework for Life Cycle Assessment. *J. Open Source Softw.*, 2(12), 236. https://doi.org/10.21105/joss.00236

Nossent, J., Elsen, P., and Bauwens, W. 2011. Sobol' sensitivity analysis of a complex environmental model. *Environ. Model. Softw.*, 26(12), 1515-1525. https://doi.org/10.1016/j.envsoft.2011.08.010

Oni, B.A., Oziegbe, O., and Olawole, O.O. 2019. Significance of biochar application to the environment and economy. *Ann. Agric. Sci.*, 64, 222-236. https://doi.org/10.1016/j.aoas.2019.12.006

Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., Cournapeau, D., Brucher, M., Perrot, M., and Duchesnay, É. 2011. Scikit-learn: Machine Learning in Python. *J Mach. Learn. Res.*, 12, 2825-2830.

Quinlan, J.R. 1993. *C4.5: Programs for Machine Learning*, Morgan Kaufmann, San Mateo, CA.

Rockström, J., Steffen, W., Noone, K. Persson, Å., Chapin III, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., and Foley, J.A. 2009. A safe operating space for humanity. *Nature*, 461, 472–475. https://doi.org/10.1038/461472a

Sakhiya, A.K., Anand, A., and Kaushal, P. 2020. Production, activation, and applications of biochar in recent times. *Biochar*, 2**,** 253–285. https://doi.org/10.1007/s42773-020-00047-1

Sobol, I.M. 2001. Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. *Math. Comput. Simul.*, 55(1-3), 271-280. https://doi.org/10.1016/S0378-4754(00)00270-6

Spokas, K.A. 2010. Review of the stability of biochar in soils: predictability of O:C molar ratios. *Carbon Manag.*, 1(2), 289-303. https://doi.org/10.4155/cmt.10.32

Steubing, B., de Koning, D., Haas, A., and Mutel, C. L. 2020. The Activity Browser — An open source LCA software building on top of the brightway framework. *Softw. Impacts*, 3, 100112. https://doi.org/10.1016/j.simpa.2019.100012

Tanzer, S.E., and Ramírez, A. 2019. When are negative emissions negative emissions? *Energy Environ. Sci.*, *12*, 1210-1218. https://doi.org/10.1039/C8EE03338B

Terlouw, T., Bauer, C., Rosa, L., and Mazzotti, M. 2021. Life cycle assessment of carbon dioxide removal technologies: a critical review. *Energy Environ. Sci.*, 1701–1721. https://doi.org/10.1039/d0ee03757e

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B. 2016. The ecoinvent database version 3 (part I): overview and methodology. *Int J Life Cycle Assess*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Woolf, D., Amonette, J., Street-Perrott, F., Lehmann, J., and Joseph, S. 2010. Sustainable biochar to mitigate global climate change. *Nat. Commun.*, 1, 56. https://doi.org/10.1038/ncomms1053

Woolf, D., Lehmann, J., Ogle, S., Kishimoto-Mo, A.W., McConkey, B., and Baldock, J. 2021. Greenhouse Gas Inventory Model for Biochar Additions to Soil. *Environ. Sci. Technol.*, 55, 14795−14805. https://doi.org/10.1021/acs.est.1c02425