CHALMERS
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Combining biochar production, electricity generation and district heating at Händelöverket district heating plant

Assessing climate impact and economic viability through LCA and LCCA

Master's thesis in Industrial Ecology (MPTSE)

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Abstract

With recognition of the adverse effects of climate change, the IPCC has in a 2018 report put heavy emphasis on the need for carbon dioxide removal technologies to meet the global target of limiting global warming to 1.5 °C. There currently exists no one technology that can reverse the historical emissions of humanity, but instead there is a large spectrum of negative emission technologies. One of them is the process of turning biomass into a stable form of biochar through a pyrolyzing process, thereafter the biochar can be applied to agricultural fields to increase soil health and sequester the carbon in the soil. Pyrolyzing is the process of heating biomass in an anaerobic environment, dividing the biomass into three parts; biochar, bio-oil and synthetic gases. This thesis aims to determine the climate impact and the total cost of biochar production with subsequent soil application. Since large scale biochar production is in an early development phase, this is achieved by performing a life cycle assessment (LCA) as well as a life cycle costing assessment (LCCA). The chosen biochar production process was designed to pyrolyze wood residues ("GROT") and combine the process with electricity and district heating production at the E.ON-owned district heating plant Händelöverket located in Norrköping, Sweden. This was to utilize the residual heat that is generated when pyrolyzing biochar and utilize the existing boiler "P13" as the combusting chamber for the process, circumventing the need to acquire a new combustion chamber. A cradle-to-grave LCA was performed with the software OpenLCA and the results showed that the sequestered carbon dioxide heavily outweighs the emissions that are generated to produce and apply the biochar. An alternative case was explored where a standalone combustion chamber was utilized to maximize the amount of operation hours. The results showed that the alternative case had a higher climate impact per functional unit, but a lower climate impact on a yearly basis. The costs for the LCCA in the alternative case were higher per functional unit but lower on a yearly basis. A cradle-to-gate LCCA was performed according to existing LCCA methodology found in literature. The costs and revenue were split up in a best-case and worst-case scenario. The two categories with the largest spread between the best- and worst case were: difference in revenue due to uncertainties of the biochar density and auxiliary installation costs such as piping, electronics etc. An NPV calculation was performed and showed a heavily positive NPV for the best-case scenario and a slightly negative NPV for the worst-case scenario. A sensitivity analysis was done for biochar carbon content, initial moisture of the feedstock, transport losses, feedstock price and discount rate. It was concluded that biochar is a viable path to achieve negative emissions from an environmental and cost perspective. The existence of a market for the produced biochar is vital for keeping biochar production economically viable, and market studies show that there exists a small-scale market today with large potential for expansion in 5-10 years. More cost-efficient options to sequester carbon dioxide exists, but with additional benefits of applying biochar to soil such as improved structure, porosity, water retention capacity and microbial properties gives biochar a competitive edge. Electricity generation and district heating production from the biochar process also gives additional benefits to using this method as a negative emission technology.

Keywords: Biochar, Pyrolysis, Negative Emission Technology, Life Cycle Assessment, Life Cycle Costing, Wood residue

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Abbreviations

DM	Dry Matter
CDR	Carbon Dioxide Removal
CFB	Circulating Fluidized Bed
CHP	Combined Heat and Power
$CO_{2,eq}$	Carbon Dioxide Equivalents
EPA	Environmental Protection Agency
F.U	Functional Unit
GHG	Greenhouse Gas(es)
GROT	Grenar & trädtoppar (Branches & Treetops)
GWP_{100}	Global Warming Potential over 100 years
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCCA	Life Cycle Costing Assessment
NET	Negative Emission Technology
NPV	Net Present Value
O&M	Operating and maintenance
SEK	Svenska Kronor (Swedish Crowns)

1 Introduction

In 2018 the IPCC released a special report on the 1.5 °C global warming target. In this report it was recognized that: *"All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 GtCO2 over the 21st century."* (IPCC, 2018). To meet this target, different technologies to reverse emission are needed and one of these is the process of returning carbon to the earth through pyrolyzing biomass into a stable form of biochar and applying it to soils. In Sweden it's estimated that more than 1 000 000 tons $CO_{2,eq}$ per year can be mitigated by the use of biochar as a soil additive (SOU, 2020). This would, however, demand a large expansion of biochar producing infrastructure. Biochar has been produced for over a thousand years and one example of this is the "terra preta" (Black earth) that can be found in the amazon basin, indicating that biochar mixed with soil has created a particularly fertile layer of topsoil. However, it's only in recent years that its large potential as a Negative Emission Technology (NET) has been explored more thoroughly (Shackley, Ruysschaert, Zwart, & Glaser, 2016). Multiple studies have been done on the environmental and economic viability of biochar in different settings (Homagain, Shahi, Luckai, & Sharma, 2016) (Azzi, Karltun, & Sundberg, 2019) with varying results depending on choice of feedstock and utility of secondary effects, e.g. how much the residual heat from the pyrolyzing process that can be used. What has been shown is that from an environmental perspective, efficient climate mitigation is hard to achieve without using waste biomass as the feedstock input, which is also consistent with the findings in (Shackley, Ruysschaert, Zwart, & Glaser, 2016). Land requirement for biochar is low. It can be spread directly onto the soil, and since biochar can be utilized in soils for food crops, biochar carbon sequestration and food crop agriculture can be performed in the same space (Smith, 2015).

(Shackley, Ruysschaert, Zwart, & Glaser, 2016) reported biochar as having a large potential for economic development, environmental benefits and agricultural improvements, a so-called win-win-win situation. The expectations of these multi-benefits have been lowered in the last few years after trials and more recent scientific proof has shown that even if there is a large potential in biochar production technology, it has probably been overestimated in the years 2000-2010. There is, however, still a large potential for both biochar production and utilization. In Sweden, there could be a potential market for biochar for applications like soil improvement or animal feed additives. These quantities are, however, hard to define with only a theoretical market for animal feed being estimated to ~150 000 tons biochar per year and the soil additive market being unquantifiable but showing a willingness to pay at 2600-3000 SEK/ton (Avfall Sverige, 2018).

Reports on biochar that showcase specific conditions do exist, but there is a need for more detailed studies showing the Swedish context for biochar production, which is pointed out in (Avfall Sverige, 2018).

When timber is harvested from forestry activities, many parts of the tree are not used such as the branches and the top of the tree. In Swedish these parts are called "GROT" and have a low heating value due to moisture and is a cheap source of biomass. Due to these properties, GROT is an interesting feedstock to explore for biochar production since it's a waste product and would not require additional land-use for utilization in a biochar production facility.

Biochar and E.ON

E.ON is one of the largest energy solutions providers in Europe employing about 80.000 people. In Sweden, E.ON is managing waste energy recovery, electricity production and district heating in four major cities (Stockholm, Norrköping, Malmö and Örebro). Due to the availability of woody biomass in Sweden, an interest was sparked in the possibility of turning the biomass into biochar, enabling carbon sequestration simultaneously with electricity and district heat production.

In Sweden, biochar has recently received attention in the form of varying reports such as market research (Avfall Sverige, 2018) and has even gone as far as to be mentioned over 200 times in a national proposition for Swedish climate strategy for 2050 (SOU, 2020). The Swedish EPA is also issuing grants to startup biochar facilities which can cover up to 70% of necessary investment costs called "the climate step" (Naturvårdsverket, 2020).

Aim

The aim of the thesis is to show if the case of biochar production from forest residue in one of E.ON's district heating plants can contribute to a negative climate impact from a cradle-to-grave life cycle perspective and be economically viable from a cradle-to-gate life cycle perspective. The intended audience for this LCA is decisionmakers within E.ON with the intent of deciding how to go forward with Swedish biochar production. Other audiences include energy industry professionals, farmers, NET interested decisionmakers and citizens with a general interest in biochar, climate change or sustainability.

2 Background

2.1 Life Cycle Assessment

Life cycle assessment (LCA) is a tool to determine the environmental impacts that a product, good, service or activity has throughout its lifetime. LCA is standardized in ISO 14044 and 14040, which describes how to perform the different steps in an LCA.

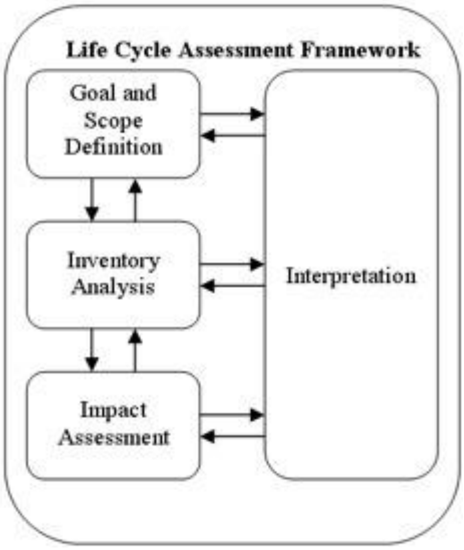

Figure 1: Life Cycle Assessment Process
Source: UNEP. Evaluation of environmental impacts in life cycle assessment. Meeting Report, 2003

Goal and Scope Definition is where the LCA is defined. The boundaries of the LCA are described as well as the intended application. In this step, the system is defined as well as the questions; what is being studied, why is it studied, where is the system located, how will it be modelled, and which specific question is the LCA trying to answer. A system description is constructed to describe the modelled system in its entirety and assumptions and limitations of the study is brought up. The functional unit is defined, which is used to determine the impacts of the studied item or activity based on a unit of its function, e.g. instead of describing the impacts of producing and using one liter of paint, the impacts of producing and using paint to cover 1 m^2 of area is described instead. A cradle-to-grave LCA means that the associated impacts are measured from where the raw material is extracted until where the associated materials finally ends up, such as incineration for energy or put in a landfill. The LCA can be attributional, consequential or a mix of the two. An attributional LCA determines that the presented results are treated as absolute, they are not presented in relation to any other results. An attributional LCA is appropriate when an LCA should determine the full impact of a product, e.g. determining the ecological footprint of a product for the purpose of displaying it on an ecolabel. A consequential LCA is change oriented in its nature, multiple variations of a process are considered, and the results are presented in relation to each other. A consequential LCA is appropriate for example when a production company can choose between multiple different production methods for a product and want to find out which of them has the lowest environmental impacts.

Inventory analysis is the part that collects all data needed for the LCA. The inputs and outputs of every activity are stated and quantified, examples of these are; electricity use, plastic use, chemicals used, transports and emissions to air, soil or water.

Impact Assessment is the part of the LCA that shows what the results are. Impact categories such as global warming, acidification or eutrophication are chosen depending on what the intentions of the study is. The results are classified depending on what impact they have, such as CO_2 and CH_4 both contributing to global warming. The emissions are then characterized, which means that they are translated into a comparable measurement, such as CH_4 emissions being expressed as $CO_{2,eq.}$

Interpretation is where the data, results and scope are evaluated continuously to more accurately fit the proposed initial research question. This is done iteratively along with the other steps and the LCA can be adjusted to more accurately describe the proposed system as the project gets more refined and accurate. The results of an LCA can be difficult to interpret so a discussion around the results is performed and presented to the audience.

2.2 Life Cycle Costing

Life cycle costing is a method to map all costs of a product or service over the span of its lifecycle. Costs in life cycle costing are usually referred to as internal and external costs. (Sigma, 2016). An LCCA is tied closely to an LCA and utilizes the same model when drawing the system boundaries.

Internal costs are costs that are purely economic and are incurred by the studied organization. **External Costs** are costs that are not directly associated with the production of the product or service. Such costs can be social or environmental and are commonly borne by local communities, the general public or other actors.

Net Present Value is a tool that is used in LCC to determine the cost effectiveness of a solution. It's implemented by calculating the discounted profit over a period and subtracting the initial investment.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

t = amount of time periods
C_t = Net cash inflow during period "t" (revenue – running costs)
C_0 = Initial investment cost
r = discount rate

LCCA reports of biochar are fairly scarce but do exist, such as (Homagain, Shahi, Luckai, & Sharma, 2016) which models the costs of biochar production from wood residue in Canada. The report borrows parts of LCA methodology but does not utilize the LCA steps in a "strict" sense, which this thesis is aiming to cover. Most reports that cover the economics of biochar don't explicitly mention LCCA as the utilized assessment method. However, the methodology for how to present costs, revenue and profitability of a biochar investment is similar to LCC even if it is not stated as peforming an LCCA, such as (Ahmed, Zhou, Ngo, & Guo, 2016) or (Keske, Godfrey, Hoag, & Abedin, 2019). The results from the aforementioned reports are compared to the results of this thesis in chapter 4.1.2.

2.3 Literature review of biochar and its effects

There exists a sizeable amount of literature on biochar and its effect on soils (Shackley, Ruysschaert, Zwart, & Glaser, 2016) (Tisserant & Cherubini, 2019), (Ding, liu, & Li, 2016), (Lehmann, Czimczik, Laird, & Sohi, 2009). Multiple reports that focuses on pyrolysis process parameters and its effect on biochar yield can be found and many of them from the last few years (Brownsort, 2009), (Hemlin & Lalangas, 2018), (Kesraoui, et al., 2019). Unfortunately, many of these studies are done on soil and agricultural conditions that are not representative of the conditions that are present in Sweden. This is highlighted in (Shackley, Ruysschaert, Zwart, & Glaser, 2016) and from current literature, even if soil health can be improved with biochar, one cannot draw a certain conclusion that biochar will increase plant growth in northern European soils, since this depends on which agricultural practices that are already utilized on the soil. This means that for the performed LCA, a general decrease in GHG emissions from an increase in crop growth cannot be expected. Market reports on biochar for

Swedish context are scarce and the main one is the report “the market for biochar in Sweden” (Avfall Sverige, 2018). Even if general biochar reports can be found, there is some scarcity for case specific biochar production systems, and their economic and environmental viability. This report is born out of an identified knowledge gap for more case specific studies regarding biochar in Swedish conditions, where general reports are more commonplace. This is to facilitate an increase in understanding of what environmental impacts and costs an entire biochar production system entail. Life cycle assessments of biochar commonly focuses on cradle-to-grave methodology to consider every aspect of the life cycle for presenting accurate results. This is not surprising as the final application of biochar heavily influences the overall results of the life cycle assessment (Azzi, Karltun, & Sundberg, 2019), (Tisserant & Cherubini, 2019). It is observed that life cycle assessment is a commonly used tool to estimate potential effects of biochar on climate, carbon sequestration potential, fossil fuel substitution and land use. In a review of 34 LCAs of biochar production and soil application, (Tisserant & Cherubini, 2019) shows that the result of LCAs can vary wildly, depending on input parameters such as the feedstock type and origin, type of end-of-life application and the pyrolysis conditions. Many LCAs do however utilize many similar assumptions about biochar production, such as biochar stability, reduced fertilizer use, reduced soil N_2O emissions, biochar yield effect etc. (Tisserant & Cherubini, 2019). This is also the case for this report with the exception of difference in climate change contribution from soils after biochar has been applied, which is omitted due to uncertainties of the effects on soil in northern European conditions (Shackley, Ruysschaert, Zwart, & Glaser, 2016). In the report by (Tisserant & Cherubini, 2019), it’s presented that the studied LCAs have a range of climate change emissions between 0,04 and -1,67 $tCO_{2,eq}$ per ton of feedstock. (Dutta & Raghavan, 2014) presents in an LCA that the largest contributor to a difference in climate change comes from the sequestration of the carbon in the soil. All other categories (transports, pyrolysis, co-benefits etc.) combined does not affect the results to the extent that the sequestered carbon does. This report will compare the results of the aforementioned reports with the results from this LCA, which is presented in chapter 4.1.1.
(Azzi, Karltun, & Sundberg, 2019) utilizes LCA to quantify the cascading effects of biochar on animal husbandry instead of studying its application on soil. The report gives a good overview of how the environmental benefits compares to each other when deciding how to utilize biomass, but it does also leave room for a consequential LCA to show the direct benefit of producing biochar which is the intention if this thesis.
This thesis aims to aid the existing literature with assessing both the climate impact and the cost of large-scale biochar production in the same model in alignment with standardized LCA methodology.

Carbon sequestration in soils from biochar
Carbon sequestration is the capture and storage of carbon, which otherwise would be emitted or remain in the atmosphere. Scenarios for most of the integrated assessment models include deployment of large-scale negative emission technologies to reach the 2-degree target. Studies have suggested that biochar has a useful negative emission potential of 0.7 GtCeq per year, with very low impact on land, water use, energy requirement and cost (Smith, 2015). Biochar is comparatively more recalcitrant than soil organic matter and thus has a high application rate to soil (Lehmann, Czimczik, Laird, & Sohi, 2009). Compared to other NETs for land-use, biochar has no competition as it can be added to managed land without changing its current use. The type of the soil and the climate region highly influences the soil carbon sequestration rate (Smith, 2015). When converting biomass to biochar and then adding it to the soil as an end use application increases the residence time of the carbon in the soil than when biomass is simply added directly. This is because the carbon in biochar is more stable and with increased residence time over a set timescale it leads to net withdrawal of atmospheric carbon (Lehmann, Czimczik, Laird, & Sohi, 2009). One of the drawbacks of carbon

sequestration with biochar is sink saturation. The negative emission potential of biochar decreases as a new carbon equilibrium is approached inside the soil (Smith, 2015).
The stability of carbon in biochar is one of the reasons why it finds its application in carbon sequestration. The carbon structure found in biochar is more recalcitrant than in the biomass due to its different spectrum of carbon compounds, which are more stable. Biochar is not a well-defined material with specific characteristics, and its physical and chemical properties highly depend on its production process and the type of feedstock. Therefore, there is no standardized method to calculate the stability of the biochar (Helena, 2019). It is important to know the stability of biochar for several reasons; how long will carbon be sequestered in the soil, where it is added to be considered as mitigation of climate change and for how long does the added biochar benefit the soil? (Lehmann, Czimczik, Laird, & Sohi, 2009)

The impact of biochar on soil health

Biochar has the potential to improve the soil at large scale as well as reducing greenhouse production levels. (Semida, Beheiry, Setamou, & Simpson, 2019). It is reported to have a positive influence on the soil's chemical and physical properties. When biochar is added to the soil, it enhances the soil's structure, porosity, water retention capacity and microbial properties. The improvements in production of crops and plant growth may be dependent on the chemical and physical properties of the biochar and soil (Ding, liu, & Li, 2016). There is a relatively small but statistically significant positive effect (approximately 10%) of biochar application on crop production in some experiments. Biochar impacts the soil nutrients by increasing or decreasing the bioavailability of these nutrients. This is achieved by reducing or increasing the emissions and leaching via sorption and retention (Tisserant & Cherubini, 2019). However, it is important to consider the uncertainties like the type of soil, biochar composition, amount of biochar added and longevity of the positive effects. Studies have shown that liming effect and water retention capacity are the two main domains of yield improvement (Jeffery, Verheijen, Velde, & Bastos, 2011). These properties of biochar are highly dependent on the pyrolysis temperature, residence time, type of pyrolysis and the type of feedstock used. While using biochar, selection of biochar composition, rate compatibility with crops and cropping system should be taken into consideration for maximizing positive effects.
A change in GHG emissions because of a change in plant growth is assumed to be non-existent because Northern European soils that already utilize modern agriculture practices haven't shown a significant increase in growth when applying biochar (Shackley, Ruysschaert, Zwart, & Glaser, 2016).

Relevance of elemental components of biochar

The elemental concentration of C, H, O, and N are one of the parameters to assess biochar production. H/C and O/C ratios are known to be used to measure the degree of aromaticity and maturation (Evelyn, Jeff, & ronald, 2009). These ratios are a function of the combustion conditions. The combustion conditions of importance are the temperature at which the charring takes place, the time for which the biomass is charred to produce biochar and the moisture content of the feedstock. GROT, which is used as the fuel, which is similar to wood char, is observed to have lower H/C and O/C ratios of about 0.54 and 0.32 at high temperature of 350 degree Celsius and prolonged heating. The composition of original biomass is retained if the biochar is produced below 500 to 600 degree C which affects the type of C and N released during weathering and the resistance of biochar to weathering process (Evelyn, Jeff, & ronald, 2009).
The ash content of the residues from charring is highly influenced by H/C and O/C ratios. High C content biochar produces lesser amounts of ash compared to low C content biochar. The efficiency of the charring influences the ash content of the residue. If there is complete combustion of carbon into to CO_2, this increases the ash content.

3 Methodology

3.1 Goal & Scope

System description – Base case

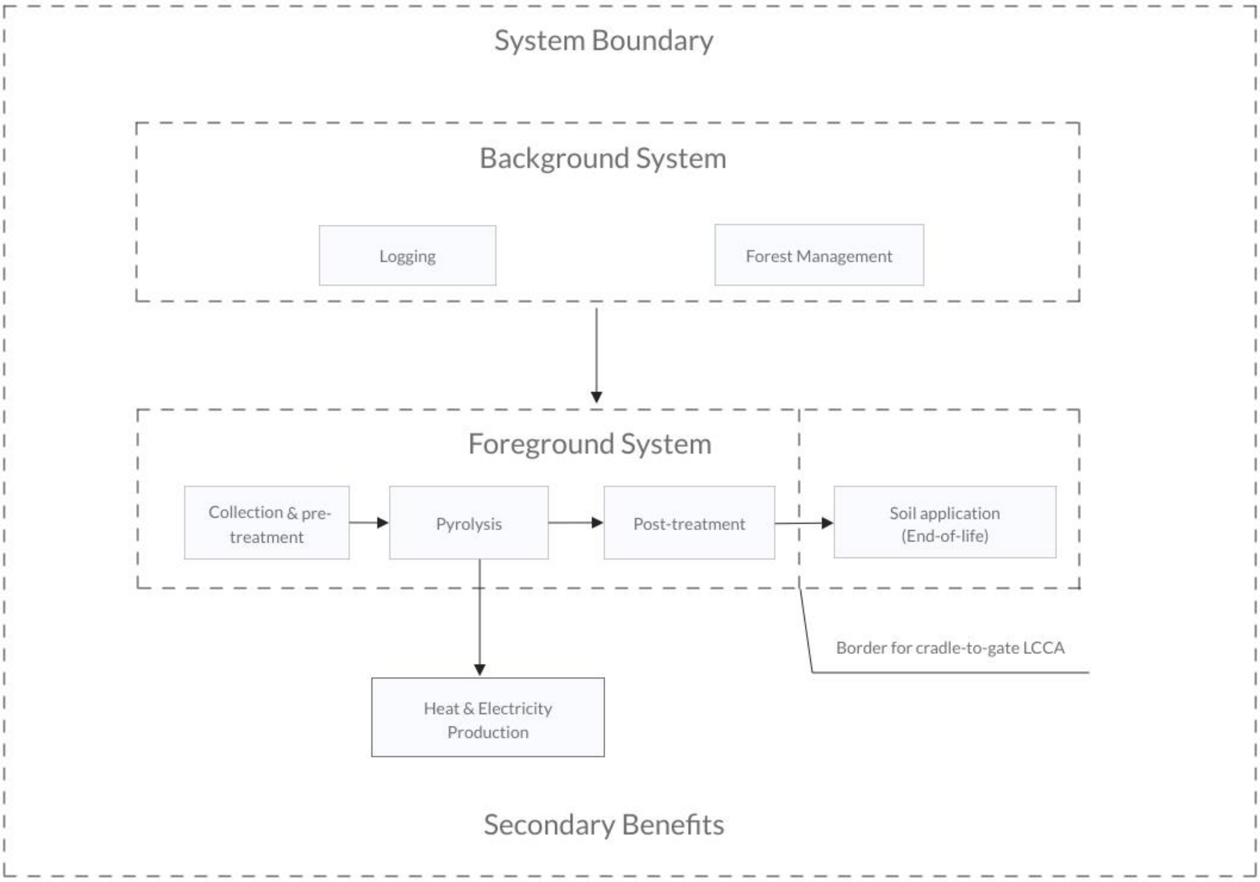

Figure 2: System boundaries for biochar production

GROT is collected as a by-product of forestry activities such as logging and are left on piles to dry for ~6 months until it reaches a moisture content of 30 wt.%. After 6 months all leaves and needles have decayed, and only twigs and branches remain. The ashes that are present in the feedstock are assumed to remain in the feedstock and subsequent biochar throughout the entire process. The GROT is sent to Händelö where it's grinded down to chip sized particles, dried to 15 wt.% moisture content and then pyrolyzed for 1 hour at 500 °C in a rotary kiln. The wood gases and vaporized bio-oil produced by the pyrolyzed biomass is sent to one of E.ON's biomass and waste fired boilers (boiler "P13") where the gas is incinerated, producing hot flue gases that are used to produce steam for electricity production and district heating, substituting direct incineration of GROT. This substitution is modelled with a system expansion. The flue gases that are normally produced in P13 are put through a flue gas condenser to maximize the heat that can be extracted. This flue gas condensation

is assumed to be negligible for the flue gases produced from incinerating syngas since the moisture content of syngas is low.
A fraction of the flue gas is redirected back into the rotary kiln to sustain the 500 °C environment needed to maintain the pyrolyzing process. The now cooled flue gas is then sent back into the boiler. A fraction of the low temperature steam coming out of the turbine is used in the drying process, the cooled steam is then sent to a condenser to produce district heating. The hot biochar is mixed with an amount of water equal to 30 % of the mass of the biochar to cool down and become more manageable. Due to the biochar's porous structure, the water is absorbed, and the total volume is maintained. The biochar is then packed in polyethylene bags and transported to farmers that can apply it to soil in the surrounding region. Then, the biochar is spread out and mixed in with the soil where it will remain for hundreds of years, releasing 20% of its stored carbon during the first 100 years. Environmental and economic impacts from change in crop growth from applying biochar to soils are excluded due to lack of proof for biochar use under Swedish conditions. GROT has an ash content of about 5% (Norin, 2020), which ends up in the final product and is applied to the soil with the biochar.
The process was chosen to be sized at producing 1 ton dry biochar/hour, contributing to around 5 MW of excess heat to the existing E.ON system. This number was chosen because it's relatively small compared to the connected boiler (130 MW) while still being large enough to be considered as large-scale biochar production, which is of intent to E.ON. The process is ongoing throughout the year with over summer when the boiler P13 is turned off due to low demand. The yearly uptime for the process is 5800 hours, this is particularly relevant when calculating the cost of equipment per functional unit.

LCA modeling method

The LCA is modelled with the open source program OpenLCA. This LCA will evaluate the environmental impact of biochar production from a cradle-to-grave perspective. It's determined that the most appropriate type of LCA for the purpose of biochar production from E.ON is an attributional LCA. This is due to one of the intended outcomes of the thesis being finding the possibility of biochar having a net negative climate impact. E.ON has expressed interest in exploring biochar and its possibilities for the purpose of decreasing atmospheric carbon, therefore it's most vital that the LCA can display a net effect on global warming without being compared to anything else. Biochar has many different factors that determine the efficiency of the process, such as; type of feedstock, pyrolysis temperature, residence time, utilization of secondary benefits, etc. These factors are explored in other papers (Hemlin & Lalangas, 2018), (Lopez-Capel, et al., 2016) and the purpose of this LCA is to show the absolute effects of a biochar production system with subsequent soil application.

LCC modeling method

The LCC is modeled after the methodology presented in (Sigma, 2016). The LCCA is performed as a cradle-to-gate LCCA due to the cost perspective of E.ON being of primary concern and for uncertainties regarding costs of the use phase (soil application). The implications of this methodological choice will be further discussed in chapter 5, when LCCA results have been presented. Cost for equipment are calculated and divided by the functional unit with the lifespan of the system considered. Variable costs are calculated as well. The expected revenue from selling biochar is calculated and the cost avoidance that stems from supplying the boiler P13 with syngas to avoid direct burning of GROT is calculated through a system expansion. All costs and revenue are subjected to an NPV test to assess the profitability of the investment. Since cost and revenue assessment are complex, all values are presented as a “best-case” and a “worst-case” scenario, named “low bound” for the worst-case scenario (high costs and low revenue) and “high bound” for the best-case scenario (low costs and high revenue). All numbers for costs and revenue are presented without taxation. At the date of writing, the exchange rate for USD to SEK 9,93. It’s rounded to be 10 SEK/USD throughout the report.

Functional Unit

The functional unit is defined as 1 000 kg dry and packed biochar that is applied to fields. The purpose of choosing the functional unit as a weight is due to the purpose of the LCA being to explore if biochar production can be utilized as a negative emission technology. While the purpose of biochar can be argued to be improvement of soil, this LCA takes the viewpoint of the producer, E.ON.

Geographical and temporal system boundaries

The CHP plant Händelöverket is located in the middle of the Swedish city Norrköping. The feedstock that is used in the CHP plant is sourced from nearby wooded areas and the biochar can be utilized by local farmers as shown in the associated map. Thus, a geographical boundary of a 100 km radius originating from Norrköping is used. 30 years is used as a temporal boundary. This was determined according to the expected lifespan of the equipment. As large-scale biochar production is a relatively new technology, the production method is expected to change within 30 years as well. The efficiency of the system is assumed to remain at 100 % throughout its entire lifespan.

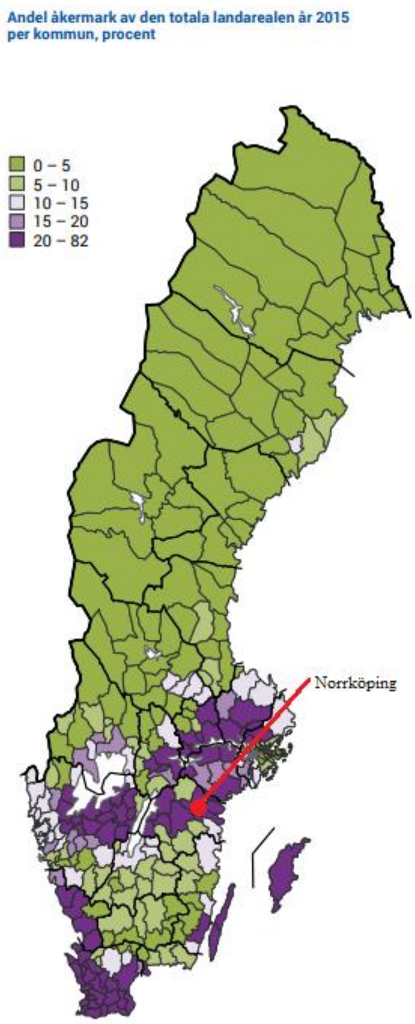

Figure 3: "Percentage of farmland compared to the total available land area per municipality (2015)" Source: The Swedish Agricultural Agency (data) and the Swedish Central Statistical Agency (Map)

Data Quality Requirements

Primary data are sourced from internal E.ON documentation and operational data. The data can be written or communicated directly by E.ON staff. Regarding the biochar production process, where E.ON does not have as much experience, data are mainly sourced from published journal articles, preferably relating to Swedish conditions for producing or applying biochar. Master’s and bachelor’s theses are utilized, as well as the database of Ecoinvent. Orally communicated sources in those theses are accepted as data input in the LCA if no other sources for the required data input can be found.

Impact Assessment method, Classification and Characterization

The chosen impact assessment method is IPCC 2013. This method was chosen due to it being based on the thorough report on climate change from the IPCC (Stocker, 2013) and its wide use as a basis for calculating global warming potential for other lifecycle impact assessment methods (ESU-services Ltd., 2020). Impacts are classified and categorized according to the IPCC 2013 framework.

Impact Categories

The studied category is global warming, expressed in the LCA as kg $CO_{2,eq}$. While other impact categories could be of importance (e.g. land-use for biomass cultivation or eutrophication) they are outside of the intended scope of this attributional LCA. The ambition for this LCA is to accurately model carbon sequestration and $CO_{2,eq}$ release to study if biochar production and soil application will have an absolute negative GWP and strengthen its position as a NET.

Delimitations
Biochar has many different uses (Schmidt & Wilson, 2014), but for the purpose of this LCA, the only application will be biochar as a soil additive.
Environmental impact from physical capital (machines, facilities etc) are not included as to narrow the scope of the LCA.

Treatment of secondary benefits
The LCA includes a system expansion to accurately model the benefits that are brought from producing electricity and district heating. This is done by subtracting the environmental impacts from direct incineration of GROT that would become electricity and district heating along with upstream processes.

System description - Alternative case
Due to variability in heat and electricity demand over the year, the boiler P13 is not always running. Uptime for P13 can be found in Appendix B.

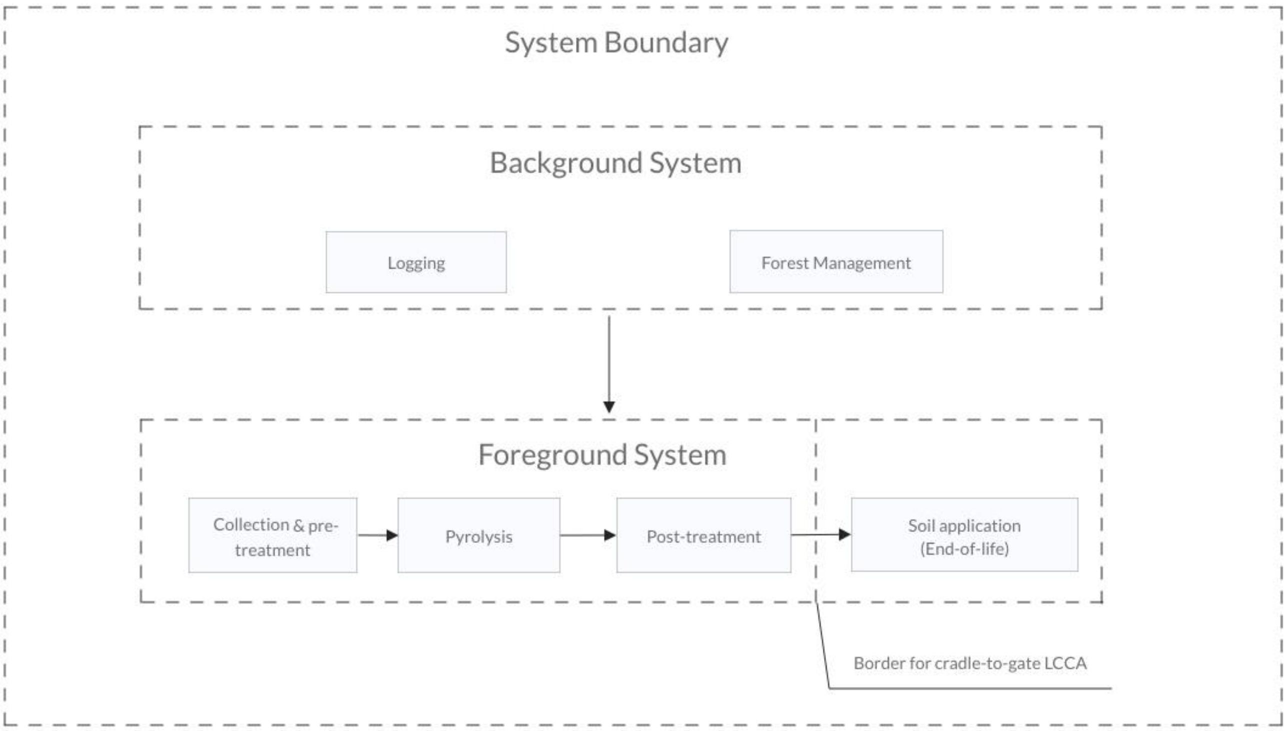

Figure 4: Alternative case system boundaries, summer production

To study the benefit of running the pyrolysis approximately from May to September (when there is low demand for heat and electricity and P13 is turned off), an alternative case with a standalone combustion chamber is analyzed. Therefore, the LCA and LCC for the alternative case will not consider any co-benefits from heat and electricity production, to accurately model the case of running the biochar production while P13 is turned off. However, on a yearly basis, P13 can still be utilized even with standalone combustion when its operational. Therefore, when calculating yearly emissions and NPV, co-benefits and the system expansion performed in the base case is applied, but for the purpose of calculating emissions per functional unit for summer production, there are no co-benefits. These time periods are applied to both the LCA and LCCA when calculating yearly values. On a yearly basis, it's assumed that approximately 2 weeks of downtime is required for maintenance. Therefore, the yearly uptime is estimated to be 8400 hours, whereas 5800 of these are hours that can supply heat and electricity for co-generation.

3.2 Inventory Analysis

Flowchart

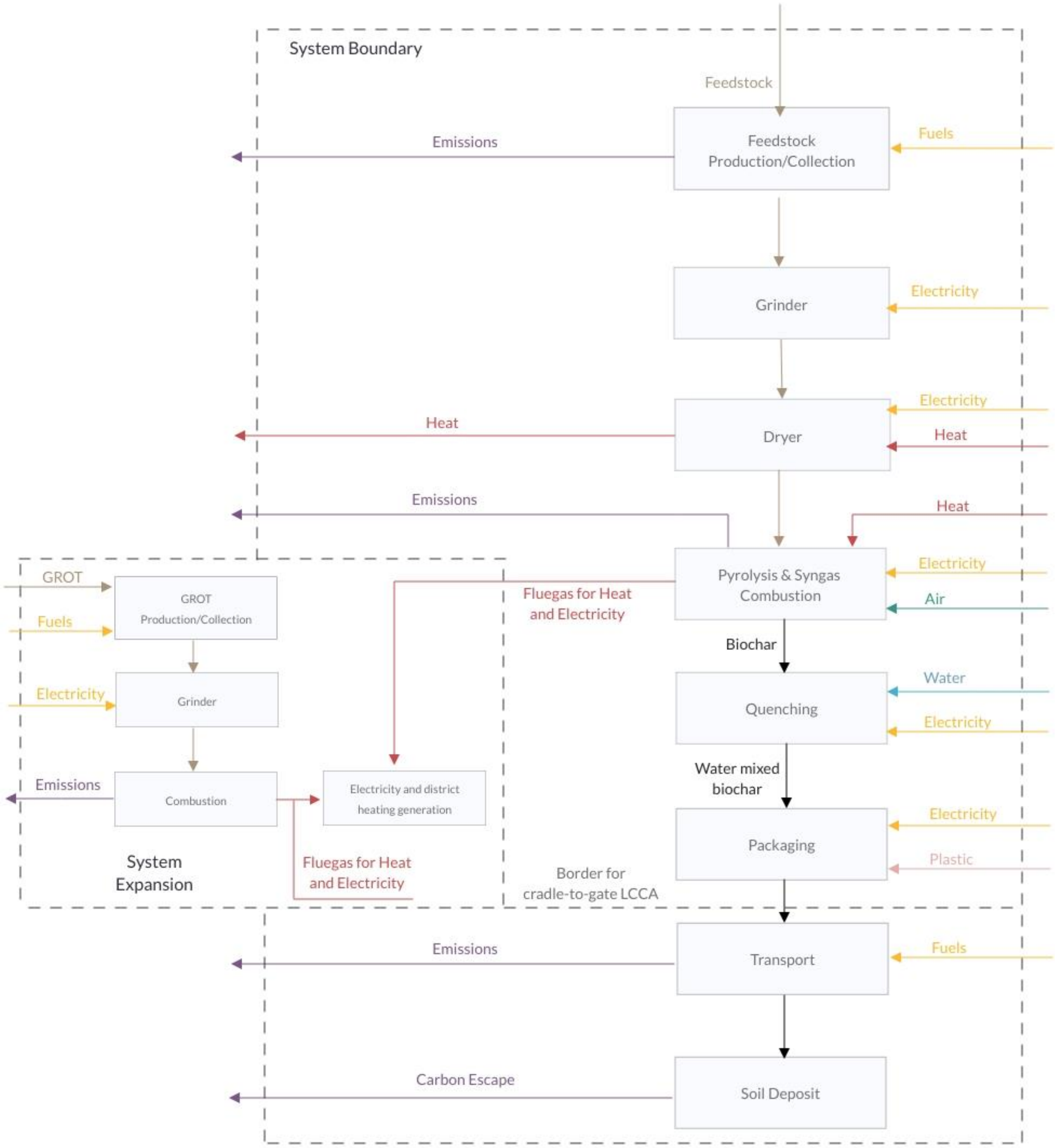

Figure 5: Biochar production flowchart

Feedstock collection & transports

GROT is transported by diesel fueled lorry 100 km to Händelö. (Norin, 2020). 29 wt.% of the feedstock (DM) will by pyrolyzed into biochar (Brownsort, 2009) 5473 kg GROT is required (Appendix A). It is assumed that 10% of collected GROT is lost during transportation to Händelö.

Activity	
Feedstock demand	5473 kg per ton produced dry biochar (Appendix A)
Feedstock transport distance	100 km
Feedstock cost	180 SEK per MWh GROT (Norin, 2020)

Grinding

The particle size of the feedstock can have significant impact on what percentage of the feedstock is pyrolyzed into biochar instead of bio-oil or syngas, and since the purpose of the process is to yield biochar the most appropriate particle size should be chosen. In experiments it's shown that the biochar fraction yielded from pyrolysis increases with an increased particle size up to 20 mm (maximum studied size) (Wang, Kersten, Prins, & Swaaij, 2005). However, as highlighted in (Antal M. J., 1985) the chemical interactions in particles that sizes >5 mm are complex and relate to internal heating rates, pressure, absolute temperatures, and secondary reactions. It Is assumed that rough grinding of the feedstock into forestry slivers is sufficient for the scope of this LCA.

Activity	
Electricity requirement for feedstock grinding	17 MJ per ton produced dry biochar (Appendix A)
Electricity cost	400 SEK per MWh electricity (Vattenfall, 2020)
Grinder investment cost	1 MSEK (Thunman, Lind, & Johnsson, 2008)

Drying

To pyrolyze the feedstock, the water content needs to be evaporated for the cascading reactions to occur. The wetter the feedstock entering the pyrolysis kiln is, the more energy is needed to pyrolyze the feedstock since vaporizing the water is energy demanding. Therefore, it's a logical step to dry the feedstock prior to the pyrolyzing step utilizing a lower temperature heat instead of the more valuable high temperature heat that is required for the pyrolysis. The presence of moisture in the pyrolysis process has, however, shown to increase the biochar fraction of the pyrolyzed feedstock (Antal & Grønli, 2003), while dried feedstock has been shown to increase the bio-oil fraction (Thunman, Lind, & Johnsson, 2008). Previous studies of large-scale commercial biochar production systems have utilized the residue heat from the pyrolysis step as an input into the drying step (Kesraoui, et al., 2019), but there are also real world cases of the feedstock being fed directly into the pyrolysis without any prior drying (Gustafsson M. , 2013), (Söderqvist, 2017). The feedstock entering the facility has a moisture content of 30 wt.% and is dried to 15 w.t% in a drying step prior to the pyrolysis. The drying requires 3138 MJ of energy (Appendix A) per ton of produced biochar which is supplied by low temperature steam. Before being utilized for drying, the steam is used for electricity and district heating generation, lowering its temperature, since low temperature steam is appropriate for drying and high temperature steam is more suitable for electricity and district heating production. To reduce the complexity of the drying process the specific heat capacity of water vapor is assumed to be constant throughout the entire process.

Activity	
Electricity requirement for feedstock drying	70 MJ per ton produced dry biochar (Appendix A)
Heat requirement for feedstock drying	3138 MJ per ton produced dry biochar (Appendix A)
Electricity cost	400 SEK per MWh electricity (Vattenfall, 2020)
Dryer investment cost	11-13 MSEK (Thunman, Lind, & Johnsson, 2008)

Pyrolysis and syngas combustion

Pyrolysis in Greek, Pyro = fire and lysis = breakdown/separation. Pyrolysis is the thermal decomposition of organic matter at a high temperature in absence of air. Pyrolysis of biomass leads to formation of three final products; syngas, bio-oil and biochar (Dhyani & Bhaskar, 2019). Pyrolysis takes place in a pyrolytic reactor. Inside the reactor the first stage is the moisture evaporation where all the moisture accumulated is evaporated to initiate the carbonization stage. Depending on the type of feedstock and the drying step, this stage can take up to a few minutes. The next stage is the degasification stage where the temperature is maintained between 370 to 400 degree Celsius and the removal of volatile particles like nitrogen, carbon monoxide, carbon dioxide and hydrogen are the most efficient. These gases are flammable and are a mixture of gases called synthetic gas, commonly dubbed syngas, which can be further used for energy production. The next stage is the carbonization, where the dried and degasified biomass is subjected to high temperature. Such conditions lead to disappearance of fibrous structures and a higher concentration of elemental carbon. Thus, the char is formed. The calorific value of the char depends on the temperature maintained in the reactor and the length of the carbonization stage.

The bio-oil created in the pyrolysis step exists in gas form due to the high temperature conditions and is combusted along with the syngas, which is consistent with research shown in (Bojler Görling, 2012) and the Pyreg small scale biochar plant studied in (Söderqvist, 2017).

The produced biochar has a carbon content of 80%. The remaining 20% consist of ashes and other elemental residues.

Activity	
Heat requirement for pyrolysis	16 449 MJ per ton produced dry biochar (Appendix A)
Electricity requirement for pyrolysis	70 MJ per ton produced dry biochar (Appendix A)
Biochar carbon content	80 %
Combustion emissions	**Emissions per ton produced dry biochar (Appendix A)**
N_2	6890 kg
CO_2*	2578 kg
H_2O	1916 kg
SO_2	1,1 kg
NO_2	0,34 kg
Other gases:	21 kg (disregarded in LCA model)
Electricity cost	400 SEK per MWh electricity (Vattenfall, 2020)
Rotary kiln pyrolizer investment cost	70-100 MSEK (Gustafsson M. , 2020)

*CO_2 is treated as a biogenic emission and will therefore not be a factor when calculating the GWP of the biochar process but is added for transparency.

Substituting fuel for electricity & district heating production

Remaining flue gases that are not utilized by the pyrolysis process are used to generate electricity and heat. The boiler P13 is fired with a mix of 25% rubber, 25% waste wood and 50% GROT. GROT is the most expensive fuel type that is used in the boiler and as such is the one that will be replaced. The amount of replaced GROT is modelled with a system expansion that accounts for impacts of combusting GROT and associated upstream processes for the GROT. After utilizing part of the energy for the drying and pyrolyzing process, 1533 kg GROT can be substituted. Revenue gained from this activity is defined as the avoided cost of purchasing GROT for direct combustion.

Activity	
P13 GROT substitution	1533 kg per ton produced dry biochar (Appendix A)
GROT substitution cost avoidance	180 SEK per MWh (Norin, 2020)

Quenching

The hot biochar coming from the pyrolysis process is subsequentially mixed with water to make it more manageable and easier to transport. One research paper shows a common value to be between 10 wt.% and 50 wt.% water content (Brewer & Levine, 2015), and other studies have utilized a final moisture content of 30 wt.% in the biochar (Hemlin & Lalangas, 2018) (Shackley, Ruysschaert, Zwart, & Glaser, 2016). 30 wt.% is used in this LCA which means the amount of required water will be 429 kg (Appendix A). Biochar has an incredibly porous structure, and can absorb water up to six times its own weight (Lopez-Capel, et al., 2016), keeping the volume constant and increasing the density.

Activity	
Water requirement for quenching	429 kg per ton produced dry biochar (Appendix A)
Pump electricity demand	0,18 kWh per ton produced dry biochar (Appendix A)
Water cost	7,4 SEK per m^3 water (Nodra, 2018)
Electricity cost	400 SEK per MWh electricity (Vattenfall, 2020)

Packaging and sale of biochar

Packaging is modeled after packaging used for transporting fertilizers, where 2 grams of polyethylene is required to ship 1 kg of product. The electricity use for wood packaging is assumed to be equal to that of packaging wood pellets, leading to 2,57 MJ of electricity (Appendix A).
Since the price of biochar is defined by volume, the density of biochar must be known to calculate the total revenue. Biochar density is not an obvious matter since there are different ways to define biochar density. The different densities are defined as; skeletal density, bulk density and envelope density (Brewer & Levine, 2015). This report utilizes bulk density, which is defined as the volume that is required to contain a specific amount of biochar, with the air in between the biochar pellets being included. This is chosen due to it being the way that the biochar would be weighed on the industry floor i.e. packed in bags that are put directly on a scale.

Activity	
Polyethylene requirement for packaging	2,86 kg per ton produced dry biochar (Appendix A)
Electricity requirement for packaging	2,57 MJ per ton produced dry biochar (Appendix A)
Packaging material cost	0,83$ per 2 cb.ft biochar (PolyPak, 2020)
Electricity cost	400 SEK per MWh electricity (Vattenfall, 2020)
Packaging machine investment cost	1 MSEK (Assumption)
Biochar revenue from sales	2600-3000 SEK per m^3 biochar (Avfall Sverige, 2018)
Biochar density	0,28-0,44 ton/m^3 (Brewer & Levine, 2015)

End application of biochar

The biochar is transported 100 km by small lorry to local actors in the region which use the biochar to apply it to agricultural soil.

Activity	
Amount of transported packed biochar	1432 kg per ton produced dry biochar (Appendix A)
Packed biochar transport distance	100 km

Sequestration and stability of biochar

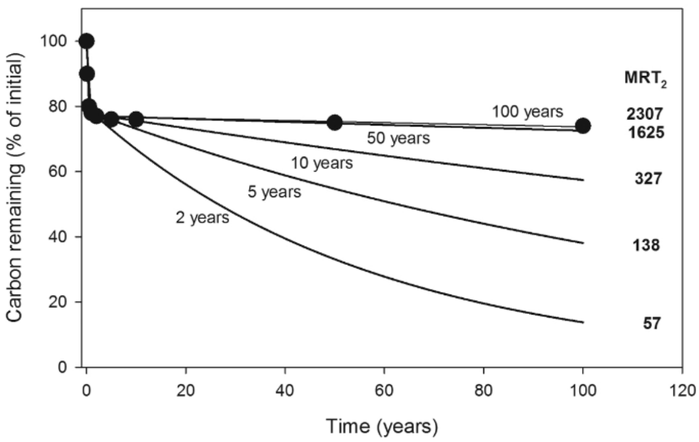

Figure 6 : Double-exponential model for recalcitrance of biochar after 100 year (Lehmann, Czimczik, Laird, & Sohi, 2009)

There is ample scientific evidence that clearly states biochar is the most stable form of organic matter that could be added to soil. When the organic matter is converted to biochar by pyrolysis, there is a change in the composition. The cellulose and lignin are destructed completely to form aromatic structure which significantly increases the recalcitrance of C in biomass (Lehmann, Czimczik, Laird, & Sohi, 2009). Fig. 6 is a double exponential model for the carbon remaining in the soil over a period of time, for hypothetical data of biochar decay after 0.1, 0.5, 2, 5, 10, 50 or 100 years after biochar application. We can conclude that carbon remaining after 100 years, for stable environmental conditions has a recalcitrance value of about 80%, implying that 80% of the applied biochar will remain after 100 years. The calculation is a simpler way of presenting a complicated decay process and hence there are uncertainties related to this value which are discussed further in chapter 5.

Activity	
Carbon leakage during the first 100 years	20%
Carbon remaining in soils after 100 years	640 kg per ton produced dry biochar (Appendix A)

Additional investment costs
In addition to direct equipment cost, labor and auxiliary equipment also goes into installing the equipment in the form of labor, piping etc. Due to these costs being particularly varied from project to project, a broader range of costs have been utilized when compared to the somewhat static costs of equipment.

Equipment	
Installation costs	6-14 % of total equipment cost (Peters & Timmerhaus, 1991)
Instruments & controls costs	2-8 % of total equipment cost (Peters & Timmerhaus, 1991)
Piping costs	3-20 % of total equipment cost (Peters & Timmerhaus, 1991)
Electrical costs	2-10 % of total equipment cost (Peters & Timmerhaus, 1991)

Additional running costs
Cost of labor are based on a biochar plant in Stockholm of roughly twice the size of the one in this report. This potential overcapacity of labor is assumed to cover the extra step of bagging and loading the biochar that is presented in this report but missing in the labor costs of the larger plant.

Activity	
Labor cost	502 SEK/operation hour (Kesraoui, et al., 2019)

End of life costs

Activity	
Decommission costs	2 MSEK (Lind, 2020)*

*based on decommission of 16 MW CFB boiler at Chalmers university of Technology

External costs

External costs are absent in this LCCA due to it being defined as a cradle-to-gate LCCA. An external cost or benefit in a cradle-to-grave LCCA could be the difference in plant growth that happens due to biochar being applied to soils. However, when applied in the Northern European region, there is no guarantee that the plant growth will change (Shackley, Ruysschaert, Zwart, & Glaser, 2016).

3.3 Alternative case: seasonal variation & standalone combustion

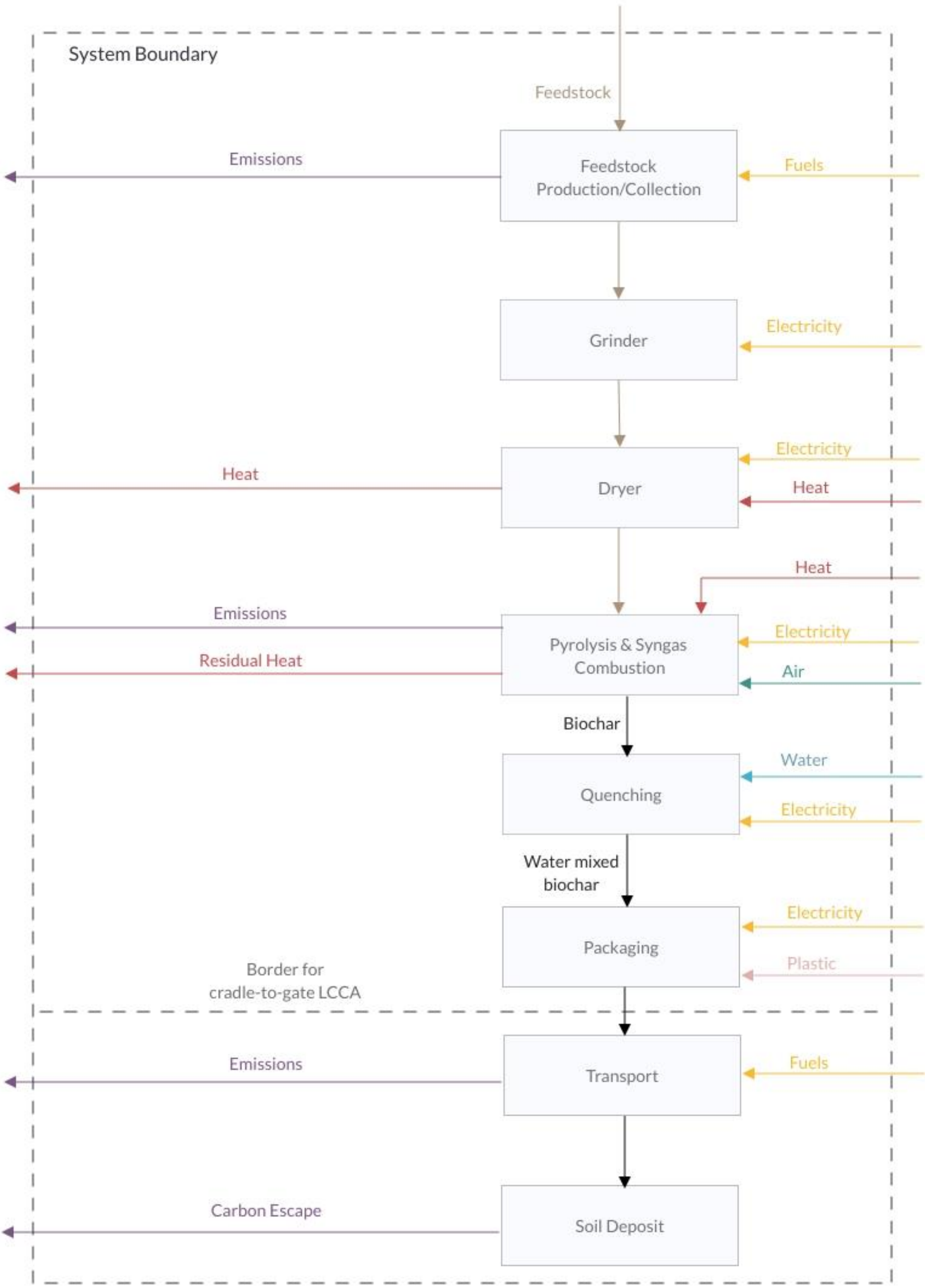

Figure 7: Biochar production alternative case flowchart (summer production)

Since the boiler P13 is shut down during the summer months, the biochar process cannot be carried out because the combusting step is inaccessible. The standalone combustion would supply the boiler with hot flue gases during the warming period and vent the heat during the summer period. In this alternate case, the summer period is the studied timeframe. The process is identical to the base case with the exception of the system expansion being absent.

Additional investment costs

Equipment	
Combustion Chamber investment cost	11-13 MSEK (Thunman, Lind, & Johnsson, 2008)

4 Results

4.1 Base case Results

4.1.1 Climate Change

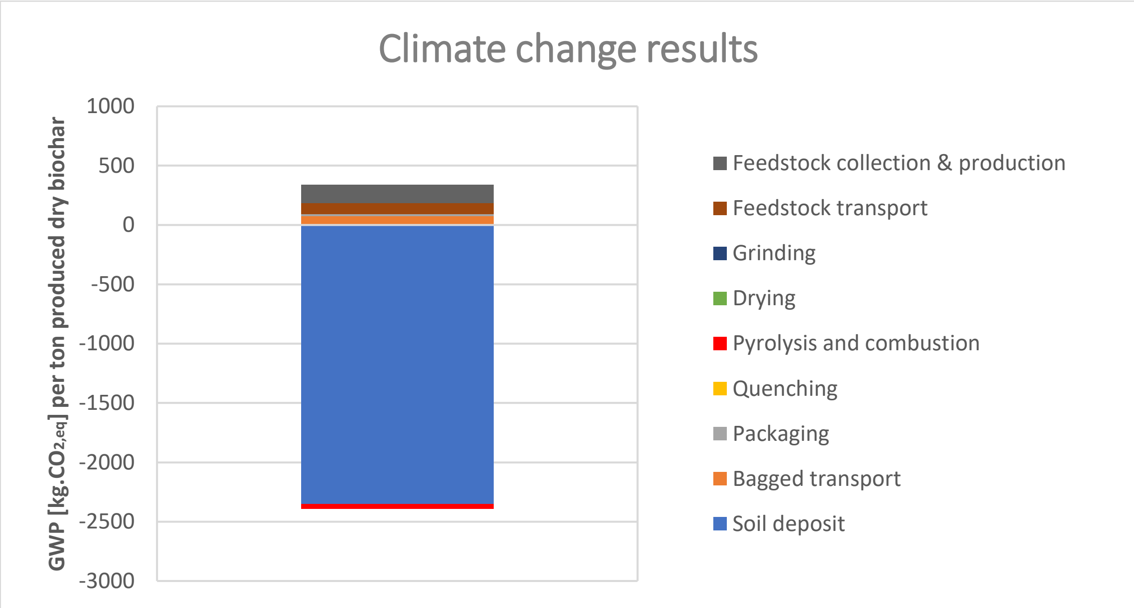

Figure 8: Climate change contribution breakdown

Base case climate change results	
Climate change per ton produced dry biochar	-2053 kg_{CO2eq}
Yearly climate impact*	-11,9 kt_{CO2eq}

*Based on 1 ton biochar produced/h, 5800 h per year

As can be seen in figure 8, carbon sequestration from the soil deposition overshadows the other steps in the LCA. What can be noted is that the emissions from pyrolysis and combustion is negative. This is due to the GROT that is being substituted in the system expansion and the feedstock being of biogenic origin. Meaning that the syngas doesn't contribute to an increase of atmospheric fossil CO_2 when it's combusted. Transports for the GROT in the system expansion were not included in OpenLCA. This does however not have a significant impact due to it being the same calculation as the feedstock transport step, while only concerning roughly one third of the feedstock that is present in the feedstock transport step. This correction would change the result with roughly 1% in a positive direction.
(Tisserant & Cherubini, 2019) shows a range of 0,04 to -1,67 $tCO_{2,eq}$ per ton of feedstock when comparing 34 LCAs of biochar production with soil application. Converting the functional unit of this report to $tCO_{2,eq}$ per ton of feedstock gives a result of -0,38 $tCO_{2,eq}$ per ton of feedstock. -0,38 $tCO_{2,eq}$ per ton of feedstock is a worse result than the average of the LCAs in (Tisserant & Cherubini, 2019), the reason for this result is most likely due to multiple LCAs in (Tisserant & Cherubini, 2019) accounting for a reduction in soil emissions when biochar is applied, which this LCA has omitted due to the uncertainties of applying biochar in northern European conditions, which is highlighted in (Shackley, Ruysschaert, Zwart, & Glaser, 2016). (Tisserant & Cherubini, 2019) also reports that the

majority of the studied LCAs produces a net negative climate change from avoided emissions due to fossil fuels being replaced with bio-oil and syngas, with most LCAs showing a reduction of 0,2-0,4 $tCO_{2,eq}$ per ton of feedstock. This is not the case for this LCA since no fossil fuels are replaced in the system and the avoided emissions are in the form of GROT substitution that is accounted for in P13. Converting the functional unit of this report again gives a result of -0,008 $tCO_{2,eq}$ per ton of feedstock in reductions from avoided emissions, which is significantly lower than most LCAs in (Tisserant & Cherubini, 2019).
(Dutta & Raghavan, 2014) presents results with similar relations between the contributing categories for climate change when compared to this report. The LCA by (Dutta & Raghavan, 2014) is a short, comparative LCA and therefore the methodological choices and inventory is not as extensively presented as they are in the LCA presented in this thesis, which makes finding the reason for the similarities difficult. However, the similarities of the relation between categories in results does likely stem from similarities in the methodological choices.

The role of carbon sequestration and stability
The amount of sequestered carbon from applying biochar to soil is determined by the formula: *"Net stable carbon stored (as tC per oven dry ton feedstock = char yield (t per oven dry ton feedstock) × carbon content of char x Carbon Stability Factor"* (Shackley, Ruysschaert, Zwart, & Glaser, 2016). This can be phrased as three questions that this report needed to find answers for in existing literature to maximize the amount of carbon that is stored in the soil:
1. How is the biochar yield from the feedstock maximized?
2. How is the fraction of carbon that is transformed into biochar maximized?
3. How is the biochar that is applied to the soil made to be as stable as possible?

Questions one and two are both determined by pyrolysis temperature and residence time. The optimal temperature and residence time for this is likely to be around 400-500 °C and a residence time of a few minutes (Brownsort, 2009). However, the residence time is also an important factor for making the biochar stable, and while a few minutes does yield more biochar, it also makes the biochar less stable than if the residence time would be increased to about 1 hour. This makes the task of maximizing all three factors in the aforementioned formula a balance act between the optimal residence time, pyrolysis temperature, feedstock chip size, feedstock type and feedstock moisture content. This is further explained in chapter 3.2. For the stability of the biochar, the elemental constitution of the biochar is of high importance. A low H/C and O/C ratio is preferable (Hemlin & Lalangas, 2018), which is determined by the type of feedstock as well as the pyrolysis parameters. In the performed LCA these parameters have been evaluated based on existing literature and process parameters has been chosen to fit the purpose of maximizing carbon sequestration from pyrolyzing GROT. This is also explained further in chapter 2.4. However, due to the unknown interactions between the parameters and the uncertainty of how they affect each other, it's recommended to be cautious and not rely too much on theoretical estimates. Samples from the process should be taken and evaluated with parameters adjusted for an optimal process. For future estimates of carbon sequestration possibilities, a range between worst-case and best-case scenario was deemed appropriate to present instead of one final figure. The reasoning for this is due to the unstable nature of pyrolysis and the lack of real-world cases of large-scale biochar production. One possibility for improving the LCA results is to utilize a so-called flue gas condensation system to extract energy out of the evaporated feedstock moisture. If such a system would be implemented the initial feedstock moisture would not be as detrimental to the end results, since the energy in the evaporated moisture will be recovered when the steam condenses in the flue gas condenser. This is however only applicable to when secondary benefits of the system can be utilized, i.e. in the base case.

4.1.2 Costs and revenue

Due to the uncertain nature of costs and the variables that affects them, a range of costs is used instead.

Low bound = highest costs and lowest revenue, “worst case”

High bound = lowest costs and highest revenue, “best case”

Biochar costs

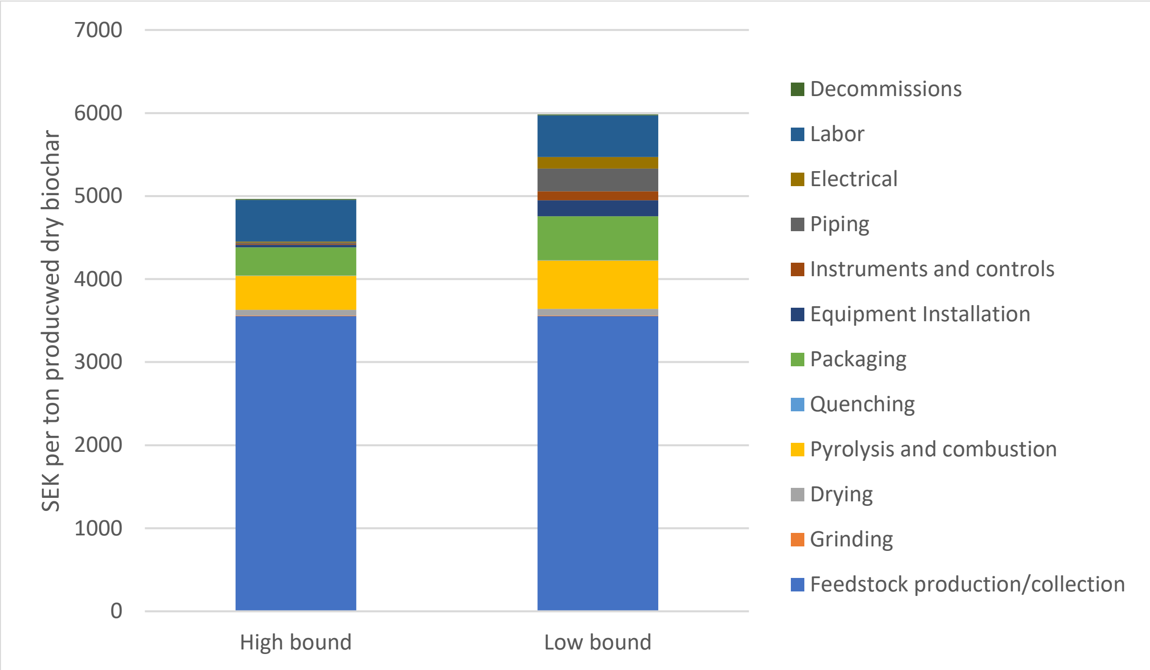

Figure 9: Base case - Life cycle costs

The results show that there is not a large difference in costs between the best- and worst-case scenarios. The main difference comes from the cost of the auxiliary installations electrical, piping, instruments & controls and installation. When combining the costs for biochar production with reductions in $CO_{2,eq}$ the range of 2418-2914 SEK/ton $CO_{2,eq}$ is achieved. When comparing the results with the presented results in (Homagain, Shahi, Luckai, & Sharma, 2016), the most striking difference is between pyrolysis cost and feedstock cost. (Homagain, Shahi, Luckai, & Sharma, 2016) shows that 36% of the costs in their report are due to pyrolysis, while only 12 % are feedstock costs. Unfortunately, the report by Homagain doesn’t relate the costs to a functional unit which complicates the comparison between the results. The report mentions that the utilization of forest residue would be a relatively new business, which could explain why the feedstock costs are relatively low compared the results shown in this report.

(Keske, Godfrey, Hoag, & Abedin, 2019) presents a result for cost of biochar production around 500 USD/Mg biochar for both fixed and variable costs. Converting this to SEK with June 2020 exchange rates, the results end up being about 4700 SEK/ton, which is similar to the results presented in this LCCA.

Comparing these results to the economic assessment of biochar performed in (Ahmed, Zhou, Ngo, & Guo, 2016) is difficult due to Ahmed et. al not presenting a final figure for the total cost of biochar production with subsequent soil application. However, the methodology used is similar to the LCCA methodology used in this report, with the exception of (Ahmed, Zhou, Ngo, & Guo, 2016) going into more detailed factors regarding market forces, such as policy influence.

Effectiveness of biochar as a NET

Producing biochar at a cost between 2418-2914 SEK/ton $CO_{2,eq}$ is not a particularly cost effective carbon mitigation method when comparing to other methods.

Negative Emission Technology	**Cost per ton $CO_{2,eq}$ [SEK]**
Bioenergy Carbon Capture and Storage (BECCS)	1000-2000
Direct Air Carbon Capture and Storage (DACCS)	1000-3000
Afforestation and re-forestation	50-500
Enhanced weathering	500-2000
Ocean Fertilization	0-4600 (uncertain)
Biochar	300-1200
Soil carbon sequestration	0-1000

Costs of NETs (Sabine, et al., 2018)

The largest cost of biochar production identified in this LCCA is the cost of feedstock. This cost could drastically be reduced by utilizing unwanted waste instead of GROT. GROT can be directly incinerated for heat and electricity production and is for this reason sought after by other actors. However, that would come with a large uncertainty in what constitutes the feedstock and could lead to an unreliable biochar product which may not sequester the same amount of carbon. Still, one of the greatest strengths of biochar is that it can be sold as a product, generating revenue for the producer. In the LCCA presented in this report it's identified that it's likely that the biochar production process will yield a positive NPV. The assumption is that the buyer will purchase the biochar on the premise that the effects of biochar is worth the cost, even if the carbon sequestration doesn't play a role. In the future there's a possibility that biochar can be a part of a carbon reduction credit system. If this would be the case, then if the buyer would benefit from the credits, the attractiveness of the biochar will increase. At the time of writing the EU ETS price is about 250 SEK/ton CO_2 (Markets Insider, 2020). This would correspond to about 500 SEK per ton of produced biochar, which would cover around 20% of the costs, and the Swedish carbon tax is currently at 1 190 SEK/ ton CO_2 (Swedish Government, 2020), corresponding to about 2400 SEK/ton biochar which would cover almost all costs for production.

There is also a possibility of getting a public grant of up to 70 % of investment costs for the biochar production facility (Swedish EPA, 2020). Dubbed "the climate step", this program aims to steer the industry towards a more sustainable production and could drastically reduce costs.

Biochar revenue

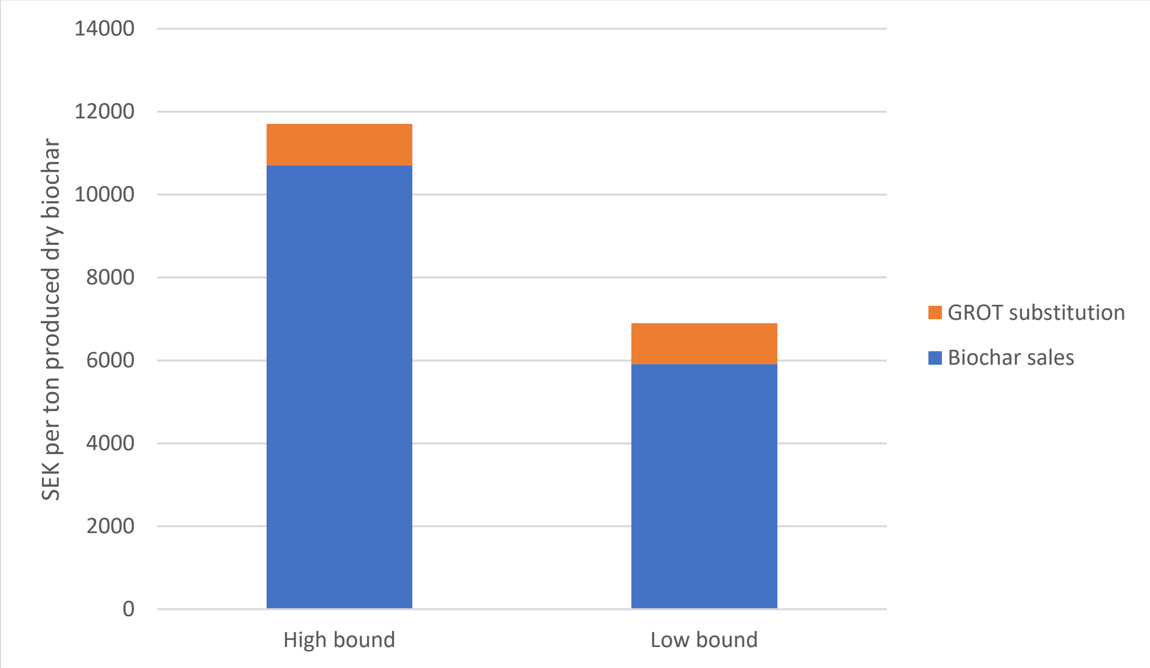

Figure 10: Base case - Life cycle revenue

There is significant difference between the revenue of the worst-case and best-case scenario. While substitution of GROT remains constant between the bounds, the revenue from the biochar differs. The difference between the low bound and high bound in biochar sales stems from the price of the sold biochar and its density. The biochar selling price is determined by a willingness-to-pay study published in (Avfall Sverige, 2018). Optimally, a price that is more anchored in a current biochar market would be chosen, but due to large scale biochar production not existing in Sweden at this moment, this study was deemed more reliable for the price.

4.1.3 Net present value

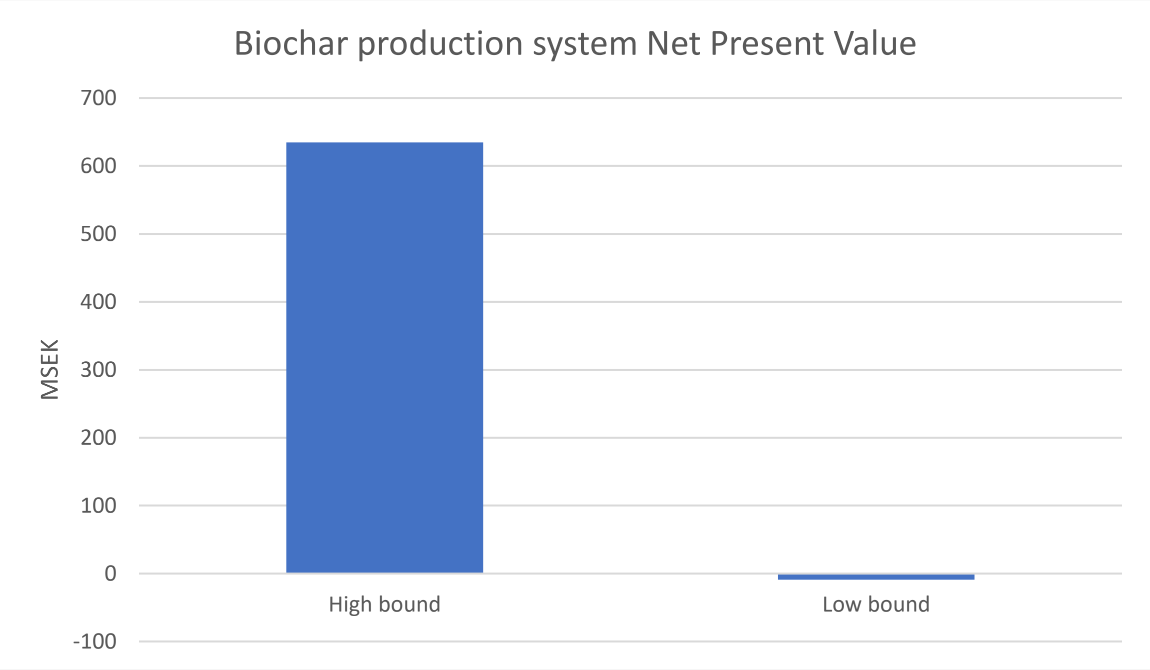

Figure 11: Base case - Net present value

While there is not much difference in the life cycle costs between the ranges that can be observed in fig. 9, and there being a fairly large difference in revenue that can be observed in fig. 10, the difference between the high bound and low bound cases for NPV is immense. This difference can be explained by the discounted revenue that biochar accumulates over time, and how it compares to investment costs. The low bound has a total cost of 6000 SEK per ton produced dry biochar and a revenue of about 6700 SEK per ton produced dry biochar, but the NPV is still negative. This is due to the investment costs happening at year one while the running costs and revenue happens continuously over the span of 30 years, which are subjected to the yearly discount rate of 4%. This implies that the discounted profit from 30 years of operation is not sufficient to cover the investment costs. The combined fixed costs are 95,4 MSEK for the high bound and 239,6 MSEK for the low bound, the costs can be viewed by category in appendix D.

The influence of biochar density

As is shown in figure 10, the revenue from biochar sales is the largest contributor to the total revenue of the system. The difference in revenue when comparing the low and high bound for the biochar price is 13%, while the difference for comparing the low and high bound of the biochar density is 64%, and this has a large impact on the NPV. It’s complex to accurately estimate the biochar density due to the process being complicated on a chemical level, and for the scope of this thesis, the narrowed range is deemed sufficient and presented.

4.2 Alternative case results

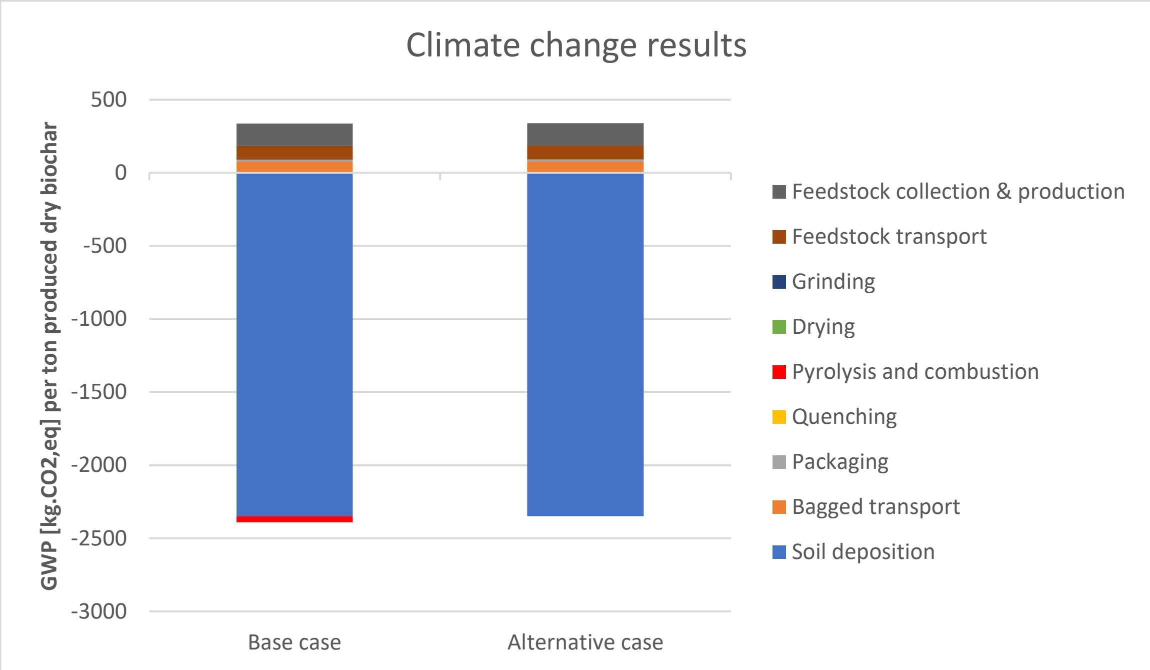

Figure 12: Climate change contribution breakdown – Alternative case. Base case is shown alongside for comparison

Alternative case climate change results	
Climate impact per ton biochar (summer period, alternative case)	-2010 kg_{CO2eq}
Climate impact per ton biochar (rest of year, same as base case)	-2053 kg_{CO2eq}
Yearly climate impact*	-17,1 kt_{CO2eq}

*Based on 1 ton biochar produced/h, summer period for 2600 hours per year + rest of year for 5800 hours per year

It's concluded that per functional unit, the alternative case is less beneficial for carbon sequestration due to the absence of replacing direct incineration of GROT. However, on a full year the amount of sequestered carbon is higher in the alternative case due to the utilization of the 2600 extra hours in the summer.

Alternative case cost and revenue

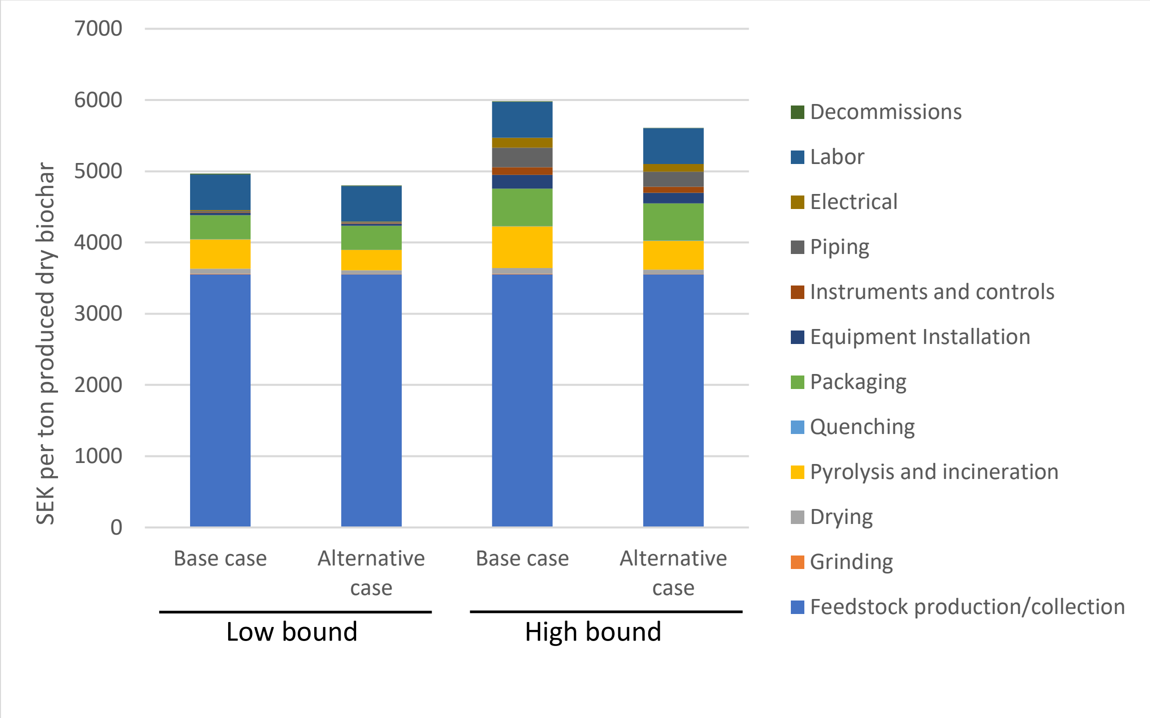

Figure 13: Life cycle costs contribution breakdown – Alternative case. Base case is shown alongside for comparison

Comparing the alternative case costs shown in Fig. 12 to the base case costs shown in fig. 9 it's observed that the costs for the alternative case are lower. Initially, this appears faulty since the total costs for the alternative case are higher due to the extra purchase of incineration equipment. However, since in the alternative case the amount of operation hours goes from 5800 to 8400, the increase in operation hours that the investment costs can be split by has a larger effect than the added cost of buying incineration equipment, implying that it's cheaper overall to increase yearly uptime, at the cost of purchasing a new incinerator.

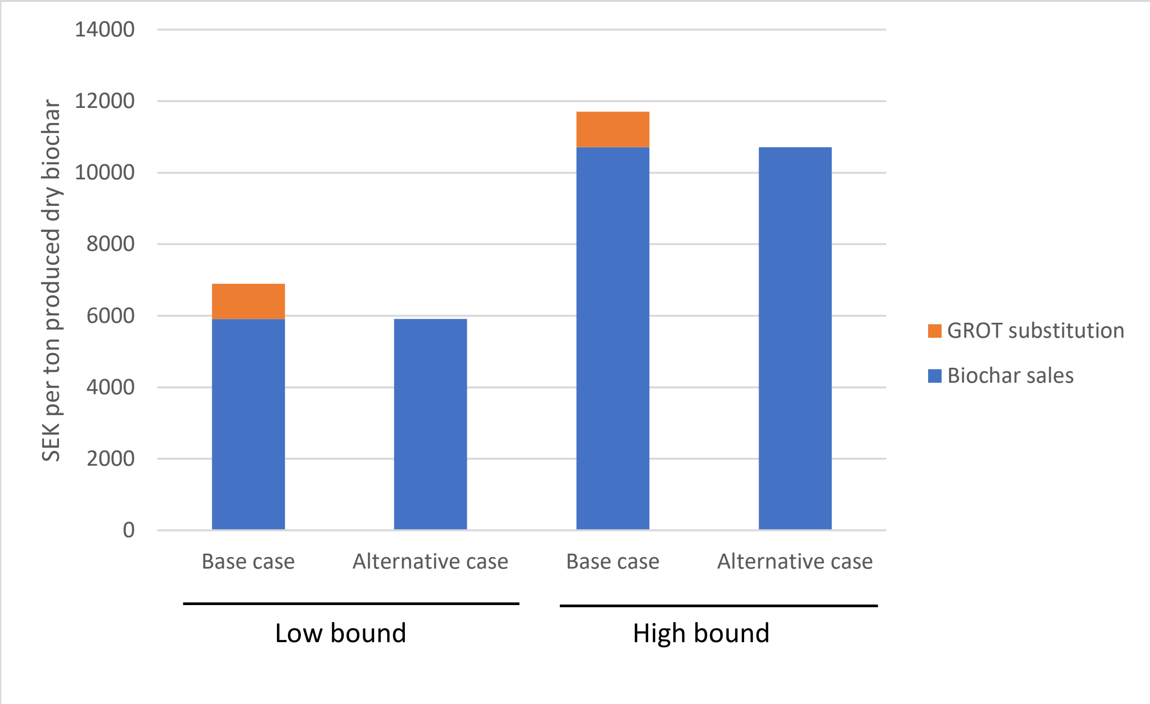

Figure 14: Life cycle revenue contribution breakdown – Alternative case. Base case is shown alongside for comparison

The revenue from biochar sales remains unchanged compared to the base case. This is due to the unit being presented as SEK per ton produced dry biochar, meaning that even if the total revenue from biochar sales goes up from an increase in operating hours, the revenue per functional unit remains the same. The revenue from the system expansion is absent compared to the base case, that is because the revenue per functional unit is shown for summer production. If the diagram would show the revenue over an entire year, there would still be a revenue from GROT substitution.

Net present value

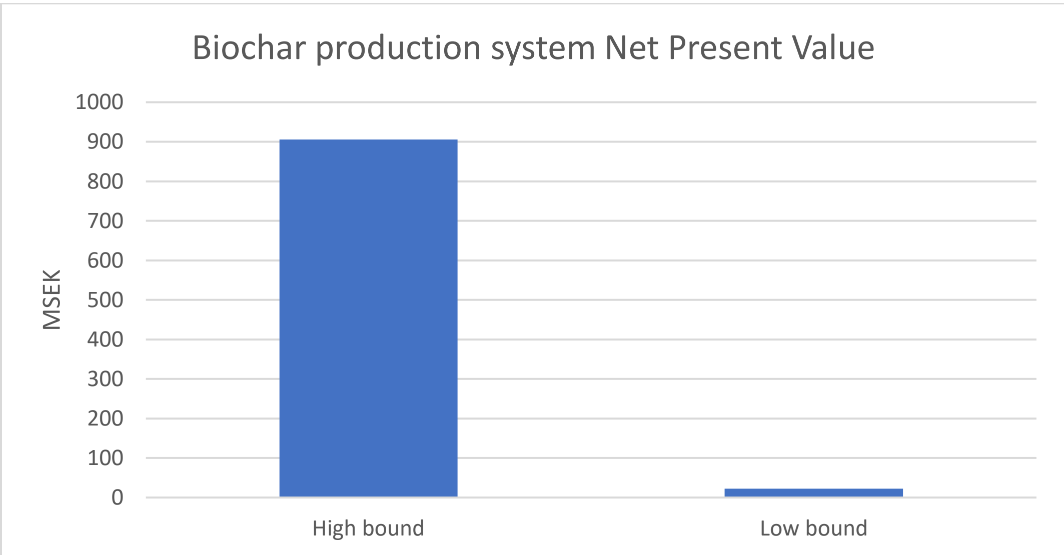

Figure 15: Alternative case - Net present value

When calculating the NPV for the alternative case the revenue for the system expansion will still be present for the 5800 hours when it's possible to utilize the extra flue gases. It's important to distinct the result per functional unit, which is taken in a single point in time where the boiler P13 is turned off, and the yearly result which is a combination of the 2600 summer hours where biochar is produced without adding benefits to the boiler P13, and the 5800 hours that are during the rest of the year when P13 can be supplied by flue gases. The results show that the alternative case is more beneficial than the base case when looking at the NPV. This mainly stems from the increase in uptime from 5800 hours to 8400 hours. From fig. 12 and 13, it's observed that the costs decrease by about 300-700 SEK per ton produced dry biochar while the revenue decreases by about 1000 SEK per ton produced dry biochar. Since the NPV is higher in the alternative case compared to the base case, the remaining explanation is that the benefit of the increased uptime outweighs the drawback of making less money per functional unit of produced dry biochar.

It's important to consider the fact that the worst-case (low bound) and best-case (high bound) scenarios cannot be attained outside of a theoretical situation. This is because some inputs are related to the same factors, e.g. if the biochar has low density, more plastic would be needed to package the biochar, making the costs go up, and at the same time, revenue from selling biochar would increase with lower density since the price is volume based, making revenue go up. The results show that the biochar production process will likely have a positive NPV, since the real value will likely be somewhere in between the low bound and the high bound, putting the result well above zero.

Influence of cradle-to-gate LCCA

The choice to model the LCCA as a cradle-to-gate influences the result somewhat but likely not to a huge degree. Costs that exist after the bagging step would be transport costs and labor costs for applying the biochar to the soil. There is also a potential for revenue in the form of crop productivity or a lower number of unhealthy crops and the potential for carbon credits. These benefits are however theoretical at this moment (Shackley, Ruysschaert, Zwart, & Glaser, 2016) and would be difficult to quantify from only forecasting. Due to the geographical boundary being 100 km, the transport costs are likely small, and in the performed LCCA, labor costs are notable but not significant. The soil application step could also potentially incur some additional benefits that can be expressed as a revenue, which would help offset the costs as well.

4.3 Sensitivity Analysis

The sensitivity analysis shows how the results of the LCA and the LCCA shifts when input data is changed. chosen inputs and the reasons for choosing them are presented below.

Biochar final carbon content (LCA)

Due to carbon soil sequestration being the overwhelming contributing category in the LCA results, the impact that the final carbon content of biochar has on the results is modeled.

Initial moisture content in the feedstock (LCA and LCCA)

When discussing combustion and the technical aspects of the pyrolysis process with a combustion expert at E.ON, he believed that one of the largest barriers of achieving secondary benefits in the form of heat and electricity production would be drying step, where most of the moisture in the feedstock is removed. To check this, initial moisture content in the feedstock was chosen as a sensitivity analysis category.

Transport losses during/after feedstock collection (LCA and LCCA)

Due to the large presence of the feedstock procurement category in the LCCA costs and to the feedstock-to-biochar ratio being 5.5 (Appendix A), feedstock transport losses were identified as potentially having a large effect on the results of the LCA and LCCA.

Feedstock procurement price (LCCA)

Similar to the transport losses, due to the large presence in the LCCA costs, the feedstock procurement price was chosen to be analyzed.

Discount rate (LCCA)

When interpreting the results from the LCCA base case and comparing the NPV to the costs and revenue, it was determined that the discount rate could play a big role in the outcome of the NPV, therefore it was chosen to be analyzed.

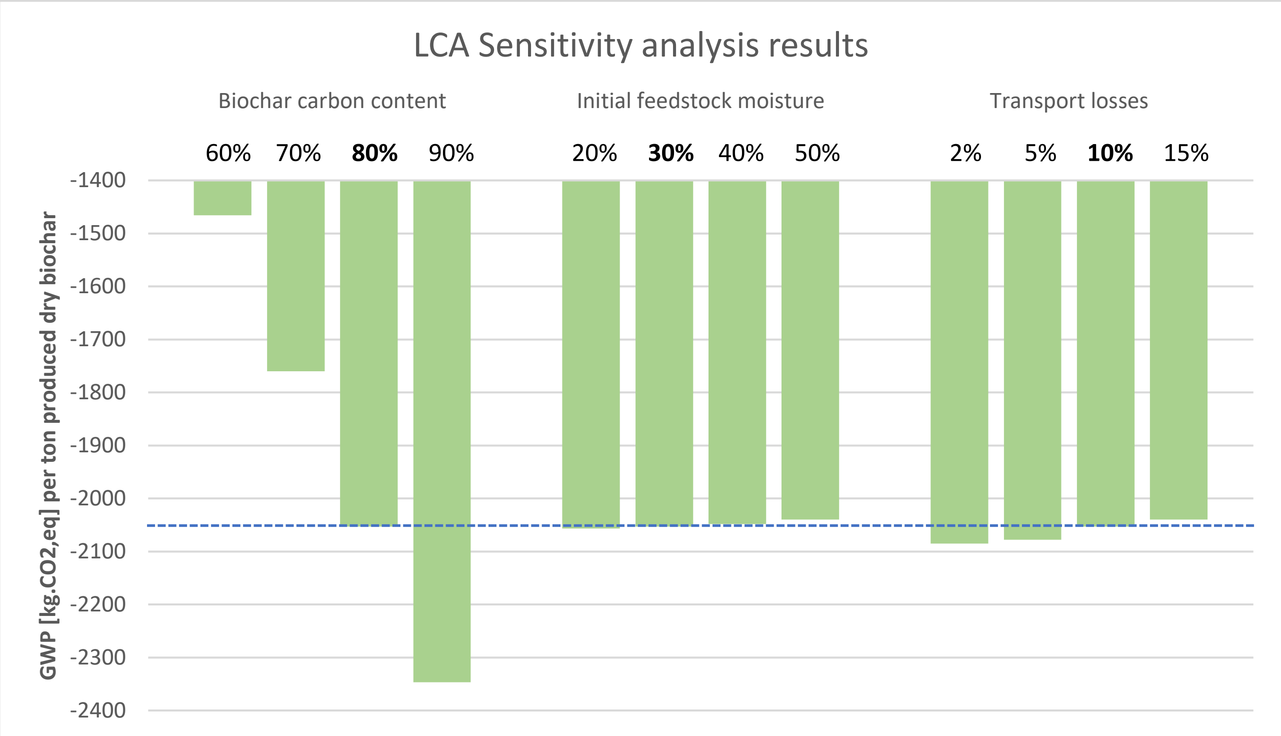

Figure 16: Sensitivity analysis results for LCA. Value used in the LCA is shown in bold text. The blue line shows the LCA base case climate change result.

The sensitivity analysis shows that there are very slim changes in results for all categories except for the biochar carbon content. This shows that there is heavy emphasis on the feedstock type, which is one of the biggest determining factors for receiving a high carbon content. This value can be compared to the final carbon content of other feedstock types presented in (Shackley, Ruysschaert, Zwart, & Glaser, 2016), which show a lower carbon content for most other feedstocks than woody biomass. Therefore, the importance of woody biomass as a feedstock becomes more apparent when the goal of biochar production is carbon sequestration.

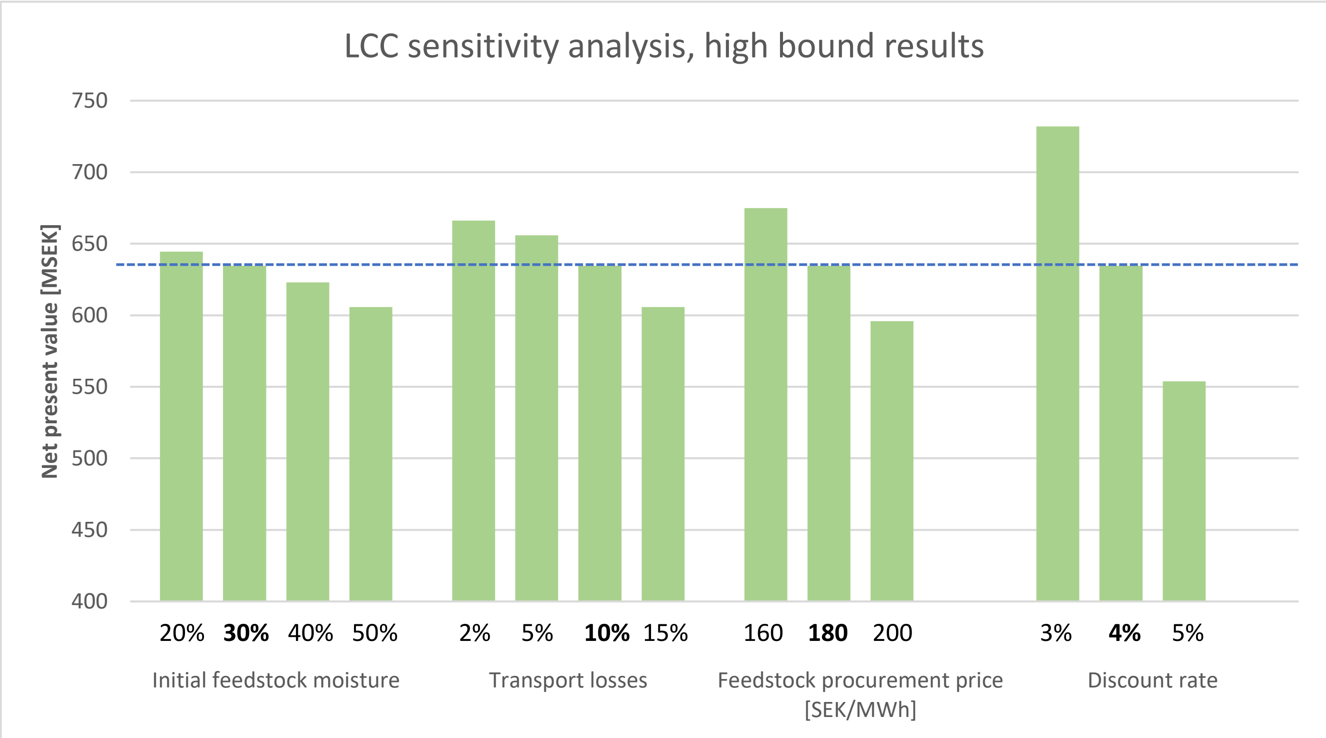

Figure 17: Sensitivity analysis results for the high bound of the LCC. Value used in the LCC is shown in bold text. The blue line shows the LCC base case net present value result.

For the high bound NPV (best-case scenario) there is no significant change in outcome except for the applied discount rate. This puts emphasis on the importance of choosing an appropriate discount rate for the investment. 30 years is not an unusual period for industrial equipment to remain functional but applying the interest rate over that many years it's shown that the outcome can be fairly different.

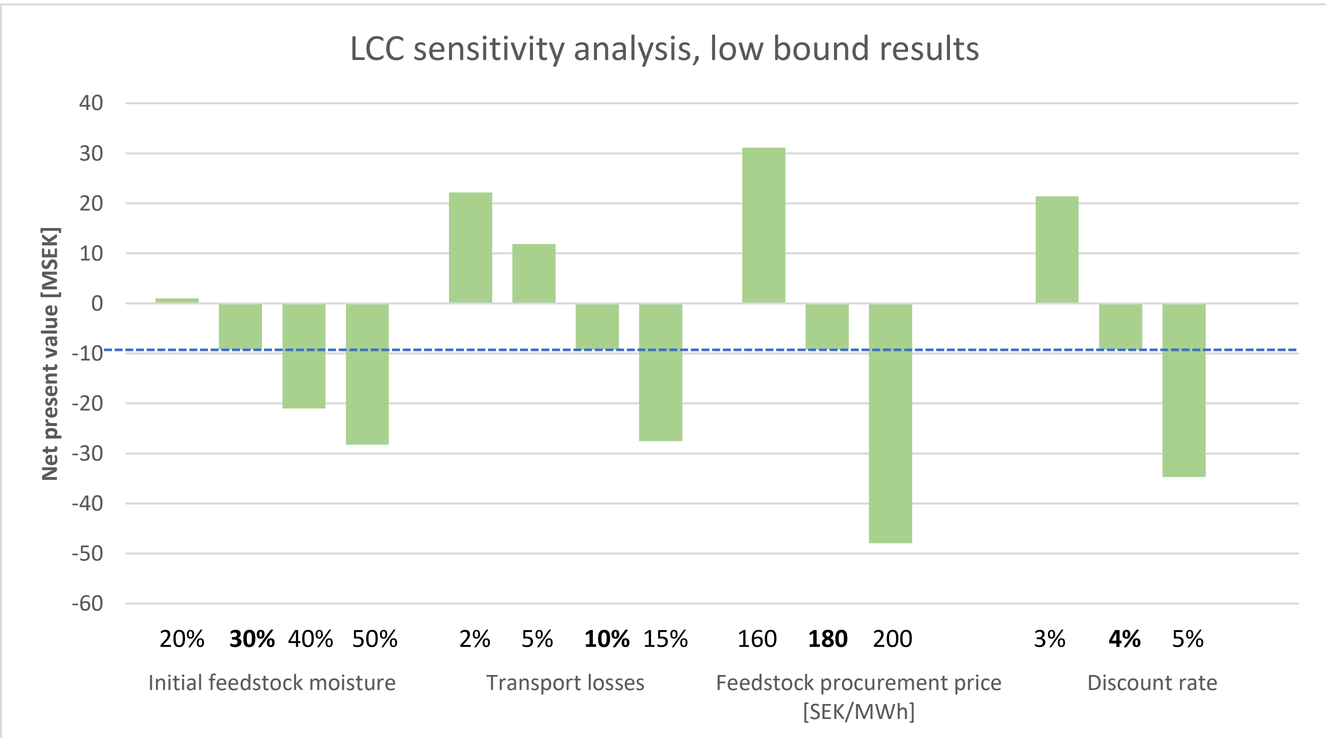

Figure 18: Sensitivity analysis results for the low bound of the LCC. Value used in the LCC is shown in bold text. The blue line shows the LCC base case net present value result.

The low bound (worst-case) NPV results shows a significant change between the inputs. It's noteworthy that even if the absolute change between the results seem significant, the relative differences does not differ much when compared to the difference between the high bound results. The feedstock procurement price does have a larger influence in the low bound results than the discount rate, which is the opposite when compared to the high bound results. This shows the difference of initial investment between the bounds. It takes a longer time for the low bound NPV to cover all the initial investment costs, and with a discount rate being applied, every subsequent year the net profit gets smaller and smaller. The results show that for the low bound NPV it's more important to get a good price on the feedstock than it is to get a more accurate assessment of the discount rate.

4.4 Markets for biochar

The LCCA assumes that all revenues from sold biochar will be realized, i.e. that there exists a market for the biochar at the price that is presented in the LCCA. When considering that almost all of revenue from the base case LCCA comes from biochar sales, it's extremely important that there are actors willing to purchase biochar. If this would not be the case, there is little hope that a biochar production system will be economically viable. Carbon sequestration benefits in the form of carbon credits can also be considered when applying biochar to soils (Homagain, Shahi, Luckai, & Sharma, 2016). However, there is a lack of existing infrastructure for carbon sequestration reporting which can make it difficult to convince actors to move into biochar. Especially if the sole reason is that there might be benefits from carbon credits in the future.

4.4.1 Sweden

In the report "the market for biochar in Sweden" (Avfall Sverige, 2018), the authors point out that the only existing Swedish market is for soil and soil additives. They do, however, go on to specify multiple different actors that could be interested in purchasing biochar.

Sector	Market readiness (sourced 2018)
Soil improvement (small scale)	Exists today
Filter material	2-3 years
Animal feed	5 years
Construction material	8-10 years
Agriculture	8-10 years

The only quantified market is in animal feed if every Swedish farm animal would have biochar mixed into its feed. This would correspond to a market of 150 000 tons of biochar per year (Avfall Sverige, 2018).

However, the drive towards biochar may be sped up even more. In 2020, the Swedish government received a report on what the national Swedish plan to reach net zero emissions by 2045 will consist of (SOU, 2020). This plan mentions biochar over 200 times and categorizes biochar production as a "potential technology" and describes it as:

"The investigation judges that the use of biochar as a method for long term storage and as additional soil improver is one of the studied technologies with the largest realizable potential to contribute to negative emissions in Sweden until the middle of this century, with reservation for lack of knowledge of the subject" (SOU, 2020)

4.4.2 International

The international market is likely to have a larger potential than the Swedish market. One important aspect is that biochar is particularly effective in poor and/or dry soils and on fields where modern agricultural practices aren't as widely used (Shackley, Ruysschaert, Zwart, & Glaser, 2016). In central Europe, most of the produced biochar is used in animal feed (Kammann, et al., 2018). The biochar industry is however fast growing, which results in an increased production capacity with improved biochar quality which in turn drives an available and affordable in market (Petelina, Sanscartier, Macwilliam, & Ridsdale., 2014).

4.5 The future of biochar

Biochar applied to soils is a well-studied method for achieving negative emissions. However, the largest barrier would be whether a market for biochar will exist in the future. (SOU, 2020) accounts for a potential of sequestering about 1 Mton $CO_{2,eq}$ per year in 2045, which corresponds to around 500 000 tons of biochar. However, the report implies that the government need to implement considerable frameworks for carbon accounting and funds to stimulate market growth for this change to take place. (Avfall Sverige, 2018) identified that biochar can be sold for 2600-3000 SEK/m^3, which is generally sufficient for a positive NPV in the studied case. Biochar is currently a popular topic with multiple books and reports having been released in only the last few years, and actors looking into how to utilize biochar in different ways, such as biochar in steel production (Biofuel Region, 2016) or as activated carbon. Biochar and activated carbon have similar properties, so biochar used as activated carbon could be another application worth further study. This can be particularly important if the market for soil applicable biochar is lacking, as activated carbon is an entirely separate market from soil improvement.

5 Conclusions

The purpose of this thesis was to assess the climate impact and the economic viability of biochar production and subsequent soil application. This was performed in the style of a cradle-to-grave LCA and a cradle-to-gate LCCA.

5.1 Conclusions from the LCA

The results show that it's possible to utilize biochar production as a method to achieve negative carbon emissions. The carbon sequestration step has the largest impact with accounting for 85-90% of the GWP from a life cycle perspective. This puts emphasis on the design the pyrolysis step for enabling maximum carbon sequestration, since different residence times and temperatures will affect the carbon stability in the soil and determine how much of the applied carbon will remain after 100 years (Lehmann, Czimczik, Laird, & Sohi, 2009). On a yearly basis, the amount of carbon that can be captured is the equivalent of the yearly emissions of almost 2600 passenger cars (US EPA, 2020). The results showed that the presented alternative case that utilizes an additional boiler which can produce biochar during the summer period, produces less emissions from a holistic perspective when compared to the presented base case. Due to the impact results being dwarfed by the carbon soil sequestration category, there are not any relevant benefits to be had from improving on other parts of the system from a climate change perspective. In a sensitivity analysis it was shown that initial feedstock moisture content and feedstock transport losses does not play a significant role for the impact on climate change, but the percentage of final carbon in the biochar does play a significant role, with lower carbon content in the biochar leading to a higher climate change potential.

5.2 Conclusions from the LCCA

The results from the LCCA were presented in a worst-case and a best-case scenario, and the results shows a significant difference between the two scenarios. This is mostly due to the uncertainties in investment cost and the effect of applying a discount rate to the 30-year lifespan of the system. Biochar density also plays a big role in the profitability of biochar since the market price is commonly defined as a volume, and the density of biochar can vary wildly depending in the different pyrolysis parameters. The results showed that the presented alternative case that utilizes an additional boiler which can produce biochar during the summer period impacts the net present value beneficially, this was true for both the worst-case and best-case scenario. A sensitivity analysis showed that for the best-case scenario, differences in initial feedstock moisture content and transport losses had a relatively small effect, but differences in feedstock procurement price and discount rate had a relatively high effect. A sensitivity analysis of the worst-case scenario showed that differences in all four studied inputs (initial feedstock moisture content, transport losses ,feedstock procurement price and discount rate) resulted in a significant change in the net present value.

5.3 Suggested further research

Substituting fossil fuels

The largest area of improvement for the system is to utilize the benefits of the system expansion to substitute a fossil fuel instead of a biofuel that is substituted in the modeled case. This would lead to a significant increase of avoided $CO_{2,eq}$. However, the amount of fossil fuels that are used for electricity or heat production in Sweden today ranges from zero to a few percent (Energimyndigheten, 2019). A biochar production system that would be tailored for replacing fossil fuels would then produce secondary benefits for only a few hours every year. There is a case to be made for a biochar production system that can replace fossil fuels when there is a need to utilize fossil fuels (e.g. on the very coldest of days), and for the rest of the year it can substitute direct incineration of biofuels. It is however unknown if the benefits from such a hybrid system would be greater than the extra equipment that would be required for it. Regardless, it could be a topic worth further study for the purpose of eliminating fossil fuel use in the Swedish heat and electricity production sector.

Tracking the flow of soil nutrients

During the presentation of the master thesis it was questioned if the thesis had considered that when GROT is taken out of the forest, the nutrients in the GROT will not return to the forest soil. This had not been considered and all ashes are assumed to end up in the final biochar product. To study the effects of this on forest soils and a potential remedy by returning biochar to forest soils, a study of nutrients flows is suggested. Coverage of soil nutrient cycling does exist in literature (Tisserant & Cherubini, 2019) but since biochar results can vary wildly depending on circumstances and input parameters, a case for forest residue in Swedish conditions could be of interest.

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Appendix A – Equations

Table of contents

1. LCA calculations

1.1. *Required feedstock*

Dry Feedstock is pyrolyzed into biochar with 29 wt.% efficiency

$$m_{feedstock,dry} = \frac{m_{dry\ biochar}}{0{,}29} = \frac{1000}{0{,}29} = 3448\ kg$$

The feedstock initially contains 30 % moisture

$$m_{feedstock} = \frac{m_{feedstock,dry}}{1 - moisture\ content} = \frac{3448}{1 - 0{,}3} = 4926\ kg$$

Then added 10 % for losses in process and transportation (Shackley, Ruysschaert, Zwart, & Glaser, 2016)

$$\frac{4926\ kg}{1 - 0{,}1} = 5473\ kg$$

1.2. *Energy for grinding*

Electricity use: 0,01-0,001 $MJ/kg_{dry\ feedstock}$ (Thunman, Lind, & Johnsson, 2008). 0,005 $MJ/kg_{dry\ feedstock}$ electricity is used.

$$3448 \bullet 0{,}005 = 17\ MJ$$

1.3. *Water & electricity usage in Quenching process*

70% biochar, 30 % water

$$m_{water} = \frac{m_{dry\ biochar}}{1 - 0{,}3} - m_{dry\ biochar} = \frac{1000}{0{,}7} - 1000 = 429\ kg_{water}$$

Electricity: $0{,}00043\ kWh/kg_{water}$ (Ecoinvent)

$$0{,}00043 \bullet 429 = 0{,}18\ kWh \bullet 3{,}6 = 0{,}65\ MJ$$

1.4. *Drying heat requirement*

Feedstock dry matter = $m_{feedstock,DM} = 3448\ [kg]$
Initial water in feedstock = $\varepsilon_{H2O,ini}$ = 30 %
Final water in feedstock = $\varepsilon_{H2O,fin}$ = 15 %
Water incoming = $m_{H2O,ini} = \frac{m_{feedstock,DM}}{1-\varepsilon_{H2O,ini}} - m_{feedstock,DM} = \frac{3448}{1-0{,}30} - 3448 = 1478\ [kg]$
Water outgoing = $m_{H2O,fin} = \frac{m_{feedstock,DM}}{1-\varepsilon_{H2O,fin}} - m_{feedstock,DM} = \frac{3448}{1-0{,}15} - 3448 = 608\ [kg]$
Water evaporated = $m_{H2O,evap} = m_{H2O,ini} - m_{H2O,fin}\ 1478 - 608 = 870\ [kg]$

All water is heated to 100 °C
Initial temperature of water: 10 °C
Final temperature of water (steam): 100 °C
Energy required for heating (water heating + evaporation):

$$m_{H2O,ini}[kg] \bullet Cp_{H2O,l}[kJ/kg,K] \bullet \Delta t_l[K] + m_{H2O,evap}[kg] \bullet \Delta H_{vap}[kJ/kg]$$
$$= 1478[kg] \bullet 4{,}19[kJ/kg,K] \bullet (374 - 284)[K] + 870[kg] \bullet 2254[kJ/kg]$$
$$= 557\,354\,[kJ] + 1\,960\,980\,[kJ] = 2\,518\,334\,[kJ] = 2\,518\,MJ$$

Heating of feedstock (DM):
Mass dry feedstock: $3448\ [kg]$
Initial temperature of feedstock: 10 °C
Final temperature of feedstock: 100 °C

$$m_{feedstock,dm}[kg] \bullet Cp_{wood}[kJ/kg,K] \bullet \Delta t_{feedstock}[K] = 3448 \bullet 2 \bullet (374 - 284) = 620\,640\,kJ$$
$$= 621\,MJ$$

Sum of required energy: $2518 + 621 = 3139\,MJ$

Liquid water specific heating capacity: (Engineering ToolBox, 2020)
Evaporation enthalpy: (Engineering ToolBox, 2020)
Steam specific heating capacity: (Engineering ToolBox, 2020)
Specific heat capacity of wood: (Engineering Toolbox, 2020)

Drying electricity requirement
0,08 MJ/kg_{h20} (Thunman, Lind, & Johnsson, 2008)

$$0{,}08 * 870 = 69{,}6 = 70\,MJ$$

1.5. Heat requirement for pyrolysis

1. Evaporating 100 °C water into 500 °C steam
2. Heating the feedstock to 500 °C
3. Conversion of the feedstock into biochar and syngas

1)

Mass feedstock in: 4056 kg
Initial water in feedstock: 15 %
Final water in feedstock: 0 %
Water incoming: $4056\ [kg] \bullet 0{,}15 = 608\ [kg]$
Water evaporated: 608 kg
Initial temperature of water: 100 °C
Final temperature of water (steam): 500 °C
Energy required for heating (evaporation + steam superheating):

$$m_{feedstock,dm}[kg] \bullet Cp_{wood}[kJ/kg,K] \bullet \Delta t_{feedstock}[K] \bullet Cp_{H2O,g}[kJ/kg,K] \bullet \Delta t_g[K]$$
$$= 608[kg] \bullet 2254[kJ/kg] + 608[kg] \bullet 1{,}89[kJ/kg,K] \bullet (774 - 374)[K]$$
$$= 1\,370\,432\,[kJ] + 459\,648\,[kJ] = 1\,830\,080\,[kJ] = 1\,830\,MJ$$

2)

Mass feedstock in: 4056 kg
Mass dry feedstock: $4056\ [kg] \bullet 0{,}85 = 3448\ [kg]$
Initial temperature of feedstock: 100 °C
Final temperature of feedstock: 500 °C

$$m_{feedstock,dm}[kg] \bullet Cp_{wood}[kJ/kg,K] \bullet \Delta t_{feedstock}[K] = 3448 \bullet 2 \bullet (774 - 374) = 2\,758\,400\ kJ = 2\,758\ MJ$$

3)

Mass feedstock (DM): 3448 kg
Enthalpy of reaction: 2963 kJ/kg (garden waste) (Kesraoui, et al., 2019)

$$m_{feedstock,dm}[kg] \bullet \Delta H_{garden\,waste}[kJ/kg] = 3448 \bullet 2963 = 10\,216\,424\ kJ = 10\,216\ MJ$$

Total energy demand
$1\,830 + 2\,758 + 10\,216 = 14\,804\ MJ$

Assuming 90 % efficiency in pyrolizer
$$\frac{14\,804}{0{,}9} = 16\,449\ MJ$$

Pyrolysis electricity requirement, assume same as for drying = 70 MJ

1.6. ***Emissions from syngas combustion***

Mass percentage of gases in outlet for syngas combustion (Kesraoui, et al., 2019)
N_2: 60,4 %
CO_2: 22,6 %
H_2O: 16,8%
SO_2: 0,01%
NO_2: 0,003%
Other gases: 0,187% (disregarded in LCA model)

Gases entering combustion chamber:
$100\%_{feedstock} - 29\%_{biochar\ yield}$ = 71% of feedstock gasifying
$0{,}71 \bullet 3448 = 2448\ kg$

Air requirement for complete combustion of syngases: 3,66 kg/kg (Kesraoui, et al., 2019)

Total outlet of emissions:

N_2: $0{,}604 \bullet (2448 + 2448 \bullet 3{,}66) = 6890\ kg$
CO_2: $0{,}226 \bullet (2448 + 2448 \bullet 3{,}66) = 2578\ kg$
H_2O: $0{,}168 \bullet (2448 + 2448 \bullet 3{,}66) = 1916\ kg$
SO_2: $0{,}0001 \bullet (2448 + 2448 \bullet 3{,}66) = 1{,}1\ kg$
NO_2: $0{,}00003 \bullet (2448 + 2448 \bullet 3{,}66) = 0{,}34\ kg$
Other gases: 0,187% (disregarded in LCA model)

1.7. Substitution of existing fuels

The energy contained in the flue gases contain 3683 kJ/kg (Kesraoui, et al., 2019)

The flue gases in P13 can utilize 88 % of the energy contained in the fuel supplying it (Appendix B)

$3683 \bullet 0{,}88 = 3241\ kJ/kg$

Mass of flue gases
$2448 + 2448 \bullet 3{,}66 = 11\ 408\ kg$

Total energy delivered from flue gases
$11\ 408\ [kg] \bullet 3241\ [kJ/kg] = 36\ 973\ MJ$

Subtracting internally used heat for drying and pyrolysis

$36\ 973\ MJ - 3139\ MJ - 16\ 449 = 17\ 385\ MJ$

This is used to substitute GROT that's used as fuel, combusted at the same efficiency as the syngases (88%)

GROT heating value (30% moisture): 3,58 MWh/ton (Skogforsk, 2019)

GROT required: $\frac{\frac{17385\ [MJ]}{3600\ [MJ/MWh]}}{0{,}00358[MWh/kg] \bullet 0{,}88} = 1\ 533\ kg$

1.8. Packaging electricity use

Packaging based on wood pellet packaging machine (Amiagus, 2020)

Productivity: 8000 kg/h
Power: 4 kW
Packaged product: 1429 kg

$$\frac{1429\ [kg]}{8000\ [kg/h]} \bullet 3600[s/h] \bullet 4[kJ/s] = 2572\ kJ = 2{,}57\ MJ$$

Polyethylene required: 2 g/kg shipped product
Total amount of polyethylene required: $2[g/kg] \bullet 1429\ [kg] = 2{,}86\ kg$

1.9. CO_2 sequestration

Carbon fraction in dry biochar: 80 % (Shackley, Ruysschaert, Zwart, & Glaser, 2016)
Carbon remaining in soil after 100 years: 80% (Lehmann, Czimczik, Laird, & Sohi, 2009)
Dry biochar applied to soil: 1000 kg

Carbon added to soil: $1000 \bullet 0{,}8 \bullet 0{,}8 = 640\ kg\ C$
C to CO_2 factor = 44/12 = 3,67 kg CO_2/kg C
CO_2 sequestration added to OpenLCA: $640 \bullet 3{,}67 = 2349\ kg\ CO_2$

1.10. LCA results calculations

1.10.1. Base case

Sequestration per FU: -2053 kg $CO_{2,eq}$
Yearly sequestration (1 ton/h, 5800 h)
$-2053 \bullet 5800 = -11\,907\,400\ kg\ CO_{2,eq} \approx -11{,}9\ kt\ CO_{2,eq}$

1.10.2. Alternative case

Sequestration per FU (summer): -2053 kg $CO_{2,eq}$
Yearly sequestration (summer) 1 ton/h, 5800 h
Sequestration per FU (rest of year): -2010 kg $CO_{2,eq}$
Yearly sequestration (rest of year) 1 ton/h, 8400-5800 = 2600 h
$-2053 \bullet 5800 + -2010 \bullet 2600 = -17\,133\,400\ kg\ CO_{2,eq} \approx -17{,}1\ kt\ CO_{2,eq}$

2. Cost calculations

2.1. Investment costs

Cost range for auxiliary equipment of total investment costs: (Peters & Timmerhaus, 1991)

Installation: 6-14 %
Instruments & controls: 2-8 %
piping: 3-20 %
electrical:2-10 %

High Bound:
Equipment costs:
Rotary Kiln: 70 MSEK
Shredder: 1 MSEK
Dryer: 11 MSEK
Packaging equipment: 1 MSEK
Sum of equipment: 83 MSEK

Auxiliary costs:
Installation: 6%
Instruments & controls: 2%
piping: 3%
electrical:2%
Sum of percentages: 13 %

Cost of equipment = 83 MSEK = 100-13 = 87 % of total costs

Cost of auxiliaries = $\frac{83\ MSEK}{0,87} - 83MSEK = 12,4\ MSEK$

Total costs: $83 + 12,4 = 95,4\ MSEK$
Auxiliary costs:
Installation: 6% = 95,4 • 0,06 = 5,7 MSEK
Instruments & controls: 2% = 95,4 • 0,02 = 1,9 MSEK
piping: 3% = 95,4 • 0,03 = 2,9 MSEK
electrical: 2% = 95,4 • 0,02 = 1,9 MSEK

Low Bound:
Equipment costs:
Rotary Kiln: 100 MSEK
Shredder: 1 MSEK
Dryer: 13 MSEK
Packaging equipment: 1 MSEK
Sum of equipment: 115 MSEK

Auxiliary costs:
Installation: 14%
Instruments & controls: 8%
piping: 20%
electrical:10%
Sum of percentages: 52 %

Cost of equipment = 115 MSEK = 100-52 = 48 % of total costs

Cost of auxiliaries = $\frac{115\ MSEK}{0,48} - 115MSEK = 124,6\ MSEK$

Total costs: $115 + 124,6 = 239,6\ MSEK$
Auxiliary costs:
Installation: 14% = 239,6 • 0,14 = 33,5 MSEK
Instruments & controls: 8% = 239,6 • 0,08 = 19,2 MSEK
piping: 20% = 239,6 • 0,20 = 47,9 MSEK
electrical: 10% = 239,6 • 0,10 = 24 MSEK

Costs per functional unit

Lifespan: 30 years
Operating hours: 5800 hours/year (Appendix B)
Production volume: 1 ton dry biochar/h
Total produced biochar: $1 \bullet 5800 \bullet 30 = 174\ 000\ ton$

High Bound:
Equipment costs:
Rotary Kiln: $\frac{70\ MSEK}{174\ 000} = 402\ SEK/ton$

Shredder: $\frac{1\ MSEK}{174\ 000} = 6\ SEK/ton$

Dryer: $\frac{11\ MSEK}{174\ 000} = 63\ SEK/ton$

Packaging equipment: $\frac{1\ MSEK}{174\ 000} = 6\ SEK/ton$

Installation: $\frac{5{,}7\ MSEK}{174\ 000} = 33\ SEK/ton$

Instruments & controls: $\frac{1{,}9\ MSEK}{174\ 000} = 11\ SEK/ton$

piping: $\frac{2{,}9\ MSEK}{174\ 000} = 17\ SEK/ton$

electrical: $\frac{1{,}9\ MSEK}{174\ 000} = 11\ SEK/ton$

Sum of equipment: 549 SEK/ton

Low Bound:
Equipment costs:
Rotary Kiln: $\frac{100\ MSEK}{174\ 000} = 575\ SEK/ton$

Shredder: $\frac{1\ MSEK}{174\ 000} = 6\ SEK/ton$

Dryer: $\frac{13\ MSEK}{174\ 000} = 75\ SEK/ton$

Packaging equipment: $\frac{1\ MSEK}{174\ 000} = 6\ SEK/ton$

Installation: $\frac{33{,}5\ MSEK}{174\ 000} = 193\ SEK/ton$

Instruments & controls: $\frac{19{,}2\ MSEK}{174\ 000} = 110\ SEK/ton$

piping: $\frac{47{,}9\ MSEK}{174\ 000} = 275\ SEK/ton$

electrical: $\frac{24\ MSEK}{174\ 000} = 138\ SEK/ton$

Sum of equipment: 1 378 SEK/ton

Decommission

Cost: 2 MSEK
Produced biochar: 174 000 tons
Cost per F.U: $\frac{2\ MSEK}{174\ 000} = 11\ SEK/ton$

2.2. *Running costs*

2.2.1. *Labor*

Costs of labor is based on the report (Kesraoui, et al., 2019) which utilize data from a biochar production plant in Stockholm (10 000 tons biochar/year)

Position	Occupancy	Cost [SEK/Y]
Operations Engineer	80 %	700 000
Maintenance Engineer	80 %	700 000
Operations technician	50 %	350 000
Maintenance technician	50 %	350 000
Plant engineer	40 %	350 000
Fuel Engineer	20 %	175 000
EHS engineer	10 %	87 500
Other labor	30 %	210 000
Total	*360 %*	*2 922 500*

Table 1: Labor occupancy and costs for a biochar plant in Stockholm (Kesraoui, et al., 2019)

These values are used in the biochar plant is this report as well, although the production is only 5800 tons/year, it's reasonable to assume that the equipment is similar and will require the same amount of attention since the operations have the same steps. There is also a factor of bagging and loading the biochar which isn't covered in the aforementioned study, this labor is unknown but can be said to be contained within the possible overcapacity generated from using the same costs as a larger plant.

2.2.2. *Feed*stock

Purchase price: 180 SEK/MWh (Norin, 2020)
GROT heating value (30% moisture): 3,58 MWh/ton (Skogforsk, 2019)
Yearly amount: $5{,}5\ [ton/h] \bullet 5800 = 31\ 900\ tons$

Yearly cost:
$180[SEK/MWh] \bullet 31900[ton/year] \bullet 3{,}58[MWh/ton] = 20{,}6\ MSEK/year$

Cost per F.U: $\frac{20{,}6\ MSEK}{5800} = 3552\ SEK/ton$

2.2.3. *Electricity*

Price: $0{,}4\frac{SEK}{kWh} = \frac{0{,}4\ [SEK/kWh]}{3{,}6\ [MJ/kWh]} = 0{,}11\ [SEK/MJ]$ (Vattenfall, 2020), Based on the average electricity price 2014-2019
Amount per F.U: $E_{Grinder} + E_{Dryer} + E_{Pyrolysis} + E_{Quenching} + E_{Packaging}$ = 17 + 70 + 70 + 0,65 + 2,67 = 160,3 MJ
$160{,}3 \bullet 0{,}11 = 17{,}6\ SEK/ton$

Amount per year:
$17{,}6 \bullet 5800 = 0{,}1\ MSEK$

2.2.4. Water

Price: 7,4 SEK/m3 (Nodra, 2018)
amount: 429 kg

1 m3 = 1000 kg

Cost per F.U: 0,429 • 7,4 = 3,2 SEK

Yearly cost: 3,2 • 5800 = 0,02 MSEK

2.2.5. ***Packaging***

Price: 0,83$/2 cubic feet = 8,3 SEK/0,057m^3 (PolyPak, 2020)
Density of biochar: 0,28-0,44 ton/m^3 (Brewer & Levine, 2015)
Since biochar is sold by volume, the added water won't affect the price

Low bound
Cost per FU: $\frac{8{,}3[SEK]}{0{,}057[m^3]\bullet 0{,}28[ton/m^3]} = 520\ SEK/ton$

Yearly cost: 520 • 5800 = 3,0 MSEK

High bound
Cost per FU: $\frac{8{,}3[SEK]}{0{,}057[m^3]\bullet 0{,}44[ton/m^3]} = 331\ SEK/ton$

Yearly cost: 520 • 5800 = 1,9 MSEK

2.3. Revenue

2.3.1. Biochar

Selling price: 2600-3000 SEK/m^3 sold biochar
Bulk density of biochar: 0,28-0,44 ton/m^3 (Brewer & Levine, 2015)
Since biochar is sold by volume, the added water won't affect the price
Low bound
Price per ton biochar: $\frac{2600\ [SEK/m^3]}{0{,}44} = 5909\ SEK/ton\ sold\ biochar$

Yearly revenue: $5909 \bullet 5800 = 34{,}3\ MSEK$

High bound
Price per ton biochar: $\frac{3000\ [SEK/m^3]}{0{,}28} = 10\ 714\ SEK/ton\ sold\ biochar$
Yearly revenue: $10714 \bullet 5800 = 62{,}1\ MSEK$

2.3.2. GROT substitution

Purchase price: 180 SEK/MWh (Norin, 2020)
GROT heating value (30% moisture): 3,58 MWh/ton (Skogforsk, 2019)
Amount: $1{,}533\ ton$

Cost per FU:$180[SEK/MWh] \bullet 1{,}533\ ton \bullet 3{,}58[MWh/ton] = 988\ SEK/ton$

Yearly Revenue: $988\ \bullet 5800 = 5{,}7\ MSEK$

2.4. NPV

$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$

t = amount of time periods
C_t = Net cash inflow during period "t" (revenue – running costs)
C_0 = Initial investment cost
r = discount rate

Time period is set to 30 years and the discount rate is set to 4 % as this is a standard rate in public sector projects (Sigma, 2016).

Years 1-29 are identical with year 30 having an added decommission cost of 2MSEK (counted as a one-time running cost).

High bound

Yearly costs: 20,6+2,92+0,1+0,02+1,9 = 25,54 MSEK
Decommission at end of year 30: 2 MSEK

Investment cost: 95,4 MSEK
Yearly revenue
Biochar: $10714\ [SEK/ton] \cdot 5800[ton/year] = 62{,}1\ MSEK/year$
GROT substitution: $988\ [SEK/ton] \cdot 5800[ton/year] = 5{,}7\ MSEK/year$

t [year]	Ct [MSEK]	r	Yearly NPV [MSEK]	Investment cost [MSEK]
1	42,26	0,04	40,6	
2	42,26	0,04	39,1	
3	42,26	0,04	37,6	
4	42,26	0,04	36,1	
5	42,26	0,04	34,7	
6	42,26	0,04	33,4	
7	42,26	0,04	32,1	
8	42,26	0,04	30,9	
9	42,26	0,04	29,7	
10	42,26	0,04	28,5	
11	42,26	0,04	27,5	
12	42,26	0,04	26,4	
13	42,26	0,04	25,4	
14	42,26	0,04	24,4	
15	42,26	0,04	23,5	
16	42,26	0,04	22,6	
17	42,26	0,04	21,7	
18	42,26	0,04	20,9	
19	42,26	0,04	20,1	
20	42,26	0,04	19,3	
21	42,26	0,04	18,5	
22	42,26	0,04	17,8	
23	42,26	0,04	17,1	
24	42,26	0,04	16,5	
25	42,26	0,04	15,9	
26	42,26	0,04	15,2	
27	42,26	0,04	14,7	
28	42,26	0,04	14,1	
29	42,26	0,04	13,6	
30	40,26	0,04	12,4	
SUM			730,1	95,4
Result [MSEK]				634,7

Low bound

Yearly costs: 20,6+2,92+0,1+0,02+3 = 26,64 MSEK
Decommission at end of year 30: 2 MSEK

Investment cost: 239,6 MSEK
Yearly revenue
Biochar: 5909 $[SEK/ton]$ • 5800$[ton/year] = 34{,}3\ MSEK/year$
GROT substitution: 988 $[SEK/ton]$ • 5800$[ton/year] = 5{,}7\ MSEK/year$

t [year]	Ct [MSEK]	r	Yearly NPV [MSEK]	Investment cost [MSEK]
1	13,36	0,04	12,8	
2	13,36	0,04	12,4	
3	13,36	0,04	11,9	
4	13,36	0,04	11,4	
5	13,36	0,04	11,0	
6	13,36	0,04	10,6	
7	13,36	0,04	10,2	
8	13,36	0,04	9,8	
9	13,36	0,04	9,4	
10	13,36	0,04	9,0	
11	13,36	0,04	8,7	
12	13,36	0,04	8,3	
13	13,36	0,04	8,0	
14	13,36	0,04	7,7	
15	13,36	0,04	7,4	
16	13,36	0,04	7,1	
17	13,36	0,04	6,9	
18	13,36	0,04	6,6	
19	13,36	0,04	6,3	
20	13,36	0,04	6,1	
21	13,36	0,04	5,9	
22	13,36	0,04	5,6	
23	13,36	0,04	5,4	
24	13,36	0,04	5,2	
25	13,36	0,04	5,0	
26	13,36	0,04	4,8	
27	13,36	0,04	4,6	
28	13,36	0,04	4,5	
29	13,36	0,04	4,3	
30	11,36	0,04	3,5	
SUM			230,4	239,6
Result [MSEK]				-9,2

3. Alternative case costs

3.1. Investment costs

Cost range for auxiliary equipment of total investment costs: (Peters & Timmerhaus, 1991)

Installation: 6-14 %
Instruments & controls: 2-8 %
piping: 3-20 %
electrical:2-10 %

High Bound:

Equipment costs:
Rotary Kiln: 70 MSEK
Shredder: 1 MSEK
Dryer: 11 MSEK
Packaging equipment: 1 MSEK
Combustion chamber: 11 MSEK
<u>Sum of equipment: 94 MSEK</u>

Auxiliary costs:
Installation: 6%
Instruments & controls: 2%
piping: 3%
electrical:2%
<u>Sum of percentages: 13 %</u>

Cost of equipment = 94 MSEK = 100-13 = 87 % of total costs

Cost of auxiliaries = $\frac{94\ MSEK}{0,87} - 94MSEK = 14,0\ MSEK$

Total costs: $94 + 14,0 = 108\ MSEK$
Auxiliary costs:
Installation: 6% = 108 • 0,06 = 6,5 MSEK
Instruments & controls: 2% = 108 • 0,02 = 2,2 MSEK
piping: 3% = 108 • 0,03 = 3,2 MSEK
electrical: 2% = 108 • 0,02 = 2,2 MSEK

Low Bound:

Equipment costs:
Rotary Kiln: 100 MSEK
Shredder: 1 MSEK
Dryer: 13 MSEK
Packaging equipment: 1 MSEK
Combustion chamber: 13 MSEK
<u>Sum of equipment: 128 MSEK</u>

Auxiliary costs:
Installation: 14%
Instruments & controls: 8%
piping: 20%
electrical:10%
<u>Sum of percentages: 52 %</u>

Cost of equipment = 128 MSEK = 100-52 = 48 % of total costs

Cost of auxiliaries = $\frac{128\ MSEK}{0,48} - 128MSEK = 138,7\ MSEK$

Total costs: $128 + 138,7 = 266,7\ MSEK$
Auxiliary costs:

Installation: 14% = 266,7 • 0,14 = 37,3 MSEK
Instruments & controls: 8% = 266,7 • 0,08 = 21,3 MSEK
piping: 20% = 266,7 • 0,20 = 53,3 MSEK
electrical: 10% = 266,7 • 0,10 = 26,7 MSEK

Costs per functional unit:

Lifespan: 30 years
Operating hours: 8400 hours
Production volume: 1 ton dry biochar/h
Total produced biochar: $1 \bullet 8400 \bullet 30 = 252\,000\ ton$

High Bound:
Equipment costs:
Rotary Kiln: $\frac{70\ MSEK}{252\,000} = 278\ SEK/ton$

Shredder: $\frac{1\ MSEK}{252\,000} = 4\ SEK/ton$

Dryer: $\frac{11\ MSEK}{252\,000} = 44\ SEK/ton$

Packaging equipment: $\frac{1\ MSEK}{252\,000} = 4\ SEK/ton$

Combustion chamber: $\frac{11\ MSEK}{252\,000} = 44\ SEK/ton$

Installation: $\frac{6{,}5\ MSEK}{252\,000} = 26\ SEK/ton$

Instruments & controls: $\frac{2{,}2\ MSEK}{252\,000} = 9\ SEK/ton$

piping: $\frac{3{,}2\ MSEK}{252\,000} = 13\ SEK/ton$

electrical: $\frac{2{,}2\ MSEK}{252\,000} = 9\ SEK/ton$

Sum of equipment: 431 SEK/ton

Low Bound:
Equipment costs:
Rotary Kiln: $\frac{100\ MSEK}{252\,000} = 397\ SEK/ton$

Shredder: $\frac{1\ MSEK}{252\,000} = 4\ SEK/ton$

Dryer: $\frac{13\ MSEK}{252\,000} = 52\ SEK/ton$

Packaging equipment: $\frac{1\ MSEK}{252\,000} = 4\ SEK/ton$

Combustion chamber: $\frac{13\ MSEK}{252\,000} = 52\ SEK/ton$

Installation: $\frac{37{,}3\ MSEK}{252\ 000} = 148\ SEK/ton$

Instruments & controls: $\frac{21{,}3\ MSEK}{252\ 000} = 85\ SEK/ton$

piping: $\frac{53{,}3\ MSEK}{252\ 000} = 212\ SEK/ton$

electrical: $\frac{26{,}7\ MSEK}{252\ 000} = 106\ SEK/ton$

Sum of equipment: 1 060 SEK/ton

Decommission

Cost: 2 MSEK
Produced biochar: 252 000 tons
Cost per F.U: $\frac{2\ MSEK}{252\ 000} = 8\ SEK/ton$

3.2. Running costs

3.2.1. Labor

Cost with 5800 operating hours: 2.92 MSEK
Cost with 8400 operating hours:2,92 • $\frac{8400}{5800} = 4{,}23\ MSEK$

3.2.2. Feedstock

Purchase price: 180 SEK/MWh (Norin, 2020)
GROT heating value (30% moisture): 3,58 MWh/ton (Skogforsk, 2019)
Yearly amount: $5{,}5\ [ton/h] \bullet 8400 = 46\ 200\ tons$

Yearly cost:
$180[SEK/MWh] \bullet 46\ 200[ton/year] \bullet 3{,}58[MWh/ton] = 29{,}77\ MSEK/year$

Cost per F.U: $\frac{29{,}77\ MSEK}{8400} = 3544\ SEK/ton$ (difference from base case is due to rounding)

3.2.3. Electricity

Amount per F.U: $E_{Grinder} + E_{Dryer} + E_{Pyrolysis} + E_{Quenching} + E_{Packaging}$ = 17 + 70 + 70 + 0,65 + 2,67 = 160,3 MJ
$160{,}3\ \bullet 0{,}11 = 17{,}6\ SEK/ton$

Amount per year:
$17{,}6 \bullet 8400 = 0{,}15\ MSEK$

3.2.4. Water

Price: 7,4 SEK/m^3 (Nodra, 2018)
amount: 429 kg
1 m^3 = 1000 kg

Cost per F.U: 0,429 • 7,4 = 3,2 SEK

Yearly cost: 3,2 • 8400 = 0,03 MSEK

3.2.5. Packaging

Low bound

Cost per FU: $\frac{8,3[SEK]}{0,057[m^3]\bullet0,28[ton/m^3]} = 520\ SEK/ton$

Yearly cost: 520 • 5800 = 4,37 MSEK

High bound

Cost per FU: $\frac{8,3[SEK]}{0,057[m^3]\bullet0,44[ton/m^3]} = 331\ SEK/ton$

Yearly cost: 520 • 8400 = 2,78 MSEK

3.3. Revenue in alternative case

3.3.1. Biochar

Low bound

Price per ton biochar: $\frac{2600\ [SEK/m^3]}{0,44} = 5909\ SEK/ton\ sold\ biochar$

Yearly revenue: $5909 \bullet 8400 = 49,6\ MSEK$

High bound

Price per ton biochar: $\frac{3000\ [SEK/m^3]}{0,28} = 10\ 714\ SEK/ton\ sold\ biochar$
Yearly revenue: $10714 \bullet 8400 = 90,0\ MSEK$

3.3.2. GROT substitution

GROT can only be replaced when P13 is running (5800 hours)
Cost per FU: $180[SEK/MWh] \bullet 1,533\ ton \bullet 3,58[MWh/ton] = 988\ SEK/ton$

Yearly Revenue: $988\ \bullet 5800 = 5,7\ MSEK$

3.4. Alternative case NPV

$$NPV\ =\ \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

t = amount of time periods
C_t = Net cash inflow during period "t" (revenue – running costs)
C_0 = Initial investment cost
r = discount rate

Time period is set to 30 years and the discount rate is set to 4 % as this is a standard rate in public sector projects (Sigma, 2016).

Years 1-29 are identical with year 30 having an added decommission cost of 2MSEK (counted as a one-time running cost).

High bound

Yearly costs: 29,77+4,23+0,15+0,03+2,78 = 37,06 MSEK
Decommission at end of year 30: 2 MSEK

Investment cost: 108 MSEK
Yearly revenue
Biochar: $10714\ [SEK/ton] \bullet 8400[ton/year] = 90{,}0\ MSEK/year$
GROT substitution: 988 $[SEK/ton] \bullet 5800[ton/year] = 5{,}7\ MSEK/year$

t [year]	Ct [MSEK]	r	Yearly NPV [MSEK]	Investment cost [MSEK]
1	58,64	0,04	56,4	
2	58,64	0,04	54,2	
3	58,64	0,04	52,1	
4	58,64	0,04	50,1	
5	58,64	0,04	48,2	
6	58,64	0,04	46,3	
7	58,64	0,04	44,6	
8	58,64	0,04	42,8	
9	58,64	0,04	41,2	
10	58,64	0,04	39,6	
11	58,64	0,04	38,1	
12	58,64	0,04	36,6	
13	58,64	0,04	35,2	
14	58,64	0,04	33,9	
15	58,64	0,04	32,6	
16	58,64	0,04	31,3	
17	58,64	0,04	30,1	
18	58,64	0,04	28,9	
19	58,64	0,04	27,8	
20	58,64	0,04	26,8	
21	58,64	0,04	25,7	
22	58,64	0,04	24,7	
23	58,64	0,04	23,8	
24	58,64	0,04	22,9	
25	58,64	0,04	22,0	
26	58,64	0,04	21,2	
27	58,64	0,04	20,3	
28	58,64	0,04	19,6	
29	58,64	0,04	18,8	
30	56,64	0,04	17,5	
SUM			1013,4	108
Result [MSEK]				905,4

Low bound

Yearly costs: 29,77+4,23+0,15+0,03+4,37 = 38,55 MSEK
Decommission at end of year 30: 2 MSEK

Investment cost: 266,7 MSEK
Yearly revenue

Biochar: 5909 $[SEK/ton]$ • $8400[ton/year] = 49{,}6\ MSEK/year$
GROT substitution: 988 $[SEK/ton]$ • $5800[ton/year] = 5{,}7\ MSEK/year$

t [year]	Ct [MSEK]	r	Yearly NPV [MSEK]	Investment cost [MSEK]
1	16,75	0,04	16,1	
2	16,75	0,04	15,5	
3	16,75	0,04	14,9	
4	16,75	0,04	14,3	
5	16,75	0,04	13,8	
6	16,75	0,04	13,2	
7	16,75	0,04	12,7	
8	16,75	0,04	12,2	
9	16,75	0,04	11,8	
10	16,75	0,04	11,3	
11	16,75	0,04	10,9	
12	16,75	0,04	10,5	
13	16,75	0,04	10,1	
14	16,75	0,04	9,7	
15	16,75	0,04	9,3	
16	16,75	0,04	8,9	
17	16,75	0,04	8,6	
18	16,75	0,04	8,3	
19	16,75	0,04	8,0	
20	16,75	0,04	7,6	
21	16,75	0,04	7,4	
22	16,75	0,04	7,1	
23	16,75	0,04	6,8	
24	16,75	0,04	6,5	
25	16,75	0,04	6,3	
26	16,75	0,04	6,0	
27	16,75	0,04	5,8	
28	16,75	0,04	5,6	
29	16,75	0,04	5,4	
30	14,75	0,04	4,5	
SUM			289,0	266,7
Result [MSEK]				22,3

4. Sensitivity analysis calculations

4.1. Carbon fraction in biochar

60%
Per FU (OpenLCA): -1466 kg $CO_{2,eq}$
Yearly: $-1466 \bullet 5800 = -8{,}5\ kt\ \mathrm{CO2, eq}$

70%
Per FU (OpenLCA): -1760 kg $CO_{2,eq}$
Yearly: $-1760 \bullet 5800 = -10{,}2\ kt\ \mathrm{CO2, eq}$

90%
Per FU (OpenLCA): -1760 kg $CO_{2,eq}$
Yearly: $-2347 \bullet 5800 = -13{,}6\ kt\ \mathrm{CO2, eq}$

4.2. Initial moisture content of feedstock

Feedstock dry matter = $m_{feedstock,DM} = 3448\ [kg]$
Initial water in feedstock = $\varepsilon_{H2O,ini}$ = (20-50%)
Final water in feedstock = $\varepsilon_{H2O,fin}$ = 15 %
Water incoming = $m_{H2O,ini} = \frac{m_{feedstock,DM}}{1-\varepsilon_{H2O,ini}} - m_{feedstock,DM}$
Water outgoing $= m_{H2O,fin} = \frac{m_{feedstock,DM}}{1-\varepsilon_{H2O,fin}} - m_{feedstock,DM}$
Water evaporated $= m_{H2O,evap} = m_{H2O,ini} - m_{H2O,fin}$
All water is heated to 100 °C
Initial temperature of water: 10 °C
Final temperature of water (steam): 100 °C
Energy required for heating (water heating + evaporation):

$$m_{H2O}[kg] \bullet Cp_{H2O,l}[kJ/kg,K] \bullet \Delta t_l[K] + m_{H2O,evap}[kg] \bullet \Delta H_{vap}[kJ/kg] + m_{H2O,evap}[kg] \bullet Cp_{H2O,g}[kJ/kg,K] \bullet \Delta t_g[K]$$

Heating of feedstock (DM)
Mass dry feedstock: $3448\ [kg]$
Initial temperature of feedstock: 10 °C
Final temperature of feedstock: 100 °C

$$m_{feedstock,dm}[kg] \bullet Cp_{wood}[kJ/kg,K] \bullet \Delta t_{feedstock}[K] = 3448 \bullet 2 \bullet (374 - 284) = 620\,640\ kJ = 621\ MJ$$

Water content	**20%**	**40%**	**50%**
Initial water [kg]	862	2299	3448

Final water [kg]	608	608	608
m,h2o,evap [kg]	254	1690	2840
DM heating [MJ]	621	621	621
h2o, heat + evap [MJ]	897	4677	7701
Total drying Heat [MJ]	1518	5298	8322
Pyrolysis heat [MJ]	16449	16449	16449
Total woodchips replaced [kg]	1676	1343	1076
F.U GWP [kg,co2,eq]	-2057	-2048	-2040
Yearly GWP [kt]	-11,9	-11,9	-11,8
Revenue [SEK/FU]	1080	865	693
Yearly revenue [MSEK]	6,26	5,02	4,02
NPV High bound [MSEK]	644,5	622,9	605,7
NPV Low bound [MSEK]	0,5	-21,0	-38,2

4.3. Feedstock losses in transports

Required feedstock = $m_{collected} = \frac{\mathrm{m}_{feedstock\ input}}{1-\varepsilon_{losses}}$

$\mathrm{m}_{feedstock\ input} = 4926\ [kg]$

$\varepsilon_{losses} = [2\%, 5\%, 15\%]$

Transport losses	**2%**	**5%**	**15%**
Required feedstock [kg]	4926	4926	4926
Feedstock with losses [kg]	5027	5185	5795
F.U GWP [kg,co2,eq]	-2085	-2078	-2039
Yearly GWP [kt]	-12,1	-12,1	-11,9
Cost [SEK/FU]	3239	3341	3734
Yearly Cost [MSEK]	18,8	19,4	21,7
NPV High bound [MSEK]	666,1	655,8	616,4
NPV Low bound [MSEK]	22,2	11,9	-27,5

4.4. Feedstock price

Purchase price = $P_{feedstock}$ = [160,200] SEK/MWh
GROT heating value (30% moisture) = h_{GROT} = 3,58 MWh/ton (Skogforsk, 2019)
Amount = $m_{feedstock}$= 5,5 ton

FU Cost: $\mathrm{P}_{feedstock}[SEK/MWh] \bullet h_{GROT}[MWh/ton] \bullet \mathrm{mfeedstock} = \mathrm{C}_{feedstock}\ [\mathrm{SEK}]$

Feedstock price [SEK/MWH]	**160**	**200**
GROT heating value [MWh/ton]	3,58	3,58

Feedstock amount [ton]	5,5	5,5
Cost [SEK/FU]	3150	3938
Yearly Cost [MSEK]	18,3	22,8
NPV High bound [MSEK]	675,0	596,0
NPV Low bound [MSEK]	31,1	-47,9

4.5. Discount rate

3% discount rate, high bound

t [year]	Ct [MSEK]	r	Yearly NPV [MSEK]	Investment cost [MSEK]
1	42,26	0,03	41,0	
2	42,26	0,03	39,8	
3	42,26	0,03	38,7	
4	42,26	0,03	37,5	
5	42,26	0,03	36,5	
6	42,26	0,03	35,4	
7	42,26	0,03	34,4	
8	42,26	0,03	33,4	
9	42,26	0,03	32,4	
10	42,26	0,03	31,4	
11	42,26	0,03	30,5	
12	42,26	0,03	29,6	
13	42,26	0,03	28,8	
14	42,26	0,03	27,9	
15	42,26	0,03	27,1	
16	42,26	0,03	26,3	
17	42,26	0,03	25,6	
18	42,26	0,03	24,8	
19	42,26	0,03	24,1	
20	42,26	0,03	23,4	
21	42,26	0,03	22,7	
22	42,26	0,03	22,1	
23	42,26	0,03	21,4	
24	42,26	0,03	20,8	
25	42,26	0,03	20,2	
26	42,26	0,03	19,6	
27	42,26	0,03	19,0	
28	42,26	0,03	18,5	
29	42,26	0,03	17,9	
30	40,26	0,03	16,6	
SUM			827,5	95,4
Result [MSEK]				732,1

3% discount rate, low bound

t [year]	Ct [MSEK]	r	Yearly NPV [MSEK]	Investment cost [MSEK]
1	13,36	0,03	13,0	
2	13,36	0,03	12,6	
3	13,36	0,03	12,2	
4	13,36	0,03	11,9	
5	13,36	0,03	11,5	
6	13,36	0,03	11,2	
7	13,36	0,03	10,9	
8	13,36	0,03	10,5	
9	13,36	0,03	10,2	
10	13,36	0,03	9,9	
11	13,36	0,03	9,7	
12	13,36	0,03	9,4	
13	13,36	0,03	9,1	
14	13,36	0,03	8,8	
15	13,36	0,03	8,6	
16	13,36	0,03	8,3	
17	13,36	0,03	8,1	
18	13,36	0,03	7,8	
19	13,36	0,03	7,6	
20	13,36	0,03	7,4	
21	13,36	0,03	7,2	
22	13,36	0,03	7,0	
23	13,36	0,03	6,8	
24	13,36	0,03	6,6	
25	13,36	0,03	6,4	
26	13,36	0,03	6,2	
27	13,36	0,03	6,0	
28	13,36	0,03	5,8	
29	13,36	0,03	5,7	
30	11,36	0,03	4,7	
SUM			261,0	239,6
Result [MSEK]				21,4

5% discount rate, high bound

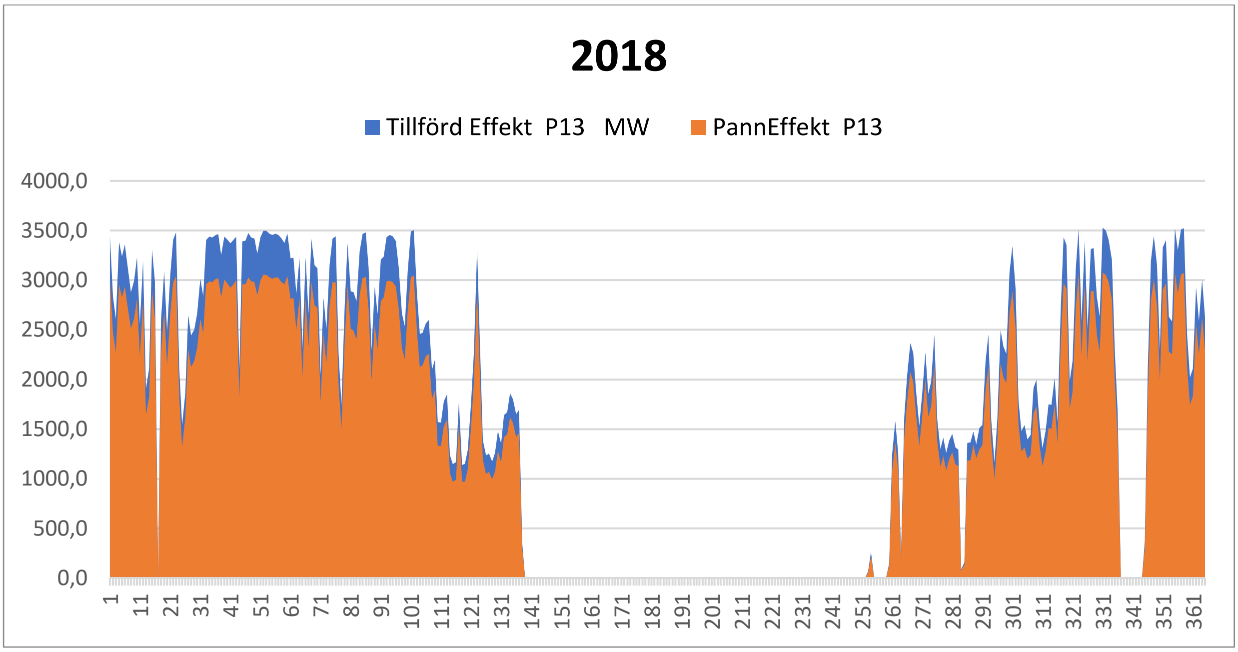
t [year]	Ct [MSEK]	r	Yearly NPV [MSEK]	Investment cost [MSEK]
1	42,26	0,05	40,2	
2	42,26	0,05	38,3	
3	42,26	0,05	36,5	
4	42,26	0,05	34,8	
5	42,26	0,05	33,1	
6	42,26	0,05	31,5	
7	42,26	0,05	30,0	
8	42,26	0,05	28,6	
9	42,26	0,05	27,2	
10	42,26	0,05	25,9	
11	42,26	0,05	24,7	
12	42,26	0,05	23,5	
13	42,26	0,05	22,4	
14	42,26	0,05	21,3	
15	42,26	0,05	20,3	
16	42,26	0,05	19,4	
17	42,26	0,05	18,4	
18	42,26	0,05	17,6	
19	42,26	0,05	16,7	
20	42,26	0,05	15,9	
21	42,26	0,05	15,2	
22	42,26	0,05	14,4	
23	42,26	0,05	13,8	
24	42,26	0,05	13,1	
25	42,26	0,05	12,5	
26	42,26	0,05	11,9	
27	42,26	0,05	11,3	
28	42,26	0,05	10,8	
29	42,26	0,05	10,3	
30	40,26	0,05	9,3	
SUM			649,2	95,4
Result [MSEK]				553,8

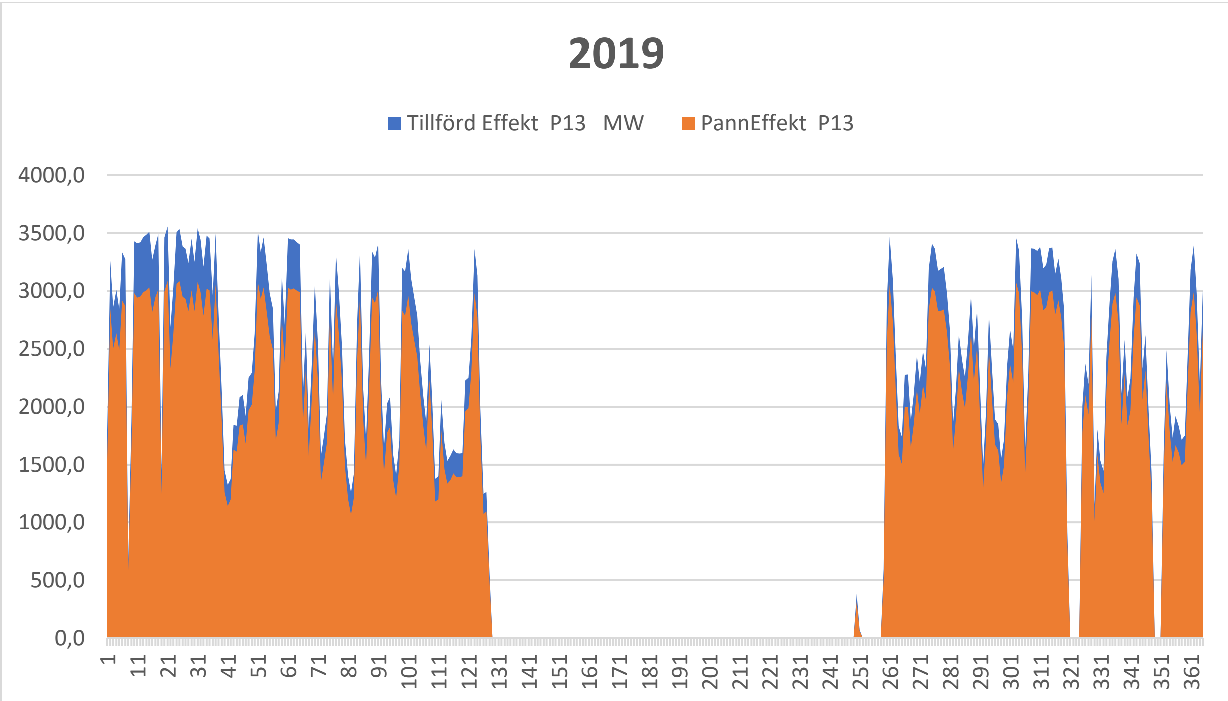
5% discount rate, low bound

t [year]	Ct [MSEK]	r	Yearly NPV [MSEK]	Investment cost [MSEK]
1	13,36	0,05	12,7	
2	13,36	0,05	12,1	
3	13,36	0,05	11,5	
4	13,36	0,05	11,0	
5	13,36	0,05	10,5	
6	13,36	0,05	10,0	
7	13,36	0,05	9,5	
8	13,36	0,05	9,0	
9	13,36	0,05	8,6	
10	13,36	0,05	8,2	
11	13,36	0,05	7,8	
12	13,36	0,05	7,4	
13	13,36	0,05	7,1	
14	13,36	0,05	6,7	
15	13,36	0,05	6,4	
16	13,36	0,05	6,1	
17	13,36	0,05	5,8	
18	13,36	0,05	5,6	
19	13,36	0,05	5,3	
20	13,36	0,05	5,0	
21	13,36	0,05	4,8	
22	13,36	0,05	4,6	
23	13,36	0,05	4,3	
24	13,36	0,05	4,1	
25	13,36	0,05	3,9	
26	13,36	0,05	3,8	
27	13,36	0,05	3,6	
28	13,36	0,05	3,4	
29	13,36	0,05	3,2	
30	11,36	0,05	2,6	
SUM			204,9	239,6
Result [MSEK]				-34,7

Appendix B – Supplementary input data

EO.N Händelö P13 operating hours





Appendix C – OpenLCA model

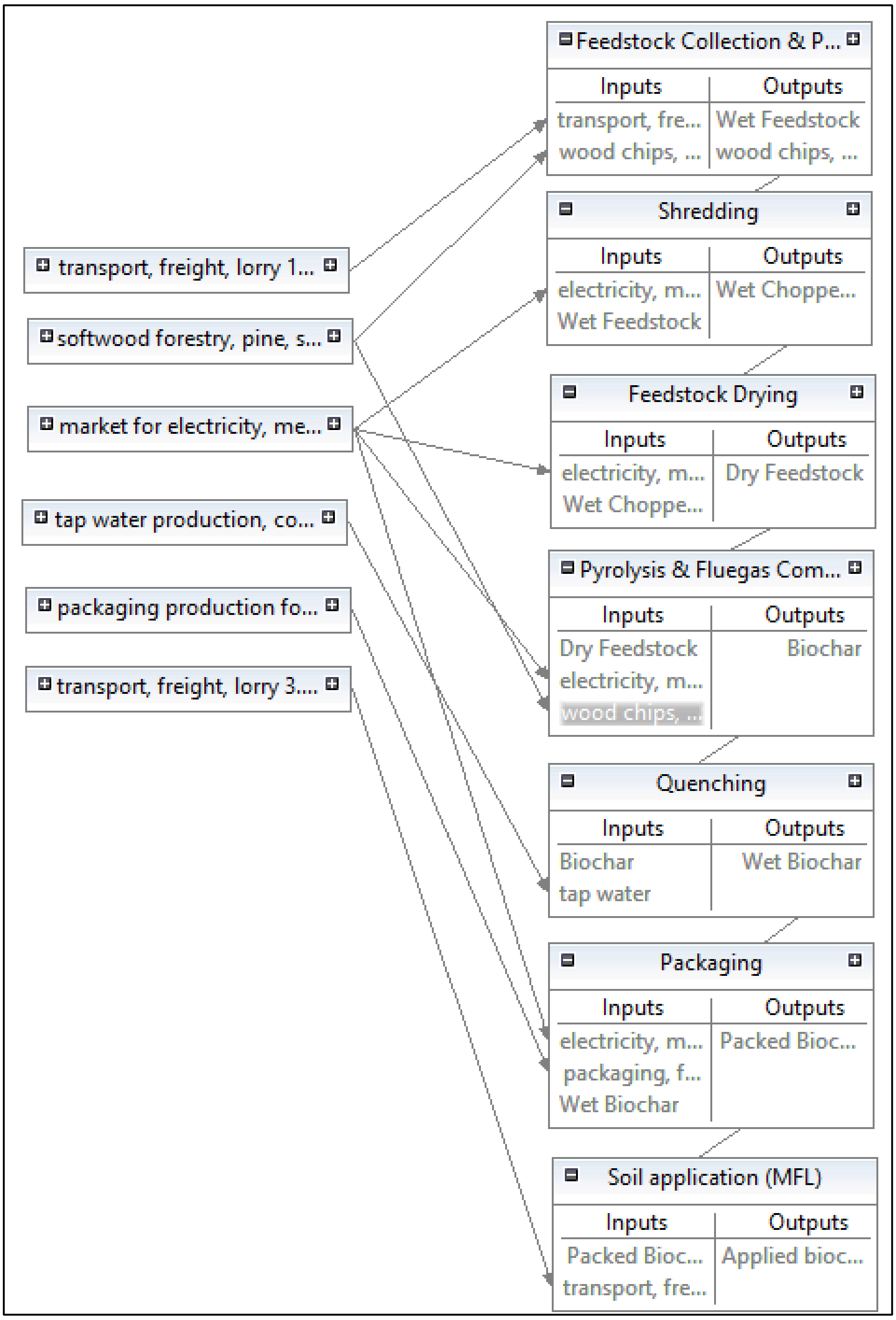


Figure: OpenLCA 1.10.2

Appendix D – Cost results breakdown

Base Case

Step	Cost per FU, high bound	Cost per FU, low bound
Feedstock production/collection	3552 SEK/ton	3552 SEK/ton
Grinding	8 SEK/ton	8 SEK/ton
Drying	71 SEK/ton	83 SEK/ton
Pyrolysis	410 SEK/ton	583 SEK/ton
Quenching	3 SEK/ton	3 SEK/ton
Packaging	337 SEK/ton	526 SEK/ton
Additional costs		
Equipment Installation	33 SEK/ton	193 SEK/ton
Instruments & controls	11 SEK/ton	110 SEK/ton
Piping	17 SEK/ton	275 SEK/ton
Electrical	11 SEK/ton	138 SEK/ton
Labor	502 SEK/ton	502 SEK/ton
Decommissions	11 SEK/ton	11 SEK/ton
Sum	**4966 SEK/ton**	**5984 SEK/ton**

Costs

Revenue

Category	Revenue per FU, low bound	Revenue per FU, high bound	Yearly revenue, low bound	Yearly revenue, high bound
Biochar	5909 SEK/ton	10 714 SEK/ton	34,3 MSEK	62,1 MSEK
GROT substitution	988 SEK/ton	988 SEK/ton	5,7 MSEK	5,7 MSEK
Sum	**6897 SEK/ton**	**11 702 SEK/ton**	**40 MSEK**	**67,8 MSEK**

Alternative Case

Costs

Step	**Cost per FU, high bound**	**Cost per FU, low bound**
Feedstock production/collection	3552 SEK/ton	3552 SEK/ton
Grinding	6 SEK/ton	6 SEK/ton
Drying	52 SEK/ton	60 SEK/ton
Pyrolysis	286 SEK/ton	405 SEK/ton
Quenching	3 SEK/ton	3 SEK/ton
Packaging	335 SEK/ton	524 SEK/ton
Additional costs		
Equipment Installation	26 SEK/ton	148 SEK/ton
Instruments & controls	9 SEK/ton	85 SEK/ton
Piping	13 SEK/ton	212 SEK/ton
Electrical	9 SEK/ton	106 SEK/ton
Labor	502 SEK/ton	502 SEK/ton
Decommissions	8 SEK/ton	8 SEK/ton
Sum	**4966 SEK/ton**	**5984 SEK/ton**

Revenue

Category	**Revenue per FU, low bound**	**Revenue per FU, high bound**	**Yearly revenue, low bound**	**Yearly revenue, high bound**
Biochar	5909 SEK/ton	10 714 SEK/ton	49,6 MSEK	90,0 MSEK
GROT substitution (rest of year)	988 SEK/ton	988 SEK/ton	5,7 MSEK	5,7 MSEK
Sum	**6897 SEK/ton**	**11 702 SEK/ton**	**55,3 MSEK**	**95,7 MSEK**

Fixed costs

Equipment	**Cost per FU, high bound**	**Cost per FU, low bound**	**Total cost, high bound**	**Total cost, low bound**
Rotary kiln	402 SEK/ton	575 SEK/ton	70 MSEK	100 MSEK
Shredder	6 SEK/ton	6 SEK/ton	1 MSEK	1 MSEK
Dryer	63 SEK/ton	75 SEK/ton	11 MSEK	13 MSEK
Packaging equipment	6 SEK/ton	6 SEK/ton	1 MSEK	1 MSEK
Installation	33 SEK/ton	193 SEK/ton	5,7 MSEK	33,5 MSEK
Instruments & controls	11 SEK/ton	110 SEK/ton	1,9 MSEK	19,2 MSEK
Piping	17 SEK/ton	275 SEK/ton	2,9 MSEK	47,9 MSEK
Electrical	11 SEK/ton	138 SEK/ton	1,9 MSEK	25 MSEK
Sum	**549 SEK/ton**	**1 378 SEK/ton**	**95,4 MSEK**	**239,6 MSEK**

Running costs

Activity	**Cost per FU, high bound**	**Cost per FU, low bound**	**Yearly cost, high bound**	**Yearly cost, low bound**
Labor	502 SEK/ton	502 SEK/ton	2,92 MSEK	2,92 MSEK
Feedstock	3552 SEK/ton	3552 SEK/ton	20,6 MSEK	20,6 MSEK
Electricity	17 SEK/ton	17 SEK/ton	0,1 MSEK	0,1 MSEK
Water	3 SEK/ton	3 SEK/ton	0,02 MSEK	0,02 MSEK
Packaging	331 SEK/ton	520 SEK/ton	1,9 MSEK	3 MSEK
Sum	**4405 SEK/ton**	**4594 SEK/ton**	**25,54 MSEK**	**26,64 MSEK**

End-of-life costs

Activity	**Cost per FU**	**Total cost**
Decommissions	11 SEK/ton	2 MSEK

Revenue

Category	**Revenue per FU, low bound**	**Revenue per FU, high bound**	**Yearly revenue, low bound**	**Yearly revenue, high bound**
Biochar	5909 SEK/ton	10 714 SEK/ton	34,3 MSEK	62,1 MSEK
GROT substitution	988 SEK/ton	988 SEK/ton	5,7 MSEK	5,7 MSEK
Sum	**6897 SEK/ton**	**11 702 SEK/ton**	**40 MSEK**	**67,8 MSEK**

Net present value

Scenario	**NPV**
High bound (best case)	634,7 MSEK
Low bound (worst case)	-9,2 MSEK

Alternative case LCC results

Investment costs

Equipment	**Cost per FU, high bound**	**Cost per FU, low bound**	**Total cost, high bound**	**Total cost, low bound**
Rotary kiln	278 SEK/ton	397 SEK/ton	70 MSEK	100 MSEK
Shredder	4 SEK/ton	4 SEK/ton	1 MSEK	1 MSEK
Dryer	44 SEK/ton	52 SEK/ton	11 MSEK	13 MSEK
Packaging equipment	4 SEK/ton	4 SEK/ton	1 MSEK	1 MSEK
Combustion chamber	44 SEK/ton	52 SEK/ton	11 MSEK	13 MSEK
Installation	26 SEK/ton	148 SEK/ton	6,5 MSEK	37,3 MSEK
Instruments & controls	9 SEK/ton	85 SEK/ton	2,2 MSEK	21,3 MSEK
Piping	13 SEK/ton	212 SEK/ton	3,2 MSEK	53,3 MSEK
Electrical	9 SEK/ton	106 SEK/ton	2,2 MSEK	36,7 MSEK
Sum	**431 SEK/ton**	**1 060 SEK/ton**	**108 MSEK**	**266,7 MSEK**

Running costs

Activity	Cost per FU, high bound	Cost per FU, low bound	Yearly cost, high bound	Yearly cost, low bound
Labor	502 SEK/ton	502 SEK/ton	4,23 MSEK	4,23 MSEK
Feedstock	3552 SEK/ton	3552 SEK/ton	29,77 MSEK	29,77 MSEK
Electricity	17 SEK/ton	17 SEK/ton	0,15 MSEK	0,15 MSEK
Water	3 SEK/ton	3 SEK/ton	0,03 MSEK	0,03 MSEK
Packaging	331 SEK/ton	520 SEK/ton	2,78 MSEK	4,37 MSEK
Sum	**4405 SEK/ton**	**4594 SEK/ton**	**37,06 MSEK**	**38,55 MSEK**

End-of-life costs

Activity	Cost per FU	Total cost
Decommissions	8 SEK/ton	2 MSEK*

*based on decommission of 16 MW CFB boiler at Chalmers university of Technology

Revenue

Category	Revenue per FU, low bound	Revenue per FU, high bound	Yearly revenue, low bound	Yearly revenue, high bound
Biochar	5909 SEK/ton	10 714 SEK/ton	49,6 MSEK	90,0 MSEK
GROT substitution	988 SEK/ton	988 SEK/ton	5,7 MSEK	5,7 MSEK
Sum	**6897 SEK/ton**	**11 702 SEK/ton**	**55,3 MSEK**	**95,7 MSEK**

Net present value

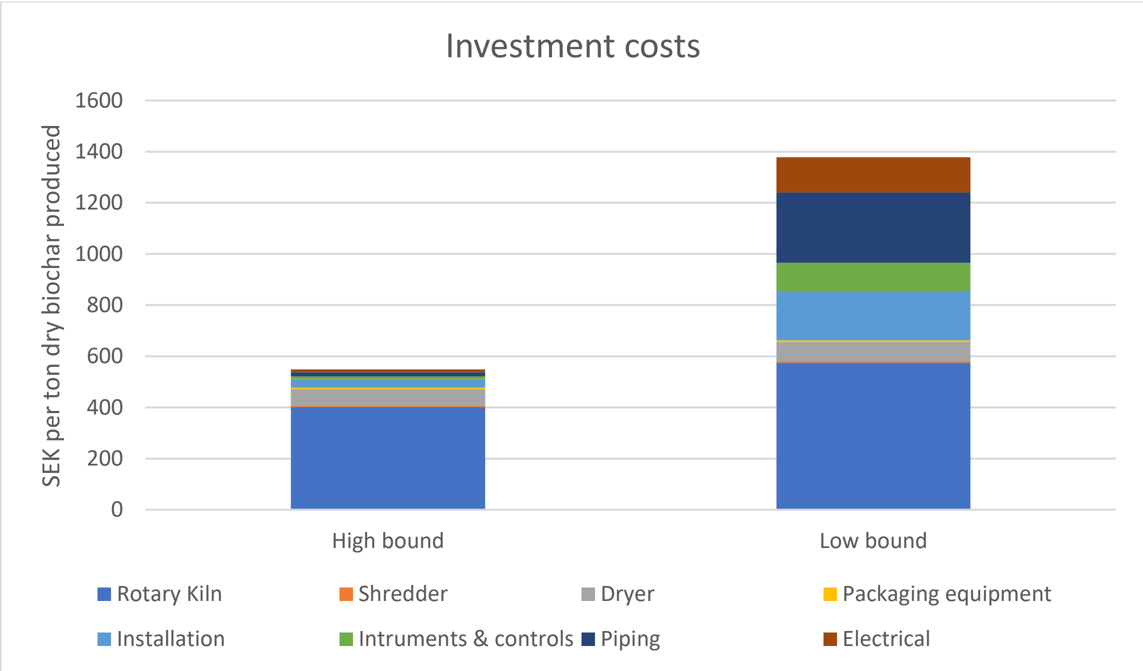
Scenario	NPV
High bound (best case)	905,4 MSEK
Low bound (worst case)	22,3 MSEK

Sensitivity analysis

NC = No change

Alternative	FU GWP [kg_{CO2eq}]	Yearly GWP [kt_{CO2eq}]	High bound NPV [MSEK]	Low bound NPV [MSEK]
Biochar carbon content				
50 %	-1172	-6,8	NC	NC
60 %	-1466	-8,5	NC	NC
70 %	-1760	-10,2	NC	NC
80 % (initial value)	-2053	-11,9	NC	NC
90%	-2347	-13,6	NC	NC
Feedstock initial moisture content				
20%	-2057	-11,9	644,5	0,5

30 % (initial value)	-2053	-11,9	634,7	-9,2
40 %	-2048	-11,9	622,9	-21
50 %	-2040	-11,8	605,7	-28,2
Feedstock losses in transports				
2 %	-2085	-12,1	666,1	22,2
5 %	-2078	-12,1	655,8	11,9
10 % (initial value)	-2053	-11,9	634,7	-9,2
15 %	-2039	-11,8	616,4	-27,5
Feedstock price				
160 SEK/MWh	NC	NC	675	31,1
180 SEK/MWh (initial value)	NC	NC	634,7	-9,2
200 SEK/MWh	NC	NC	596	-47,9
Discount Rate				
3 %	NC	NC	732,1	21,4
4 % (initial value)	NC	NC	634,7	-9,2
5 %	NC	NC	553,8	-34,7



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