Life Cycle Assessment of Biochar to Soil Systems: A Parametric Analysis

Master Thesis

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Abstract

Carbon dioxide removal is needed in all scenarios from the Intergovernmental Panel on Climate Change (IPCC) to keep global warming under 1.5°C in 2100. The application of biochar to soil is one possible option for carbon dioxide removal. Biochar to soil systems carbon dioxide removal potential depends on various factors such as feedstock and production process temperature. Therefore, a parametric analysis is necessary. Life cycle assessments of biochar to soil systems in literature normally focus on specific cases but a parametric analysis with a tool that allows the user to choose the inputs has been missing. Therefore, in this thesis, a tool was made to calculate the life cycle assessment results of biochar produced via slow pyrolysis and applied to mineral soil based on various user inputs for various impact categories. Pyrolysis gas and tar, which are by-products of the biochar production process, were assumed to be burned in a combined heat and power plant to produce electricity and heat. The electricity and heat not used by the pyrolysis process are considered, applying a substitution approach, as avoided electricity and heat production.

The climate change potential (GWP100) results were analysed for a variety of cases to see the contribution of each process and to see the effect of pyrolysis process temperature, different feedstocks and the type of avoided electricity and heat. For all cases, the climate change potential was negative (positive climate change abatement potential) but the range was from -1771 kg CO_2eq (96% CDR) to -6658 kg CO_2eq (35% CDR) per tonne biochar applied to soil. The negative climate change potential is partly avoided emissions due to avoided electricity and heat production, and partly carbon dioxide removal because of biochar application to soil. The negative climate change potential is therefore heavily influenced by the type of heat and electricity being replaced. In a sensitivity analysis, the results were found to be most sensitive to pyrolysis process temperature when the avoided heat and electricity were from natural gas. However, when the avoided heat was from wood and avoided electricity from wind, the results were most sensitive to the carbon stability factor.

Summary

Biochar is one option for carbon dioxide removal and can therefore help in the fight against the climate crisis. Biochar is a carbon-rich product made from thermal decomposition of biomass with no or limited oxygen supply. Different types of biomass can be used as inputs for the biochar production process, including different kinds of wood and straw. Biochar can be produced through various processes including slow pyrolysis, fast pyrolysis and gasification. Biochar can be applied to soil to store carbon. The biomass used for biochar production has taken up carbon dioxide during its lifetime and a part of the carbon from the biomass goes to the biochar, but biochar carbon is more stable than biomass carbon. Biochar carbon stability factor is the fraction of organic carbon in the biochar that is stable in the soil after a certain time has passed, in this thesis 100 years.

In this project, the focus is on biochar produced via slow pyrolysis and applied to mineral soil. The focus is on mineral soil since in the study by Woolf et al. (1), which gives the carbon stability factor for different conditions, it is recommended that their methodology is only used for mineral soils. In slow pyrolysis, biochar is the desired product with pyrolysis gas and bio-oil (water+tar) as by-products. The tar and pyrolysis gas are assumed to be burned in a combined heat and power plant (CHP plant) to produce electricity and heat. Part of the electricity and heat is needed for drying the feedstock and heating up the process. What is not needed by the process is considered, applying a substitution approach, as avoided electricity and heat production and its environmental impact subtracted from the system. Biochar application to soil can reduce fertiliser needs but these qualities depend on various factors such as biochar properties, soil properties and application conditions but some uncertainties remain.

Life cycle assessment is necessary to quantify the net impact on climate change and to assess the overall environmental impact of biochar to soil systems. Biochar to soil systems life cycle assessment results depend on various factors such as feedstock and

process temperature. Therefore a parametric analysis is necessary. In literature, life cycle assessments of biochar to soil systems are normally done for specific cases but a parametric analysis with a tool that allows the user to choose various inputs and calculates the life cycle assessment results has been missing. The main output of this thesis is a tool that calculates the life cycle assessment results for biochar to soil systems for a variety of impact categories based on various user inputs. The goal is to assist in further research and in decision-making regarding biochar for authorities and companies. The user inputs in the tool are the feedstock, pyrolysis process temperature, location, type of avoided heat, type of avoided electricity, transport distances, feedstock moisture content, combined heat and power plant efficiencies, soil temperature and various fertiliser inputs. In the tool, the user can choose whether to include fertiliser reduction or not. If fertiliser reduction is included, the environmental burden of the fertiliser avoided is subtracted from the environmental burden of the system.

The inputs that are location specific in the tool are avoided heat, avoided electricity if the country average electricity mix is chosen, and the avoided fertilisers. Furthermore, the transport is based on Europe as a whole and the feedstock on a specific European country that is assumed to be representative of all of Europe. This has to be taken into account if using the tool for locations outside of Europe as will be discussed in chapter 7.3.

The yields of the different products in the pyrolysis were calculated based on feedstock composition and pyrolysis temperature and by using mass balances as explained in a study by Woolf et al. (2). The composition of the biochar was found based on pyrolysis temperature and feedstock ash content, and the composition of the tar based on the feedstock composition. The energy requirements for the process are based on the moisture content of the feedstock for drying, but assumed to be constant per unit energy in the feedstock for the energy requirements besides drying. The energy content in the pyrolysis gas and tar is found and used along with the CHP plant efficiencies to find the produced electricity and heat. The avoided electricity and heat production is then found by subtracting the energy requirements of the process. The climate change impact of biochar addition to soil is calculated by multiplying the amount of biochar with the organic carbon fraction of the biochar, the carbon stability factor and a conversion factor between carbon and carbon dioxide.

The analysis in this report focuses on the climate change potential (GWP100) category. All of the cases investigated have negative climate change potential and can therefore be helpful in the fight against climate change. The negative climate change potential is partly avoided emissions because of avoided electricity and heat production, and partly carbon dioxide removal because of biochar application to soil. The results of the cases analysed in this report ranged from -1771 kg CO_2eq (96% CDR) to -6658 kg CO_2eq (35% CDR) per tonne biochar. However, in the tool, a variety of inputs can be chosen so the range of possible results is broader.

The contribution analysis showed that the factors with the highest impact on the climate change potential results were biochar application to soil and in some cases avoided heat and electricity, depending on what type of heat and electricity is replaced. Feedstock supply was normally the biggest emission factor (not for waste feedstock), followed by transport. Other emission factors had a small impact on the results. The avoided fertiliser use because of biochar application to soil also had only a minor impact on the climate change potential results for the cases analysed in this report.

To emphasise the contribution of the type of avoided heat and electricity, figure 0.1 compares the climate change potential (GWP100) results per tonne biochar applied to soil for different types of electricity and heat replaced. Here, the location chosen is Europe, the feedstock is willow and the process temperature is 500°C. Fertiliser reduction is not included. The other assumptions are described in the figure caption. The biochar to soil is shown by a separate bar in the figure to distinguish between carbon dioxide removal and avoided emissions. Furthest to the right in the figure, the avoided electricity is from coal and the avoided heat from natural gas, representing the heat and electricity combination with the highest climate change potential impact. Furthest to the left in the figure, the avoided electricity is from wind and avoided heat from wood, representing the heat and electricity combination with the lowest climate change potential impact. In the middle, the avoided electricity is from natural gas combined cycle and the avoided heat from natural gas. It can be seen that the case with avoided electricity from coal and avoided heat from natural gas has more than double the negative climate change potential of the case with avoided electricity as electricity from wind and avoided heat as heat from wood. This thereby shows how big of an effect the choice of avoided heat and electricity has. However, this difference is only in the avoided emissions but not the actual carbon dioxide removal.

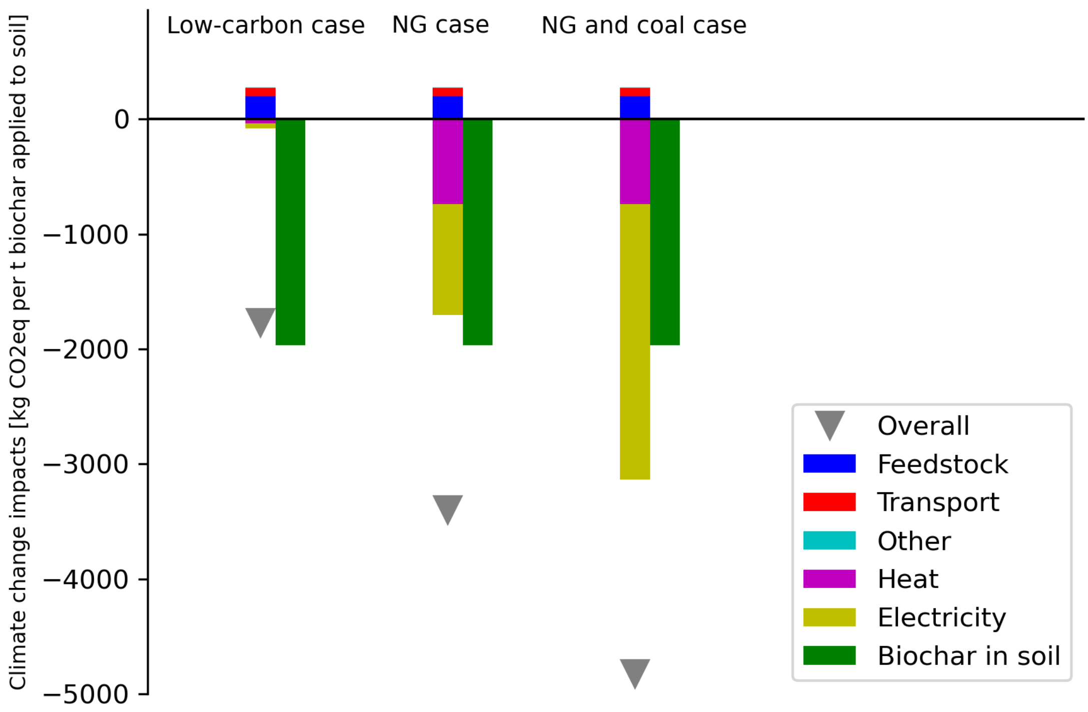

Figure 0.1: The climate change potential (GWP100) results per tonne biochar applied to soil are shown for willow for different types of avoided electricity and heat. Biochar application to soil is carbon dioxide removal and avoided heat and electricity are avoided emissions. Furthest to the right, the replaced heat is from natural gas and the replaced electricity is from coal. In the middle, the replaced heat is from natural gas and the replaced electricity from natural gas (combined cycle). Furthest to the left, the replaced heat is from wood and the replaced electricity is electricity from wind. Other parameters are as such: Pyrolysis temperature: 500°C, Location: Europe, fertiliser reduction not included, CHP efficiency (based on HHV): 22.8% to electricity, 57.2% to heat. Transport distances: feedstock to pyrolysis plant: 100 km, pyrolysis plant to farm: 100 km, farm to field: 5 km, collection point to lorry: 5km. Soil temperature: 14.9°C. Moisture content of willow (% wet basis): 40%.

Different feedstocks were compared. The waste wood feedstocks showed the most net carbon dioxide removal per tonne dry feedstock because of their high lignin content and low ash content. Waste wheat straw had the most negative climate change potential (the most climate change abatement potential) out of the compared feedstocks per tonne dry feedstock, but less energy is needed for drying in the case of waste wheat

straw than wood. The effect of the pyrolysis temperature was also investigated and it was found in the case analysed that the higher the pyrolysis temperature, the more negative the climate change potential (more climate change abatement potential).
The carbon dioxide removal factor, the fraction of carbon from the feedstock that is stable in soil 100 years after biochar application to soil, was also compared for the different feedstocks for different conditions. It was highest for rice husk out of the compared feedstocks, for pyrolysis temperature of 600°C out of the compared pyrolysis temperatures and for the lowest soil temperature investigated, 5°C.
A sensitivity analysis was conducted for two different cases. The first case had avoided electricity as electricity from natural gas combined cycle and avoided heat as heat from natural gas. The second case had avoided electricity as electricity from wind and avoided heat as heat from wood. The other parameters were the same in the two different cases. In the first case, the results were most sensitive to a change in the pyrolysis temperature out of the investigated parameters. This is since temperature affects both the amount of avoided electricity and heat and the carbon stability factor. In the second case, the results were most sensitive to a change in the carbon stability factor since the climate change impacts of the avoided heat and electricity are low in this case.
For other impact categories, there is a big difference in land use between non-waste and waste feedstocks, as expected. Therefore, this has to be carefully evaluated before biochar deployment on a large scale. Furthermore, the type of heat and electricity replaced have a big impact in all impact categories as shown in table 4.2.
Limitations to this project include that albedo change effects due to biochar application to soil are not included. Indirect land use change is not included. However, for the non-waste feedstocks, sustainable forest management processes are used for birch, oak and spruce. Furthermore, willow and miscanthus can be grown on marginal soil. Not including indirect land use change is therefore a reasonable assumption for the feedstocks in the tool. However, if using this tool for other specific cases, indirect land use change effects and carbon stock changes should be added if relevant. The yield calculations in this tool are based on the pyrolysis temperature and the properties of the feedstock (C, H, O, lignin and ash content) based on a method by Woolf et al. (2; 1) but other things such as residence time and heating rate are not taken into account. The energy requirements besides drying are based on many assumptions as will be described in chapter 3.3.4. Furthermore, the economic aspect was not

investigated. These aspects are something that would be interesting to incorporate in further research.

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Abbreviations

C	Carbon
CDR	Carbon dioxide removal
CHP plant	Combined heat and power plant
CH4	Methane
CO	Carbon monoxide
CO2	Carbon dioxide
CO2eq	Carbon dioxide equivalent
C2H2	Ethyne
DAF	Dry ash-free basis
GHG	Greenhouse gas
GWP 100	Global warming potential over 100 years
H	Hydrogen
H2	Hydrogen molecule
HHV	Higher heating value
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
LCA	Life cycle assessment
N	Nitrogen
N2O	Nitrous oxide
O	Oxygen
P	Phosphorus
UNFCCC	United Nations Framework Convention on Climate Change
wt%	weight percent

1 Introduction

The climate crisis is arguably one of the biggest challenges humankind is facing. In the context of fighting climate change, not only emission reductions are discussed but also carbon dioxide removal. The aim of the Paris Agreement, which was signed at the Conference of the Parties in 2015 (COP 15), is to limit global warming to 2°C and preferably to 1.5°C from pre-industrial times (3). In the IPCC report on global warming of 1.5°C, all scenarios to limit global warming to 1.5°C in 2100 compared to pre-industrial levels, use some carbon dioxide removal (4).

Biochar is a carbon rich product derived from the thermal decomposition of biomass under no or a limited oxygen supply (5; 6; 7). There are various types of biomass that can be used as inputs to produce biochar, including wood waste (8; 9), agricultural waste (9), manure (10), wood (11; 10; 8), food waste (5), straw (11; 8) and rice husk (11). Biochar is one option for carbon dioxide removal (12) since the biomass used to produce the biochar has taken up carbon dioxide during its lifetime and the carbon in the biochar is more stable than in the biomass (13). Biochar can be applied to soil to store carbon and is also believed to have other potential benefits for soil, including increased fertility (14). Biochar carbon stability factor is the fraction of organic carbon in the biochar that is stable in the soil after a certain time has passed (8; 1). Biochar can be produced in several production processes, including slow pyrolysis (7), fast pyrolysis (7), gasification (7; 15; 16) and torrefaction (7; 15).

In this project, the focus will be on biochar produced via slow pyrolysis and applied to mineral soil. This is done since that for slow pyrolysis, biochar is the desired product and since application to soil offers the possibility of carbon dioxide removal. In the slow pyrolysis process, pyrolysis gas and bio-oil, consisting of water and tar, are formed along with biochar (17; 7; 18). In this project, the pyrolysis gas and tar are assumed to be burned in a combined heat and power plant to produce electricity and heat.

Life cycle assessment (LCA) is a method to analyse the impacts of a product on the environment over the whole life cycle (19). It includes four steps; goal and scope definition, inventory analysis, impact assessment and interpretation (20). Biochar has been extensively studied in literature. A paper by Matustik et al. reviewed papers that had performed an LCA on biochar produced via pyrolysis and used as soil amendment (21). It is noted that comparison is hard since the papers use different system boundaries, functional units, feedstocks, locations and production conditions. However, all the papers reviewed found that biochar to soil systems were beneficial from a climate change perspective.

Life cycle assessments of biochar to soil systems most often focus on specific cases but a parametric analysis with a tool which allows the user to choose the production conditions and other parameters has been missing. To close this literature gap, a tool was made which calculates life cycle assessment results for slow pyrolysis biochar to soil systems for a variety of impact categories based on different user inputs. Furthermore, the climate change potential results are analysed to answer the question of how different input parameters affect the climate change potential results of biochar to soil systems. The inputs the user can choose include type of feedstock, pyrolysis process temperature, location and transport distances. The results were calculated for two functional units, one tonne biochar and one tonne dry feedstock.

An overview of biochar, biochar production processes, biochar applications and existing biochar studies is covered in chapter 2. The research case and the methods used, including a detailed description of the user inputs in the tool, are described in chapter 3. The results are described in chapter 4 and finally discussion and limitations in chapter 5.

2 Theoretical background

2.1 Biochar qualities and production processes

Biochar is a carbon rich product derived from the thermal decomposition of biomass under no or a limited oxygen supply (5; 6; 7). There are various types of biomass that can be used as inputs to produce biochar, including wood waste (8; 9), agricultural waste (9), manure (10), wood (11; 10; 8), food waste (5), straw (11; 8) and rice husk (11). There are a few different processes to produce biochar but these include slow pyrolysis (7), fast pyrolysis (7), gasification (7; 15; 16) and torrefaction (7; 15). An overview of the key parameters of the different processes can be seen in table 2.1.

During pyrolysis, biochar, bio-oil (water+tar) and combustible gas (mainly consisting of CO, CO_2, CH_4, and H_2) are formed (17; 7).

In slow pyrolysis, biochar is the main product but the other two are by-products while in fast pyrolysis bio-oil is the main product with the other two as by-products (7). In gasification, biochar, syngas and bio-oil are formed with the main product being syngas (16; 7).

The processes happen at different conditions. Slow and fast pyrolysis happen in the absence of oxygen (2). Slow pyrolysis happens at temperatures about 300-700°C according to Wang et al. (7), and 350-800°C according to Mohan et al[1] (23). Fast pyrolysis happens at about 350-700°C according to Wang et al. (7), 500–1000°C according to Qambrani et al. (24) and 400-600°C according to Mohan et al[2](23). Heating rate is the rate at which the temperature is increased to the process temperature and it has an effect on the yield and properties of pyrolysis products (25). Slow pyrolysis happens at a slow heating rate (<10°C/min) while fast pyrolysis happens at a very fast heating rate (about 1000°C/s) (23; 22). For fast pyrolysis, particles should be small (<3mm) but for slow pyrolysis larger particles are also fine (26). For slow pyrolysis,

[1]Taken and modified from (22)

[2]Taken and modified from (22)

the feedstock is normally put into the reactor at the beginning of the pyrolysis process while for fast pyrolysis the feedstock is put into the reactor when a certain temperature is reached (27). Gasification happens at 700-1200°C according to Wang et al. (7) and at 700-1500°C according to Mohan et al[3](23), with limited oxygen (7; 16; 23), at a moderate to very fast heating rate (23). Gasification process conditions are decided based on the goal to get maximum energy from the process (16). Torrefaction happens at 200-300°C in the absence of oxygen[4](7; 23), at a slow heating rate (23; 22). Residence time is the time which the process is held at peak temperature (11) but this can affect yield and properties of biochar (28). The residence time differs between the processes with torrefaction typically with the longest residence time, followed by slow pyrolysis, then gasification and fast pyrolysis with the shortest residence time (23; 24). Pyrolysis and gasification normally require a drying process (27). Torrefaction also needs dry biomass or a drying step (29).

According to a review by Mohan et al. (23), slow pyrolysis yields about 35% biochar (wt%), fast pyrolysis 10% and gasification 10%, and according to Qambrani et al. torrefaction about 80% (24). Slow pyrolysis yields about 30% bio-oil and 35% gas, fast pyrolysis about 70% bio-oil and 20% gas, gasification about 5% bio-oil and 85% gas (23) and torrefaction about 20% gas (24). However, these values depend on the conditions and the type of biomass feedstock (7). Therefore, this is variable. Many studies have looked at the yield from a specific process for a specific feedstock. For example, a review paper by Wang et al. (7) and a thesis by Brownsort (30) give the biochar yield for different feedstocks.

Table 2.1: Key parameters of the different biochar production processes from (7; 23; 22; 24; 16)

	Slow pyrolysis	**fast pyrolysis**	**Gasification**
Main product	biochar	bio-oil	syngas
Typical biochar yield [wt%]	35	10	10
Typical bio-oil yield [wt%]	30	70	5
Typical syngas yield [wt%]	35	20	85
Oxygen	absent	absent	limited
Temperature [°C]	300-800	350-1000	700-1500
Heating rate	slow	very fast	moderate to very fast

[3]Taken and modified from (22)
[4]Taken and modified from (22)

For slow pyrolysis, the biochar yield and quality depend on the pyrolysis conditions and the feedstock (7). With relatively high temperature, low heating rate and long residence time, biochar with higher carbon content can be obtained for slow pyrolysis (7), but the biochar quality relates closely to its carbon content (31; 32). Other things that the quality of biochar is related to is the biochar pH value, specific surface area, porosity and nutrients (7). For gasification, the quality of the biochar depends on the gasification conditions and feedstock properties with equivalence ratio as one of the most important parameters (7). Properties of biochar can be modified through chemical- (e.g. acid modification) and physical modification to better fit different applications (27).

Only a fraction, often 10-50%, of the carbon in biomass is converted to biochar (26). Carbon in biochar can be split up into labile and recalcitrant carbon, where the recalcitrant carbon can last in the soil for a long time while the labile carbon can enhance the carbon mineralization in the beginning after soil amendment with biochar (27; 33). Masek et al. found that with increasing the temperature (tested 350°C, 450°C and 550°C) in a pyrolysis process for wood pellets, mixed larch and spruce wood chips (MLS), and pine, with a residence time of 60 minutes, the fraction of the stable carbon in the biochar increased while the yield decreased. These effects together resulted in the stable carbon yield (wt%) being similar for all temperatures for MLS and pine (34). In the review paper by Qambrani et al. (24), a decreasing biochar yield with increasing temperature is also mentioned.

A study by Woolf et al. gives an empirical formula to calculate biochar yield on a dry ash-free basis based on pyrolysis process temperature and lignin content of biomass (2). Furthermore, it gives an empirical formula for the yield of gases and elemental composition (C, H, O content) of biochar based on pyrolysis temperature, and a method to calculate other yields based on mass balance. They also give a method to find tar (part of the bio-oil along with water) composition based on feedstock composition (2). This method will be discussed in detail in chapter 3.

2.2 Biochar applications

One possible application of biochar is to use it as soil amendment (35). A review paper by Kavitha et al. states that biochar's advantages for soil have been shown in many studies but they depend on the specific conditions such as biomass source, temperature and so on (35). A review paper by Wang et al. also points out that biochar advantages for soil highly depend on the conditions (7). Biochar has great potential to increase soil fertility according to a review paper by Ding et al. by being a nutrient source, by improving physical and chemical properties of the soil, by improving biological properties of the soil and by storing and slowly releasing nutrients (14). Due to this increased fertility, biochar can reduce fertiliser needs (9). However, these qualities depend on various factors such as biochar properties, soil properties and application conditions and some uncertainties remain (14). Biochar has been found to reduce N_2O emissions from soil (36; 14). Furthermore, biochar has the potential to serve as a sorbent for contaminants in water and soil (37). However, it depends on factors such as feedstock and pyrolysis conditions which contaminants can be remediated and some studies show that toxic metal mobility can increase in soil with biochar addition (37). Plants, trees and other organisms capable of photosynthesis take carbon dioxide from the atmosphere during their lifetime and when used as biomass input to produce biochar, they have the potential to remove emissions since biochar is more resistant to degradation than biomass (24). By applying biochar to soil, carbon dioxide emissions are removed by carbon storage in soil (38) but the biochar carbon is resilient to microbial decomposition due to the formation of aromatic structures during the heating process (24). The biochar stability in soil depends on many factors such as feedstock, production conditions and soil type (21). Biochar carbon stability factor is one of the most important factors in biochar potential for carbon dioxide removal. Studies use different assumptions for the carbon stability factor over 100 years, i.e. the fraction of biochar organic carbon that is still in the soil 100 years after biochar application (1). In many studies in a review paper by Matustik et al. about pyrolysis biochar to soil systems, it is assumed to be around 80% and sometimes lower (21). An article by Woolf et al. (1) gives a method to calculate the carbon stability factor based on soil temperature and either pyrolysis process temperature or the molar fraction of hydrogen to organic carbon in the biochar. In this project, values from the study by Woolf et al. (1) are used based on soil temperature and pyrolysis process temperature (1).

Biochar can also be used as an energy source (39; 40) as will be further elaborated on in chapter 2.3 and as a way of waste management (41). Organic waste releases methane when landfilled. Furthermore, anaerobic digestion of animal waste releases both methane and nitrous oxides (41). Using biochar as a waste management strategy

can therefore decrease emissions compared to these strategies (41). Biochar can also be used as an additive in composting (42; 26).
Biochar can act as a catalyst for example for bio-diesel production (27), often with certain pre-treatment (43), but as mentioned above properties of biochar can be modified through chemical- and physical modification to better fit different applications (27). A review paper by Bartioli et al. (44) mentions the possible use of biochar in battery production, for example as an anode in lithium-ion batteries. Furthermore, biochar shows potential in supercapacitor electrodes (45; 27; 44). Biochar has also been used in cement and concrete production (44). Furthermore, modified biochar can serve in the sorption of antibiotics (46). In this thesis, the focus is on biochar application to mineral soil.

2.3 Life cycle assessment of biochar

Life cycle assessment (LCA) is a method to analyse the impacts of a product on the environment over the whole life cycle (19). It includes four steps; goal and scope definition, inventory analysis, impact assessment and interpretation (20). Sometimes, a process has multiple outputs. Multi-functionality of processes can be dealt with in different ways in an LCA. One way is to use system expansion where the most likely way to produce the by-products is subtracted from the system (20). Another way is allocation, dividing the inputs and outputs between the different products, preferably using physical parameters (20).
A review paper by Matustik et al. reviewed papers that had performed a life cycle assessment (LCA) on biochar produced via pyrolysis and used as soil amendment (21). The papers reviewed used different types of biomass, different locations, different functional units, different ways of dealing with by-products and different assumptions. However, it is noted that all studies find that biochar systems are beneficial from a climate change perspective (21). Establishing some kind of unification methodology is proposed in the review article to make the different studies more comparable (21). In total 27 papers were reviewed in the article and most of the studies used system expansion to account for by-products. Regarding impact categories, 17 of the papers only assessed the climate change impact, 9 also assessed eutrophication effects and 8 acidification effects (21).

Two of the studies compared different types of feedstock. One of them is by Hammond et al. but they conducted an LCA of slow pyrolysis biochar to soil system for different feedstocks for the UK (8). Forestry residue chips showed the highest possible carbon abatement or 3.9 t CO_2eq per tonne biochar for a large-scale biochar system, followed by sawmill residues with 3.7 t CO_2eq per tonne biochar. Three different types of straws investigated all have the carbon abatement potential of 2.7 t CO_2eq per tonne biochar on a large scale (8). Other feedstocks investigated were small round wood, short rotation coppice and forestry, miscanthus and Canadian residue chips (8). System expansion was used to deal with by-products so part of the carbon abatement is from avoided electricity use and agricultural impacts (8).

In a study by Hamedani et al. (10), an LCA was conducted on biochar production by slow pyrolysis and use for soil amendment. The feedstocks investigated were willow and pig manure and the location was Belgium. They used system expansion for the syngas and bio-oil formed in the biochar production process. The syngas was assumed to be burned in a CHP plant to serve the electricity and heat requirements of the pyrolysis. Furthermore, they used system expansion for the avoided fertiliser use. Both cases investigated showed negative global warming potential (positive carbon abatement potential), -2.06 t CO_2eq per tonne biochar for willow and -0.472 t CO_2eq per tonne biochar for manure. The biggest part of the negative climate change potential was due to biochar application to soil (10). The categories showing the worst effect on environmental impacts after normalization for the willow case were land occupation (land use for willow production) and terrestrial ecotoxicity (mainly from fertiliser and agricultural machinery in willow production). For manure, the worst effect on environmental impacts after normalization was from non-renewable energy, mainly due to the drying needed before pyrolysis. For the willow case, only 12% of the produced electricity from the syngas was needed for the pyrolysis but extra heat was needed since the heat produced from the syngas covered only 73% of the need (10).

Ibarrola et al. conducted a life cycle assessment to compare biochar to soil systems from different biodegradable waste and residues for slow pyrolysis, fast pyrolysis and gasification (47). They found that slow pyrolysis had the best performance in terms of emission reduction/abatement. For slow pyrolysis, the storage of carbon plays the biggest role in the environmental benefits since the biochar yield is the highest. For fast pyrolysis and gasification, the avoided emissions because of the produced electricity to replace fossil fuels have the highest impact (47).

Roberts et al. compared the greenhouse gas emission reductions for using biochar to replace coal in an integrated gasification combined cycle (IGCC) plant and for a biochar to soil system. They used corn stover as a feedstock and performed an LCA using system expansion and assuming a carbon stability factor of 80%. In this scenario, the greenhouse gas emission reduction was 29% higher for the biochar to soil scenario (40).

An article by Matustik et al. talks about the effect of methodological decisions in the life cycle assessment of biochar (5). They state that mostly waste biomass should be used for biochar production (5). In a review article by Terlouw et al. (12), it is noted that alternative options to waste biomass feedstock have to be investigated since waste might be less in the future (48) and because of increased competition for the use of waste biomass feedstock (49). For example, biochar and bioenergy production are competing for feedstock (50). Therefore, in this project, both waste and non-waste biomass will be investigated.

There are also other things to note regarding biochar application to soil. Biochar application has been found to reduce the albedo (51). A study by Meyer et al. found that the change in albedo caused the climate change mitigation benefits of biochar systems to reduce by 13-22% (51). However, Lehmann et al. (26) note that Meyer et al. assume longer persistence of the albedo change than the data they based their measurements on from Genesio et al. (52).

If the biomass used for biochar production is grown for that purpose, there is a danger that the climate change abatement potential of the biochar system might be reduced or completely lost due to direct land use change and indirect land use change (26). However, if the biomass is produced on unproductive land with low C stock or integrated with other land use, these effects can be minimized (26).

Lehmann et al. (53) estimate that the technical climate change abatement potential for biochar systems, globally, is 2.4-3.9 Pg CO_2eq per year for biochar from waste and organic residues (44-49% CDR). They estimate that the potential grows to 3.4-6.3 Pg CO_2eq per year if also including biomass crops grown on abandoned cropland [5] (49-59% CDR) (53).

Woolf et al. (54) estimate for biochar, a technically possible climate change abatement of 1.0-1.8 Pg CO_2-Ce [6] or 3.7-6.6 Pg CO_2eq per year (26), by taking into account the

[5] The abandoned cropland has not become forest, urban or pasture

[6] CO_2-C equivalent, amount of C. Multiplied with 44/12 to get CO_2

preservation of food security, biodiversity and ecosystem stability (54). This comes from carbon sequestration (50%), by using the energy from the pyrolysis process to replace fossil energy (30%) and N_2O and CH_4 emissions avoided (20%) (54). They find that biochar has 22-27% more climate change abatement potential than combustion of biomass to produce energy although this is of course dependent on various conditions such as carbon intensity of the energy replaced [7].

In this project, a tool was made to calculate LCA results for biochar produced through slow pyrolysis and applied to mineral soil, based on various user inputs. This is since in slow pyrolysis, biochar is the main product and for soil amendment, emissions are not only avoided but carbon dioxide removal is possible. The research case is covered in detail in section 3.1.

[7] Assuming carbon intensity of 17.5 kg C per GJ for the offset energy

3 Methods

3.1 Research case

As mentioned above, the first step of an LCA is the goal and scope definition. Here, the purpose of the LCA is to assess the environmental impacts of biochar produced by slow pyrolysis and applied to mineral soil for various conditions. This is done to see if the environmental benefits outweigh possible environmental harm, to quantify the carbon dioxide removal effectiveness and to see which parameters affect the result the most. The functional unit chosen is one tonne of produced biochar since biochar production is the main goal of the system. The analysis is also conducted for the functional unit of one tonne dry biomass.

This study is aimed at helping in decision making regarding support of biochar for e.g. authorities, for companies to help them evaluate the feasibility of biochar production and for use in further research. Biochar to soil systems life cycle assessment results depend on various factors such as feedstock and process temperature. Therefore, a parametric analysis is necessary. The tool provided in this project allows the user to choose a variety of inputs and thereby evaluate the feasibility of biochar production and application to soil under specific conditions. This tool covers a variety of feedstocks and production conditions and is therefore able to generate a variety of results. It allows the user to experiment with changing different parameters and see the effect on the LCA results.

As mentioned above, biochar can be produced through different processes and has different applications. The focus of this project is on biochar produced via slow pyrolysis and application to mineral soil. This case is chosen since for slow pyrolysis, biochar is the main product while for gasification and fast pyrolysis it is a by-product. Soil application is chosen since application to soil offers possibilities for carbon dioxide removal. Here, the focus is on mineral soil since in the study by Woolf et al. (1) which gives the carbon stability factor for different conditions, it is recommended that their methodology is only used for mineral soils to be on the safe side due to possible positive priming in organic soil (1). Positive priming refers to increased soil organic carbon mineralization following biochar addition to soil (1; 55; 26).

In this thesis, a tool is made which conducts a life cycle assessment of biochar made from slow pyrolysis and application to mineral soil based on various input parameters. Different European countries can be chosen for the analysis as well as different types of feedstock and conditions as will be discussed in detail in chapter 3.3. How the tool uses these inputs to calculate the yields and the environmental impact will also be described in chapter 3.3.

The process system of biochar production via slow pyrolysis and its application to soil is shown in figure 3.1. For waste feedstock, the production of the original feedstock is outside of the system boundary. This is consistent with the used EcoInvent v3.8 cutoff background model (56). The by-products of the pyrolysis process, bio-oil and pyrolysis gas can be used to produce electricity and heat. In this project, it is assumed that the pyrolysis gas and tar (the part of the bio-oil that is not water) are burned in a CHP plant to produce electricity and heat as in the article by Tisserant et al. (18). The efficiencies of the CHP plant are taken as an input from the user to find the amount of electricity and heat produced. Part of the electricity and heat produced is used to serve the electricity and heating needs of the pyrolysis process (including feedstock drying). The heat and electricity used by the process are subtracted from the produced heat and electricity to find the avoided heat and electricity. System expansion is used to account for the avoided electricity and heat production. The environmental burdens of the avoided heat and electricity production are subtracted from the environmental burdens of the biochar system. As mentioned above, biochar can reduce fertiliser requirements. System expansion is also used to account for this so the environmental burdens of the fertiliser that is avoided are subtracted from the environmental burdens of the biochar system. For the system expansion for fertiliser reduction, the user can choose whether to include it in the calculations or not. Possible changes in N_2O emissions from soil and albedo are not included as will be covered in chapter 5.2.

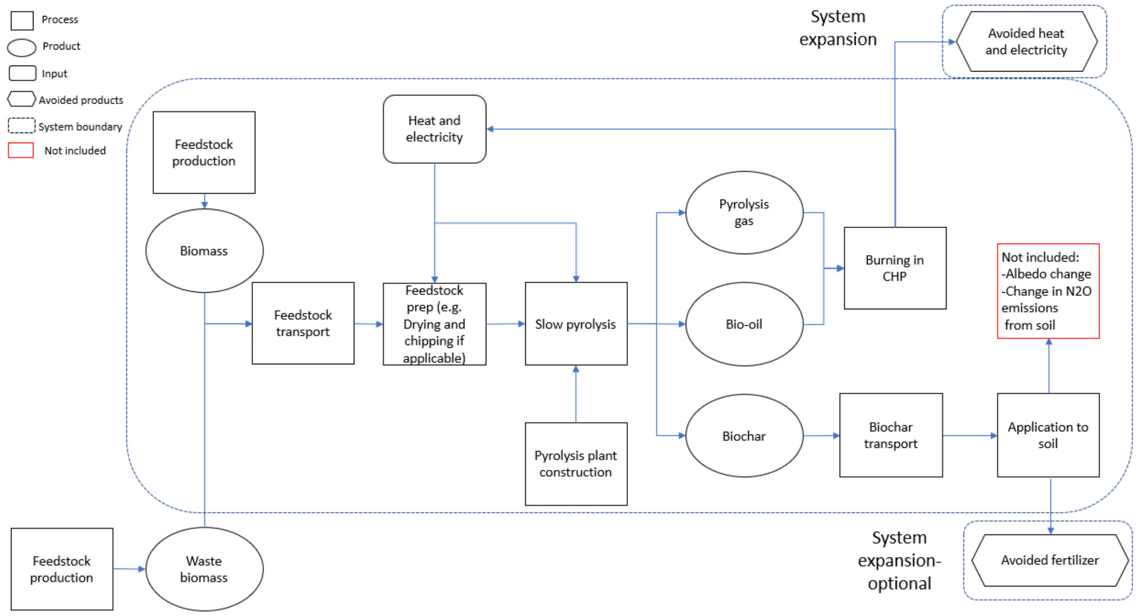

Figure 3.1: The slow pyrolysis biochar to soil process system used in this thesis.

3.2 Data

The data used in this thesis is from academic literature. The yield and mass balance calculations for the tool were based on a study by Woolf et al. (2) as will be explained in detail in chapter 3.3.2. The data on the carbon stability factor comes from another study by Woolf et al. (1). Other data used mainly comes from three different projects, one in Belgium (10), one in the UK (8) and one in Norway (18). The EcoInvent 3.8 cutoff database (56) is used to find the environmental impact for the different processes, using Activity Browser (version 2.6.9) (57) which builds on brightway2 (58). The feedstock data includes waste feedstocks, sustainable forestry feedstocks and purpose-grown feedstocks. The life cycle inventory data for the non-waste feedstocks is from EcoInvent. The elemental composition of the different feedstocks is from the Phyllis2 database (59).

3.3 Tool to calculate the parametric LCA results for a variety of inputs

The tool to calculate the LCA results for biochar produced via slow pyrolysis and applied to mineral soil for various user inputs is now described. As mentioned, it is assumed that the pyrolysis gas and tar are burned in a CHP plant to produce heat and electricity. The benefit of the tool is that the user can choose from a variety of feedstocks and other parameters such as process temperature and type of heat and electricity replaced. Instead of providing LCA results for only a single case, the tool can therefore provide the LCA results for a variety of cases. The underlying calculations of the tool are described as well as the inputs from the user and the chosen impact categories.

3.3.1 User inputs

Various parameters are taken as an input from the user to calculate the LCA results for each case. These inputs are shown in table 3.1.

The user can choose the location of the LCA from a list of European countries and get the results for that country. The user can also choose Europe as a whole as a location. The list of countries is in the appendix. The chosen location affects the avoided electricity if average country electricity mix is chosen as the type of electricity replaced. The location also affects the avoided heat and avoided fertiliser since those processes are location specific in EcoInvent.

The temperature of the pyrolysis process is taken as an input but this affects the yields of the slow pyrolysis process, the elemental composition of the biochar and the carbon stability factor. The temperatures allowed in the tool are from 350 to 800°C.

Different feedstocks can be chosen from a drop down menu and thereby the tool calls the correct carbon, hydrogen, oxygen, ash and lignin content to use for the yield and energy calculations. The list of feedstocks can be found in the appendix. The feedstock moisture content is also taken as an input since this affects the energy requirements of the process and thereby the avoided heat and electricity production as will be further explained in chapter 3.3.4. Suggested values for moisture content for the different feedstocks are given based on values from the Phyllis2 database (59) and an assumption in a study by Tisserant et al. (18).

The user can choose whether fertiliser reduction due to biochar application to soil is counted towards reduced emissions. For the fertiliser, application rate of biochar, application of N, K and P fertilisers (the total application before biochar application, without reduction) and percentage reduction in N, K and P fertiliser are taken as inputs. Values for the fertiliser assumptions are suggested based on the article by Hammond et al. (8).

As mentioned, the pyrolysis gas and tar are assumed to be burned in a CHP plant to produce electricity and heat. The efficiencies of the CHP plant to heat and electricity are taken as user inputs. The CHP plant efficiency inputs are based on higher heating values of the fuels since all the calculations are based on higher heating values. The CHP plant efficiencies affect the amount of avoided electricity and heat production. The user can choose whether the heat that is replaced is from wood or from natural gas, affecting the climate change impact of avoided heat production. The user can also choose whether the electricity replaced is from coal, natural gas combined cycle, natural gas conventional, onshore wind or the average electricity mix of the chosen location, thereby affecting the climate change impact of avoided electricity production. The transport distances from collection point to feedstock transport point[1], from feedstock transport point to the pyrolysis plant, from the pyrolysis plant to farm and from farm to field are further taken as user inputs.

The soil temperature is taken as a user input but this is since the carbon stability factor values used in the tool, from Woolf et al., depend on the pyrolysis temperature and the soil temperature (1).

[1]The transport of the feedstock from the point where it is collected to the point where it enters a lorry

Table 3.1: User inputs that the tool uses to calculate the LCA results

User input	**type**	**unit**
Feedstock	choose from list	unitless
Location	choose from list	unitless
Type of heat replaced	choose from list	unitless
Type of electricity replaced	choose from list	unitless
Include fertiliser reduction	choose yes/no	unitless
Pyrolysis temperature	choose from list	°C
Feedstock moisture content before drying	user input	percentage wet basis
CHP efficiency to electricity	user input	unitless
CHP efficiency to heat	user input	unitless
Biochar application rate	user input	tonne/ha
Total N fertiliser application [2]	user input	kg/ha
Total P fertiliser application [3]	user input	kg/ha
Total K fertiliser application [4]	user input	kg/ha
Percentage reduction N fertiliser	user input	percentage
Percentage reduction P fertiliser	user input	percentage
Percentage reduction K fertiliser	user input	percentage
Transport distance feedstock to pyrolysis plant	user input	km
Transport distance pyrolysis plant to farm	user input	km
Transport distance farm to field	user input	km
Transport distance collection point to lorry	user input	km
Soil temperature	choose from list	°C

A picture of the user interface is shown in figure 3.2.

[2]Total N fertiliser application before biochar application and without reduction.
[3]Total P fertiliser application before biochar application and without reduction.
[4]Total K fertiliser application before biochar application and without reduction.

		Values allowed if not from list
Feedstock	waste spruce	
Location	Norway	
Type of heat replaced	Heat from wood	
Type of electricity replaced	country mix	
Include fertiliser reduction	No	
Pyrolysis temperature (°C)	500	
Feedstock moisture content before drying (% wb)	40	Whole number between 0 and 99
Soil temperature (°C)	14,9	
CHP efficiency to electricity (as 0,X)	0,228	Decimal between 0 and 1
CHP efficiency to heat (as 0,X)	0,572	Decimal between 0 and 1
Biochar application rate (tonne/ha)	30	Positive whole number
Total N fertilizer application (kg/ha)	200	Positive whole number
Total P fertilizer application (kg/ha)	70	Positive whole number
Total K fertilizer application (kg/ha)	70	Positive whole number
percentage reduction in N fertilizer	10	Whole number between 0 and 100
Percentage reduction in P fertilizer	5	Whole number between 0 and 100
Percentage reduction in K fertilizer	5	Whole number between 0 and 100
Transport distance feedstock to pyrolysis plant (km)	100	Positive whole number
Transport distance pyrolysis plant to farm (km)	100	Postitive whole number
Transport distance farm to field (km)	5	Postive whole number
Transport distance collection point to lorry (km)	5	Postive whole number
	blue cells	User input
	orange cells	Choose from list

Figure 3.2: The user interface of the tool

3.3.2 Yields and elemental composition

A study by Woolf et al. gives methods to calculate the yields of a slow pyrolysis process on a dry ash-free basis (DAF) based on lignin content of the feedstock, elemental composition of the feedstock (carbon(C), hydrogen(H) and oxygen(O) composition (DAF)) and the temperature of the pyrolysis process (2). The yields are calculated as a fraction of the dry ash-free feedstock mass. These methods were implemented in this project with the goal of being able to calculate the LCA results automatically for different pyrolysis temperatures and for different feedstocks, based on their lignin content and elemental composition. The lignin, carbon, hydrogen and oxygen content (wt%) of the feedstocks is from the Phyllis 2 database (59). An empirical equation was provided in the study by Woolf et al. to calculate the biochar yield (DAF) from the feedstock lignin content and the pyrolysis temperature (2). Furthermore, empirical equations were provided to calculate the yields of CO, H_2, CH_4 and C_2H_2 (DAF) based on pyrolysis temperature. Equations were given to calculate the carbon, hydrogen and oxygen composition of the tar (the part of the bio-oil that is not water) and the biochar (DAF). All these equations, from the supplementary information of the study by Woolf et al. (2), can be found in the appendix (section 7.1). Based on this information, the yield of tar, CO_2 and water (DAF) could be calculated from mass balances since the carbon, hydrogen and oxygen composition of feedstock, biochar and tar was known

(2). The yield calculations are shown in the tab "Yield calculation" in the excel tool and the mass balance calculations are shown in the tab "Mass balance and HHV". The matrix used for the mass balance calculation is also shown in the appendix.
The yield calculations described here are on a dry ash-free basis. However, this was then converted to a dry basis (including ash) to account for the different ash contents of the feedstocks. The ash content for the different feedstocks is from the Phyllis2 database (59). To calculate the ash content of the biochar, it is assumed that the ash from the feedstock goes to the biochar as in Woolf et al. (1) but the equation to do that is shown in the appendix. Based on the ash content of the feedstock and the assumption that all the ash goes to the biochar, the yield of the bio-oil, pyrolysis gas and biochar on a dry basis can be calculated. The elemental composition of biochar on a dry basis can also be calculated. These calculations are shown in the appendix (section 7.1).

3.3.3 Feedstock

In this tool, the user can choose from a variety of feedstocks for the analysis. As mentioned above, the yield calculations depend on, among other parameters, the C, H, O, lignin and ash content of the feedstock. This information was found for a variety of feedstocks from the Phyllis 2 database (59) to be able to have a variety of feedstocks for the user of the tool to choose from. This information was found for willow wood, birch wood, spruce wood, oak wood, miscanthus, waste wheat straw, waste rice straw, rice husk, waste willow wood, waste oak wood, waste spruce wood and waste birch wood. It was assumed that the waste feedstock had the same elemental composition as the corresponding non-waste feedstock. The Phyllis2 database has many samples for each feedstock so a mean of all the available samples was used. In the tool, the user can choose the type of feedstock from a list and thereby it calls the right input of C, H, O, lignin and ash content for the yield calculations. As mentioned above, the waste feedstock production was assumed to be out of the system boundary (free of environmental burdens), which is consistent with the used EcoInvent v3.8 cutoff background model (56). For the non-waste feedstocks, the corresponding process in EcoInvent was found but the feedstock production processes were most often only available for one location in Europe. It was therefore assumed that this location was representative of all of Europe.

The EcoInvent (v3.8 cut-off) processes for spruce, birch and oak production were used which assume sustainable forest management. For willow, the EcoInvent process for short rotation coppice is used. The non-waste feedstocks that are not sustainable forest management processes in the tool are willow and miscanthus, which can both be produced on marginal soils (10; 60). Therefore, it is reasonable to not include indirect land use change for the feedstocks in the tool. However, if using this tool for some of these feedstocks for a specific case where it is known that indirect land use change takes place, the results should be complemented with that. Furthermore, if using the tool for specific cases where a change in carbon stocks is expected, this should also be included. This will be further covered in chapter 5.

3.3.4 Energy calculations

Here, the calculations of the higher heating values of the products of the slow pyrolysis process and the feedstock, the energy requirements of the slow pyrolysis process and the calculated amount of the avoided heat and electricity will be explained.

Higher heating values

The higher heating values of the products of the slow pyrolysis process and of the feedstock were found to be able to calculate their energy content. The Channiwala Parikh equation was used (61) to find the higher heating value (HHV) of the biochar, feedstock and tar based on their elemental composition (C, O and H content) as suggested in the article by Woolf et al., assuming that the contribution from nitrogen and sulfur is negligible for the HHV (2).
The HHV of the pyrolysis gas was calculated based on the yield and HHV of each gas component but the HHV for each component was given in the supplementary information of the article by Woolf et al. (2). The equations used for the higher heating value calculations can be found in the appendix.

Energy requirements of the process

The slow pyrolysis process needs an energy input. Part of the thermal energy needed is for drying the feedstock and part is for heating up the process (62). The energy requirements of drying the feedstock depend on the moisture content of the feedstock which the tool takes as an input. The thermal energy requirement of a dryer (MJ/kg water evaporated) is taken from a study by Manouchehrinejad and Mani (63) which simulated a biomass torrefaction process. Using this, the thermal energy needed for drying the feedstock can be found since the feedstock moisture content is known. The ratio between electrical and thermal energy required for drying is assumed to be the same as for the torrefaction process simulated in the study by Manouchehrinejad and Mani (63). Therefore, the electrical energy needed for drying can be found, using this ratio and the thermal energy required to dry the biomass.

To find the energy needed for the pyrolysis process excluding drying, back-calculated data from the article by Tisserant et al. was used with some assumptions (18). The thermal energy needed by the process in the study by Tisserant et al. (18) could be calculated based on data in the supplementary information. The assumed thermal energy required to dry the biomass was calculated based on the thermal energy requirement of a dryer from Manouchehrinejad and Mani (63), using the amount of feedstock and the moisture contents given in the article by Tisserant et al. (18). This was subtracted from the total thermal energy required to find the thermal energy needed for the pyrolysis without drying. The thermal energy needed for the pyrolysis without drying was calculated per unit energy in the feedstock to be able to use it for the tool. The Channiwala Parikh equation (61) and the amount of dry feedstock were used to find the energy in the feedstock, assuming that the contribution from nitrogen and sulfur are negligible (2). The ratio between electrical and heat requirements in a torrefaction process (63) was used to find the electrical energy required for the pyrolysis without drying per unit energy in the feedstock.

To sum up, the pyrolysis energy requirement without drying is assumed to be fixed per unit energy in the feedstock while the drying energy needed is a function of the moisture content of the feedstock. Here, it has to be noted that there is significant uncertainty on the energy needed for the pyrolysis process without drying since this is based on many assumptions. Furthermore, in this project, the feedstock is assumed to be dried to zero moisture content to be on the safe side in accounting for the energy requirements of evaporating water on all stages, while in the article by Tisserant et al., it is dried down to 10% before entering the pyrolysis process (18). Therefore, the energy input of the process is a conservative value, to be careful not to overestimate the possible avoided emissions from heat and electricity production. All yield calculations in this project are on a dry basis.

Amount of avoided electricity and heat

As mentioned, the pyrolysis gas and tar (part of the bio-oil that is not water) are assumed to be burned in a CHP plant to produce heat and electricity. The efficiencies for the CHP plant heat and electricity conversion (based on higher heating values) are taken as an input in the tool. The total energy embodied in the tar and pyrolysis gas is calculated based on their higher heating values (HHV) and their yields. The heat and electricity output from burning the tar and pyrolysis gas in a CHP plant can therefore be found based on the total energy embodied in the pyrolysis gas and tar and the CHP plant efficiencies. The extra heat and electricity are calculated by subtracting the heat and electricity requirements of the process from the heat and electricity output from the CHP plant. This extra heat and electricity are considered as avoided heat and electricity production and their environmental impacts subtracted from the environmental impacts of the biochar production system. Here, it has to be noted that these avoided emissions from heat and electricity production are emission reductions because of emissions that were otherwise assumed to have happened. However, this is not carbon dioxide removal.

3.3.5 Carbon dioxide removal by biochar application to soil

Applying biochar to soil is the part of the process which provides actual carbon dioxide removal. This is since the biomass used to produce the biochar has taken up carbon dioxide during its lifetime and the carbon in the biochar is more stable than in the biomass (13). The carbon stability factor of biochar over 100 years is an important parameter that gives information on the fraction of organic carbon in the biochar that will still be in the biochar and thereby in the soil in 100 years (1). The period of 100 years is chosen since it is recommended in Woolf et al. (1) and since this is the basis that UNFCCC uses for global warming potential calculations of national inventories and climate change mitigation targets (1).

As mentioned in chapter 3.3.2, the elemental composition of biochar was first calculated on a dry ash-free basis. The ash content of biochar is then used to find the elemental composition of biochar on a dry basis.

Woolf et al. (1) give two different methods to calculate the carbon stability factor. One of the methods uses the molar ratio of hydrogen to organic carbon in the biochar and the other uses the pyrolysis process temperature. Both of them use soil temperature.

Since the biochar elemental composition is based on regression equations but not actual measurement for the specific biochar, it was decided to use the method that uses pyrolysis process temperature. The carbon stability factor is given for three different temperature ranges of the pyrolysis process, 350-450°C (not including 450), 450-600°C (not including 600) and higher than or equal to 600°C, as well as for different soil temperatures (1). The carbon stability factor is given for soil temperatures of 5, 10, 14.9, 15, 20 and 25°C but the global mean soil temperature is 14.9°C (1). The tool chooses the right stability factor from the study by Woolf et al. (1) based on the chosen soil temperature and pyrolysis process temperature. The carbon stability factors from Woolf et al. (1) are shown in table 3.2.

Table 3.2: The carbon stability factor for different pyrolysis and soil temperatures. pt: pyrolysis temperature.

Soil temperature	**pt: [350-450)°C**	**pt: [450-600)°C**	**pt: >= 600°C**
5°C	0.84	0.89	0.94
10°C	0.72	0.79	0.88
14.9°C	0.63	0.71	0.82
15°C	0.63	0.71	0.82
20°C	0.57	0.67	0.79
25°C	0.54	0.64	0.76

The carbon dioxide removal by biochar application to soil can then be calculated by the following equation:

$$C_{bcd} * csf * mass_{bc} * 44/12 \tag{3.1}$$

C_{bcd} is the carbon fraction (not including ash carbon) of the biochar on a dry basis, csf is the carbon stability factor, $mass_{bc}$ is the amount of biochar and 44/12 is the conversion factor between carbon and carbon dioxide.
The carbon stability factor has a big impact on the overall climate change potential result as will be discussed in chapter 4. Therefore, if data on the molar fraction of hydrogen to organic carbon in the biochar is available, it is recommended by Woolf et al. that those are used instead since it is more accurate (1).

Here, the time frame is 100 years but in the article by Woolf et al. (1), values for the carbon stability factor are also given for a 500-year and a 1000-year time frame. These values also depend on soil temperature and pyrolysis temperature. As an example, for a soil temperature of 14.9°C and medium pyrolysis temperature [450-600)°C, the carbon stability factor is 0.71 for a 100-year time frame but goes down to 0.32 for 500 years and 0.16 for 1000 years. The carbon stability factor is higher for higher pyrolysis temperature and lower soil temperature. The highest carbon stability factor (soil temperature 5°C and pyrolysis temperature higher than 600°C) for 500 years is 0.78 and for 1000 years 0.63. The lowest carbon stability factor (soil temperature 25°C and pyrolysis temperature [350-450)°C) for 500 years is 0.13 and for 1000 years 0.06. It can be seen from that, that the soil and pyrolysis temperature have a large effect on the carbon stability factor, especially for longer time frames than 100 years.

3.3.6 General comments on interdependencies

Table 3.3 summarizes the main trends in terms of interdependencies. The right hand side of the table shows what happens when the parameter on the left hand side of the table increases (keeping other parameters constant).

Table 3.3: Interdependencies, general trends.

Parameter	**Effect when this parameter is increased**
Pyrolysis temperature	Lower biochar yield Higher carbon fraction of biochar Higher yield of pyrolysis gas Lower yield of tar Higher heating value of pyrolysis gas higher Carbon stability factor higher
Soil temperature	Lower carbon stability factor
Lignin content of feedstock	Higher biochar yield
Feedstock moisture content	More energy needed to dry Less avoided electricity and heat production
Ash content	Lower ash-free biochar yield Lower organic carbon fraction of biochar
Carbon stability factor	More carbon dioxide removal
Biochar carbon fraction	More carbon dioxide removal

As mentioned, the carbon dioxide removal potential of biochar application to soil depends on the carbon stability factor, the biochar yield (when using one tonne dry feedstock as a functional unit) and the organic carbon fraction of the biochar. Biochar yield is lower for higher pyrolysis temperature (keeping other parameters constant) but the carbon fraction of biochar increases with higher pyrolysis temperature, which partly counteracts the biochar yield decrease in terms of carbon dioxide removal potential of biochar application to soil. Furthermore, the carbon stability factor is higher with higher pyrolysis process temperature according to the values used by Woolf et al. (1), which increases the carbon dioxide removal of biochar application to soil. As mentioned, the ash from the feedstock is assumed to go to the biochar. The higher the ash content of the feedstock and thereby the biochar, the lower the carbon fraction (not including ash carbon) of the biochar. Another factor affecting the carbon dioxide removal potential of biochar application to soil is soil temperature. The carbon stability factor and thereby the carbon dioxide removal is higher for lower soil temperature according to the values from Woolf et al. if all other parameters are constant (1). As mentioned, the lignin content of the feedstock affects the biochar yield, with higher lignin content corresponding to higher biochar yields. Higher biochar yield means more carbon dioxide removal can be achieved.

Using the regression equations from Woolf et al. (2), the yield of CO, CH_4, H_2 and C_2H_2 in the slow pyrolysis process increases with pyrolysis temperature while the yield of tar decreases. The higher heating value of the pyrolysis gas also increases with increasing pyrolysis temperature. Therefore, the energy content of the pyrolysis gas increases with temperature while for tar it decreases with temperature. The higher the energy content of the by-products is, the higher the amount of avoided heat and electricity.

The feedstock moisture content affects the energy requirements of drying. The lower the moisture content of the feedstock, less energy is needed for drying and more heat and electricity production is avoided. Therefore, the climate change abatement potential increases with lower moisture content.

3.3.7 Fertiliser

As mentioned above, biochar application to soil can increase fertility and thereby decrease the need for fertilisers. However, these qualities depend on various factors such as biochar properties, soil properties and application conditions (14). The reduction of N, P and K fertiliser in percentage is taken as an input in the tool but in the article by Hammond et al. (8), a maximum reduction of 10% N, 5% P and 5% K fertiliser is used for wheat crops. Furthermore, biochar application rate and the total amount of each type of fertiliser applied per hectare, before biochar application and not including reduction, are taken as an input in the tool. As a reference, the application rate of 30 tonnes per hectare of biochar and total 200 kg N fertiliser and 70 kg P and K fertiliser per hectare is taken from the assumptions of the article by Hammond et al. which assumes that the biochar is applied to wheat crops (8). The inputs to the model for P fertiliser should be as a mass of P2O5 and for K fertiliser as a mass of K2O since this is how the fertiliser processes are in EcoInvent. As mentioned in chapter 2.2, the fertiliser reduction potential of biochar depends on various factors such as biochar and soil properties (14). Therefore, the user can also decide to not include the fertiliser reduction in the calculations in the tool.

3.3.8 Other parts of the inventory

Other parts of the inventory consist of the construction of the pyrolysis plant, the different transport stages and the emissions from burning the tar and the pyrolysis gas in a CHP plant.

The emissions from the construction of the pyrolysis plant per tonne biochar are approximated by using the process for the construction of a 1 MW combined heat and power plant in EcoInvent. The environmental impacts of that process are multiplied by the ratio of feedstock needed for producing one tonne biochar to the feedstock processed in a lifetime. The amount of feedstock processed per year is found based on assumptions in the article by Hammond et al. (8) and a linear interpolation is used to find the amount of feedstock for a 1 MW plant. The lifetime is assumed to be 20 years as assumed in the study by Hamedani et al. (10).

Transport is assumed to happen in four stages in the process. Three of them are the same as assumed in the study by Hammond et al. (8), i.e. from feedstock transport point to the pyrolysis plant, from the pyrolysis plant to farm and from farm to field. However, it was decided to also include the transport distance from the feedstock collection point to the feedstock transport point, i.e. the transport of the feedstock from the point where it is collected to the point where it enters a lorry. All of these transport distances are taken as an input into the model. The transport from collection point to feedstock transport point and from farm to field are assumed to be in a trailer/tractor. However, the transport from the feedstock transport point to the pyrolysis plant and from the pyrolysis plant to the farm are assumed to be by lorry. When the tar and pyrolysis gas are burned in a CHP, some emissions take place that have to be included. These emissions are included in the article by Tisserant et al. (18) and were calculated per unit energy in the bio-oil and pyrolysis gas to be able to calculate these emissions for different input parameters in the tool, using the energy content of the bio-oil and the pyrolysis gas. To back-calculate the total energy content of the bio-oil and pyrolysis gas in the article by Tisserant et al., overall efficiency of 80% was assumed for the CHP plant (on a higher heating value basis). It is also assumed here as in the article that the electricity to heat ratio is 0.4 (64).

3.3.9 Impact categories

The impact categories were chosen from the different impact categories available in Activity browser (version 2.6.9) (57). The Environmental footprint (EFv3.0) impact categories were chosen (65) as well as cumulative energy demand (in MJ eq for biomass, fossil, geothermal, nuclear, primary forest, solar, water and wind) and water use [5] (in cubic meters). A list of impact categories can be found in the appendix. The focus of the analysis is on the climate change (GWP 100) category.

[5] In Activity Browser: selected LCI results, additional-resource-water

4 Results

In the analysis, the focus is on the climate change (GWP 100) category. A few examples of results from other impact categories will be discussed. Given that there are many different user inputs with many options for each, the possible cases for the analysis are many. Here, the focus will be on a few of those. In the analysis that follows, the avoided electricity and heat production because of the electricity and heat produced by the pyrolysis gas and tar and not used by the biochar production process, are avoided emissions while biochar application to soil is carbon dioxide removal. As mentioned, the carbon stability factor is the share of the organic carbon in the biochar which is stable in soil 100 years after biochar application to soil. It is used along with the amount of biochar, the organic carbon fraction of the biochar and the conversion factor between carbon and carbon dioxide to find the climate change potential (GWP 100) impact of biochar application to soil. The overall climate change potential (GWP100) results are a combination of emissions, avoided emissions and carbon dioxide removal. In this analysis, the climate change potential results (GWP100) will be analysed for different cases.

4.1 Contribution analysis

Figure 4.1 shows the comparison of the overall climate change potential (GWP100) results for the biochar to soil system for different countries. It also shows the climate change contribution of the different processes to show which factors affect the results the most and how those factors differ between countries. In this analysis, willow is the chosen feedstock for the biochar production process and the pyrolysis temperature chosen is 500°C. The heat that is replaced is heat from natural gas and the electricity that is replaced is the average electricity mix of each country. The other assumptions are as described in table 4.1. The carbon dioxide removal by biochar to soil is shown with a separate bar in the figure to distinguish between avoided emissions and carbon dioxide removal. The functional unit used in this figure is one tonne biochar.

Table 4.1: Inputs used in the tool for figures 4.1 and 4.2.

User input	**Figure 4.1**	**Figure 4.2**
Feedstock	Willow	Willow
Location	Different countries	Europe
Type of heat replaced	Natural gas	Comparison
Type of electricity replaced	Country mix	Comparison
Include fertiliser reduction	Yes	No
Temperature	500°C	500°C
Feedstock moisture content (% wet basis)	40%	40%
CHP efficiency to electricity	0.228	0.228
CHP efficiency to heat	0.572	0.572
Biochar application rate	30 t/ha	NA
Total N fertiliser application	200 kg/ha	NA
Total P fertiliser application	70 kg/ha	NA
Total K fertiliser application	70 kg/ha	NA
Percentage reduction N fertiliser	10%	NA
Percentage reduction P fertiliser	5%	NA
Percentage reduction K fertiliser	5%	NA
Transport distance feedstock to pyrolysis plant	100 km	100 km
Transport distance pyrolysis plant to farm	100 km	100 km
Transport distance farm to field	5 km	5 km
Transport distance collection point to lorry	5 km	5 km
Soil temperature	14.9°C	14.9°C

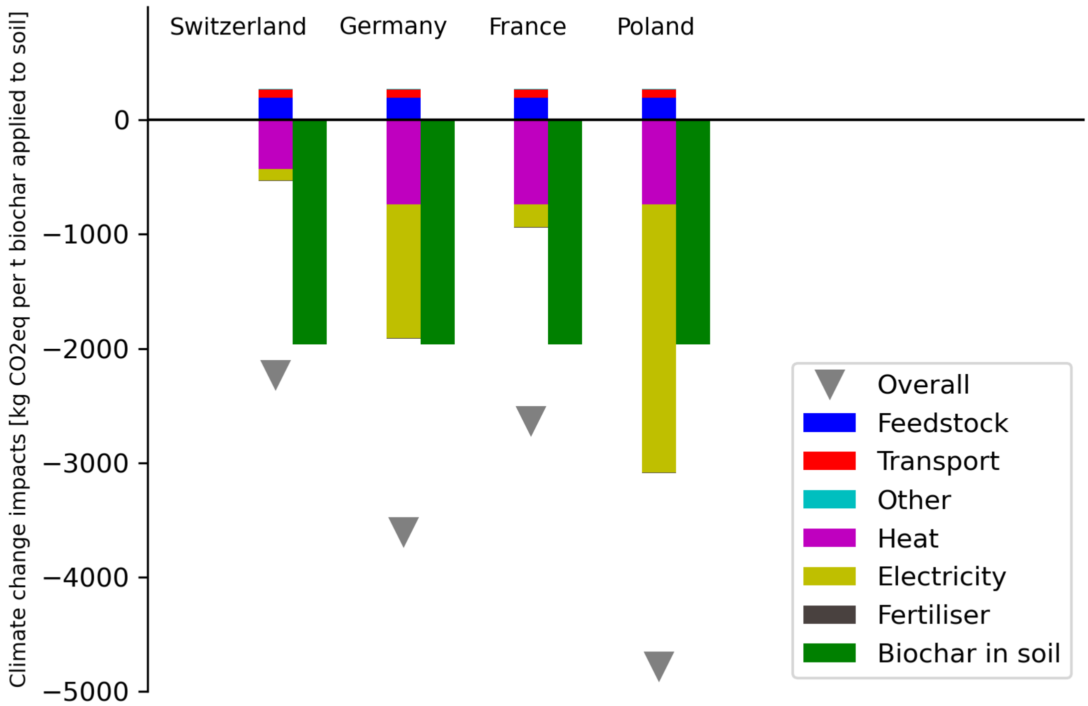

Figure 4.1: Here, the climate change impacts results (GWP100) for Switzerland, Germany, France and Poland are shown with the following parameters chosen in the tool: Feedstock: willow, pyrolysis temperature: 500°C. Fertiliser reduction included assuming a 10% decrease in N fertiliser requirements and a 5% decrease in P and K fertiliser requirements. Biochar application rate: 30 t/ha. Fertiliser application rate (N,P,K): 200,70,70 kg/ha. CHP efficiency (based on HHV): 22.8% to electricity, 57.2% to heat. Transport distances: feedstock to pyrolysis plant: 100 km, pyrolysis plant to farm: 100 km, farm to field: 5 km, collection point to lorry: 5km. Replaced electricity: country mix in each country. Replaced heat: Natural gas. Soil temperature: 14.9°C. Moisture content of willow (% wet basis): 40%.

The climate change potential results range from -2227 kg CO_2eq per tonne biochar applied to soil for Switzerland to -4781 kg CO_2eq per tonne biochar applied to soil for Poland. Poland has the most negative climate change potential (most climate change abatement potential) followed by Germany and then France. This is explained by the difference in the climate change impacts of the avoided electricity. Poland has the dirtiest electricity mix, followed by Germany and then France. Therefore, the replaced electricity from Poland has the highest climate change impacts. For the heating with natural gas, the processes from EcoInvent used in this project are one for Switzerland

and one for Europe without Switzerland which is assumed to apply to all the other countries the user can choose from in the tool. The heating from natural gas is cleaner in the EcoInvent process used for Switzerland than for the rest of Europe as can be seen in figure 4.1.

Figure 4.1 also shows the contribution of each process used in the life cycle assessment of the biochar to soil system to the climate change potential (GWP 100) results. For Switzerland and France, the carbon dioxide removal by biochar application to soil makes up most of the negative climate change potential. This is since the electricity mix in those countries is rather clean and therefore the avoided electricity has a low contribution to the climate change potential results. For Germany, the negative climate change potential contribution is rather similar for biochar to soil, and avoided heat and electricity combined. For Poland, the combined avoided heat and electricity contribute more to the negative climate change potential than the application of biochar to soil. This highlights how important the type of heat and electricity are for the climate change potential results. As mentioned, biochar application to soil has the potential to increase fertility of soil and thereby decrease fertiliser use. The climate change potential because of avoided fertiliser use is included in this analysis but it is so small that it is hardly visible. This of course depends on the assumptions of total fertiliser application rate (kg/ha), biochar application rate and percentage fertiliser reduction. Here, the assumptions are the same as used in the study by Hammond et al. for wheat crops (8). Regarding processes leading to positive emissions, the feedstock production has the biggest impact followed by transport. These contributions are minor compared to the negative climate change potential as seen in the figure.

Figure 4.2 compares the climate change potential results (GWP100) per tonne biochar applied to soil for different types of electricity and heat replaced. Here, the location chosen is Europe, the feedstock is willow and the process temperature is 500°C. Fertiliser reduction is not included. The other assumptions are as described in table 4.1.

The case of replaced electricity from wind and replaced heat from wood is investigated since it is the least carbon-intensive heat and electricity mix. The case of electricity from coal and heat from natural gas is chosen since this combination has the highest carbon intensity. The case of electricity from natural gas combined cycle and heat from natural gas is also investigated. This is since natural gas power plants are often the marginal electricity supplier because of the merit order in the electricity market.

The merit order curve shows the power generation bids in one hour ranked based on price in one supply curve (66). The clearing price is where the demand and supply meet. The price is therefore controlled by the power plant that is making up the supply curve at the intersection between supply and demand (66). Blume-Werry et al. modeled the technologies setting the power price in Europe in 2020. They found that gas power plants set the price in the highest number of hours out of all generation technologies using twenty integrated European power markets (67).

Furthest to the right in the figure, the avoided electricity is from coal and the avoided heat from natural gas, representing the heat and electricity combination with the highest climate change potential impact. Furthest to the left in the figure, the avoided electricity is from wind and the avoided heat from wood, representing the heat and electricity combination with the lowest climate change potential impact. In the middle, the avoided electricity is from natural gas combined cycle and the avoided heat from natural gas. The climate change potential (GWP100) for the case using wind as avoided electricity and heat from wood as avoided heat, the low-carbon case, is -1771 kg CO_2eq per tonne biochar applied to soil. For the case with avoided electricity as electricity from natural gas combined cycle and avoided heat as heat from natural gas, the climate change potential is -3396 kg CO_2eq per tonne biochar. For the case with avoided electricity as electricity from coal and heat from natural gas as avoided heat, the climate change potential is -4827 kg CO_2eq per tonne biochar applied to soil, or more than double the negative climate change potential of the low carbon case. It can thereby be seen how big of an effect the choice of avoided heat and electricity has. This will be further elaborated on in the sensitivity analysis. However, as noted above, this difference is only in the avoided emissions but not the actual carbon dioxide removal.

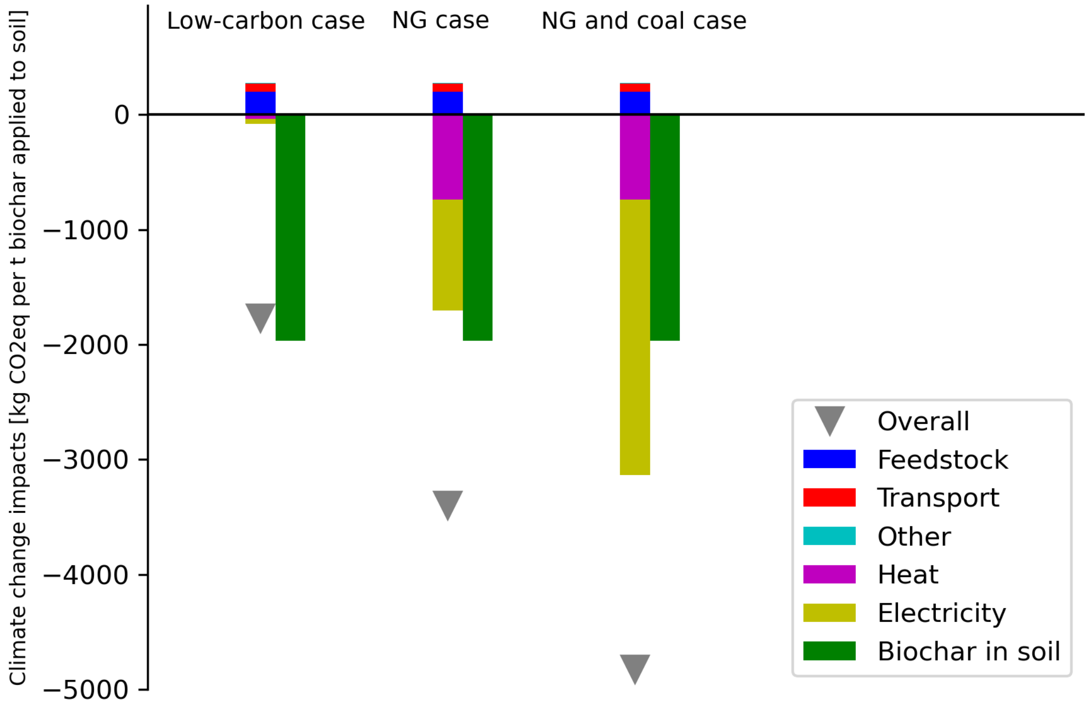

Figure 4.2: The climate change potential (GWP100) results are shown for willow for different types of avoided electricity and heat. Biochar application to soil is carbon dioxide removal and avoided heat and electricity production are avoided emissions. Furthest to the right, the replaced heat is from natural gas and the replaced electricity is from coal. In the middle, the replaced heat is from natural gas and the replaced electricity from natural gas (combined cycle). Furthest to the left, the replaced heat is from wood and the replaced electricity is electricity from wind. Other parameters are as such: Pyrolysis temperature: 500°C, Location: Europe, fertiliser reduction not included, CHP efficiency (based on HHV): 22.8% to electricity, 57.2% to heat. Transport distances: feedstock to pyrolysis plant: 100 km, pyrolysis plant to farm: 100 km, farm to field: 5 km, collection point to lorry: 5km. Soil temperature: 14.9°C. Moisture content of willow (% wet basis): 40%.

Table 4.2 shows the results of some of the other impact categories analysed in the tool for the same cases as analysed in figure 4.2. The furthest left column in the table shows the results for the case with avoided heat as natural gas and avoided electricity as electricity from coal. The middle column shows the case with avoided electricity from natural gas combined cycle and avoided heat from natural gas. The furthest right column of the table shows the results for the case with avoided heat as heat from wood and avoided electricity as electricity from wind. The results are shown per tonne biochar.

As can be seen, the majority of the impact categories show negative numbers when the replaced electricity is from coal and the replaced heat is from natural gas, that is, there is actually a positive impact on the environment for the majority of impact categories. However, in the case of replaced electricity from wind and replaced heat from wood, the impact categories besides climate change potential show mostly positive numbers which means a negative impact on the environment. As expected, the cumulative energy demand for biomass and the land use- soil quality index are high numbers in all cases because of the choice of willow, a purpose-grown feedstock, as feedstock. As seen, land use - soil quality index is the lowest in the case of avoided heat from wood and avoided electricity from wind. This is mainly since by avoiding heat from wood, land use is also avoided.

Table 4.2: Avoided electricity and heat comparison - results for chosen impact categories per tonne biochar. CED stands for cumulative energy demand. Pyrolysis temperature is 500°C. Fertiliser reduction is not included. Feedstock is willow and the location is Europe. Other inputs as for figure 4.2. The column labeled "coal,gas" represents the case with avoided electricity from coal and avoided heat from natural gas. The column labeled "gas,gas" represents the case with the avoided electricity and heat from natural gas. The column labeled "wood,wind" represents the case with the avoided electricity from wind and avoided heat from wood.

Impact category	**Unit**	**coal, gas**	**gas, gas**	**wood, wind**
acidification, ae	mol H+ eq	-4,029E+00	1,283E+00	1,482E+00
climate change (GWP100)	kg CO_2eq	-4,827E+03	-3,396E+03	-1,771E+03
ecotoxicity: freshwater	CTUe	-2,333E+04	1,926E+04	2,248E+03
eutrophication: freshwater	kg PO_4eq	-9,743E-01	2,006E-01	1,885E-01
eutrophication: marine	kg N eq	2,636E+00	3,897E+00	3,934E+00
eutrophication: terrestrial	mol N eq	-7,646E+00	4,528E+00	2,681E+00
human toxicity:carcinogenic	CTUh	3,026E-07	6,927E-07	4,005E-07
human toxicity:non-carcinogenic	CTUh	-3,133E-05	-3,645E-06	-1,037E-05
ionising radiation: human health	kBq U235 eq	-1,031E+01	9,324E+00	1,242E+01
land use-soil quality index	dimensionless	1,640E+05	1,672E+05	1,478E+05
material resources	kg Sb eq	1,925E-03	2,394E-03	7,357E-04
ozone depletion	kg CFC-11 eq	-9,395E-05	-2,514E-04	2,745E-05
particulate matter formation	disease incidence	2,244E-06	1,878E-05	5,360E-07
photochemical ozone formation	kg NMVOC-Eq	-2,420E+00	2,792E-01	7,456E-01
CED, biomass	MJ Eq	7,138E+04	7,153E+04	6,167E+04
CED fossil	MJ Eq	-3,625E+04	-2,806E+04	2,653E+03
CED geothermal	MJ Eq	-9,560E-01	8,065E-01	8,288E-01
CED nuclear	MJ Eq	-1,707E+02	6,024E+01	7,338E+01
CED primary forest	MJ Eq	7,044E-01	1,080E+00	2,448E-01
CED solar	MJ Eq	-5,951E-01	-5,100E-01	1,600E+00
CED water	MJ Eq	-3,764E+01	2,580E+01	1,931E+01
CED wind	MJ Eq	-1,461E+01	4,368E+00	-8,658E+03
resource, water	cubic meter	-5,600E+00	-2,669E+00	6,849E-01

Table 4.3 shows the results of the case in figure 4.2 for avoided heat as heat from natural gas and avoided electricity as electricity from coal in the column labeled "not included". It was decided to compare it with a case with all the same inputs besides that fertiliser reduction is included. This is shown in the column labeled "included". The results are shown per tonne biochar. The assumptions for fertiliser reduction are the same as shown in table 4.1 for figure 4.1. As mentioned in the contribution analysis for the different countries, the fertiliser reduction did not contribute much

to the climate change potential results. When looking at the absolute value of the percentage change when including fertiliser reduction compared to not including it in table 4.3, the cumulative solar energy demand has the highest change (23%) followed by particulate matter formation (-10%). It can therefore be seen that even though the fertiliser reduction has only a small impact on the climate change potential results, it has a bigger impact on some other impact categories.

Table 4.3: Fertiliser impacts - results of chosen impact categories per one tonne biochar applied to soil. CED stands for cumulative energy demand. The replaced heat is from natural gas and the replaced electricity is from coal. The feedstock is willow and the pyrolysis temperature is 500°C. The location is Europe. CHP efficiency (based on HHV): 22.8% to electricity, 57.2% to heat. Transport distances: feedstock to pyrolysis plant: 100 km, pyrolysis plant to farm: 100 km, farm to field: 5 km, collection point to lorry: 5km. Soil temperature: 14.9°C. Moisture content of willow (% wet basis): 40%. Fertiliser reduction is included in the column labeled "included" and not included in the column labeled "not included". In the case where fertiliser reduction is included, the fertiliser assumptions are the following: A 10% decrease in N fertiliser requirements and a 5% decrease in P and K fertiliser requirements. Biochar application rate: 30 t/ha. Fertiliser application rate (N,P,K): 200,70,70 kg/ha.

Impact category	**Unit**	**not included**	**included**	**% change**
acidification, ae	mol H+ eq	-4,029E+00	-4,057E+00	0,697
climate change (GWP100)	kg CO_2eq	-4,827E+03	-4,831E+03	0,079
ecotoxicity: freshwater	CTUe	-2,333E+04	-2,386E+04	2,285
eutrophication: freshwater	kg PO_4eq	-9,743E-01	-9,751E-01	0,081
eutrophication: marine	kg N eq	2,636E+00	2,632E+00	-0,173
eutrophication: terrestrial	mol N eq	-7,646E+00	-7,719E+00	0,954
human toxicity: carcinogenic	CTUh	3,026E-07	3,002E-07	-0,797
human toxicity:non-carcinogenic	CTUh	-3,133E-05	-3,139E-05	0,211
ionising radiation:human health	kBq U235 eq	-1,031E+01	-1,058E+01	2,630
land use soil quality index	dimensionless	1,640E+05	1,640E+05	-0,012
material resources	kg Sb eq	1,925E-03	1,846E-03	-4,092
ozone depletion	kg CFC-11 eq	-9,395E-05	-9,444E-05	0,528
particulate matter formation	disease incidence	2,244E-06	2,029E-06	-9,612
photochemical ozone formation	kg NMVOC-Eq	-2,420E+00	-2,429E+00	0,352
CED, biomass	MJ Eq	7,138E+04	7,138E+04	-0,001
CED fossil	MJ Eq	-3,625E+04	-3,631E+04	0,174
CED geothermal	MJ Eq	-9,560E-01	-9,843E-01	2,961
CED nuclear	MJ Eq	-1,707E+02	-1,744E+02	2,186
CED primary forest	MJ Eq	7,044E-01	6,973E-01	-1,006
CED solar	MJ Eq	-5,951E-01	-7,292E-01	22,544
CED water	MJ Eq	-3,764E+01	-3,873E+01	2,917
CED wind	MJ Eq	-1,461E+01	-1,504E+01	3,001
resource, water	cubic meter	-5,600E+00	-5,618E+00	0,316

4.2 Feedstocks

Figure 4.3 shows the climate change potential (GWP100) results for the biochar to soil system for all the different feedstocks the user can choose from in the tool. The functional unit is one tonne biochar. Here, the location chosen is Europe and the pyrolysis process temperature is 500°C. Fertiliser reduction is not included. The replaced heat is assumed to be from natural gas and the replaced electricity is assumed to be from the average European grid mix. The other assumptions can be seen in table 4.4. Table 4.5 shows the moisture content assumed for the different feedstocks (18; 59). In the article by Tisserant et al. (18), it was assumed that the moisture content of waste spruce before drying in a pyrolysis biochar to soil system was 40% on a wet basis. This is therefore used for all wood feedstocks in this analysis. The moisture content used in the analysis for miscanthus, rice husk, waste wheat straw and waste rice straw is the mean moisture content of these feedstocks in the Phyllis2 database (59).

The overall results for the climate change potential (GWP100) are shown for the different feedstocks with the bars in figure 4.3. The black dot shows the net carbon dioxide removal, i.e. the climate change impacts of biochar application to soil minus the emissions of the system.

Table 4.4: Inputs in the tool for figures 4.3 and 4.4.

User input	**Figure 4.3 and 4.4**
Location	Europe
Type of heat replaced	Natural gas
Type of electricity replaced	grid mix
Pyrolysis temperature	500°C
CHP efficiency to electricity	0.228
CHP efficiency to heat	0.572
Include fertiliser reduction	No
Transport distance feedstock to pyrolysis plant	100 km
Transport distance pyrolysis plant to farm	100 km
Transport distance farm to field	5 km
Transport distance collection point to lorry	5 km
Soil temperature	14.9°C

Table 4.5: Moisture content of the different feedstocks, used in figure 4.3 and 4.4, from Tisserant et al. (18) and the Phyllis2 database (59).

Feedstock	**Moisture content (% wet basis)**
Willow	40
Birch	40
Oak	40
Spruce	40
Miscanthus	36
Waste wheat straw	10
Waste rice straw	9
Rice husk	11
Waste willow	40
Waste Birch	40
Waste oak	40
Waste spruce	40

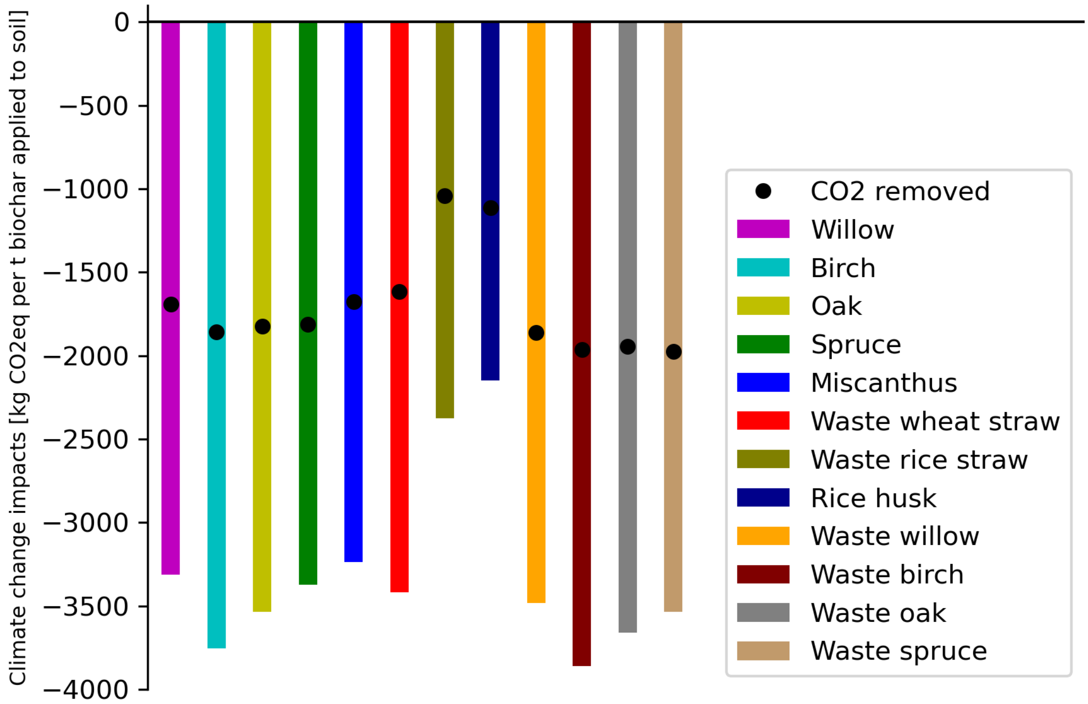

Figure 4.3: Here, the climate change potential results for all the different feedstocks are shown per tonne biochar with the following parameters chosen in the tool. Pyrolysis temperature: 500°C, location: Europe, fertiliser reduction not included, CHP efficiency (based on HHV): 22.8% to electricity, 57.2% to heat. Transport distances: feedstock to pyrolysis plant: 100 km, pyrolysis plant to farm: 100 km, farm to field: 5 km, collection point to lorry: 5km. Replaced electricity: Average European grid mix. Replaced heat: Natural gas. Soil temperature: 14.9°C. Moisture content for all wood and wood waste feedstocks: 40% (18). Moisture content for miscanthus: 36% (59), for waste wheat straw: 10% (59), waste rice straw: 9% (59), rice husk: 11% (59). The black dot represents the net CO_2 removal, i.e. the CO_2 removal by biochar application to soil minus the emissions of the system.

As shown in section 3.3.5, the carbon dioxide removal potential of biochar to soil systems depends on the yield of the biochar, the carbon stability factor and the carbon fraction of the biochar (not including ash carbon). The carbon fraction of the biochar on a dry ash-free basis is based on the pyrolysis temperature as mentioned in section 3.3.2. As mentioned, it is assumed that all the ash from the feedstock goes to the biochar. When comparing feedstocks at the same pyrolysis temperature, the organic carbon fraction of the biochar is higher when the ash content of the feedstock is lower. The yield of biochar on a dry ash-free basis depends on pyrolysis temperature and lignin content of the feedstock as described in section 3.3.2. For comparison of feedstocks at the same pyrolysis temperature, the biochar yield on a dry ash-free basis is higher for higher lignin content.

The carbon dioxide removal in this case does not depend on biochar yield since the analysis is per tonne biochar. In this analysis, waste spruce has the most net carbon dioxide removal potential but that is because it has the lowest ash content. Waste rice straw and rice husk have the highest ash content of the compared feedstocks and therefore have the least net carbon dioxide removal potential in this analysis.

Waste birch has the overall most negative climate change potential out of the investigated feedstocks (most climate change abatement potential). Since the analysis in figure 4.3 is per tonne biochar, the feedstocks with higher biochar yield have a lower yield of co-products per tonne biochar but this affects the total energy content of the tar and pyrolysis gas. However, the energy content and yield of the tar also depend on the elemental composition of the feedstock so this also affects the climate change potential results of the avoided heat and electricity. The net carbon dioxide removal is very similar for waste birch, waste oak and waste spruce but the difference in the overall climate change potential results is due to more avoided electricity and heat in the case of waste birch.

Table 4.6 shows the results for a few chosen impact categories for spruce and for waste spruce for the same inputs as in figure 4.3. This is done to see the difference between using non-waste feedstocks and waste feedstocks. As expected, there is a huge difference in the land use- soil quality index category. This is since waste spruce is a waste feedstock and therefore out of the system boundary while the feedstock supply for spruce is within the system boundary. Another category with a huge difference is the cumulative biomass energy demand. This is for the same reason, since the waste spruce is out of the system boundary. In general, the impacts are lower in all impact categories for waste spruce, as expected. For the non-waste feedstocks, land use is something that has to be investigated before biochar deployment on a large scale.

Table 4.6: Results per tonne biochar for chosen impact categories for spruce and waste spruce. The inputs are the same as in figure 4.3. CED stands for cumulative energy demand. The chosen location is Europe, the pyrolysis temperature is 500°C, the avoided electricity is the average European grid mix and the avoided heat is from natural gas. The moisture content of the spruce and waste spruce is 40% on a wet basis.

Impact category	**Unit**	**Spruce**	**Waste spruce**
acidification, ae	mol H+ eq	-3,134E+00	-3,984E+00
climate change (GWP100)	kg CO_2eq	-3,372E+03	-3,536E+03
ecotoxicity: freshwater	CTUe	-9,344E+03	-1,134E+04
eutrophication: freshwater	kg PO_4eq	-7,660E-01	-8,249E-01
eutrophication: marine	kg N eq	-3,432E-01	-6,818E-01
eutrophication: terrestrial	mol N eq	-2,393E+00	-5,754E+00
human toxicity: carcinogenic	CTUh	-1,207E-07	-3,606E-07
human toxicity: non-carcinogenic	CTUh	-5,922E-06	-1,131E-05
ionising radiation: human health	kBq U235 eq	-4,680E+02	-4,794E+02
land use soil quality index	dimensionless	3,049E+05	-2,052E+03
material resources, metals/minerals	kg Sb eq	-7,070E-03	-7,465E-03
ozone depletion	kg CFC-11 eq	-9,915E-05	-1,326E-04
particulate matter formation	disease incidence	-2,556E-06	-8,219E-06
photochemical ozone formation	kg NMVOC-Eq	9,838E-01	-1,700E+00
CED, biomass	MJ Eq	7,284E+04	-4,454E+02
CED fossil	MJ Eq	-1,963E+04	-2,191E+04
CED geothermal	MJ Eq	-5,675E+01	-5,728E+01
CED nuclear	MJ Eq	-8,254E+03	-8,304E+03
CED primary forest	MJ Eq	7,626E+00	-1,086E-01
CED solar	MJ Eq	-5,032E+02	-5,034E+02
CED water	MJ Eq	-1,613E+03	-1,630E+03
CED wind	MJ Eq	-9,717E+02	-9,772E+02
resource, water	cubic meter	-3,575E+00	-5,683E+00

To account for the difference in biochar yield between different feedstocks, the analysis was also conducted per tonne dry feedstock. The same inputs are used here as in figure 4.3. The results are shown in figure 4.4.

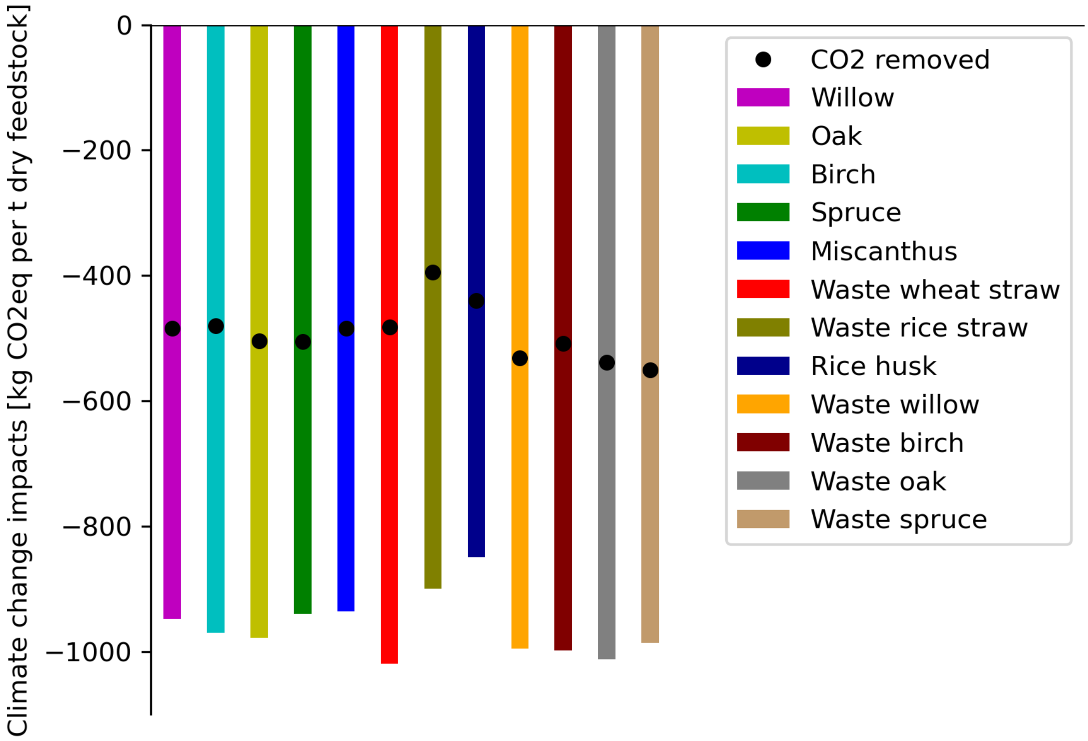

Figure 4.4: Here, the climate change potential results for all the different feedstocks are shown per tonne dry feedstock with the following parameters chosen in the tool. Pyrolysis temperature: 500°C, location: Europe, fertiliser reduction not included, CHP efficiency (based on HHV): 22.8% to electricity, 57.2% to heat. Transport distances: feedstock to pyrolysis plant: 100 km, pyrolysis plant to farm: 100 km, farm to field: 5 km, collection point to lorry: 5km. Replaced electricity: Average European grid mix. Replaced heat: Natural gas. Soil temperature: 14.9°C. Moisture content for all wood and wood waste feedstocks: 40% (18). Moisture content for miscanthus: 36% (59), for waste wheat straw: 10% (59), waste rice straw: 9% (59), rice husk: 11% (59). The black dot represents the net CO_2 removal, i.e. the CO_2 removal by biochar application to soil minus the emissions of the system.

Here the results look a bit different. Waste wheat straw has the overall most negative climate change potential (most climate change abatement potential). Waste wheat straw does have similar net carbon dioxide removal as the other feedstocks in the figure so this is due to the avoided emissions from heat and electricity. A big factor here is that the waste wheat straw has a lower moisture content than the wood feedstocks and therefore less of the produced energy is required for feedstock drying. Compared to the other feedstocks that have a low moisture content, rice husk and waste rice straw, waste wheat straw has a lower ash content which partly explains why it has more negative climate change potential.

Waste spruce wood has the most net carbon dioxide removal per tonne dry feedstock. This is partly since it has a high biochar yield because of its high lignin content. Furthermore, spruce has a low ash content so carbon fraction of the biochar (not including ash carbon) on a dry basis is high. In general, the waste wood feedstocks provide more net carbon dioxide removal because of their high lignin content and low ash content. The wood feedstocks that are not waste have a bit lower net carbon dioxide removal since the biochar system in those cases includes the emissions from the feedstock production.

4.3 Pyrolysis temperature

An analysis was made to see the effect of the pyrolysis process temperature on the climate change potential results. The feedstock chosen for this analysis is spruce. Here, fertiliser reduction is not included. The other assumptions can be seen in table 4.7. The results are shown for Switzerland, Poland and Germany. Furthermore, the carbon dioxide removed is shown, that is, the climate change potential results without including avoided heat and electricity. The carbon dioxide removed results are not country specific, i.e. they apply to all countries. This is since the processes that are location specific are as mentioned, avoided electricity, avoided heat and fertilisers.

Table 4.7: The inputs used in the tool for figure 4.5

User input	**Figure 4.5**
Feedstock	Spruce
Type of heat replaced	Natural gas
Type of electricity replaced	Country mix
CHP efficiency to electricity	0.228
CHP efficiency to heat	0.572
Include fertiliser reduction	No
Transport distance feedstock to pyrolysis plant	100 km
Transport distance pyrolysis plant to farm	100 km
Transport distance farm to field	5 km
Transport distance collection point to lorry	5 km
Soil temperature	14.9°C

Figure 4.5 shows the results per tonne biochar. The higher the pyrolysis temperature, the more negative the climate change potential (i.e. more climate change abatement potential). More carbon dioxide is also removed with higher pyrolysis temperature. One reason for this is that for higher pyrolysis temperatures, the carbon stability factor is higher according to the values used in this project from a study by Woolf et al. (1). Furthermore, the carbon fraction of biochar increases with pyrolysis temperature. For higher pyrolysis temperatures, the pyrolysis gas yield increases while the bio-oil yield decreases. The higher heating value of the pyrolysis gas also increases with temperature. In this case, the energy content of the co-products increases with pyrolysis temperature. Thereby, the heat and electricity production increases and the amount of avoided heat and electricity is higher. This also contributes to the effect that the climate change potential is more negative (climate change abatement potential is higher) for higher pyrolysis temperatures.

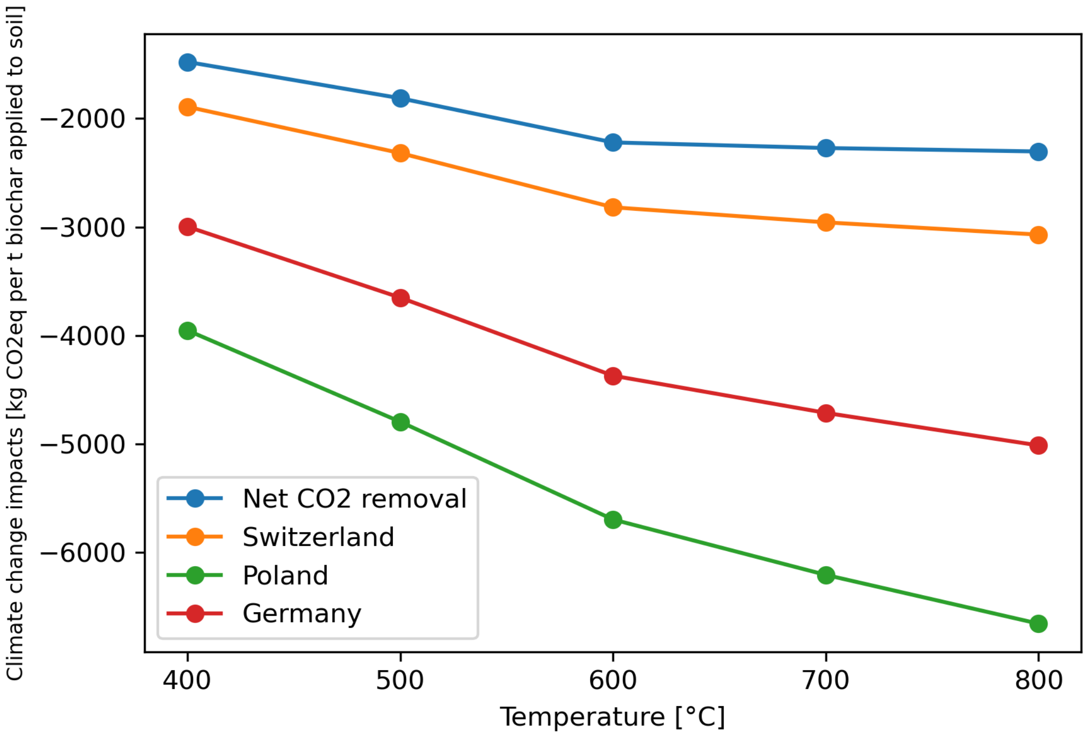

Figure 4.5: Here, the results are shown for spruce for different pyrolysis temperatures. The replaced heat is heat from natural gas and the replaced electricity is the respective country mix. The graph shows the results for different countries as well as the results when not counting avoided emissions (Net CO_2 removal). Those values are not country specific so it applies to all countries. Other parameters are as such: Fertiliser reduction is not included, CHP efficiency (based on HHV): 22.8% to electricity, 57.2% to heat. Transport distances: feedstock to pyrolysis plant: 100 km, pyrolysis plant to farm: 100 km, farm to field: 5 km, collection point to lorry: 5km. Soil temperature: 14.9°C. Moisture content of spruce wood: 40%.

4.4 Carbon dioxide removal factor

The carbon dioxide removal factor is the share of the carbon from the feedstock that is still in soil 100 years after biochar application to soil. Figure 4.6 shows the carbon dioxide removal factor for the different feedstocks for different pyrolysis temperatures for a soil temperature of 14.9°C. Here, waste willow, waste birch, waste oak and waste spruce have the same carbon dioxide removal factor as their non-waste counterparts.

The curve for all feedstocks has the same shape with the maximum at a pyrolysis temperature of 600°C.

The carbon dioxide removal factor depends on the biochar yield, the organic carbon fraction of the biochar, the carbon stability factor and the carbon fraction of the original feedstock. As mentioned, on a dry ash-free basis, the biochar yield depends on the pyrolysis process temperature and the lignin content of the feedstock, and the carbon content of the biochar depends on the pyrolysis process temperature. The values used for carbon stability factor from Woolf et al. (1) are given for three intervals of pyrolysis temperature, [350-400°C), [450-600°C) and higher than or equal to 600°C. The carbon stability factor is higher with higher pyrolysis temperature. Here, the carbon stability factor is the highest for 600°C, 700°C and 800°C out of the compared pyrolysis temperatures. The reason that the carbon dioxide removal factor is higher for 600°C than for 700°C and 800°C, despite the same carbon stability factor, is that biochar yield is lower for higher pyrolysis temperatures. However, the carbon content of the biochar is also higher for higher pyrolysis temperatures but this only partly counteracts the lower biochar yield.

Rice husk has the highest carbon dioxide removal factor. The reason for this is that it has a relatively high lignin content, and therefore a high biochar yield, and a low carbon content in the original feedstock because of high ash content. Waste rice straw has the lowest carbon dioxide removal factor. Waste rice straw has the lowest lignin content out of the compared feedstocks and since all feedstocks are at same pyrolysis temperature, it has the lowest ash-free biochar yield.

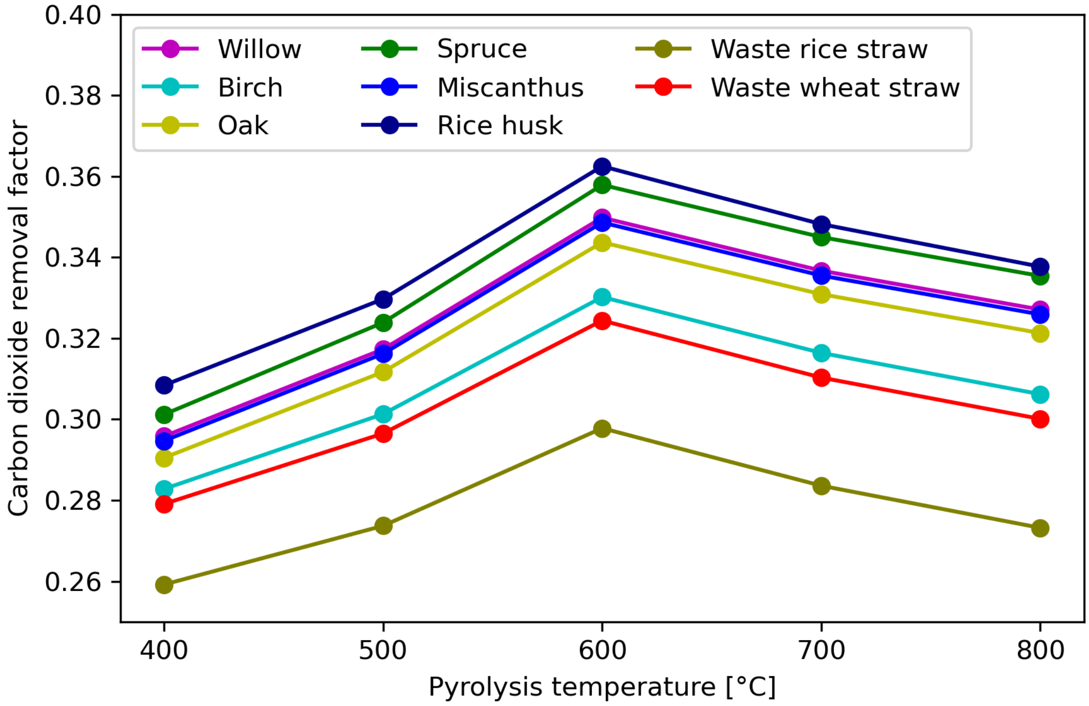

Figure 4.6: The carbon dioxide removal factor is shown for different feedstocks for different pyrolysis temperatures. Soil temperature: 14.9°C. Other parameters which the user can choose in the tool do not influence the carbon dioxide removal factor.

Figure 4.7 shows the carbon dioxide removal factor of the different feedstocks for different soil temperatures for a pyrolysis temperature of 600°C. The carbon stability factor is higher for lower soil temperatures according to the values used by Woolf et al. (1). Here, the pyrolysis process temperature is the same in all cases so the carbon stability factor, feedstock lignin content and feedstock carbon content control the carbon dioxide removal factor. The only parameter which is changing with soil temperature is the carbon stability factor so the carbon stability factor controls the shape of the curve. This is why figure 4.7 shows a lower carbon dioxide removal factor for higher soil temperatures.

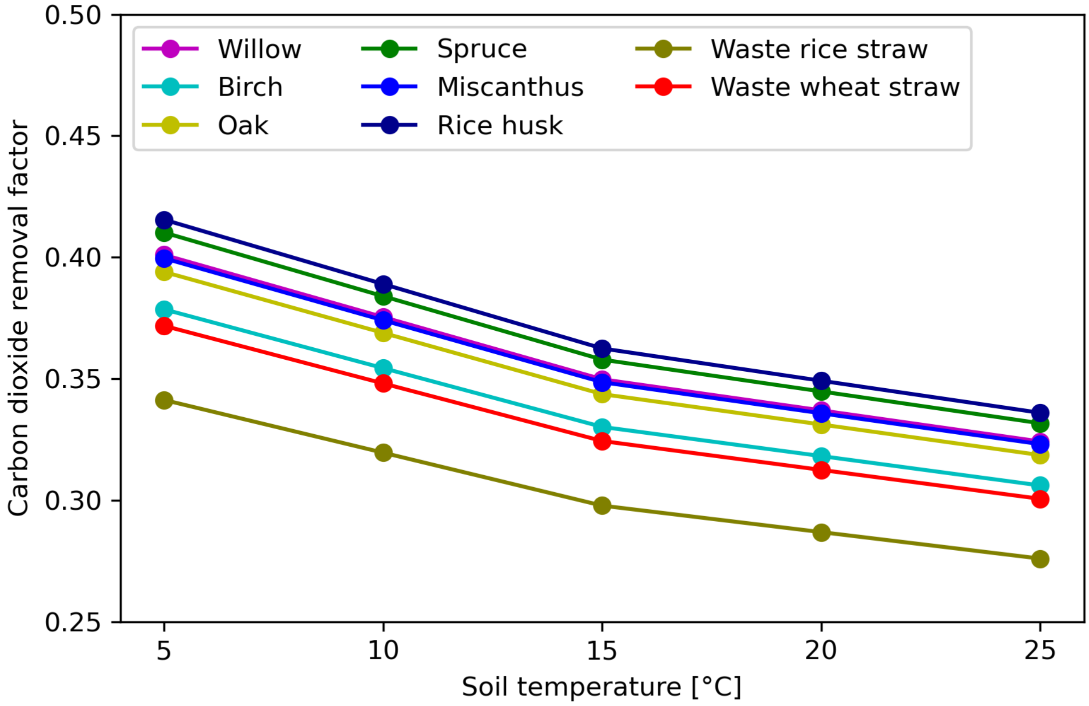

Figure 4.7: Here, the carbon dioxide removal factor is shown for different feedstocks for different soil temperatures. Pyrolysis temperature: 600°C. Other parameters which the user can choose in the tool do not influence the carbon dioxide removal factor.

4.5 Sensitivity analysis

A sensitivity analysis was conducted to see how a change in different input parameters affects the climate change potential (GWP 100) results. The amount of electricity avoided, the amount of heat avoided, the carbon stability factor, the transport distances, the pyrolysis temperature, the amount of fertiliser reduction and the CHP efficiencies were investigated in this analysis. Those parameters were increased and decreased by 20%, one at a time to see the impact on the results compared to a base case. Two different base cases were used for comparison. The assumptions of the base cases are shown in table 4.8. Both of the base cases use Europe as a location with spruce as feedstock and a pyrolysis process temperature of 500°C. For base case 1, the replaced heat is from natural gas and the replaced electricity from natural gas combined cycle but in base case 2, the replaced heat is from wood and the replaced electricity is from wind. This is done to see how the type of electricity and heat affect the sensitivities of the different parameters. Natural gas is chosen for the electricity in base case 1 since as mentioned above it can be considered the main marginal electricity supplier in Europe.

Table 4.8: Inputs in the tool for the two base cases used for the sensitivity analysis

User input	**Base case 1**	**Base case 2**
Feedstock	Spruce	Spruce
Location	Europe	Europe
Type of heat replaced	Natural gas	Heat from wood
Type of electricity replaced	Natural gas (cc)	Wind
Include fertiliser reduction	Yes	Yes
Pyrolysis temperature	500°C	500°C
Feedstock moisture content before drying(%wet basis)	40 %	40%
CHP efficiency to electricity	0.228	0.228
CHP efficiency to heat	0.572	0.572
Biochar application rate	30 t/ha	30 t/ha
Total N fertiliser application	200 kg/ha	200 kg/ha
Total P fertiliser application	70 kg/ha	70 kg/ha
Total K fertiliser application	70 kg/ha	70 kg/ha
Percentage reduction N fertiliser	10 %	10%
Percentage reduction P fertiliser	5%	5%
Percentage reduction K fertiliser	5%	5%
Transport distance feedstock to pyrolysis plant	100 km	100 km
Transport distance pyrolysis plant to farm	100 km	100 km
Transport distance farm to field	5 km	5 km
Transport distance collection point to lorry	5 km	5 km
Soil temperature	14.9°C	14.9°C

Figure 4.8 shows the climate change potential results (GWP100) for both base cases. The type of avoided heat and electricity have a big impact on the overall result. However, here it has to be noted again that the avoided heat and electricity are avoided emissions but not carbon dioxide removal. The two cases are the same in terms of actual carbon dioxide removal.

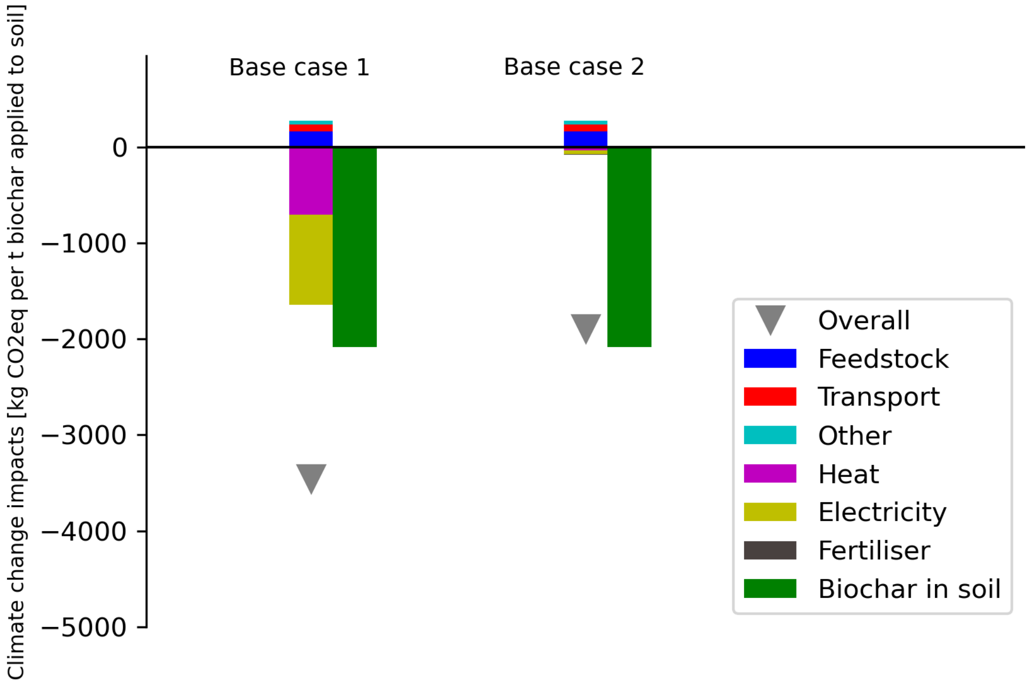

Figure 4.8: The climate change potential results (GWP100) for the two base cases used for the sensitivity analysis. Biochar to soil represents carbon dioxide removal and avoided heat and electricity avoided emissions. Both cases use spruce as feedstock, Europe as a location and a pyrolysis temperature of 500°C. In base case 1, the avoided heat is from natural gas and the avoided electricity is from natural gas combined cycle. In base case 2, the avoided heat is from wood and the avoided electricity is from wind. The other assumptions are as follows: Moisture content of spruce (% wet basis): 40%, fertiliser reduction included assuming a 10% decrease in N fertiliser requirements and a 5% decrease in P and K fertiliser requirements. Biochar application rate: 30 t/ha. Fertiliser application rate (N,P,K): 200,70,70 kg/ha. CHP efficiency (based on HHV): 22.8% to electricity, 57.2% to heat. Transport distances: feedstock to pyrolysis plant: 100 km, pyrolysis plant to farm: 100 km, farm to field: 5 km, collection point to lorry: 5km. Soil temperature: 14.9°C.

The sensitivities of the investigated parameters compared to base case 1 are shown in figure 4.9. The bars represent the change in the overall climate change potential when the different parameters are increased and decreased by 20%. The black dot represents how much of the overall change in climate change potential is due to change in carbon dioxide removal, which is the biochar to soil minus the emissions of the system. This is done to distinguish between parameters affecting avoided emissions and carbon dioxide removal.

The climate change potential results are most sensitive to pyrolysis temperature out of the investigated parameters, followed by the carbon stability factor, the CHP plant efficiency and the amount of electricity avoided.

The pyrolysis temperature has an impact on the total energy content of the pyrolysis gas and tar and thereby on the amount of avoided heat and electricity. In this case, the avoided heat is from natural gas and the avoided electricity from natural gas combined cycle, both of which have a rather high climate change impact. Therefore, anything that affects these parameters has a rather high sensitivity. In addition, the temperature affects the carbon stability factor but according to Woolf et al., the carbon stability factor is higher for higher pyrolysis temperatures (1). As seen, more than half of the change in climate change potential due to the change in pyrolysis temperature is a change in carbon dioxide removal. The temperature change effect is not symmetrical since the carbon stability factor and the yield of pyrolysis gas and tar are not linear with temperature.

The carbon stability factor affects how much carbon dioxide is actually removed and as shown in figure 4.8, biochar application to soil has a big impact on the overall climate change results of the case. Therefore, the results have a high sensitivity to a change in the carbon stability factor.

The CHP efficiency has a high sensitivity since it affects directly the amount of avoided heat and electricity. The amount of heat and electricity also have quite a high sensitivity for the same reason. However, these parameters do not affect the carbon dioxide removal results as shown by the black dot in the figure.

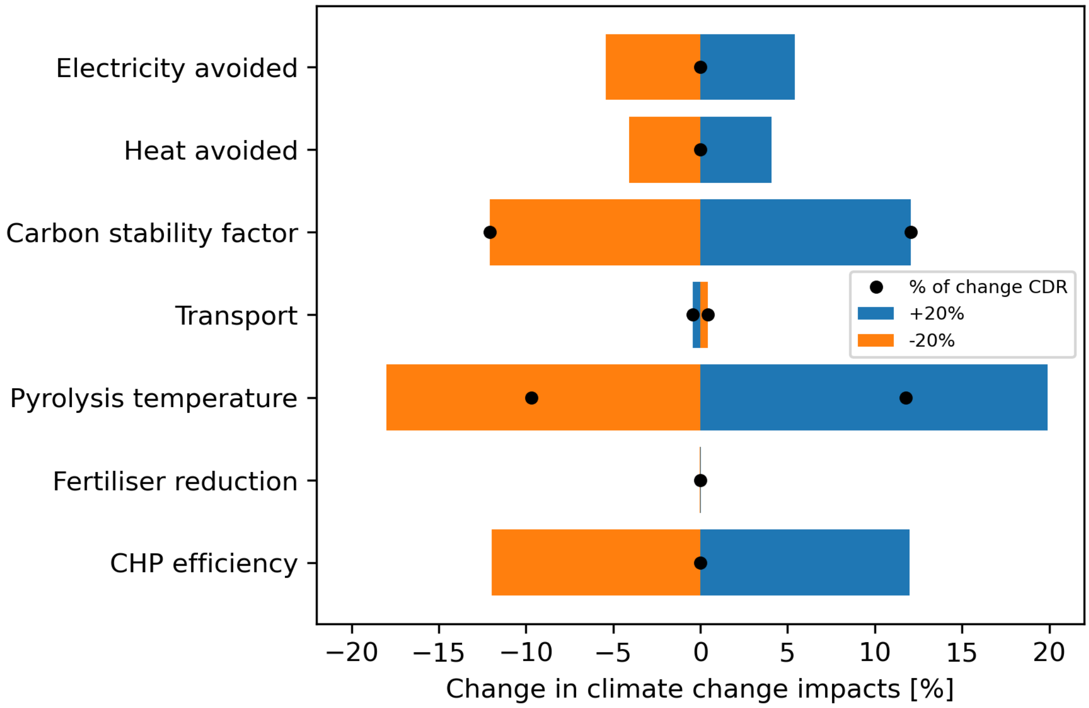

Figure 4.9: Electricity avoided, heat avoided, carbon stability factor, transport distances, pyrolysis temperature, fertiliser reduction and CHP efficiency were increased and decreased by 20% compared to base case 1 to see the effect on the climate change potential results. This is represented with the bars. The black dot represents how much of the overall change in climate change potential is due to change in carbon dioxide removal, which is the biochar to soil minus the emissions of the system. The base case used for comparison in this plot has the following inputs. Location: Europe. Feedstock: Spruce. Moisture content: 40%. Fertiliser reduction included. Biochar application rate: 30 t/ha. Fertiliser application rate (N,P,K): 200,70,70 kg/ha. Temperature: 500°C. CHP efficiency (based on HHV): 22.8% to electricity, 57.2% to heat. Transport distances: feedstock to pyrolysis plant: 100 km, pyrolysis plant to farm: 100 km, farm to field: 5 km, collection point to lorry: 5km. Replaced electricity: Natural gas combined cycle. Replaced heat: Heat from natural gas. Soil temperature: 14.9°C.

The sensitivities of the investigated parameters compared to base case 2 are shown in figure 4.10. As above, the bars represent the change in the overall climate change potential when the different parameters are increased and decreased by 20%. The black dot represents how much of the overall change in climate change potential is due

to change in carbon dioxide removal which is the biochar to soil minus the emissions of the system. In this case, the climate change potential results are most sensitive to the carbon stability factor followed by pyrolysis process temperature. For a 20% increase in the parameters, the results are equally sensitive to carbon stability factor and pyrolysis process temperature but for a 20% decrease in the parameters, the results are more sensitive to the carbon stability factor. The other parameters have low sensitivity. Here, the carbon stability factor has a higher sensitivity than in base case 1. This is since as can be seen in figure 4.8, in base case 2, the climate change potential of biochar application to soil (which is affected by the carbon stability factor) is a bigger portion of the overall climate change potential results since the avoided heat and electricity have a low climate change impact. As mentioned above, the pyrolysis temperature affects the carbon stability factor and the total energy content in pyrolysis gas and tar, and thereby the electricity and heat production. As seen, almost all of the change in climate change impacts due to the change in pyrolysis temperature is a change in carbon dioxide removal in this case. This is since here, the heat and electricity are from low-carbon sources so a change in electricity and heat production does not affect the results as much. In base case 2, the low climate change impact of the electricity from wind and heat from wood make the sensitivities of electricity avoided, heat avoided and CHP efficiency low compared to in base case 1.
Here, changing the carbon stability factor by +-20%, changes the overall climate change potential result by about 22%. This is possible since the climate change impact of biochar application to soil is more negative (higher absolute value) than the overall climate change impacts in this case. This is since the overall climate change impacts are a combination of the carbon dioxide removal by biochar application to soil, the avoided emissions from heat and electricity production, avoided emissions from decreased fertiliser use and positive emissions from feedstock production, transport and other smaller processes. In this case, the avoided emissions from avoided heat, electricity and fertiliser have a low impact so the emissions from the system make the overall climate change potential less negative (lower absolute value) than the climate change impact of biochar application to soil. When increasing the pyrolysis temperature by 20%, the climate change potential results change by about 22% as well. This is possible for the same reason since the pyrolysis temperature affects the carbon stability factor.

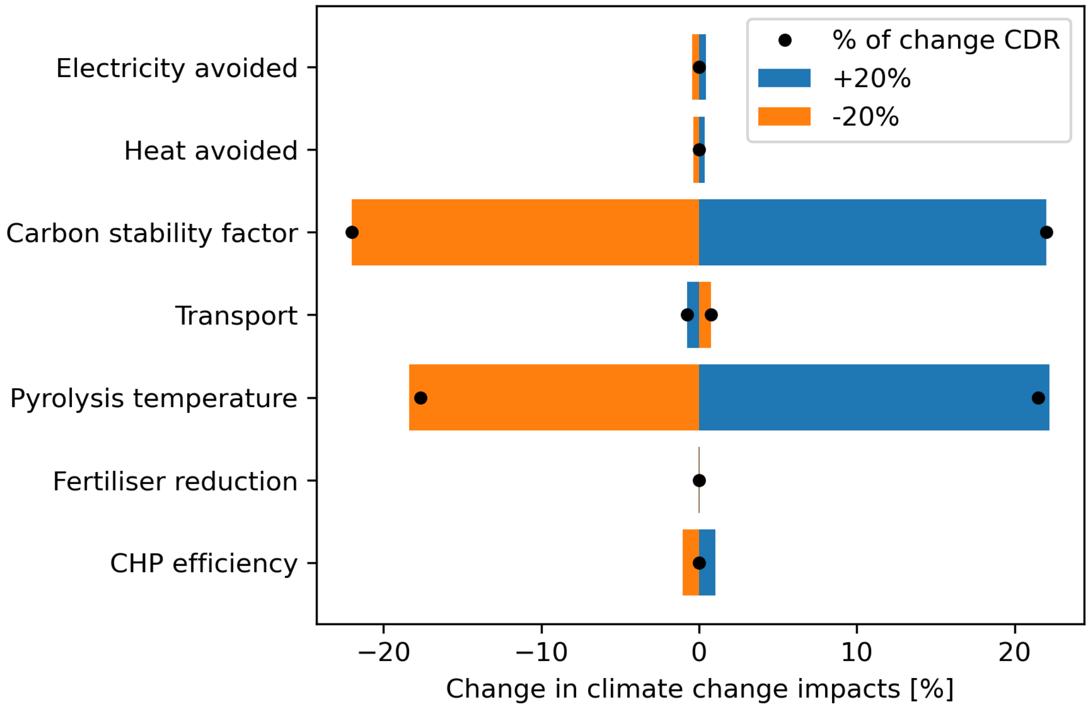

Figure 4.10: Electricity avoided, heat avoided, carbon stability factor, transport distances, pyrolysis temperature, fertiliser reduction and CHP efficiency were increased and decreased by 20% compared to base case 2 to see the effect on the climate change potential results. This is represented with the bars. The black dot represents how much of the overall change in climate change potential is due to change in carbon dioxide removal, which is the biochar to soil minus the emissions of the system. The base case used for comparison in this plot had the following inputs. Location: Europe. Feedstock: Spruce. Moisture content: 40%. Fertiliser reduction included. Biochar application rate: 30 t/ha. Fertiliser application rate (N,P,K): 200,70,70 kg/ha. Temperature: 500°C. CHP efficiency (based on HHV): 22.8% to electricity, 57.2% to heat. Transport distances: feedstock to pyrolysis plant: 100 km, pyrolysis plant to farm: 100 km, farm to field: 5 km, collection point to lorry: 5km. Replaced electricity: Wind. Replaced heat: Heat from wood. Soil temperature: 14.9°C

In both cases it can be seen that the climate change potential results have low sensitivity to a change in transport distances and fertiliser reduction. This is since as seen in figure 4.8, they have a low contribution to the climate change potential (GWP100) results in the base cases.

5 Discussions and limitations

5.1 Overall results

The main output of this thesis is a tool that calculates the life cycle assessment results for slow pyrolysis biochar to mineral soil systems for a variety of impact categories based on various user inputs. The analysis in this thesis focuses on the climate change potential (GWP100) category. The results for the climate change potential in the analysis above vary greatly for different cases. All of the cases investigated have a negative climate change potential and can therefore be helpful in the fight against climate change. The results of the cases analysed in this report range from -1771 kg CO_2eq (96% CDR) to -6658 kg CO_2eq (35% CDR) per tonne biochar applied to soil. However, in the tool, a variety of inputs can be chosen so the range in results is broader than the range of the results in the analysis here.

The contribution analysis showed that the factors with the highest impact on the climate change potential results are biochar application to soil, representing the actual carbon dioxide removal, and in some cases avoided heat and electricity, depending on what type of heat and electricity is replaced. Feedstock was normally the biggest emission factor (not for waste feedstock of course), followed by transport. Other emission factors had a small impact on the results. The avoided fertiliser use also had only a minor impact on the climate change potential results for the cases investigated in this analysis. However, it had a bigger impact in some of the other investigated impact categories.

Different feedstocks were compared. It was decided to compare the feedstocks in terms of climate change potential per tonne dry feedstock as well as per tonne biochar to allow for a better comparison. The waste wood feedstocks showed the most net carbon dioxide removal per tonne dry feedstock because of their high lignin content and low ash content. Waste wheat straw had the most negative climate change potential (most climate change abatement potential) out of the compared feedstocks per tonne dry feedstock. This is mainly because less energy is needed for drying in the case of waste wheat straw than wood.

The carbon dioxide removal factor, the fraction of carbon from the feedstock ending up stable in soil 100 years after biochar application, was also compared for the different feedstocks for different pyrolysis and soil temperatures. Rice husk had the highest carbon dioxide removal factor out of the compared feedstocks. The carbon dioxide removal factor was highest for all feedstocks at a pyrolysis temperature of 600°C out of the compared pyrolysis temperatures and for the lowest soil temperature investigated, 5°C.

A sensitivity analysis was conducted for two different cases. The first case had avoided electricity as electricity from natural gas combined cycle and avoided heat as heat from natural gas. The second case had avoided electricity as electricity from wind and avoided heat as heat from wood. The other parameters were the same in the two cases. In the first case, the climate change potential results (GWP100) were most sensitive to pyrolysis temperature. This is since pyrolysis temperature affects both the amount of avoided electricity and heat, and the carbon stability factor. As shown in figure 4.5, the climate change potential is more negative for higher pyrolysis temperatures (more climate change abatement potential for higher pyrolysis temperatures). In the second case, the climate change potential results were most sensitive to the carbon stability factor since the impact of the avoided heat and electricity on climate change potential is low in this case.

Interdependencies were discussed. Table 3.3 shows the main interdependencies. The carbon dioxide removal potential of biochar application to soil depends on the yield of biochar (when analysing per one tonne dry feedstock), the organic carbon fraction of biochar and the carbon stability factor. The reason for analysing the results per tonne dry feedstock on top of per tonne biochar is to include the difference in biochar yield between different feedstocks and conditions. Higher biochar yield, higher carbon stability factor and higher carbon fraction of biochar lead to more carbon dioxide removal. As mentioned, the ash from the biomass is assumed to go to the biochar. The higher the ash content of the feedstock and thereby the biochar, the lower the carbon fraction (not including ash carbon) of the biochar. As mentioned, the higher the lignin content of the feedstock, the higher the biochar yield and thereby more carbon dioxide removal when doing the analysis per tonne dry feedstock. The carbon stability

factor is higher with higher pyrolysis process temperature and lower soil temperature according to the values used from Woolf et al. (1).
Since there are many different possibilities in terms of process parameters and inputs to produce biochar, it can be hard to compare different studies which perform an LCA of biochar to soil systems. An article by Tisserant et al. (18), used the same method as used in this project for pyrolysis yield calculations. By using the same temperature (500°) and feedstock (waste spruce) as inputs in the tool and using assumptions for other inputs, the results obtained are very similar to the ones obtained by Tisserant et al. (18) in terms of climate change impacts.
Regarding other impact categories, there is a big difference in land use between non-waste and waste feedstocks, as expected. This has to be carefully evaluated before biochar deployment on a large scale. The type of electricity replaced and the type of heat replaced influence the avoided emissions from replaced heat and electricity. As shown in figures 4.1 and 4.2, this has a big impact on the overall climate change potential results. Therefore, when stating numbers for the negative climate change potential of biochar to soil systems, one has to be careful to separate avoided emissions from carbon dioxide removal.

5.2 Limitations and further research

5.2.1 Limitations

This tool is not case-specific which allows it to be used in a variety of scenarios but it also comes with limitations.
Limitations in this project include that the effect of biochar application on N_2O emissions from soil was not included since the numbers in literature vary greatly for different conditions. Woolf et al. (1) regard including the N_2O emissions reduction from soil because of biochar application as optional, since this effect has not been proven statistically significant over more than one year. Furthermore, the possible reduced N_2O emissions because of reduced fertiliser use are not included. Possible heavy metals in feedstock were not included since this highly depends on each case.
Indirect land use change is not included in this tool. However, as mentioned, the non-waste feedstocks are from sustainable forest management in the case of birch, oak and spruce, and miscanthus and willow can be grown on marginal soils. Therefore,

it is reasonable in this case not to include indirect land use change. However, if using the tool for a specific case where indirect land use change takes place, this should be added to the results. Furthermore, a change in carbon stocks should be added if relevant when using this tool for specific cases. According to Lehmann et al., land use change effects can partly or completely eliminate climate change benefits of biochar production (26). They state that direct and indirect land use change can be minimized or avoided by producing biomass on a land which is unproductive with low C stock or by integrating it with land use which is already in place (26). A paper by Roberts et al. (40) highlights how much effect land use change impacts can have but they investigated biochar production with switchgrass as feedstock with two different methods for accounting for land use change. One scenario showed -442 kg CO_2eq per tonne dry feedstock while the other showed +36 kg CO_2eq per tonne dry feedstock (40).

The yield calculations in this tool are based on the pyrolysis temperature and the properties of the feedstock (C, H, O, lignin and ash content) based on a method by Woolf et al. (2; 1). Woolf et al. found that pyrolysis temperature and lignin content are the most important factors for biochar yield (2). However, there is a variety of conditions that can also affect the yield and properties of the pyrolysis products, such as heating rate (25), residence time (28) and pressure (68) which are not taken into account in this method. However, the yield calculations are only based on slow pyrolysis data which as mentioned has longer residence time and slower heating rate than fast pyrolysis. The yield calculations affect the LCA results since they affect among other things the amount of carbon applied to soil and the amount avoided heat and electricity.

The heat and electricity required for the pyrolysis process besides feedstock drying are taken to be constant per unit energy in the feedstock. This value was calculated for heat from the article by Tisserant et al. (18), using the given data for the avoided heat production and moisture contents, and assuming the thermal requirements of a dryer as in Manouchehrinejad et al. (63). The electricity requirement was found by using the ratio of heat to electricity need in a study of a torrefaction process (63). In reality, this heat and electricity requirement is not constant per unit energy in feedstock. Furthermore, the emissions from burning of the pyrolysis gas and tar are assumed to be constant per unit energy in the pyrolysis gas and tar based on back-calculated values from Tisserant et al. (18).

Albedo change due to biochar application to soil was not included in this project. In the one study found which quantifies it, by Meyer et al. (51), the results were that albedo change reduces the climate benefits of biochar systems by 13-22%. Since this depends on the biochar application rate and other conditions, it is hard to justify applying this reduction here. Furthermore, according to Lehmann et al. (26), Meyer et al. assume longer persistence of the albedo change than the data they based their measurements on from Genesio et al. (52).

The carbon dioxide removal potential of biochar to soil systems is highly dependent on the carbon stability factor. In this project, the carbon stability factor over 100 years is taken from a study by Woolf et al. (1), based on the pyrolysis temperature and soil temperature. However, as mentioned, the more exact way is to use the molar fraction of hydrogen to organic carbon in the biochar but for that direct measurements are needed. The analysis in this thesis was made for 100 years but as mentioned, the time frame chosen has a big impact on the carbon stability factor according to the values used by Woolf et al. (1).

The analysis in this thesis focuses on the climate change category (GWP100). The climate change category has a robustness ranking of I in the description of the Environmental footprint impact categories (69) while many of the other categories have lower robustness ratings. Land use is assessed in the EFv3.0 land use category which considers the occupation and transformation of land area (69).

The economic aspect of biochar production is not covered in this project. Bioenergy and biochar production are competing for the same feedstocks (50). It is therefore important to analyse how economic biochar production is compared to bioenergy. In a review paper by Meyer et al., it is shown that the cost of biochar production varies greatly (50). In a paper by Yang et al. (70), which focuses on China, it is shown that the net present value of pyrolysis biochar systems can be positive but this depends on the scale and the process temperature. The economic potential of slow pyrolysis biochar to soil systems for different scenarios is something that would definitely be useful to investigate in more detail in further research.

5.2.2 Further research

In further research, it would be useful to make a model of the pyrolysis yields based on more factors than the pyrolysis temperature and composition of the feedstock to

be more exact. A way to calculate the energy requirements for the pyrolysis process besides drying, depending on process conditions, would also be useful. The change in albedo by biochar application to soil and its affect on LCA results for different scenarios is something that has to be studied in more detail.
Another aspect here, that has to be investigated in more detail, is the competition for biomass feedstocks. As mentioned, bioenergy and biochar production are competing for the same feedstocks (50). A comparison of the life cycle assessment of the different options for biomass use for different scenarios would be interesting in further research. This also depends on what the goal is. One goal could be to achieve as much carbon dioxide removal as possible while another one might be to replace as much fossil fuel based electricity as possible by electricity from biomass. Here, the economics also comes into play and an economic assessment of the different options for biomass use for different scenarios would be interesting.
Here, the focus has been on biochar application to mineral soil but as mentioned in chapter 2.2, other applications for biochar are also possible such as in concrete production, sorption of antibiotics and in battery production.

6 Conclusion

Some type of carbon dioxide removal is needed to complement emission reductions to reach the goals of the Paris agreement according to the IPCC scenarios. Biochar production and application to soil is one option for carbon dioxide removal. Biochar can be produced from various feedstocks and by various processes. In this project, the focus is on biochar produced through slow pyrolysis and applied to mineral soil. The biomass used to produce biochar has taken up carbon dioxide during its lifetime. The biochar carbon is more stable than the biomass carbon, a part of it stays in the soil and thereby contributes to carbon dioxide removal. Tar and pyrolysis gas, which are by-products of the slow pyrolysis process, are burned in a CHP plant for heat and electricity production. The heat and electricity not needed for the pyrolysis process (including feedstock drying), are assumed to replace heat and electricity from other sources by applying a substitution approach.

A life cycle assessment of biochar to soil systems that allows the user to choose various inputs has been missing in literature so far. Therefore, a tool to perform a parametric analysis was made in this project. It calculates the LCA results for biochar to soil systems based on various user inputs regarding for example feedstock, process temperature and avoided products. The tool calculates the results for a variety of impact categories but the analysis in this thesis focuses on the climate change potential (GWP100) category. The results for some other impact categories were shown for chosen cases. The results of all the cases analysed in this thesis show a negative climate change potential (positive climate change abatement potential), ranging from -1771 kg CO_2eq (96% CDR) to -6658 kg CO_2eq (35% CDR) per tonne biochar applied to soil. The negative climate change potential numbers shown in the results are not only carbon dioxide removal but also avoided emissions from electricity and heat production. Many different scenarios are possible in this tool so the results vary greatly. The biggest factors in terms of climate change potential are in general the carbon dioxide removal because of biochar application to soil as well as the avoided emissions due to replaced heat and electricity production. The replaced heat and electricity contribution is though heavily dependent on which type of heat and electricity is replaced.

Different feedstocks were compared and in general waste wood feedstocks showed the most net carbon dioxide removal potential per tonne dry feedstock for the case looked at in that context. The effect of the pyrolysis temperature was investigated while keeping other parameters constant. The higher the pyrolysis temperature, the more negative the climate change potential was (more climate change abatement potential). This is because the temperature affects the energy in the pyrolysis gas and tar as well as the carbon stability factor.

The carbon dioxide removal factor, the fraction of carbon from the feedstock ending up stable in soil 100 years after biochar application, was also compared for the different feedstocks for different conditions. It was highest for rice husk out of the compared feedstocks, for pyrolysis temperature of 600°C out of the compared pyrolysis temperatures and for the lowest soil temperature investigated, 5°C.

A sensitivity analysis was performed for two different cases. In the first case, the replaced electricity was from natural gas combined cycle and the replaced heat from natural gas. In the second case, the replaced electricity was electricity from wind and the replaced heat was heat from wood. Avoided electricity, avoided heat, carbon stability factor, transport distances, pyrolysis temperature, fertiliser reduction and CHP efficiencies were increased and decreased by 20% respectively to see the impact on the climate change potential results. In the first case, the climate change potential results were most sensitive to pyrolysis temperature but in the second case they were most sensitive to the carbon stability factor.

As mentioned, limitations to this project include that albedo change effects due to biochar application to soil are not included. The pyrolysis process yield calculations are based on feedstock composition and temperature but do not include other factors such as residence time and heating rate. Furthermore, this project does not include any economic analysis. The non-waste feedstocks in this analysis are either from sustainable forest management or can be grown on marginal soils. Therefore, if using this tool for other specific cases, indirect land use change effects and carbon stock changes should be added if necessary.

In further research, it would be useful to quantify the impacts of the albedo change for different scenarios. It would also be useful to model the pyrolysis yields based on more parameters. Furthermore, it would be interesting in further research to compare the different possible uses of biomass, for biochar production and other options, from both an environmental and an economic perspective.

ETH

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7 Appendix

7.1 Yield calculations

To calculate the yields of the slow pyrolysis process, a method to predict the yields for slow pyrolysis biochar production on a dry ash-free basis by Woolf et al. was used (2). All the yields are calculated as a fraction of dry ash-free feedstock on a weight basis. Woolf et al. derived the following empirical regression equation for biochar yield (dry ash-free) based on the pyrolysis temperature and lignin content of the feedstock.

$$Yield_{bc-daf} = 0,126 + 0,273L_f + 0,539e^{-0,004T} \tag{7.1}$$

where T is the pyrolysis temperature in Celsius and L_f is the lignin fraction of the feedstock.

Woolf et al. further provided the following empirical regression equations for the yield of CO, H_2, CH_4 and C_2H_X on a dry ash-free basis where T is the pyrolysis temperature (in K).

$$Yield_{CO-daf} = \frac{0,043}{1 + e^{(17,2-0,03T)}} + \frac{0,317}{1 + e^{(10,9-0,01T)}} \tag{7.2}$$

$$Yield_{H_2-daf} = 0,0295(1 - e^{-0,00350T})^{62,98} \tag{7.3}$$

$$Yield_{CH_4-daf} = 0,0782(1 - e^{-0,00338T})^{30,15} \tag{7.4}$$

$$Yield_{C_2H_X-daf} = 0,036(1 - e^{-0,00522T})^{154,97} \tag{7.5}$$

C_2H_X is assumed to be C_2H_2 in the mass balance calculations. For biochar elemental composition (C, H and O) on a dry ash-free basis, the following empirical equations from Neves et al. (79) were used as suggested in Woolf et al. (2).

$$C_{bc-daf} = 0,93 - 0,92e^{-0,0042T} \tag{7.6}$$

where C_{bc-daf} is the mass fraction of C in the biochar (dry, ash-free basis) and T is the pyrolysis temperature in Celsius.

$$H_{bc-daf} = -0,0041 + 0,1e^{-0,0024T} \tag{7.7}$$

where H_{bc-daf} is the mass fraction of H in the biochar (dry, ash-free basis) and T is the pyrolysis temperature in Celsius.

$$O_{bc-daf} = 0,07 + 0,85e^{-0,0048T} \tag{7.8}$$

where O_{bc-daf} is the mass fraction of O in the biochar (dry, ash-free basis) and T is the pyrolysis temperature in Celsius.
The tar composition was found with the following equations from Woolf et al. (2).

$$C_{tar} = 1,25C_{feedstock} \tag{7.9}$$

$$H_{tar} = 1,25H_{feedstock} \tag{7.10}$$

$$O_{tar} = 1,17O_{feedstock} - 0,21 \tag{7.11}$$

C_{tar}, H_{tar} and O_{tar} are the mass fractions of C, H and O in the tar on a dry ash-free basis and $C_{feedstock}$, $H_{feedstock}$ and $O_{feedstock}$ are the mass fractions of C, H and O in the feedstock on a dry ash-free basis.
To calculate the yields of tar, water and CO_2, the following matrix was solved as suggested in Woolf et al. (2).

$$\begin{pmatrix} C_{tar} & C_{CO_2} & 0 \\ O_{tar} & O_{CO_2} & O_{H_2O} \\ H_{tar} & 0 & H_{H_2O} \end{pmatrix} \begin{pmatrix} Yield_{tar-daf} \\ Yield_{CO_2-daf} \\ Yield_{H_2O-daf} \end{pmatrix} = \begin{pmatrix} C_{bc,gas,f} \\ O_{bc,gas,f} \\ H_{bc,gas,f} \end{pmatrix} \tag{7.12}$$

Where $C_{bc,gas,f}$,$O_{bc,gas,f}$,$H_{bc,f,gas}$ are the mass of C, H and O in the feedstock minus the mass of C, H and O accounted for in the biochar, CO, H_2, CH_4 and C_2H_2 as calculated in the equations above, all on a dry ash-free basis. In the calculations C_2H_X is approximated as C_2H_2. To calculate the amount of C, H and O in the different products, simple mass calculations were performed using the molar mass of the products and the elements. C_{CO_2} and O_{CO_2} are the mass fractions of C and O in CO_2 and H_{H_2O} and O_{H_2O} the mass fractions of H and O in H_2O.
As mentioned, the feedstock C, H, O, lignin and ash content was found from the Phyllis2 database (59). To find the ash content of the biochar, the ash content of the feedstock was used and assumed that all the ash would go to the biochar as in the article by Woolf et al. (1). The following equation was used to find the ash content of the biochar modified from Woolf et al. (1)

$$biochar_{ash} = \frac{feedstock_{ash}}{feedstock_{ash} + Yield_{bc-daf} * (1 - feedstock_{ash})} \tag{7.13}$$

where $biochar_{ash}$ is the mass fraction of ash in the biochar, $feedstock_{ash}$ is the mass fraction of ash in the feedstock and $Yield_{bc-daf}$ is the yield of biochar on a dry ash-free basis. The biochar yield on a dry basis can then be found with the following equation.

$$Y_{bc-dry} = Y_{bc-daf} * (1 - feedstock_{ash}) + feedstock_{ash} \tag{7.14}$$

The C, H and O fractions of the biochar on a dry basis can be found with the following equations:

$$C_{biochar-dry} = C_{biochar-daf} * (1 - biochar_{ash}) \tag{7.15}$$

$$H_{biochar-dry} = H_{biochar-daf} * (1 - biochar_{ash}) \tag{7.16}$$

$$O_{biochar-dry} = O_{biochar-daf} * (1 - biochar_{ash}) \tag{7.17}$$

The yield of bio-oil and pyrolysis gas can be found on a dry basis with the following equations:

$$Y_{biooil-dry} = Y_{biooil-daf} * (1 - feedstock_{ash}) \tag{7.18}$$

where $Y_{biooil-daf}$ is the bio oil yield on a dry ash-free basis. The bio oil yield is the sum of the water yield and the tar yield.

$$Y_{gas-dry} = Y_{gas-daf} * (1 - feedstock_{ash}) \tag{7.19}$$

where $Y_{gas-daf}$ is the pyrolysis gas yield on a dry ash-free basis.

7.2 Higher heating values

The Channiwala Parikh equation was used (61) to find the higher heating value (HHV) of the biochar, feedstock and tar based on their elemental composition (C, O and H content) as suggested in the article by Woolf et al, assuming that the contribution from N and S are negligible for the HHV (2). The equation is the following:

$$HHV[MJ/kg] = 34,91C + 117,83H - 10,34O \tag{7.20}$$

For pyrolysis gas the HHV was found from the HHV of each element which were given in the article by Woolf et al. (2) as:

- CO 10.1 MJ/kg
- H_2 141.8 MJ/kg
- CH_4 55.5 MJ/kg
- C_2H_2 49.97 MJ/kg

The following equation was used to find the HHV of the pyrolysis gas (MJ/kg).

$$\frac{Y_{CO-dry}HHV_{CO} + Y_{H2-dry}HHV_{H2} + Y_{CH4-dry}HHV_{CH4} + Y_{C2H2-dry}HHV_{C2H2}}{Y_{gas-dry}} \tag{7.21}$$

where Y_{CO-dry},Y_{H2-dry}, $Y_{CH4-dry}$ and $Y_{C2H2-dry}$ are the yields of CO, H_2, CH_4 and C_2H_2 on a dry basis. $Y_{gas-dry}$ is the sum of the yields of these gases plus the CO_2 yield.

7.3 Possible locations in the tool

The focus of this analysis is on European countries and Europe as a whole. The European countries chosen here were chosen because of the availability of processes in the EcoInvent (v3.8 cut-off) database (56). The processes that are specific to Europe or a specific European country are transport, feedstock production, avoided fertiliser (if included), avoided heat and avoided electricity if a country mix is chosen. For the non-waste feedstocks, the corresponding process in EcoInvent was found but the feedstock production processes were most often only available for one location in Europe. It was therefore assumed that this location was representative of all of Europe.

The method to calculate the slow pyrolysis yields is not location specific so this could serve as an approximation for other locations as well. The carbon stability factor is based on pyrolysis temperature and soil temperature so the carbon stable in soil can be found for other locations. Therefore, if it is assumed that feedstock production, transport and avoided heat is similar as in the processes used for Europe, the tool can serve as an approximation for other locations. The following locations can be chosen in the tool:

- Austria
- Belgium
- Bulgaria
- Check Republic
- Croatia
- Denmark
- Estonia
- Europe
- Finland
- France
- Germany
- Great Britain
- Greece
- Hungary
- Ireland
- Italy
- Latvia
- Lithuania
- Luxembourg
- Netherlands
- Norway
- Poland
- Portugal
- Romania
- Russia
- Slovakia
- Slovenia
- Spain
- Sweden
- Switzerland
- Ukraine

7.4 List of possible feedstocks

The following feedstocks can be selected in the tool:

- birch - wood, sustainable forest management
- miscanthus - purpose-grown feedstock
- oak - wood, sustainable forest management
- rice husk - waste
- spruce - wood, sustainable forest management
- waste birch - wood, waste
- waste oak - wood, waste
- waste spruce - wood, waste
- waste rice straw - waste
- waste wheat straw - waste
- waste willow - wood, waste
- willow - wood, purpose-grown feedstock

7.5 List of impact categories

The impact categories are from Activity Browser (version 2.6.9) (57) and the Environmental footprint categories, EFv3.0 are from the European commission (65). The results for the following impact categories are calculated in the tool:

- EF v3.0 | acidification | accumulated exceedance (ae)
- EF v3.0 | climate change | global warming potential (GWP100)
- EF v3.0 | climate change: biogenic | global warming potential (GWP100)
- EF v3.0 | climate change: fossil | global warming potential (GWP100)
- EF v3.0 | climate change: land use and land use change | global warming potential (GWP100)
- EF v3.0 | ecotoxicity: freshwater | comparative toxic unit for ecosystems (CTUe)
- EF v3.0 | ecotoxicity: freshwater, inorganics | comparative toxic unit for ecosystems (CTUe)
- EF v3.0 | ecotoxicity: freshwater, metals | comparative toxic unit for ecosystems (CTUe)
- EF v3.0 | ecotoxicity: freshwater, organics | comparative toxic unit for ecosystems (CTUe)
- EF v3.0 | energy resources: non-renewable | abiotic depletion potential (ADP): fossil fuels
- EF v3.0 | eutrophication: freshwater | fraction of nutrients reaching freshwater end compartment (P)
- EF v3.0 | eutrophication: marine | fraction of nutrients reaching marine end compartment (N)
- EF v3.0 | eutrophication: terrestrial | accumulated exceedance (AE)
- EF v3.0 | human toxicity: carcinogenic | comparative toxic unit for human (CTUh)

- EF v3.0 | human toxicity: carcinogenic, inorganics | comparative toxic unit for human (CTUh)
- EF v3.0 | human toxicity: carcinogenic, metals | comparative toxic unit for human (CTUh)
- EF v3.0 | human toxicity: carcinogenic, organics | comparative toxic unit for human (CTUh)
- EF v3.0 | human toxicity: non-carcinogenic | comparative toxic unit for human (CTUh)
- EF v3.0 | human toxicity: non-carcinogenic, inorganics | comparative toxic unit for human (CTUh)
- EF v3.0 | human toxicity: non-carcinogenic, metals | comparative toxic unit for human (CTUh)
- EF v3.0 | human toxicity: non-carcinogenic, organics | comparative toxic unit for human (CTUh)
- EF v3.0 | ionising radiation: human health | human exposure efficiency relative to u235
- EF v3.0 | land use | soil quality index
- EF v3.0 | material resources: metals/minerals | abiotic depletion potential (ADP): elements (ultimate reserves)
- EF v3.0 | ozone depletion | ozone depletion potential (ODP)
- EF v3.0 | particulate matter formation | impact on human health
- EF v3.0 | photochemical ozone formation: human health | tropospheric ozone concentration increase
- EF v3.0 | water use | user deprivation potential (deprivation-weighted water consumption)
- cumulative energy demand | biomass | renewable energy resources, biomass

- cumulative energy demand | fossil | non-renewable energy resources, fossil
- cumulative energy demand | geothermal | renewable energy resources, geothermal, converted
- cumulative energy demand | nuclear | non-renewable energy resources, nuclear
- cumulative energy demand | primary forest | non-renewable energy resources
- cumulative energy demand | solar | renewable energy resources, solar, converted
- cumulative energy demand | water | renewable energy resources, potential (in barrage water), converted
- cumulative energy demand | wind | renewable energy resources, kinetic (in wind), converted
- selected LCI results, additional | resource | water

Glossary

Biochar carbon stability factor The fraction of the organic carbon in the biochar that is stable in soil after a certain time has passed (1). The time frame used in this thesis is 100 years. 6

carbon dioxide removal factor The fraction of carbon from the feedstock that is stable in soil 100 years after biochar application to soil. 45

direct land use change Land use change at the place where the biomass is being produced in this context (26). 9

Heating rate Heating rate is the rate at which the temperature is increased to the process temperature and it has an effect on the yield and properties of pyrolysis products (25). 3

higher heating value "A measure of heat content based on the gross energy content of a combustible fuel" (85). 15

indirect land use change Land use change that is due to the direct land use change but happens elsewhere (26). 9

mineral soil "Soil composed principally of mineral matter, in which the characteristics of the soil are determined more by the mineral than by the organic content." (86). 11

organic soil "Soil with a high content of organic matter and water. The term usually refers to peat. The USDA defines an organic soil as one with a minimum of 20–30% organic matter, depending on the clay content." (87). 12

Positive priming Increased soil organic carbon mineralization following biochar addition to soil (1; 55; 26). 12

Residence time Residence time is the time which the process is held at peak temperature (11). 4