Life Cycle Assessment of Biochar Production and Soil Application on Danish Dairy Farms

Master Thesis

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Synopsis:

This thesis analyses the potential for the Danish dairy farming sector to reduce its environmental impacts through carbon storage, by producing biochar from pyrolysis and applying it to their soils. The analysed pyrolysis feedstocks are straw residues and digested manure. This was done through a Life Cycle Assessment, where a consequential model and a model based on the International Dairy Federation's guidelines were modelled to test methodological differences' impacts on LCA results. Research interviews were done to collect data and gain an understanding of the pyrolysis process and the agricultural context. The LCA showed impact reductions on global warming and respiratory inorganics for both feedstocks and modelling approaches when compared to the reference scenarios of applying the biomass directly to land without pyrolysis. The results were used in the context of a specific dairy farm to calculate the potential for reducing environmental impacts from the farm's available biomass. To conclude, pyrolysis can be used as a tool to reduce impacts and help dairy farmers reduce their emissions, but data is still lacking due to the pyrolysis technology being new on a commercial scale.

Resumé

Dette speciale analyserer den danske landbrugssektors potentiale til at reducere sin klimapåvirkning ved at binde kulstof i sine landbrugsjorde gennem produktion af biokul. Eftersom specialet skrives i samarbejde med Arla Foods er fokus på kvægbønder. Biokul produceres ved pyrolyse, og det kan derefter spredes på jorden for at binde kulstoffet deri i over hundrede år. På globalt plan estimeres det, at der udledes 1,9Gigaton kulstof fra jorde årligt, og dette skyldes den måde, jordene bearbejdes. Tabet af kulstof fra jordene er et problem, fordi kulstoffet omdannes til CO_2 i atmosfæren, og samtidig forværres jordenes kvalitet grundet manglen på kulstof, hvilket kan føre til reduceret afgrødeudbytte.

Landbrugssektoren er uløseligt bundet til jordbrugspraksis, og den kan derfor spille en vigtig rolle i at reducere kulstofudledningen fra jorden ved at binde kulstof i organisk materiale og lagre det i jorden. I EU har landbrugssektoren kun reduceret sine drivhusgasudledninger med 2% siden 2005, og derfor kan det argumenteres for, at sektoren mangler nye metoder til at reducere dens udledninger. Pyrolyseprocessen, som bruges til at producere biokul, resulterer også i produktion af syntetisk gas og bioolie, som kan afbrændes for at producere varme, eller raffineres til biobrændstof. I denne rapport modelleres de to produkter til at blive brændt for varmeproduktion, hvilket medfører en undgået varmeproduktion fra andre kilder.

I en dansk landbrugskontekst er de mest oplagte materialer til pyrolyse afgasset gylle og halm. Biokullet analyseres ved livscyklusanalyse (LCA), hvor to modelleringsmetoder testes for at se hvordan resultater kan variere baseret på forskellige antagelser. Der anvendes en consequential LCA modelleringsmetode, samt en metode baseret på International Dairy Federation's retningslinjer. Derudover er kvalitative interviews anvendt for at opnå en forståelse for pyrolyseprocessen, samt til indsamling af empirisk data.

LCA-resultaterne viser, at der opnås en reduktion af påvirkning på global opvarmning mellem 533,26kg CO_2-ækvivalenter og 795,88kg CO_2-ækvivalenter, når det sammenlignes med referencescenariet, hvor biomassen nedmuldes direkte på landbrugsjorden, alt efter hvilket materiale og hvilken modelleringsmetode, der anvendes. Derudover fandtes der også en reduktion på mellem 0,15kg PM2.5-ækvivalenter og 0,31kg PM2.5-ækvivalenter i kategorien 'respiratory inorganics'. Dette skyldtes primært den varmeproduktion, som kom fra afbrænding af syngas og bioolie. Måden, som varmeproduktionen blev modelleret på, spillede derfor også en rolle i de samlede miljøpåvirkninger fra pyrolyseprocessen, og dette udgjorde den største forskel på de to modelleringsmetoder.

Når resultaterne blev sat ind i en specifik kvægbondes kontekst blev resultatet, at der var potentiale til at reducere udledninger fra mælkeproduktionen med 27-29%.

Preface

This report is a Master's Thesis written by Lasse Krogh Poulsen and Philip Holger Lindholt Coenen, during their studies in the master's program, Environmental Management and Sustainability Science at Aalborg University in the period from the 1st of February until the 2nd of June 2023. The report is written with a focus on reducing the environmental impacts of dairy farming. Different carbon capture technologies within the agricultural sector have the potential for mitigating environmental impacts and pyrolysis is one of them. Dairy farmers, related industries and decision-makers can use the results from this study to help plan how to utilise the pyrolysis technology.

We want to thank our project supervisors, Jannick Schmidt and Annika Erjavec for their guidance and helpful critique. Thanks are also given to our contact at Arla Foods, Anna Flysjö, for helping facilitate data collection and contact to interview respondents. Furthermore, we would like to thank the interview respondents for providing essential data for the completion of the project; Henrik N. Pedersen for showing pyrolysis production facilities and insight within the pyrolysis sector, Tobias P. Thomsen for LCA insight within biochar, Niels H. Pedersen for using his farm as case data for this study, and Daniel O. Pedersen for providing insight in the carbon market and as an actor of launching the first commercial pyrolysis plant in Denmark.

The citations in the project are written as (author, year). If no year is applied to the referenced material it will be noted with n.d. (no date). When directly quoting from a referenced material, the page number of the quote will be applied to the citation. Some quotes have been edited in order to ease the understanding of the reader. Whenever a quote has been edited, the edited part has been marked with []. Due to the interviews being done in Danish, and the thesis being written in English, we have translated the interviews ourselves. This is also noted after the translated quotes.

Two of the interviews that have been made as part of the project have been transcribed and uploaded as a separate appendix to the report. When an appendix is assigned a letter, it is attached at the end of this report, and when an appendix is given a number, it is attached separately from the project when handed in for the examination.

Unless otherwise stated in the captions, the pictures, tables, and figures in this project are of our own production.

Aalborg University, June 1, 2023

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List of Abbreviations

Abbreviation	Description
ALCA	Attributional Life Cycle Assessment
CCT	Arla Climate Check Tool
CF	Characterization Factor
CLCA	Consequential Life Cycle Assessment
CO_2eq	Carbon Dioxide-equivalents
CSeq	Carbon Sequestration
DM	Dry Matter
EBC	European Biochar Certificate
FAO	Food and Agriculture Organization of the United Nations
FPCM	Fat and Protein Corrected Milk
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change

Table 1. Abbreviations in alphabetical order

Reading Guide

Definitions of select terms and abbreviations used in this project:

Biochar: *"(...) a porous, carbonaceous material that is produced by pyrolysis of biomass and is applied in such a way that the contained carbon remains stored as a long-term C sink or replaces fossil carbon in industrial manufacturing. It is not made to be burnt for energy generation."* (EBC, 2022, p. 10).
Biogas plant: Also known as an anaerobic digester. Organic material is broken down anaerobically in order to produce biogas, which can be used for energy production, and digestate, which is the residual material consisting of liquid and solid fractions.
Carbon sequestration: Storage of carbon in organic stocks in order to avoid emissions of CO_2 to the atmosphere. This is referred to as carbon storage in this thesis.
Digested manure: Manure from cows, which has been digested in a biogas plant, after which the fibre fraction is separated from the liquid fraction. Digested manure references the fibre fraction in this report.

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Picture: Søren Greve Olesen, LandboNord

Introduction 1

In 2015, the United Nations agreed on the Paris Agreement, where the goal was set to reach net zero greenhouse gas (GHG) emissions by 2050. In order to reach this goal, it is necessary to reduce emissions, but also to withdraw GHGs from the atmosphere (Lehmann et al., 2021). One source of GHG emissions is soil organic carbon (SOC), which is released from soils globally due to management practices. Padarian et al., 2022 estimate that globally, 1,9 Gigatonnes (10^9t) of soil organic carbon has been lost annually between 2001 and 2020 from top soils (upper 30cm soil layer). The loss of SOC is not only contributing to climate change but also leads to degraded, less productive soils, which decreases food security. FAO, 2020 estimate that 1/3 of global soils are degraded. Therefore, technologies that can reverse this trend by incorporating carbon back into the soil are essential against climate change. The agricultural sector, which is inherently tied to soil management and thereby soil carbon, was responsible for emissions equal to 9,3Gt CO_2-equivalents (CO_2eq) in 2018, of which 5,3 Gt was emitted from activities within the farm-gate, with the remaining emissions being caused by land use and land use change. Methane (CH_4) emissions from ruminant livestock (e.g. cattle) constituted the largest amount of emissions within the farm-gate at 2,1 Gt CO_2eq (FAO, 2021). Emissions from livestock manure on pastures and application of manure to cropland contributed 1 Gt CO_2eq, and therefore livestock agriculture constitutes a major part of the agriculture sector's GHG emissions. In the EU, the emissions from agriculture have decreased by 2% since 2005, and the emissions are only projected to decline by a further 2% by 2030 compared to 2005 levels. The implementation of planned measures is however expected to result in a 6% decline compared to 2005 levels, which is still insufficient to meet EU regulation targets (EEA, 2022).

FAO, 2022 argue that, due to the size of the global soils' carbon pool, even a slight increase in the net soil carbon storage constitutes 'a substantial C sink potential'. They estimate that an additional 11,31Gt carbon could be sequestered in global soils by 2040 if the return of carbon to soils increases by an increment of 20%. Therefore, reversing the loss of SOC and implementing measures that can reduce and sequester the GHG emissions from the agricultural sector back into the soil is vital in order to reach a net zero society by 2050 and can also help mitigate soil degradation. One soil carbon sequestration technology, that has gained increasing interest over the last years, is the production of biochar through pyrolysis of biomass.

1.1 Danish political landscape

In 2021, the Danish government and supporting parties made an agreement ensuring that the Danish agricultural sector reaches a GHG reduction of 1,9 million tons CO_2eq by 2030. The agreement is made as an action to the Danish climate law from 2021 (Ministeriet for Fødevarer, Landbrug og Fiskeri, 2021). The law makes the Danish government obligated to reach their goal of reducing the overall Danish GHG emissions by 70% in 2030 compared to 1990 and reaching a climate-neutral society in 2050, in accordance with the Paris agreement (Klima-, Energi- og Forsyningsministeriet, 2021). The ambition of the political parties is that the Danish agricultural sector, including the forestry sector, can reduce its GHG emissions by at least 8 million tons CO_2eq in 2030, but the agreement also says that actions should not involve dismantling the agricultural sector. Therefore, the agreement settled on economic subsidies which encourage farmers and other stakeholders to invest in e.g. green technologies, withdrawal of peat soils, and manure management. In this case, 196 million DKK are saved for pyrolysis technology improvements and testing (Ministeriet for Fødevarer, Landbrug og Fiskeri, 2021). Specifically, the agreement states that biochar in agricultural soils should sequester 2 million tons CO_2eq by 2030 (Food & Bio Cluster Denmark, 2023).

The Danish Climate Council, Klimarådet, 2023a, presented findings for how a possible CO_2 tax could influence the agricultural and forestry sector. They have recommended a price of 750 DKK per ton CO_2eq, and they concluded that a higher tax would not help the sector reduce its emissions significantly, since the sector has limited knowledge and evidence for technologies which can potentially lower the emissions efficiently. The same authors are convinced that a notable part of the reductions is correlated with carbon sequestration, where up to 50% of the CO_2eq concerning the agricultural sector can be reduced. They also proposed a deduction in the CO_2 tax to support the implementation of new technologies to reduce emissions, which could also apply to biochar production. The Danish Climate Council has announced that pyrolysis and biochar might have a high potential for sequestering carbon but some uncertainties must be taken into account. This includes the future supply and demand of biomass, and pyrolysis might therefore not be assured as a mitigation measure for Danish agriculture as it is unsure whether the supply can meet the future demand. Furthermore, they put emphasis on the pyrolysis technology being new on a commercial scale and thorough results of carbon sequestrating are needed before pyrolysis can be beneficial for climate mitigation (Klimarådet, 2023b).

1.2 Arla Foods

Arla Foods (Hereafter Arla) is a farmer-owned dairy company based in Northern Europe, with 9.700 farmer-owners distributed in Denmark, Sweden, Germany, the UK, and to a smaller extent in Belgium, the Netherlands and Luxembourg. Arla has committed to becoming carbon net zero by 2050, and to reduce their scope 1 and 2 emissions by 63% as well as their scope 3 emissions by 30% per kg milk or whey by 2030. An important aspect of reaching these targets is to reduce on-farm emissions. In order to estimate and track sustainability on their farms, Arla released the Climate Check Tool (CCT) in 2019, which covers several different topics related to on-farm sustainability. Part of the CCT is the Arla FarmTool, which is a tool for life cycle assessment (LCA) of the farmers' milk production. The tool was developed by the LCA consultancy company 2.-0 LCA Consultants. The methodology behind the tool can be seen in Schmidt and Dalgaard, 2021. Arla encourages farmers to implement sustainable measures on their farms by monetising on-farm sustainability progress. For example, the farmers get an extra 1,0 Eurocent/kg milk for completing the Climate Check survey (Arla Foods, 2021). Furthermore, the farmers will be scored on a 100-point scale depending on how they perform with regards to sustainability, earning an extra 0,03 Eurocent/kg milk/point, meaning the farmers can earn an extra up to 3 Eurocents/kg milk, excluding the extra 1 Eurocent/kg milk for completing the survey (Arla Foods, 2022b). During a meeting with Arla employees, soil carbon sequestration was identified as an important focus point for Arla's sustainability measures, and thereby biochar from pyrolysis was deemed as an essential tool in order to reach both national political goals and Arla's sustainability goals.

1.3 Biochar

Biochar is defined by the European Biochar Certificate (EBC) as *"(...) a porous, carbonaceous material that is produced by pyrolysis of biomass and is applied in such a way that the contained carbon remains stored as a long-term C sink or replaces fossil carbon in industrial manufacturing. It is not made to be burnt for energy generation."* (EBC, 2022, p. 10).

The biomass used for biochar production can vary, such as woody material, agricultural residues, and biogas digestate. The EBC has made a positive list of biomasses which are allowed to be used for biochar production (EBC, 2023). EBC also allows livestock manure and biogas digestate from livestock manure as a feedstock for biochar production, as long the temperature is at least 500°C and the pyrolysis process lasts at least 3 minutes to eliminate undesirable hazards (EBC, 2023).

In 2022, Elsgaard et al., 2022 published *Knowledge synthesis on biochar in Danish agriculture*. Here, the authors state that straw, livestock manure and separated fibres from biogas digestate are some of the most obvious biochar feedstocks in a Danish context. In the case of straw, it would usually be left after harvest to be incorporated into the soil. However, the potential for carbon sequestration is increased if the straw is converted to biochar, where about 63% of carbon will still be sequestered after 100 years in biochar, compared to only 3% for non-pyrolysed straw. The fibres from biogas digestate would also usually be incorporated into the soil, where it is assumed that 10% of the carbon content will be left in the soil after 100 years for the non-pyrolysed digestate (Elsgaard et al., 2022). The sequestration potential of biochar is dependent on several factors, such as the H/C ratio of the biochar, the pyrolysis temperature, and the temperature of the soil where the biochar is applied. If the H/C ratio is reduced, more carbon can be stored for longer (Woolf et al., 2021). Elsgaard et al., 2022's estimation of 63% carbon remaining after 100 years is based on an H/C ratio of 0,7 and a soil temperature of 10°C. Furthermore, it is believed that the addition of biochar to soils will result in a continuous build-up of carbon in the soils, whereas non-pyrolysed biomass can only build up the carbon stock until an equilibrium is reached. This is due to the decomposition rate of the biomass becoming equal to the input rate, due to the faster decomposition of non-pyrolysed biomass.

It is recommended that the biochar is mixed with slurry or water before being distributed in the soil to avoid dust emissions. This also means the biochar can be distributed in the manure spreading process, thus being incorporated into the farmers' existing workflow. However, there are no studies showing the effects on machinery and equipment, when using it to apply biochar to fields (Elsgaard et al., 2022).

The application of biochar to agricultural soils has been shown to increase crop yields in global studies. However, this is only assumed to be relevant for tropic climates, where soil conditions are sub-optimal compared to soils in temperate climates, such as Denmark. Studies in Denmark have found no significant effect of biochar application on crop yields, and some studies even reported negative effects on crop yields. This is consistent with other studies from Norway, Finland, and Belgium (Elsgaard et al., 2022). However, biochar might have positive effects on yields from acidic, sandy soils, which are present in Western and Southern Jutland, based on experiences from laboratory experiments (Beck, 2019; Elsgaard et al., 2022).

1.3.1 Pyrolysis process

Pyrolysis is a thermochemical process used for the conversion of biomass feedstock under high temperatures and without or only a little access to oxygen. Besides biochar, the pyrolysis process also results in the production of synthetic gasses (syngas) (CH_4, H_2, CO, CO_2, propane and butane), which can be burnt directly to support the pyrolysis process, for district heating, or electricity generating. Some of the syngasses can be condensed and turned into bio-oil which potentially can be used as a fuel in the transport sector, thus reducing the need for fossil fuels (H. N. Pedersen, 2023b). Pyrolysis can be done in a *slow pyrolysis process* or a *fast pyrolysis process*. The difference between the two methods lies in the retention time of the feedstock within the reactor. For slow pyrolysis, a retention time of 'a few minutes' up to several hours is needed. When using slow pyrolysis, the biochar will be more uniform, whereas fast pyrolysis results in less uniform biochar, because the feedstock is only partially degraded. The calorific value of the bio-oil is larger when using fast pyrolysis, and thus the type of pyrolysis process is chosen based on which product is demanded. More carbon-stable biochar will be produced at higher temperatures, and generally, a temperature of at least 500°C is needed to gain a H/C ratio below the required 0,7 (Elsgaard et al., 2022).

Stiesdal SkyClean A/S is the main actor for straw pyrolysis in Denmark (Elsgaard et al., 2022). At the time of writing, no full-scale commercial plant is up and running, but the first full-scale plant is projected to be built by August-September 2023. This plant will be built in connection with a biogas plant in order to create a symbiosis between local farmers and the two plants, where the farmers supply biomass for the biogas plant, whereafter the pyrolysis plant uses dried biogas digestate pellets from the biogas plant and finally, the farmers apply biochar on their cropland (H. N. Pedersen, 2023b). For the pyrolysis of digestate pellets, the digestate first has to be separated into a fibre fraction and a liquid fraction. The fibres will then be dried and pelletized (See Figure 1.1), after which the pellets can be used in the pyrolysis plant (H. N. Pedersen, 2023b). Biochar can contain toxic elements such as tar and heavy metals, which can have negative side effects on soil organisms (Elsgaard et al., 2022). However, H. N. Pedersen, 2023b claim that due to receiving their input materials in pellets, they can have a very uniform pyrolysis process, which results in the biochar's content of heavy metals and tar substances being well below the limit values with the help of technology from the Technical University of Denmark.

Figure 1.1. Pellets of straw (bottom left), biogas digestate (upper left) and biochar (right). Picture from Stiesdal SkyClean facility in GreenLab, Skive.

1.4 State of the art of LCA's regarding biochar and pyrolysis

In the following section, a state-of-the-art (SOTA) of LCAs and review articles concerning carbon sequestration through biochar are conducted.

Seeing as biochar has the potential to sequester significant amounts of carbon, it is important to achieve proper assessment methods for carbon sequestration through biochar. In addition, to properly compare the impacts of different sustainability measures, it is necessary to compensate and facilitate the correct incentives towards the measures which have the greatest potential mitigation effects. Such effects ought to be estimated by using methods such as Life Cycle Assessment. In order to correctly estimate the impacts of carbon sequestration through biochar, life cycle assessments are needed in order to account for the impacts of the entire biochar value chain and the cause-effect relationships within the value chain throughout the life cycle of the biochar. Elsgaard et al., 2022 highlight that there are different approaches for the inclusion of carbon sequestration through biochar in LCA and more methodological development work is needed. Seeing as there is no set methodology on how carbon sequestration should be modelled in LCA, a state of the art has been carried out to assess how carbon sequestration through biochar has been modelled in LCAs so far and to assess whether a consensus can be established based on the LCA results.

A search string was made and used in the Web of Science database (See Figure 1.2), with the following words and boolean operators: *"Life Cycle Assessment" OR LCA AND biochar AND soil* AND pyrolysis*. *Life Cycle Assessment* and *LCA* were included to see which biochar and pyrolysis processes were assessed in academia. The word *pyrolysis* was included primarily because relevant LCA studies may have been made for pyrolysis with the purpose of producing bio-fuels.

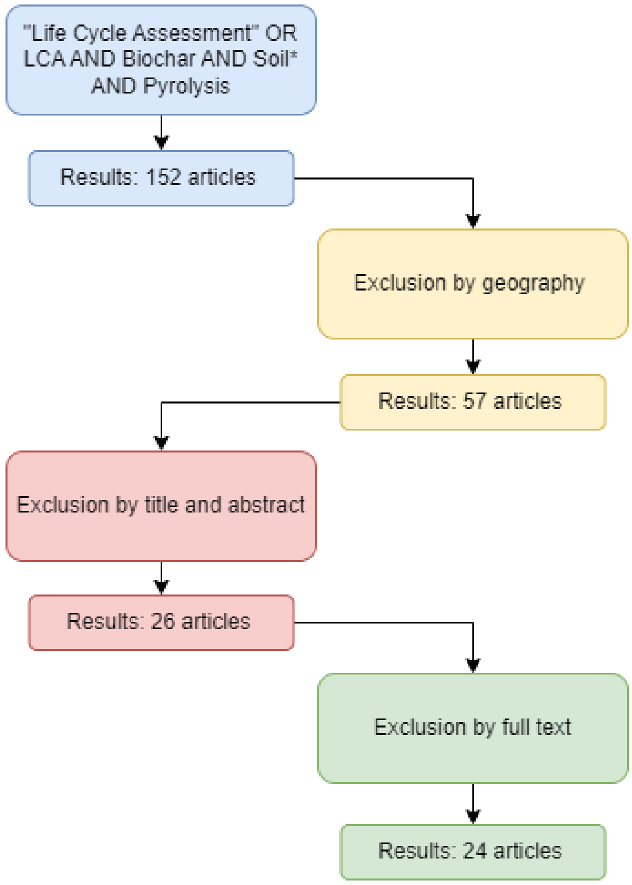

Figure 1.2. State-of-the-art process including search string. State-of-the-art was done in the Web of Science database.

The first results were filtered by geography to only include Northern and Central European countries, where soil and weather conditions were assumed to be similar to Danish conditions[1]. Other countries were excluded, as biochar's impact on different soil types and crops can vary vastly (Elsgaard et al., 2022) e.g. biochar on flooded rice fields cannot be compared to wheat production in Denmark. Therefore, it was assumed that results from the excluded countries would not be as relevant in the context of Danish dairy farms. However, the pyrolysis process might have been similar but the background data and overall assumptions would not match the context of this study's case. However, if a study took place in more than one area, and one of those areas was deemed relevant, the study was included, even though parts of the study were based in excluded countries. This was for example the case for Oldfield et al., 2018, who studied farms in Belgium, Italy and Spain. This exclusion resulted in 57 articles, which afterwards were sorted by title and abstract, resulting in 26 articles for a full reading. In Table 1.1 below, an overview of the articles and their main findings can

[1]Excluded countries: China, USA, Brazil, Australia, Canada, Italy, South Korea, Spain, Singapore, Sri Lanka, Colombia, India, Morocco, Taiwan, Bangladesh, Vietnam, Greece, Indonesia, Japan, Malaysia, New Zealand, Philippines, Chile, Ivory Coast, Egypt, Ethiopia, Pakistan, Panama, Samoa, Thailand, UAE.

be seen. A more detailed description of the articles can be found in Appendix A.

The amount of research conducted to assess biochar and pyrolysis is limited and several sources state that more research is needed within this area (Azzi et al., 2021; Brassard et al., 2021a; Fan et al., 2021; Jeswani et al., 2022; Lehmann et al., 2021; Li et al., 2023; Oldfield et al., 2018; Terlouw et al., 2021; Tisserant et al., 2022). Most of the articles also mention, that it is difficult to compare impacts across LCA's due to different methodological choices, as well as the importance of the local context (Azzi et al., 2021; Terlouw et al., 2021; Zhu et al., 2022). For instance, the studies in this state of the art differ in estimations of how much carbon can be stored depending on methodological choices and thereby making it difficult to assess the potential of biochar as a Cseq technology. As Matuštík et al., 2022 states:

> *"(...) although LCA is a standardized technique, the studies largely differ in how the standard is applied, which leads to vast methodological differences that disallow a more detailed or quantitative comparison."* (Matuštík et al., 2022, p.2)

All the reviewed articles find biochar production and utilisation to result in net negative emissions compared to the reference scenarios and the potential of using biochar for carbon sequestration has been underlined through this state-of-the-art. Some LCA studies did assess more impact categories such as acidification, eutrophication, and human health, but these categories are mostly impacted by the production of electricity and heat from the pyrolysis process and are therefore dependent on the energy system in the region of the study (Azzi et al., 2021, 2022; Brassard et al., 2021a; Matuštík et al., 2022; Oldfield et al., 2018; Tisserant et al., 2022). One article pointed out the challenges of biochar in some cases containing high concentrations of heavy metals which can influence soils negatively (Mohammadi et al., 2019). Another article included the impact of inorganic fertiliser application on managed soils (Oldfield et al., 2018). However, the overall impact reductions from pyrolysis and biochar are higher compared to the reference scenarios used in the articles. Overall, the perspective on biochar seems to be positive and the current literature agrees that biochar has the potential to store carbon in the future on a commercial level.

The current lack of academic research in this area can be seen in the number of publications on the Web of Science database. All of the reviewed articles are relatively new, with the oldest non-LCA article published in 2015, and the oldest LCA study from 2017. The total number of publications relevant to this study's research area is 57 articles released since 2011 (see Figure 1.3). However, the publications' feedstock and pyrolysis process vary by region and whether the pyrolysis process is made for energy purposes or biochar production.

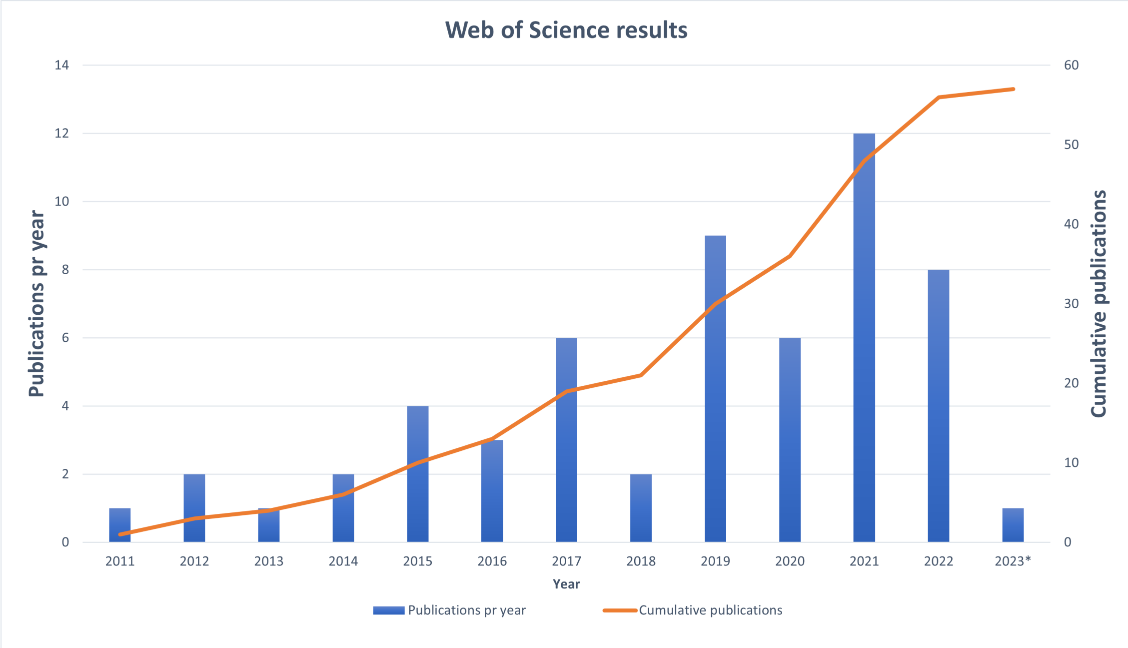

Figure 1.3. Results based on the search of relevant literature (Web of Science, 2023)

Only four of the included studies explicitly specify whether they have used an attributional or consequential LCA modelling approach (Ahmadi Moghaddam et al., 2019; Brassard et al., 2021a; Matuštík et al., 2022; Oldfield et al., 2018), and only Matuštík et al., 2022 has its main focus on how the different methodological decisions between ALCA and CLCA affect the LCA results of biochar application. Through the state of the art, it has been identified that there is a lack of local research into biochar's potential in the context of Danish dairy farming, and also a lack of research into how different methodological choices affect LCA results of impacts of carbon sequestration through biochar.

Main findings	Reference
A review of Biochar/pyrolysis LCAs that concludes there is a good carbon reduction potential. Furthermore, it is important to take the local context into account.	Zhu et al., 2022
An LCA study assessing the potential of oat residues as a feedstock for pyrolysis. The global warming mitigation potential is concluded to be 350 kg of CO_2eq pr ton oats.	Uusitalo and Leino, 2019
Norwegian LCA of four scenarios of utilizing biochar application to managed soils, from wood residues. The study argues that biochar cannot be assessed by itself, but the whole value chain is needed to understand the potential of carbon sequestration.	Tisserant et al., 2022
LCA review found emissions ranging from 0,04t to -1,67t CO_2eq per ton feedstock. Trade-offs for particulate matter, acidification and eutrophication depend on the background energy system. Biochar has a low risk of negative impacts in soils and can improve soil conditions.	Tisserant and Cherubini, 2019
Danish context of using rapeseed production for pyrolysis. A substantial reduction of GHG emissions was recognized and the CO_2 captured was between 71.5% and 86.7% between the applied scenarios.	Thers et al., 2019
Review of LCAs on carbon dioxide removal, e.g. biochar. LCAs need to take into account multiple impact categories, the temporal aspect of emissions, transparency, environmental side-effects, and the importance to distinguish between avoided emissions and negative emissions since only negative emissions are equal to permanent C sequestration.	Terlouw et al., 2021
Review on synergies between pyrolysis and anaerobic digestion of organic waste. Clear evidence of benefits on energy recovery and efficiency through the coupling of AD and pyrolysis, e.g. through the valorization of solid digestate by pyrolysis and more data is needed on the 'technico-economic' benefits.	Tayibi et al., 2021
Applying biochar to soils contaminated with heavy metals could help remediate soils and reduce plant uptake of cadmium, lead, and zink, thus reducing their toxicity. Only assesses biochar from sugarcane-straw.	Puga et al., 2015
Lower environmental impacts than the reference scenario (mineral fertiliser). The biochar-compost combination provided similar crop yields as mineral fertiliser	Oldfield et al., 2018
A review paper discussing the valorization of digestate from anaerobic digestion plants. The paper aims to analyse the different alternatives for digestate and the authors believe a liquid digestate can be used for microalgae culture and solid digestate can be converted to energy.	Monlau et al., 2015
-1,43t CO_2eq/t dry matter feedstock compared to reference scenario of landfilling. Pyrolysis had lower impacts on eutrophication and terrestrial ecotoxicity than incineration and hydrothermal carbonization.	Mohammadi et al., 2019

If biochar production has to be up-scaled as a solution for mitigating CO_2 emissions, a comprehensive LCIA should be obligatory to prevent environmental risks and concerns. Results vary depending on how biogenic CO_2 is handled.	Matuštík et al., 2022
Comprehensive review article analysing the potential development of biochar production by using crop residues in a pyrolysis process. Using a variety of tools to assess the potential feedstocks and pyrolysis plant potential.	Li et al., 2023
A study from Finland argues that willow production, pyrolysis and biochar application can compensate Finish farmers 7.7% of their overall GHG emissions if marginal land is used for growing willow.	Leppäkoski et al., 2021
A review article analysing the potential for biochar as a climate mitigation measure. Biochar can result in emission reductions of up to 6,3Pg CO_2eq globally. Half of this is due to removal of CO_2.	Lehmann et al., 2021
Using broiler manure in a pyrolysis plant can in some cases better or have the same low emissions compared to using broiler manure in a biogas plant. However, the carbon stability in biochar is a significant benefit.	Kreidenweis et al., 2021
Review of negative emission technologies (NETs), e.g. biochar. Biochar soil incorporation has the greatest potential of reviewed NETs, but results 'vary widely' between studies. Biochar can also lead to net savings in fossil depletion, acidification, and human toxicity due to co-products. It is recommended that studies on NETs consider the mass of CO_2eq removed as a functional unit.	Jeswani et al., 2022
Carbon sequestration through biochar is essential in improving the carbon footprint of bioenergy, especially when using biomass with a longer crop rotation length.	Fan et al., 2021
Pyrolysis system with soil application removed the largest part of CO_2 from the atmosphere (compared to direct combustion of feedstock). Results are dependent on the energy system, e.g. direct combustion is best if replacing coal or natural gas.	Ericsson et al., 2017
Utilizing primary forest residues for biochar has better environmental performance in 10/16 impact categories. Trade-offs in the remaining 6 impact categories are due to electricity production	Brassard et al., 2021a
-1,4 to -0,11t CO_2eq/t biochar in a decarbonised energy system (Uppsala, Sweden). Impacts on resource use, human toxicity and ecotoxicity vary depending on feedstock	Azzi et al., 2022
Net CO_2 removal, lower impacts on ozone layer depletion, but increased impacts on land use and health respiratory effects.	Azzi et al., 2021
Comparative life cycle assessment of using wood chips in either pyrolysis or combustion for heating and electricity production. Pyrolysis has a great possibility for carbon mitigation and production of energy, but it can be complex to build a pyrolysis plant for this sole purpose.	Azzi et al., 2019

Comparative LCA of utilising either willow or maize as a feedstock for biomethane production. Willow-based pyrolysis is significantly better at carbon sequestration in the reference scenarios.	Ahmadi Moghaddam et al., 2019

Table 1.1. Main findings from articles obtained through the state-of-the-art.

Research Question 2

Global warming from greenhouse gas emissions can no longer be dealt with only by lowering emissions, but storage of carbon is also needed (Lehmann et al., 2021). Carbon-capturing technologies are necessary measurements to ensure the global temperature stays below, what the Paris Agreement settled on. Therefore, several technologies for CO_2-removal are being explored, and biochar is one which can be utilised by farmers, who are also responsible for improving the management of their cropland. Biochar and pyrolysis can be accelerated in society and the political landscape has set goals for the carbon sequestration possibilities of biochar. Several actors, including Landbrug og Fødevarer, n.d. (the Danish farmers union), Arla Foods, 2022a and Stiesdal A/S, 2023 are assured that biochar is beneficial as a carbon storage technology, where the farmers play a key role in delivering biomass for pyrolysis and storing carbon in their soil. However, assurances are needed regarding the benefits of the pyrolysis technology and what environmental impacts might or might not be associated with applying biochar on their cropland. Additionally, the research of biochar and pyrolysis is quite novel, and methodological choices and local contexts are important for the LCA results. Furthermore, based on the introduction it was found that LCA knowledge of pyrolysis and biochar utilisation based on feedstocks from farming systems is novel, and methodological differences make it difficult to compare results. Therefore, a comparison of two LCA modelling approaches of carbon sequestration can be helpful to understand the two methodological approaches and what might be beneficial for carbon storage. Based on the findings of the introduction, the following research question and sub-research questions have been formulated:

What are the potential environmental impacts of soil carbon sequestration through biochar for Danish dairy farmers?

1. How do different LCA modelling assumptions affect the LCIA results of soil carbon sequestration, and what are the implications of these differences?
2. What is the potential for Danish dairy farmers to utilise pyrolysis to reduce the climate impacts of their milk production?

Sub-question 1: Since Elsgaard et al., 2022 and several articles in the state-of-the-art explained how methodological choices make it difficult to compare different LCA's and that methodological development is needed for assessments of carbon sequestration, it has been found relevant to assess how the results differ when using two different modelling methods. Therefore, the LCA will be carried out using a consequential approach as well as the approach that Arla uses in the Arla FarmTool.

Sub-question 2: The other aspect which has a lot of attention, is the potential biochar possesses as a climate mitigation measure. Since Arla has set goals for net zero emissions by 2050, this sub-question has been formulated to clarify the potential of biochar utilisation for dairy farmers in order to reach the target of carbon neutrality by utilising biochar.


Vestas
Stiesdal
SkyClean

Research Design & Methodology 3

This chapter provides the reader with an overview of the research design and the underlying methods. This includes an introduction to how interviews and LCA methodologies have been used and incorporated into this study.

The research design is created with the purpose to guide the research and the reader to create an insight into how the thesis has been carried out, thus supporting the trustworthiness and validity of this study's outcome (Farthing, 2016). Furthermore, the research design, which is illustrated in Figure 3.1, summarises how it is intended to answer the research questions with the underlying sub-questions, methods, and analysis of results. The research design has also helped to steer this project and carry out the written master thesis required for this final semester.

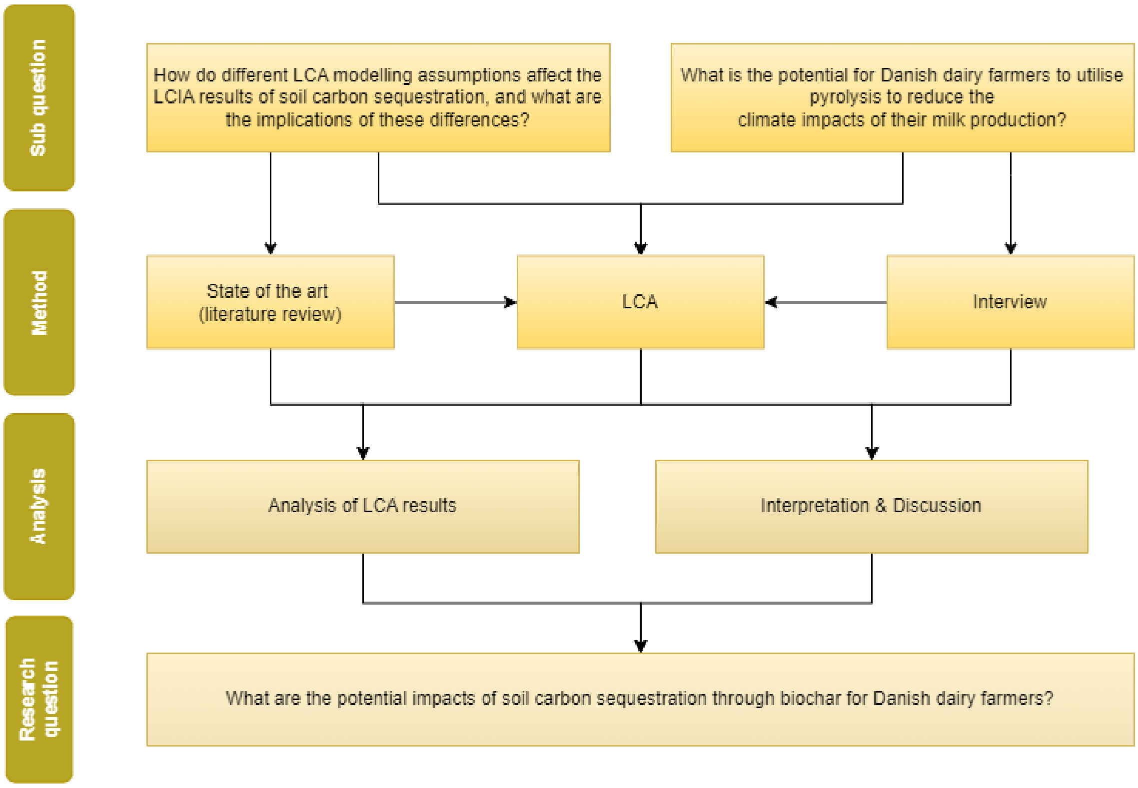

Figure 3.1. Research design

3.1 Interviews

Interviews have been conducted in this study in order to gain empirical data from actors within fields related to the research subject, such as farmers and people working with pyrolysis and/or biogas. The overall purpose of conducting these interviews was to gain crucial data for the inventory and interpretation phases of the LCA. The interviewees and their knowledge within their field are necessary to carry out the LCA as they have information which is important for the system modelling, in order to make the model reflect the 'real world' as closely as possible. However, empirical data obtained through qualitative interviews can supplement data from the literature as long as they are documented, and obtained in a methodologically correct manner. This give greater insight into these actors' perspectives and opinions on biochar and how best to utilize it in order to increase synergies between the different actors within the value chain of biochar. This gives a more holistic understanding of the research subject.

The interviews were conducted as semi-structured interviews, where an interview guide was prepared beforehand, in order to ensure that all the relevant subjects would be explored throughout the interview to increase the validity of each interview, but there was also the freedom to stray away from the interview guide in order to explore some subjects deeper if any of the respondent's answers warranted it (Kvale & Brinkmann, 2015). Some of the empirical data collection was also collected through presentations and informal conversations. Informal conversations create a more intimate space compared to structured and semi-structured interviews, e.g. respondents converse with immediate responses and thus create an environment to explore unexpected answers more thoroughly. Informal conversations are therefore not attributed to a specific context or agenda, the responses are thereby less influenced by the interviewers' bias, thus making the empiric data more valid in the eyes of the respondent. (Brinkmann & Tanggaard, 2015; Bundgaard et al., 2018)

In Table 3.1 below, an overview of the interviews can be seen. The interviews with Henrik N. Pedersen and Tobias P. Thomsen were recorded with consent from the respondents and afterwards transcribed in order to use quotes in the study.

Interview type	Respondent(s)	Organisation	Date	Length
Semi-structured	Henrik Nørskov Pedersen	Stiesdal Skyclean	02/03	01:16:36
Presentation	Henrik Nørskov Pedersen	Stiesdal SkyClean	14/03	01:00:00
Semi-structured	Niels Hedermann Pedersen	Lykkegaard / Arla	21/03	Not recorded
Semi-structured	Tobias Pape Thomsen	Roskilde University	23/03	00:44:52
Presentation	Daniel Overgaard Pedersen	BB Biogas	31/03	Not recorded

Table 3.1. Overview of this study's interviews

Henrik Nørskov Pedersen, Stiesdal SkyClean

In order to gain primary data and insight into the workings of a pyrolysis plant, Henrik N. Pedersen from Stiesdal SkyClean was interviewed. This interview was combined with a visit to the company's pilot pyrolysis plant in GreenLab, Skive. This provided an insight into how a pyrolysis plant looks and operates. Pedersen is an agronomist, who is working with sales and business development at Stiesdal. Besides Pedersen, an intern from Vestjyllands Andel, which is a farmer cooperative and a partner to Stiesdal on pyrolysis technology, participated in the tour of the pyrolysis plant. He provided further insight into the practicality of implementing the pyrolysis technology into the work routines of farmers. The interview was followed up by a formal presentation from Pedersen on the Stiesdal SkyClean project. This presentation included more data on the pyrolysis plants and also provided an opportunity to ask additional questions that had arisen since the first visit and interview.

Niels Hedermann Pedersen, Lykkegaard/Arla

Niels Hedermann Pedersen was interviewed in order for the project to take point of departure on his farm. Pedersen owns and runs Lykkegaard farm, which is part of the Arla *Regenerative Farming Pilot Farm Network*, meaning that Pedersen is among the very first to try and test new sustainability measures. Furthermore, the farm is in close vicinity to the pyrolysis plant currently under construction in Vrå, and therefore the farm was chosen as a case for this study. The interview was an opportunity to get data on Pedersen's farm, which provided information on how biochar would be implemented on the farm-level and the data could be applied in the Arla FarmTool in order to assess how the use of biochar affects the impacts of the milk produced on Pedersen's farm.

Tobias Pape Thomsen, Roskilde University

Tobias P. Thomsen, Associate Professor at Roskilde University, was interviewed as he has done several studies on biochar, such as *Climate Footprint Analysis of Straw Pyrolysis & Straw Biogas* (Thomsen, 2021). The climate footprint study is closely related to the research topic of this thesis and also uses consequential LCA. Thomsen was deemed as a leading LCA expert concerning pyrolysis and biochar in Denmark. The overall gain of the interview was understanding some of the premises of modelling biochar in an LCA study and an expert perspective of the potential environmental impacts of applying biochar on cropland. Thomsen provided information, which was used in order to assess the validity of the results of the impact assessment.

Daniel Overgaard Pedersen, pig farmer and owner of BB Biogas

The first commercial pyrolysis plant in Denmark is currently under construction at the time of writing. The plant is being built in continuation of a biogas plant and is meant to use the biogas digestate as feedstock for the pyrolysis. The construction is done as a cooperative between Daniel O. Pedersen and Stiesdal SkyClean. The data collection from Daniel Pedersen was foremost to see and get a hands-on experience of the biogas plant and the pyrolysis plant under construction. Hereafter, a conversation was had about the potential for farmers like Daniel Pedersen and Niels Pedersen to utilise pyrolysis for carbon storage and new revenue streams.

3.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is a method used for estimating the environmental and climate impacts of a product or service throughout its life cycle, which includes all stages from the extraction of resources, for the production of the product (cradle), until its disposal after it has been used for its original purpose (grave). Through LCA, different products and improvement options can be compared and the hotspots for impacts can be found in order to focus development efforts and advise decision-makers.

LCA is an iterative, four-phase process, consisting of:

- Goal and scope definition
- Inventory analysis (LCI)
- Impact assessment (LCIA)
- Interpretation

The ISO Standards ISO14040, 2006 and ISO14044, 2006 set the principles and framework, requirements, and guidelines for conducting an LCA, respectively.

When doing the inventory analysis phase of an LCA, two distinct modelling choices exist; consequential (CLCA) and attributional (ALCA) (See Figure 3.2). These two modelling approaches can be defined as:

> *"Attributional approach: System modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule.*
> *Consequential approach: System modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit."* (Sonneman & Vigon, 2011, p. 132-133)

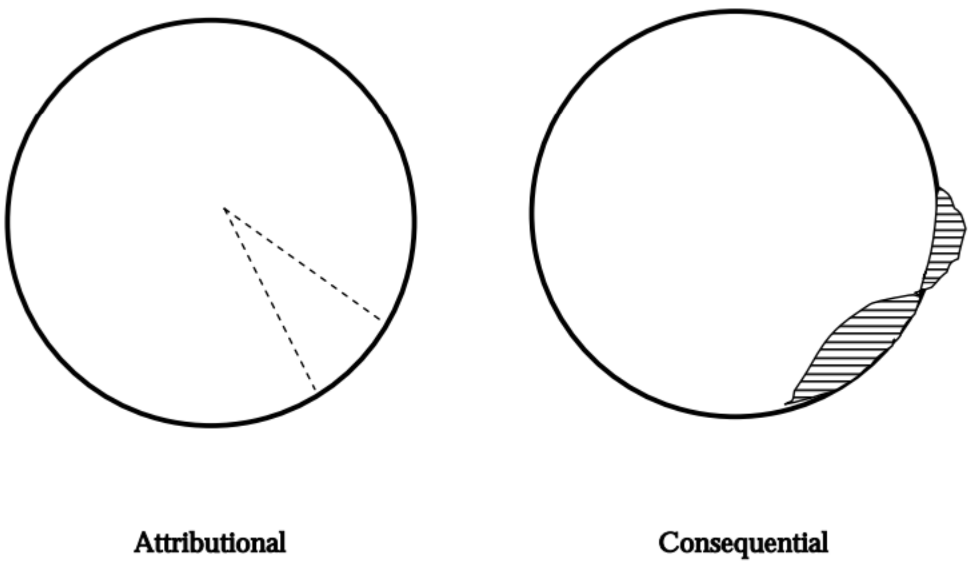

Figure 3.2. Illustration of difference between ALCA and CLCA (Weidema, 2003).

To further explain Figure 3.2, ALCA modelling cuts out the 'piece of the pie' that belongs to the specific system under study, whereas CLCA seeks to capture the consequences and changes resulting from the studied change. CLCA tries to answer what would happen if a product or the demand for a product changed. The two modelling approaches can be used to answer different questions. An attributional LCA can be used to track a specific aspect of the system under study and allocate a share of environmental impacts to this specific product (e.g. milk from a dairy cow, which also produces leather and meat throughout its life cycle (See Figure 3.3)). The shares can then be divided among these products with respect to a chosen rule of allocation, which could be a monetary value or mass (Consequential-LCA, 2021). However, ISO14044, 2006 state that allocation should be avoided wherever possible by expanding the product system to account for the extra functions that are provided by the co-products, and therefore system expansion (also referred to as substitution) will be used whenever possible in this study. ALCA has also been referred to as being 'retrospective', as it is used to analyse the environmental impacts that can be contributed to how the product has been produced. In a consequential model, the impacts from demand for e.g. cow milk cannot be separated from the other activities that the milk production also entails and impacts. This can therefore be referred to as 'prospective', as the system tries to model the future impacts of demanding/producing the product under study (See Figure 3.4). CLCA does this by using marginal data, where a marginal supplier or technology is identified, which is defined as the supplier/technology that will react to a change in demand (Schmidt, 2008; Weidema, 2003). If using Figure 3.3 as an example, reduced demand for milk on the market will lead to a reduced supply of meat, as fewer cows are needed in this scenario. The reduced supply of meat from dairy cows will therefore have effects on the market for meat, which the consequential approach should analyse and include.

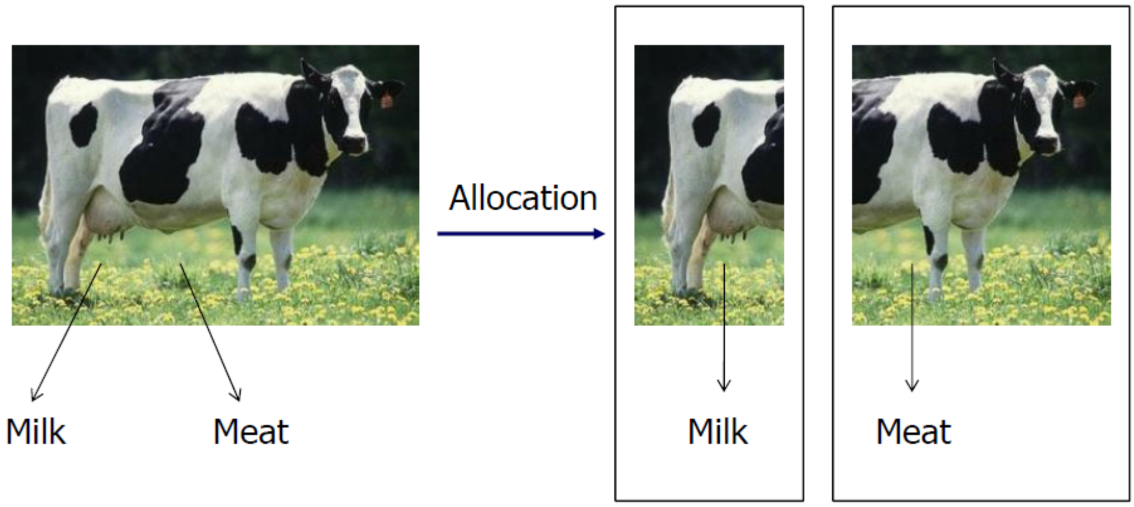

Figure 3.3. Illustration of how allocation cuts out the environmental impacts which have been allocated to a cow's milk production. This means that the impacts from the two products of a cow (milk and meat) are essentially separated from each other. Figure from (Schmidt, 2021).

	Attributional	Consequential
Retrospective	Allocation of responsibility to past actions (Who shall we blame for the way things are?)	Causal explanation of consequences of past actions (What would have happened if we had or had not done this?)
Prospective	Allocation of responsibility for future actions (Who shall we blame for the way things will become?)	Causal explanation of likely consequences of future actions (What will happen if we do or don't do this?)

Figure 3.4. Relation between ALCA/CLCA and retro-/prospective research (Weidema, 2003).

In consequential modelling, allocation of impacts is never used, as the system is expanded to include the activities that are impacted by the production of co-products (Consequential-LCA, 2015). As it was identified in the state of the art, the methodological differences make it difficult to compare LCA results, and since Arla's FarmTool allows for both a consequential and an attributional assessment of the milk production, it was deemed essential to understand the methodological differences in order to answer the research question.

The LCA will be carried out in SimaPro using the ecoinvent and exiobase databases, where all processes directly related to pyrolysis and biochar production are modelled. On-farm processes and processes for biogas production are already implemented in the FarmTool, and this data will therefore be inserted directly into the tool. This is done in order to gain results consistent with current practice. This avoids getting results for milk production that are inconsistent with the calculations already made in the FarmTool. As mentioned earlier, the FarmTool has been developed for Arla by 2.-0 LCA Consultants, and therefore the calculations in the tool are deemed valid and relevant to use as part of this LCA.

For the calculation and accounting of soil carbon stock build-up, different methodological choices have been suggested. International Dairy Federation, 2022b suggests using a responsibility window, where the credits for sequestering carbon are divided equally over the chosen length of the responsibility window. In a comment on a draft of the IDF guidelines, Schmidt, 2020 questions the use of a responsibility window because farmers will not get credit for managing the carbon stock in their soils beyond the responsibility window. Instead, he suggests not implementing a cut-off with a responsibility window in order to allow farmers to be continuously credited for maintaining good practices. Using e.g. a 20 year window means farmers are not credited for maintaining good soil management practices for more than 20 years. These methodological choices will be subject to a discussion in order to relate them to biochar and the findings of the analysis (See Section 7.2.3).

The LCA will take point of departure in a single case farm to assess how biochar utilisation affects the impacts of 1kg Fat- and Protein-corrected milk (FPCM) from that farm.

A sensitivity analysis will be carried out to assess how the results are affected if different criteria are changed in Section 6.3.

4 Goal & Scope

This section contains a clarification of the goal and scope of this LCA study, including the functional unit, system boundary, and reference scenario.

Goal

The intended goal of this study is to assess the effect of applying pyrolysis as a treatment process for straw residues and anaerobically digested manure and slurry (hereafter digested manure). For the purpose of this study, the following functional unit is used:

The functional unit
Treatment of 1000kg 90%DM feedstock

This is chosen as the functional unit, as Elsgaard et al., 2022 provides data per 1.000kg 90% DM feedstock, and since the feedstock must be dry in order to be treated in a pyrolysis plant. This will be put into the context of Danish dairy farmers. However, dairy farmers typically only have very little or no potential leftover biomass except for manure and slurry to supply biogas and pyrolysis, as straw residues are primarily used for feeding and bedding material. This is a general trend for dairy farmers since cows are ruminants, and therefore digested manure is the most obvious feedstock to use in the case of dairy farms. However, opportunities exist for utilising straw residues from other farmers, and therefore both digested manure and straw residue feedstocks are assessed.

Intended application

By understanding and assessing the impacts of biochar and the potential for carbon storage, farmer companies such as Arla can use the findings of this study to assess their potential for carbon sequestration and thereby how they can positively impact the climate and environment. Furthermore, it can help them calculate their GHG accounting. The study shall take point of departure in two LCA modelling approaches, respectively the one used by Arla, which is based on IDF's guidelines, and a consequential approach to assess how and why different modelling choices affect the results. These are henceforth called the Arla-IDF model and the consequential/CLCA model. The *reasons for carrying out this study*, is primarily due to the interest being shown in biochar as a carbon storage technology, as well as the novel practice of utilising biochar in the dairy sector. Biochar research is also dependent on the specific context (type of biomass, energy system, etc.) (See Section 1.3.1), and it is therefore interesting to get context-specific data for Danish dairy farmers. This implies that the *intended audience* for this study is the dairy industry and related dairy farmers can use this study to gain valuable insight into how their carbon storage capabilities can be increased by producing and incorporating biochar into their cropland. Furthermore, decision-makers can be interested in this study's results in order to base future policies on quantified results, such as a potential deduction in CO_2 tax for carbon sequestration as proposed by the Danish Climate Council (see Section 1.1). Lastly, other actors interested in pyrolysis and biochar can also use this study's findings. Quantifying the potential of carbon storage in biochar is important for the dairy sector and for other actors with an interest in pyrolysis.

Scope

For the LCA, the product system starts from the preparation of the feedstock for pyrolysis after being processed in a biogas plant. In the case of digested manure, the product system includes pressing, drying and pelletizing the feedstock after it has been digested in a biogas plant. Straw residues only need to be pelletized. The feedstock is pyrolysed, where biochar, syngas and bio-oil are the resulting products. The syngas and bio-oil are modelled to be combusted for heat generation, and the biochar is modelled to be transported to the farm, where it will be applied to the cropland through regular soil application methods e.g. through a slurry tanker or a fertiliser spreader. The LCA assesses carbon sequestration over a 100 year time horizon. Most data is found for sequestration over 100 years (Elsgaard et al., 2022; Thomsen, 2021; Woolf et al., 2021), and this also aligns with the IPCC's GWP100 emission factors. International Dairy Federation, 2022b also suggests aligning carbon sequestration with GWP100, and therefore this choice has been made. Emissions occurring after 100 years are therefore assigned an emission factor of 0.

The results of the LCA of biochar will be put into the context of the Arla dairy farm. The farmer's data is entered into the Arla FarmTool, where the data can be analysed through a consequential approach and the Arla-IDF approach. The FarmTool is made to estimate the farmers emissions and therefore does not consider the processing of milk after it leaves the farm, also called farm gate. The data needed to estimate the emissions are annually collected from farmers. Furthermore, data from other LCA databases, mainly ecoinvent v3, is used but ecoinvent data accounts for less than 10% of the GHG emissions (Schmidt & Dalgaard, 2021). The overall data required to run the FarmTool consist of the following topics; Animals, housing and manure storage, treatment and land application of manure, feed, crop cultivation, and energy. For animals, data on the number of animals, animal age, amount of milk produced, grassing of animals and their housing system is needed (Schmidt & Dalgaard, 2021). For housing and manure storage, treatment and land application of manure and several technologies are taken into account for estimating emissions. The technologies consist of acidification of slurry, storage cover, and whether the slurry is applied with a broad spreader, band spreading or injected within the soil or grassland. Additionally, anaerobic digestion of slurry is added to the FarmTool as well (Schmidt & Dalgaard, 2021). Data for crop cultivation can be derived from statistical data such as yields and fertiliser application rates (Dalgaard et al., 2016). The feeding topic consists primarily of what crops and by-products the farmer decides to feed the herd, thereby estimating the emissions of the different feed products. Lastly, the topic of energy consist of the diesel and electricity consumed and produced within the dairy farm (Dalgaard et al., 2016; Schmidt & Dalgaard, 2021). The Arla FarmTool is used to calculate the emissions of 1kg FPCM produced from Niels Pedersen's farm, in order to be able to relate the results of the biochar LCA to the farm data.

4.1 System boundary

Since this study will take point of departure in two biomass feedstocks, straw and digested manure, two pyrolysis scenarios have been modelled (See Figures 4.2 and 4.4), which are compared to their respective reference scenarios (See Figures 4.1 and 4.3). The numbers in the figures are based on the inventory (See Chapter 5). The farm data will be adjusted to fit what would happen in the pyrolysis scenarios (Figures 4.2 and 4.4), where the farm starts supplying biomass to a pyrolysis plant and hereafter applying and incorporating the biochar into the cropland. This means that 100% of available biomass is being modelled to be delivered for biogas production and subsequent biochar production. No other farm data has been adjusted.

Reference scenarios In both reference scenarios, the biomass will be incorporated into the soil. For straw residues, the residues are left on the field to be incorporated into the soil. For digested manure, it will be incorporated into the soil after it has been digested in a biogas plant where it will supply nutrients to the crops.

Pyrolysis scenario The pyrolysis scenario models the feedstocks as being prepared for pyrolysis by pressing and drying the digested manure, after which the feedstocks are pelletized. When the feedstocks have been converted to biochar, the biochar is spread on the farmer's cropland to sequester carbon there. The models take the nutritional value of biochar compared to digested manure into account and models this as an avoided production of mineral fertiliser.

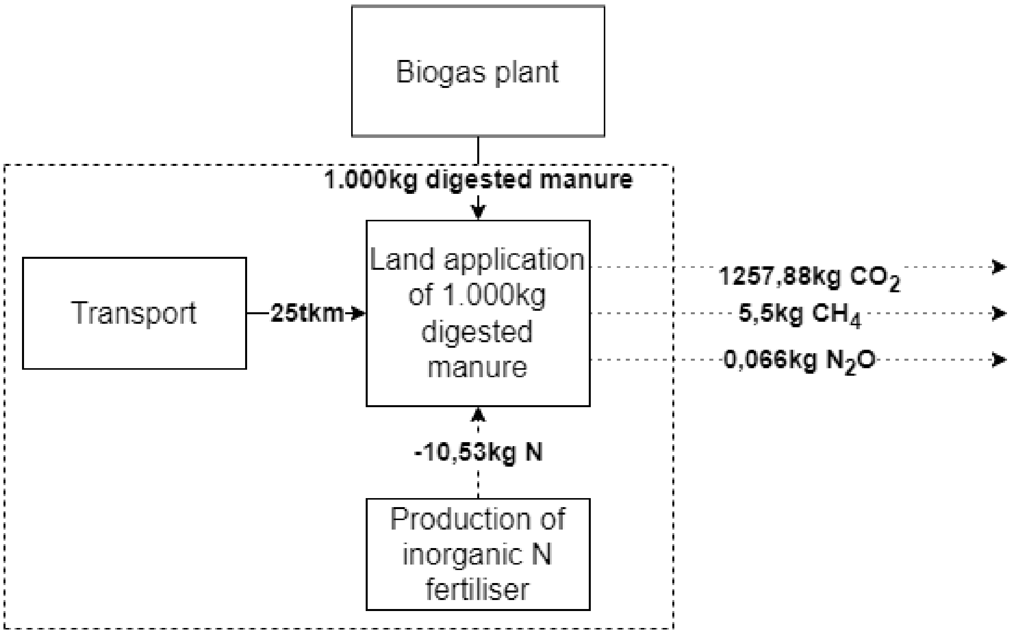

Figure 4.1. Flow chart of the reference scenario for digested manure.

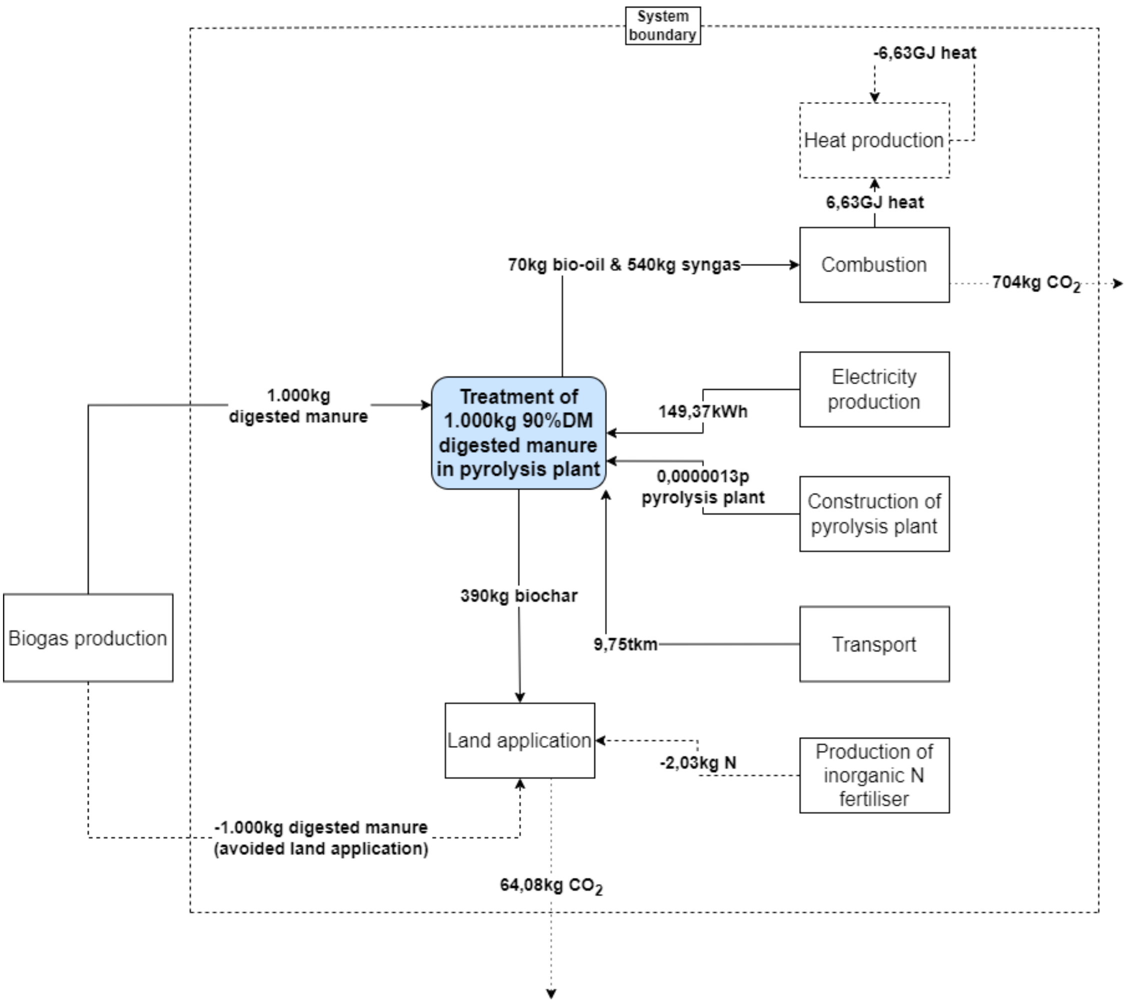

Figure 4.2. Flow chart of the pyrolysis scenario for digested manure.

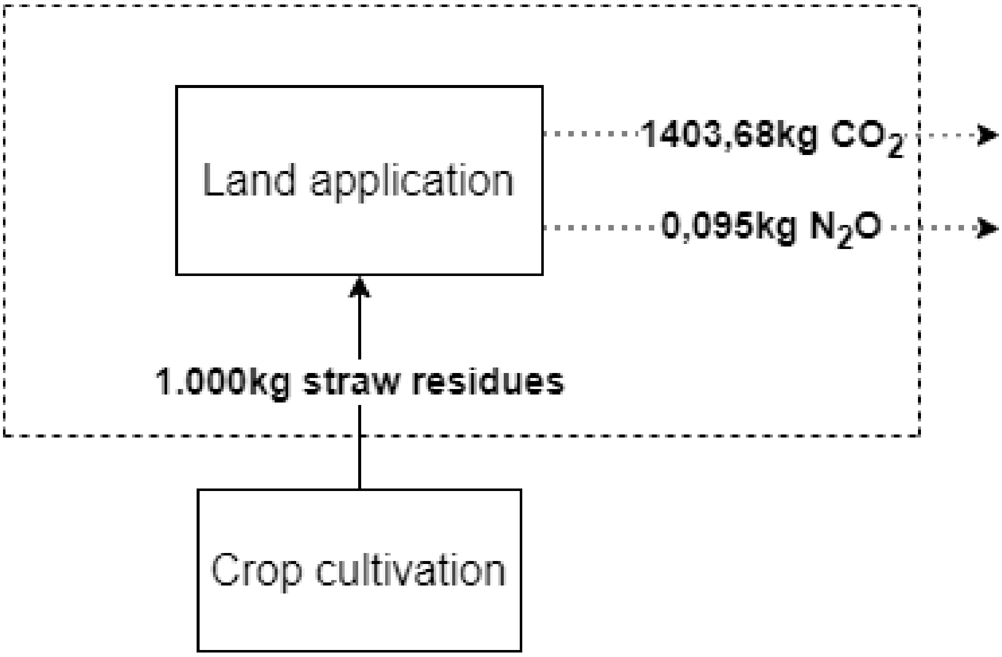

Figure 4.3. Flow chart for the reference scenario for straw residues.

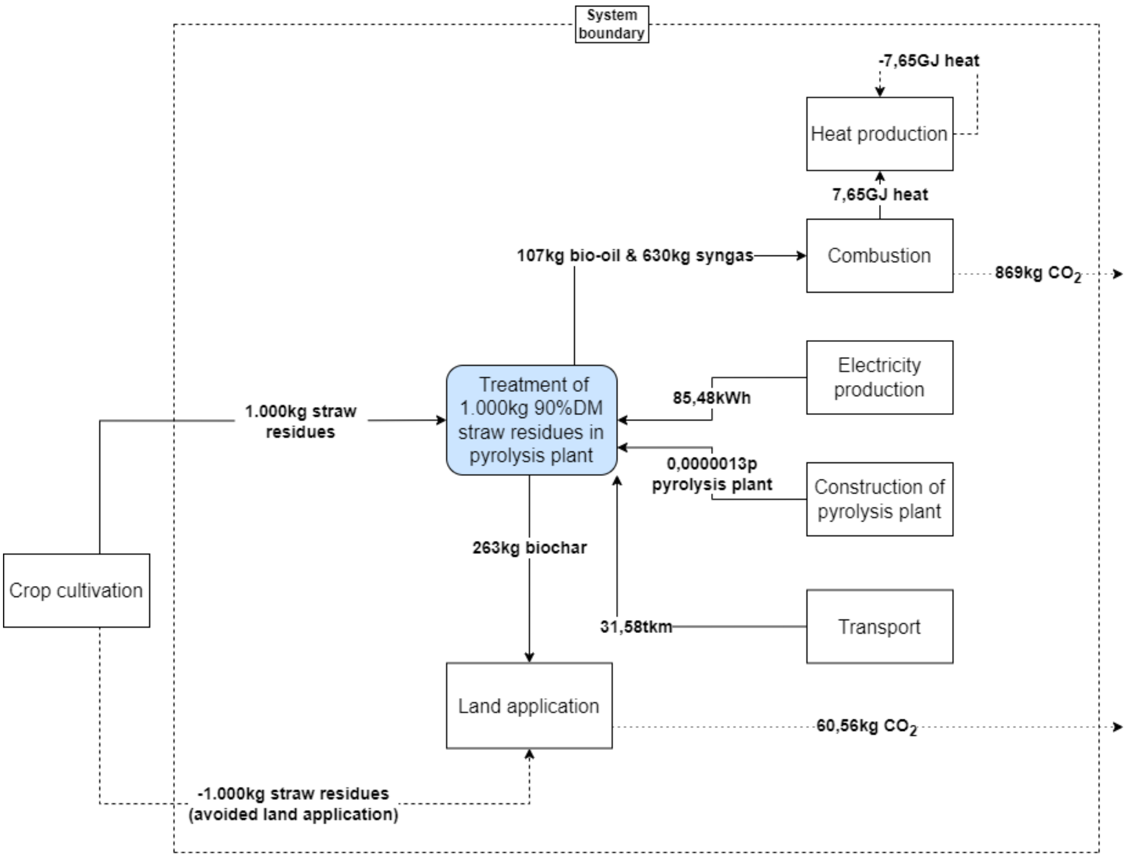

Figure 4.4. Flow chart for the pyrolysis scenario for straw residues

4.1.1 Allocation procedures:

For the consequential modelling, allocations are not used and instead by-products are modelled using substitution (See Section 3.2). For the Arla-IDF model, the study will follow how Arla has chosen to assess their farmers' impacts (Schmidt & Dalgaard, 2021), where International Dairy Federation, 2022a's guidelines are followed, with some exceptions. For the heat supply from the syngas and bio-oil co-products, system expansion is used. This follows how the Arla-IDF model already treats off-farm heat production (Schmidt & Dalgaard, 2021).

4.1.2 LCIA method

The impact assessment method used is the 'stepwise 2006 version 1,7' method, as there are several impact categories which also take iLUC, GWP and biodiversity impacts into account. The results are assessed and interpreted based on the characterized results. The following impact categories have been chosen for further analysis based on the results of the LCIA, where the results have been normalized by the EUR2003 impact/person and the two most impactful categories (both negative and positive values) have been chosen: *Global warming* and *Respiratory inorganics*. Results for all impact categories can be seen in Appendix B.


Stiesdal
SkyClean

Inventory 5

This chapter contains the life cycle inventories for the LCA models. Firstly, the carbon balance of biochar and the two types of biomass is calculated. Afterwards, the inventory data is explained and presented.

5.1 Decay of biochar and associated emissions

In order to calculate the sequestration potential of the biochar, point of departure is taken in the following equation from Woolf et al., 2021. The authors provide an equation (5.1) for calculating the percentage of original carbon left in the biochar, which is dependent on time period, average soil temperature, and pyrolysis temperature:

Estimating carbon emitted from biochar after 100 years

$$F_{perm} = c_{hc} - m_{hc} * (H/C_{org}) \tag{5.1}$$

Where:
$\mathbf{F}_{perm}$ (*%*): The amount of C sequestered after 100 years, and
$\mathbf{c}_{hc}$ (*dimensionless*): The intercept, see Table 3 in Woolf et al., 2021
$\mathbf{m}_{hc}$ (*dimensionless*): The slope, see Table 3 in Woolf et al., 2021
$\mathbf{H}/\mathbf{C}_{org}$ (*dimensionless*): The H/C ratio of the biochar.

By using data from Woolf et al., 2021, based on a 100-year time period, a H/C ratio of 0,3 based on lab results from H. N. Pedersen, 2023a, and an average soil temperature of 10°C, which is based on a 5-year average of Danish soils (Elsgaard et al., 2022), the calculations are as follows:

Estimating carbon emitted from biochar after 100 years

$$1,10 - 0,59 * 0,3 = 0,153 = 15,3\% \tag{5.2}$$

This means that 84,7% of the original carbon will remain in the biochar after 100 years. This is in line with results from Table 3 in Woolf et al., 2021 and from Thomsen, 2021. Note that this differs from the 63% mentioned by Elsgaard et al., 2022 (See Section 1.3). This is because Elsgaard et al., 2022 assumes a H/C ratio of 0,7, due to that being the upper limit allowed by the EBC.

As the majority of carbon is still left in biochar after 100 years, emissions will continue to occur as the biochar decays. However, since GWP100 is chosen as the characterization factor of emissions, any GHG emissions occurring after 100 years will have a factor of 0, and therefore also an impact of 0.

The carbon is not emitted at an equal rate throughout the 100 years, as emissions from biochar are exponential (Elsgaard et al., 2022). In order to calculate the C emissions from biochar in a given year, the following exponential equation is used

Biochar carbon stock in year t

$$Y(t) = C * e^{-k*t} \tag{5.3}$$

Where:
Y(t) (dimensionless): Carbon stock in year t
C (dimensionless): Initial amount of carbon input
e (*dimensionless*): Euler's number = 2, 718
k (*dimensionless*): Decay rate of carbon
t (*year(s)*): time (years after biochar soil application)

From the earlier calculations, it has been found that 84,7% of the carbon stock is remaining in biochar in year 100 ($Y(100) = 0,847$). This information can be used to solve for k to find the yearly emissions of C from biochar utilisation.

Calculating biochar carbon decay rate

$$0,847 = 1*e^{-k*100} \Rightarrow ln(0,847) = -k*100 \Rightarrow k = -(ln(0,847)/100) \Rightarrow k = 0,0017 \tag{5.4}$$

When calculating emissions from straw residues, the remaining carbon stock after 20 years is 13%, and 3% after 100 years (Elsgaard et al., 2022; Thomsen, 2021) which means $Y(20) = 0,130$.

Calculating straw residues carbon decay rate

$$0,130 = 1*e^{-k*20} \Rightarrow ln(0,130) = -k*20 \Rightarrow k = -(ln(0,130)/20) \Rightarrow k = 0,1020 \tag{5.5}$$

By applying this function to the C contents of straw residues, it can be seen that there is 3% carbon left after approximately 34 years, whereafter the remaining carbon is assumed to be stable, and thus no more C is emitted from the straw residues.

For digested manure, a carbon stock of 22% remaining after 20 years and 3% remaining after 100 years was identified (Thomsen, 2021).

Calculating digested manure carbon decay rate

$$0,22 = 1{*}e^{-k*20} \Rightarrow ln(0,22) = -k{*}20 \Rightarrow k = -(ln(0,22)/20) \Rightarrow k = 0,0757 \quad (5.6)$$

When doing the same exercise as was done for straw residues, the carbon decay is assumed to stop at 3% remaining after 46 years.

It should be noted that data for the carbon decay rate of the fibre fraction from biogas plants is lacking, and therefore the carbon decay rate might be different in reality (Elsgaard et al., 2022).

By applying the decay rates (k) to Equation 5.3 the following graph has been made (Figure 5.1).

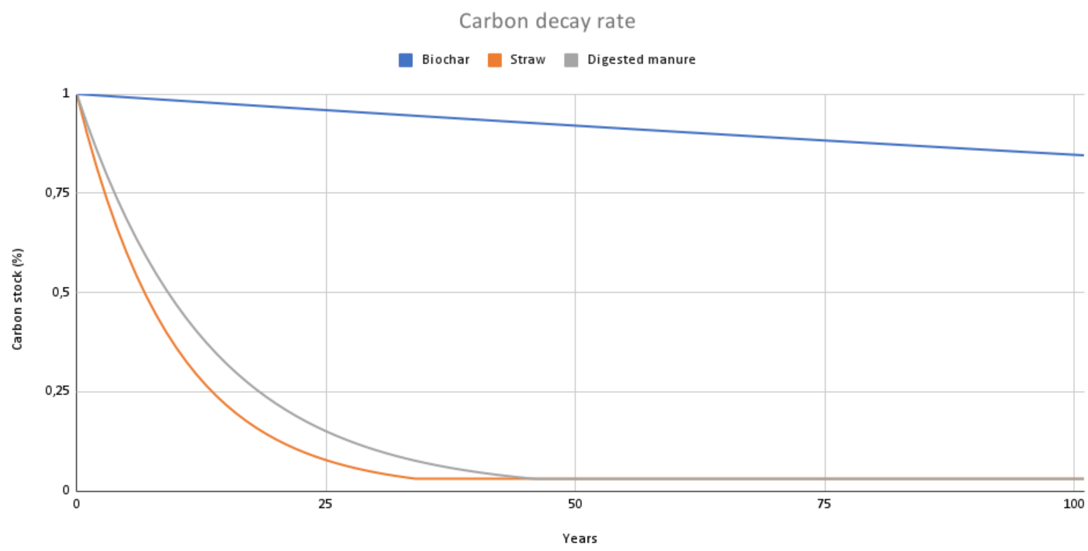

Figure 5.1. Carbon decay rate of biochar, straw, and manure over 100 years. Note that the decay rate for biochar produced from both feedstocks is identical, as the decay rate solely depends on soil temperature and H/C ratio, which depends on the pyrolysis temperature.

The original carbon input to the soils sequestered after 100 years varies depending on the feedstock. Since biochar is known for its stability, only 15,3% of the carbon is decayed after 100 years, whereas 97% of digested manure and straw residues C is decayed after 100 years. Figures 5.2, 5.3, 5.4 and 5.5 show the carbon balance of the reference scenarios and biochar.

The decay rates can be used to calculate temporal C balances of the feedstocks and biochar. This is coupled with the amount of C emitted to the atmosphere as CO_2, through the combustion of the pyrolysis co-products. This accounts for the original C contents of each feedstock, which can be seen in Tables 5.1, 5.2, 5.3 and 5.4. These tables also contain the IPCC's GWP100 characterization factors (CF), which applies a factor to delayed emissions, such as those from the decay of biochar. Since the emissions from the combustion of pyrolysis co-products happen in year 0, they are not accounted for in the 'Decay emissions x CF' column.

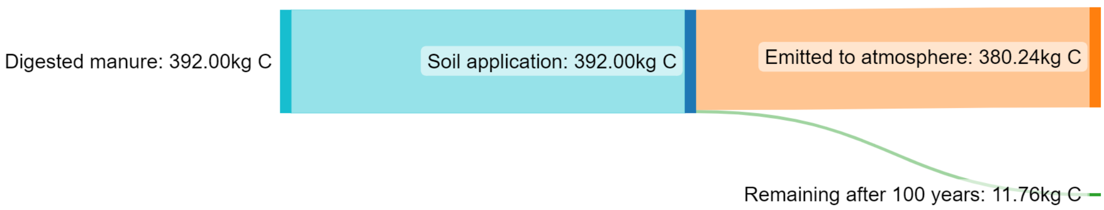

Figure 5.2. Carbon balance of digested manure over 100 years.

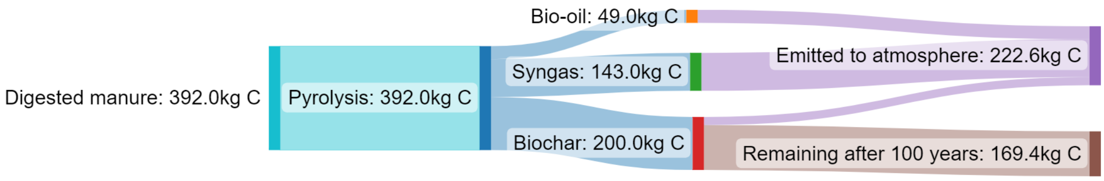

Figure 5.3. Carbon balance of biochar from digested manure over 100 years.

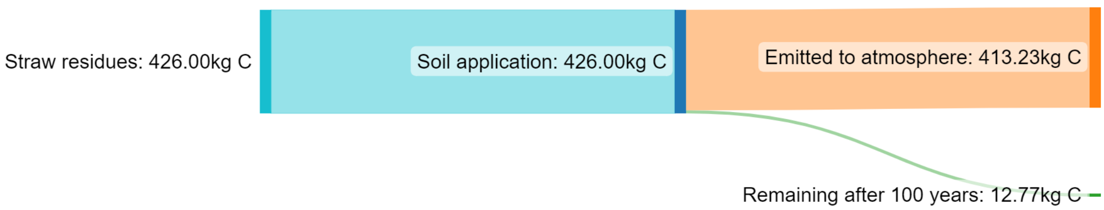

Figure 5.4. Carbon balance of straw residues over 100 years.

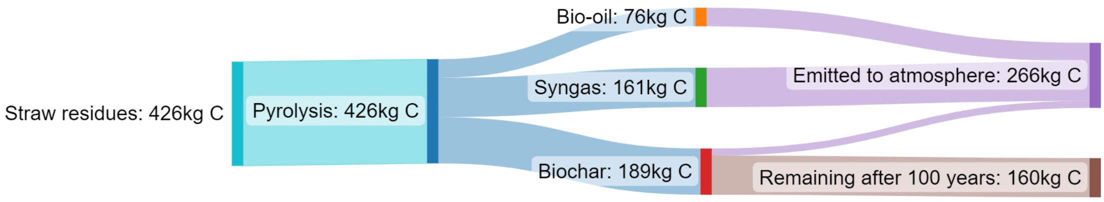

Figure 5.5. Carbon balance of biochar from straw residues over 100 years.

Year	Emissions from decay (kg CO_2)	Characterization Factor (kg CO_2/kg CO_2 emitted at time t)	Decay emissions x CF (kg CO_2)	Storage (kg CO_2)
0	0,000	1,000	-	1562
1	151,48	0,9923	150,317	1410,52
2	136,79	0,9846	134,686	1273,72
3	123,53	0,9768	120,66	1150,2
...	...	...	...	...
100	0,00	0,0188	0,00	48,68
SUM	1513,32	-	1403,676	48,68

Table 5.1. Emissions and C storage of straw residues over 100 years.

Year	Emissions from decay (kg CO_2)	Combustion of bio-oil and syngas (kg CO_2)	Characterization Factor (kg CO_2/kg CO_2 emitted at time t)	Decay emissions x CF (kg CO_2)	Storage (kg CO_2)
0	0,000	869,00	1,000	-	693,00
1	1,150	0,00	0,9923	1,141	691,85
2	1,148	0,00	0,9846	1,130	690,70
3	1,146	0,00	0,9768	1,119	689,56
...	...	...	...	...	...
100	0,00	0,00	0,0188	0,018	586,97
SUM	106,029	869,00	-	60,558	586,97

Table 5.2. Emissions and C storage of biochar from straw residues over 100 years.

Year	Emissions from decay (kg CO_2)	Characterization Factor (kg CO_2/kg CO_2 emitted at time t)	Decay emissions x CF (kg CO_2)	Storage (kg CO_2)
0	0,000	1,000	-	1437,33
1	104,798	0,9923	103,9914	1332,54
2	97,157	0,9846	95,6611	1235,38
3	90,073	0,9768	87,9837	1145,3
...	...	...	...	...
100	0,00	0,0188	0,00	44,17
SUM	1393,163	-	1257,875	44,17

Table 5.3. Emissions and C storage of digested manure over 100 years.

Year	Emissions from decay (kg CO_2)	Combustion of bio-oil and syngas (kg CO_2)	Characterization Factor (kg CO_2/kg CO_2 emitted at time t)	Decay emissions x CF (kg CO_2)	Storage (kg CO_2)
0	0,000	704,00	1,000	-	733,33
1	1,217	0,00	0,9923	1,141	732,12
2	1,215	0,00	0,9846	1,196	730,90
3	1,213	0,00	0,9768	1,185	729,69
...	...	...	...	...	...
100	1,03	0,00	0,0188	0,019	621,13
SUM	112,2	704,00	-	64,082	621,13

Table 5.4. Emissions and C storage of biochar from digested manure over 100 years.

5.2 Inventory

In this section, the inventories of pyrolysis and reference scenarios are presented. Firstly, the consequential model inventories are presented for the two types of feedstock: straw residues and digested manure. Afterwards, the Arla-IDF model inventories are presented in the same manner.

Similar for both the consequential and the Arla-IDF approach is that there is no pyrolysis plant construction process in the ecoinvent database. The construction of a pyrolysis plant has therefore been modelled from 'Synthetic gas factory RoW| construction' as done in Brassard et al., 2021b. This process was then adjusted to fit the treatment of 1.000kg 90% DM feedstock. This amount was divided by the expected amount of biomass that a pyrolysis plant will process throughout its lifetime in order to adjust 'how much' of a pyrolysis plant is used for the pyrolysis of 1.000kg feedstock. The lifetime of the pyrolysis plant is set to 20 years, as this is what is the expected standard lifetime of a new plant (H. N. Pedersen, 2023b, line 730). According to Pedersen, a 20MW Stiesdal facility can process 38.600t biomass per year, which is equal to $13*10^{-7}$p[1].

5.2.1 Consequential inventories

CLCA Digested manure

The inventory can be seen in Table 5.7. The manure is modelled as coming from the case farm and the biochar created from the digested manure is returned to the same farm. As the life cycle starts with the treatment of digested manure, only the transport from the pyrolysis plant back to the farm is modelled. The distance between the pyrolysis plant and the farm has been set to 25km based on Google Maps directions. In the reference scenario, 1.000kg of digested manure needs to be transported, whereas 390kg of biochar is transported in the pyrolysis scenario. Furthermore, both the digested manure and biochar are assumed to supply nutrients to the soil. According to Elsgaard et al., 2022, phosphorous (P) and potassium (K) are assumed to remain in biochar. However, some nitrogen (N) will be lost to the syngas fraction in the form of N_2, NH_3 and HCN. The N supply is modelled as an avoided production of inorganic nitrogen fertiliser. Based on information supplied by H. N. Pedersen, 2023a, 1.000kg digested manure feedstock contains 13,16kg N. However, according to the fertiliser announcement (Gødskningsbekendtgørelsen) of 2020, the utilization rate for nitrogen can be set to 80% in digested manure. This means that of the 13,16kg N, 10,53kg N can be classified as available nitrogen for plant uptake. Biochar can due to the current legislation and knowledge be classified as a product with a 40% utilisation rate. Therefore, biochar with a nitrogen content of 5,07kg N has 2,03kg N available for plant uptake. (Ministeriet for Fødevarer, Landbrug og Fiskeri, 2020; Thomsen, 2023) Elsgaard et al., 2022 models an electricity consumption of the pyrolysis process, including pressing, drying and pelletizing of digested manure of 383kWh per ton biochar produced, equalling a consumption of 149,37kWh per 1.000kg 90% DM digested manure treated, as 390kg biochar is produced from this process. Elsgaard et al., 2022 has written, that 7,8GJ worth of energy is produced by the combustion of syngas and bio-oil co-products per 1.000kg 90% DM digested manure. H. N. Pedersen, 2023b assumes a 15%

[1] 1.000kg/(38.600.000kg/year)/20years

energy loss throughout the process, meaning that 6,63GJ energy is gained as a co-product from pyrolysis. In order to model the correct energy source that will be replaced by this extra heat production, a backcasting method has been used as in Muñoz and Weidema, 2021. The data for heat generation sources was gained from International Energy Agency, 2022 looking at the heat supply sources in the years 2015 and 2021 and then finding the development of each heat source between these two years. Based on the calculations the long-term marginal heat mix is 74% biofuels (incl. waste), 3,5% solar-thermal and 22,5% 'other sources'. International Energy Agency, 2022 define other sources as heat pumps and electric boilers. Based on the general energy production in Denmark, this has been modelled as wind energy (See Table 5.5). Therefore, an avoided heat production from this mix is modelled. This will be subject to a sensitivity analysis in Section 6.4.

Flow	Unit	Amount	LCI Data
Reference flow			
CLCA heat mix	GJ	1	Reference flow
Inputs			
Heat from biomass	GJ	0,74	Heat, district or industrial, other than natural gas {DK}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Conseq, U
Heat from wind power	GJ	0,225	Electricity, high voltage {DK}| electricity production, wind, 3MW turbine, onshore | Conseq, U
Heat from solar-thermal	GJ	0,035	Heat, central or small-scale, other than natural gas {RoW}| operation, solar collector system, Cu flat plate collector, multiple dwelling, for hot water | Conseq, U

Table 5.5. Inventory of the consequential heat mix

In the reference scenario, digested manure is stored in a manure heap, where the organic matter degrades and emits ammonia, N_2O and CH_4. The current data of emissions from digested manure is limited, but the data used in Elsgaard et al., 2022 based on Olesen et al., 2021 is used for this study. Therefore, the emissions are modelled as the following; 5,5kg CH_4, 0,023kg N_2O from storage and 0,043kg N_2O from on-field emissions in the reference scenario per 1.000kg 90% DM digested manure. Finally, the CO_2eq emissions and storage found in Section 5.1 have been modelled.

Flow	Unit	Amount	LCI Data
Reference flow			
Land application of 90%DM Digested manure	kg	1000	Reference flow
Inputs			
Transport	tkm	25	Transport, freight, lorry, unspecified {RER}| transport, freight, lorry, all sizes, EURO6 to generic market for | Conseq, U
Inorganic nitrogen fertiliser	kg	-10,53	inorganic nitrogen fertiliser, as N {DK}| market for inorganic nitrogen fertiliser, as N | Conseq, U
CO_2 from decay of digested manure (GWP100)	kg	1257,88	Carbon dioxide
CH_4 emission from storage in manure heap	kg	5,5	Methane
N_2O emission from decay of digested manure	kg	0,066	Dinitrogen monoxide

Table 5.6. Consequential inventory of the land application of 90%DM Digested manure

Flow	Unit	Amount	LCI Data
Reference flow			
Pyrolysis of 90%DM Digested manure	kg	1000	Reference flow
Inputs			
Construction of pyrolysis plant	p	0,0000013	Synthetic gas factory {RoW}| construction | Conseq, U
Transport	tkm	9,75	Transport, freight, lorry, unspecified {RER}| transport, freight, lorry, all sizes, EURO6 to generic market for | Conseq, U
Inorganic nitrogen fertiliser	kg	-2,03	inorganic nitrogen fertiliser, as N {DK}| market for inorganic nitrogen fertiliser, as N | Conseq, U
Electricity for general consumption of pyrolysis plant	kWh	149,37	Electricity, medium voltage {DK}| market for | Conseq, U
CLCA heat mix	GJ	-6,63	Table 5.5
CO_2 from syngas and bio-oil combustion	kg	704	Carbon dioxide
CO_2 from decay of biochar (GWP100)	kg	64,08	Carbon dioxide
Land application of 90%DM Digested manure	kg	-1000	Table 5.6

Table 5.7. Consequential inventory of the pyrolysis of 1.000kg 90%DM digested manure

CLCA Straw residues

Inventory can be seen in Table 5.9. For straw residues, the reference scenario models the feedstock being applied to the soil and never leaving the farm. Therefore, only the emissions from the decomposition of the straw residues which is the inputs in the reference scenario. In order to find the N_2O emissions from the decay of straw residues, IPCC conversions have been used (Hergoualc'h et al., 2019). The amount of N in straw residues is 0,67%, derived from Jensen, 2019 based on an average of seven different crops. By using the FU of 90% DM feedstock, the amount of nitrogen can be calculated as follows: (1000∗0,90)*0,0067 = 6,03kg N. By using the emission factor of 0,01 from Hergoualc'h et al., 2019 and the conversion from N_2O-N to N_2O, which is found by multiplying by 44/28, the total amount is found to be 0,095kg N_2O.

In the pyrolysis scenario of straw residues, the feedstock is modelled to be transported 25km to the biogas/pyrolysis plant, and afterwards the biochar is transported back to the farm. For straw residues, pressing and drying are not needed, and therefore only energy for pelletization and general energy consumption of running the pyrolysis plant is modelled. The electricity consumption of the pyrolysis plant per ton of biochar produced from straw residues is 325kWh, equalling 85,48kWh per FU. A larger amount of straw residue C is contained in the syngas and bio-oil co-products than for digested manure (Elsgaard et al., 2022), and therefore the avoided heat production is larger at 9GJ∗0,85=7,65GJ.

Flow	Unit	Amount	LCI Data
Reference flow			
Land application of 90%DM Straw residues	kg	1000	Reference flow
Inputs			
CO_2 from decay of straw residues (GWP100)	kg	1403,68	Carbon dioxide
N_2O emissions from straw residues	kg	0,095	Dinitrogen monoxide

Table 5.8. Consequential inventory of the reference scenario for 1000kg 90% DM straw residues

Flow	Unit	Amount	LCI Data
Reference flow			
Pyrolysis of 90%DM Straw residues	kg	1000	Reference flow
Inputs			
Construction of pyrolysis plant	p	0,0000013	Synthetic gas factory {RoW}| construction | Conseq, U
Transport	tkm	31,58	Transport, freight, lorry, unspecified {RER}| transport, freight, lorry, all sizes, EURO6 to generic market for | Conseq, U
Electricity for general consumption of pyrolysis plant	kWh	85,48	Electricity, medium voltage {DK}| market for | Conseq, U
CLCA heat mix	GJ	-7,65	Table 5.5
CO_2 from syngas and bio-oil combustion	kg	869	Carbon dioxide
CO_2 from decay of biochar (GWP100)	kg	60,56	Carbon dioxide
Land application of straw residues	kg	-1000	Table 5.8

Table 5.9. Consequential inventory of the pyrolysis of 1.000kg 90% DM straw residues.

5.2.2 Arla-IDF inventories

For the Arla-IDF inventories, the main difference is that Cut-off processes are chosen instead of Conseq processes in SimaPro. For the avoided heat, a mix of sources has been modelled based on historical heat supply data from 2021 International Energy Agency, 2022. Therefore, a mix of heat from natural gas (11,4%), coal (6%), wind (9,5%), wood chips (34,5%), and oil (38,6%) is modelled (See Table 5.10).

Flow	Unit	Amount	LCI Data
Reference flow			
Arla-IDF heat mix	GJ	1	Reference flow
Inputs			
Heat from natural gas	GJ	0,114	Heat, district or industrial, natural gas {Europe without Switzerland}| market for heat, district or industrial, natural gas | Cut-off, U
Heat from coal power	GJ	0,06	Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, hard coal briquette, stove 5-15kW | Cut-off, U
Heat from wind power	GJ	0,095	Electricity, high voltage {DK}| electricity production, wind, 3MW turbine, onshore | Cut-off, U
Heat from biomass	GJ	0,345	Heat, district or industrial, other than natural gas {DK}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U
Heat from oil	GJ	0,386	Heat, district or industrial, other than natural gas {DK}| heat and power co-generation, oil | Cut-off, U

Table 5.10. Inventory of the heat mix in the Arla-IDF model.

Arla-IDF digested manure

Flow	Unit	Amount	LCI Data
Reference flow			
Land application of 90%DM Digested manure	kg	1000	Reference flow
Inputs			
Transport	tkm	25	Transport, freight, lorry, unspecified {RER}| transport, freight, lorry, all sizes, EURO6 to generic market for | Conseq, U
Inorganic nitrogen fertiliser	kg	-10,53	inorganic nitrogen fertiliser, as N {DK}| market for inorganic nitrogen fertiliser, as N | Cut-off, U
CO_2 from decay of digested manure (GWP100)	kg	1257,88	Carbon dioxide
CH_4 emission from storage in manure heap	kg	5,5	Methane
N_2O emission from decay of digested manure	kg	0,066	Dinitrogen monoxide

Table 5.11. Arla-IDF inventory of the reference scenario for 1000kg 90% DM digested manure.

Flow	Unit	Amount	LCI Data
Reference flow			
Pyrolysis of 90%DM Digested manure	kg	1000	Reference flow
Inputs			
Construction of pyrolysis plant	p	0,0000013	Synthetic gas factory {RoW}| construction | Conseq, U
Transport	tkm	9,75	Transport, freight, lorry, unspecified {RER}| transport, freight, lorry, all sizes, EURO6 to generic market for | Conseq, U
Inorganic nitrogen fertiliser	kg	-2,03	inorganic nitrogen fertiliser, as N {DK}| market for inorganic nitrogen fertiliser, as N | Cut-off, U
Electricity for general consumption of pyrolysis plant	kWh	149,37	Electricity, medium voltage {DK}| market for | Conseq, U
Arla-IDF heat mix	GJ	-6,63	Table 5.10
CO_2 from syngas and bio-oil combustion	kg	704	Carbon dioxide
CO_2 from decay of biochar (GWP100)	kg	64,08	Carbon dioxide
Land application of 90%DM Digested manure	kg	-1000	Table 5.11

Table 5.12. Arla-IDF inventory of the pyrolysis of 1.000kg 90% DM digested manure

Arla-IDF Straw residues

Flow	Unit	Amount	LCI Data
Reference flow			
Land application of 90%DM Straw residues	kg	1000	Reference flow
Inputs			
CO_2 from decay of straw residues (GWP100)	kg	1403,68	Carbon dioxide
N_2O emissions from straw residues	kg	0,095	Dinitrogen monoxide

Table 5.13. Arla-IDF inventory of the reference scenario for straw residues.

Flow	Unit	Amount	LCI Data
Reference flow			
Pyrolysis of 90%DM Straw residues	kg	1000	Reference flow
Inputs			
Construction of pyrolysis plant	p	0,0000013	Synthetic gas factory {RoW}| construction | Conseq, U
Transport	tkm	31,58	Transport, freight, lorry, unspecified {RER}| transport, freight, lorry, all sizes, EURO6 to generic market for | Conseq, U
Electricity for general consumption of pyrolysis plant	kWh	85,48	Electricity, medium voltage {DK}| market for | Conseq, U
Arla-IDF heat mix	GJ	-7,65	Table 5.10
CO_2 from syngas and bio-oil combustion	kg	869	Carbon dioxide
CO_2 from decay of biochar (GWP100)	kg	60,56	Carbon dioxide
Land application of straw residues	kg	-1000	Table 5.13

Table 5.14. Arla-IDF inventory of the pyrolysis of 1.000kg 90% DM straw residues.

5.3 Description of Arla dairy farm

In order to answer the second sub-research question: *"What is the potential for Danish dairy farmers to utilise pyrolysis to reduce the climate impacts of their milk production?"*, the results of the pyrolysis LCA will be put into the context of an Arla dairy farm to assess the potential of pyrolysis for Danish dairy farmers. The farmer's data is going to be inserted into the Arla FarmTool in order to calculate the emissions of 1kg FPCM from that specific farm. This includes the operation of the farm and the production of biomass, which is then treated as being used as feedstock for biochar production, based on how this new activity would most likely be implemented at the farm. This is based on primary data from Niels Pedersen's farm. This means that the impacts related to milk production are based on the FarmTool results in both modelling approaches.

Pedersen has 1328 jersey cows, which produced 9.973.785kg of milk in the reference year (2022). His crops are mainly grass, corn silage and fodder beets which are all used for feeding. Pedersen does not buy soy-based feed for his cows, he instead buys rye, barley, rapeseed meal, molasses and potato pulp. Pedersen's cows produced 70.581 tons of manure (incl. slurry) in the reference year. When calculating the dry matter contents of the manure, there was 5308,5 tons dry matter. Of this 85% was treated in a biogas plant (N. H. Pedersen, 2023).

By using the amount of biomass he delivers off-farm, both for biogas plants and other purposes, as well as the DM content of the biomass, the total amount of biochar that can be produced from the biomass supply can be calculated. For the sake of this study, all biomass is modelled to be delivered to a biogas plant, even though this is not the case at the time of writing. However, it can be assumed to be the case in the near future, due to the projection for future biogas production in Denmark (Thomsen, 2021).

Calculating biomass available from biogas digestate

Total DM manure and slurry [tons] / 0,90 = 90% DM feedstock for pyrolysis [tons]

5308,5ton DM / 0,90 = 5894ton 90% DM

When entering the farmer's 2021 data into the Arla FarmTool, an impact of 0,989kg CO_2eq per kg FPCM is found for the consequential model, and 1,286kg CO_2eq per kg FPCM for the Arla-IDF model.

As the impacts of milk production are calculated per kg FPCM, the total milk yield for one year has to be converted from kg milk to kg FPCM. This is done using the following equation (International Dairy Federation, 2022a):

Total FCPM can be calculated with the following equation:

$$FPCM[kg] = Milk\ production[kg] * (0.1226 * Fat\% + 0.0776 * Protein\% + 0.2534)$$

$$FPCM[kg] = 9.973.785kg * (0{,}1226 * 6{,}04\% + 0{,}0776 * 4{,}43\% + 0{,}2534) = 13.341.652{,}93kg$$

By multiplying the total annual FPCM production with the emissions per kg FPCM, the total annual emissions from FPCM production from Pedersen's farm can be calculated:

CLCA: 13.341.652,93kg FPCM ∗ 0,989kg CO_2eq/kg FPCM = 13.194.894,75kg CO_2eq

Arla-IDF: 13.341.652,93kg FPCM ∗ 1,286kg CO_2eq/kg FPCM = 17.157.365,67kg CO_2eq

These total CO_2eq emissions are coupled with the results of the pyrolysis LCA in order to estimate the farmer's potential to reduce his CO_2eq emissions in Section 6.3.


Arla

Impact Assessment 6

In the impact assessment chapter, the results of the LCIA are shown and analysed. The LCIA is divided into sections of the two impact categories: global warming and respiratory inorganics. In each of these sections, the feedstocks will be analysed separately to compare how the results for each feedstock differ between the two modelling types. This impact assessment has been done in SimaPro using the Stepwise method. Afterwards, the results are related to the dairy farm, and finally, a sensitivity analysis is carried out.

6.1 Global warming

On Figures 6.1 and 6.2 it can be seen that the reduction of impacts on global warming is larger for the Arla-IDF modelled biochar from both feedstocks. It can also be seen that the main impacts on global warming come from the carbon decay of biochar and the combustion of co-products. These emissions are the same for both models, as it is based on the calculations of physical flows of carbon and nitrogen (Section 5.1 and 5.2). The main difference between the models is from the avoided heat mix, where the difference can be explained by the Arla-IDF mix containing oil and coal, which has an impact of 18,4 and 9,9kg CO_2eq per GJ heat, respectively.

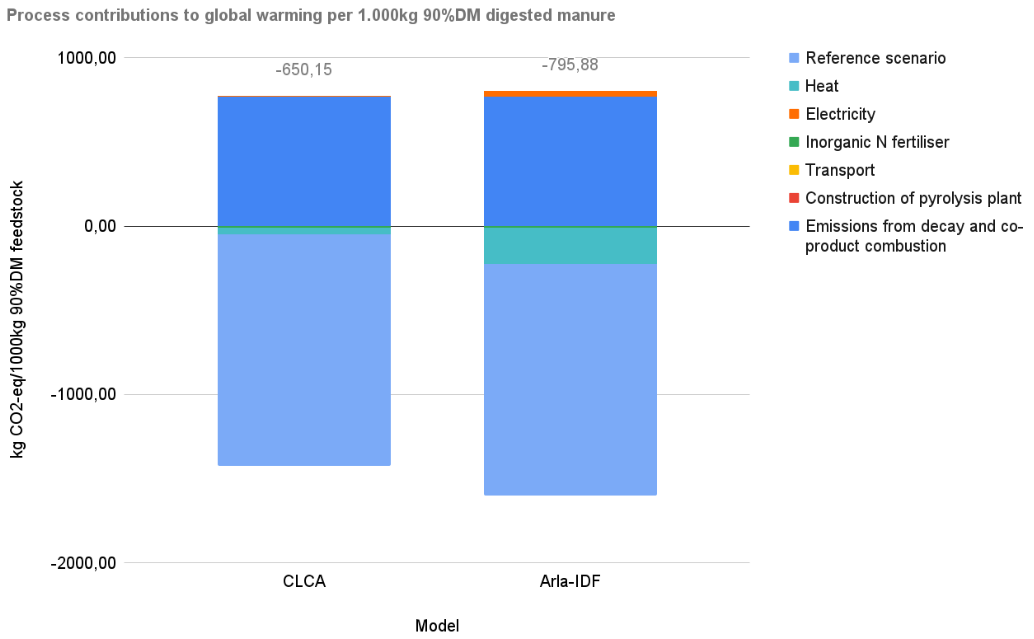

Figure 6.1. LCIA results for global warming impacts per 1.000kg 90%DM digested manure feedstock for both modelling approaches. Method: Stepwise.

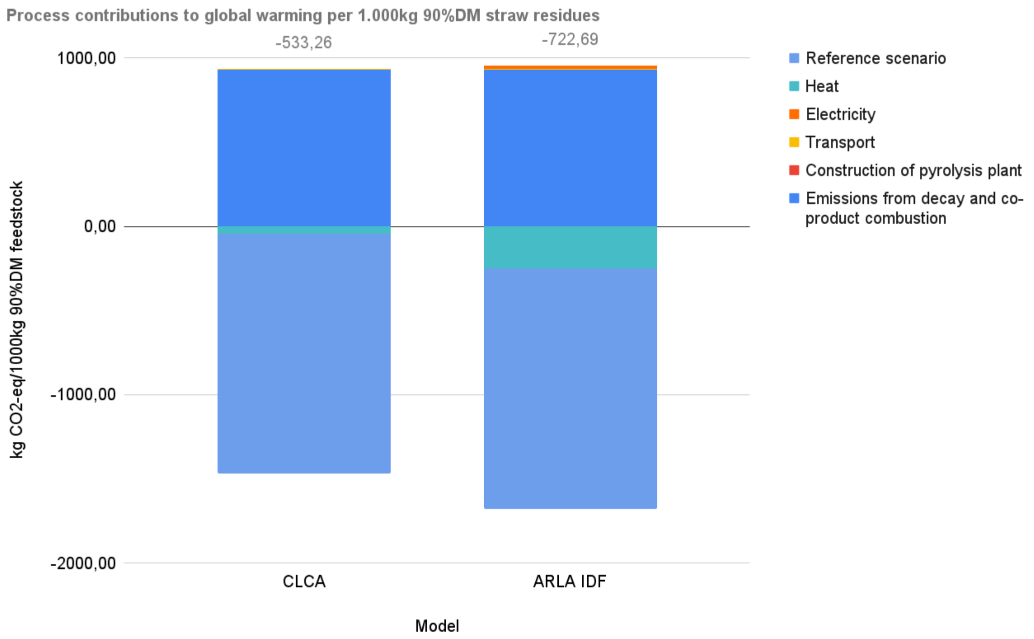

Figure 6.2. LCIA results for global warming impacts per 1.000kg 90%DM straw residue feedstock for both feedstocks and modelling approaches. Method: Stepwise.

6.2 Respiratory inorganics

In the respiratory inorganics impact category (Figures 6.3 and 6.4) the avoided heat production contributes to the main reduction of impacts with the Arla-IDF mix contributing with a larger impact reduction than the consequential mix. Similar to the global warming impact category, this is mainly due to avoided production of heat from coal and oil (See Figure 6.5). However, it can also be seen that heat from wood chips and wind power has impacts. According to Bonou et al., 2016 and Laurent et al., 2012, when the energy mix changes to being based on renewable sources, impacts on environmental factors other than global warming might stay the same or even increase, partly due to the materials and infrastructure needed for the construction of the energy production facilities (e.g. wind turbines). This also highlights why it is important to not only focus on global warming when making decisions. Bonou et al., 2016 highlight that human toxicity and respiratory inorganics should be taken into account when analysing the environmental impacts of wind power. For digested manure, the extra need for inorganic N fertiliser also contributes to impacts in this category, which are the impacts contributed to 'reference scenario' in the figures.

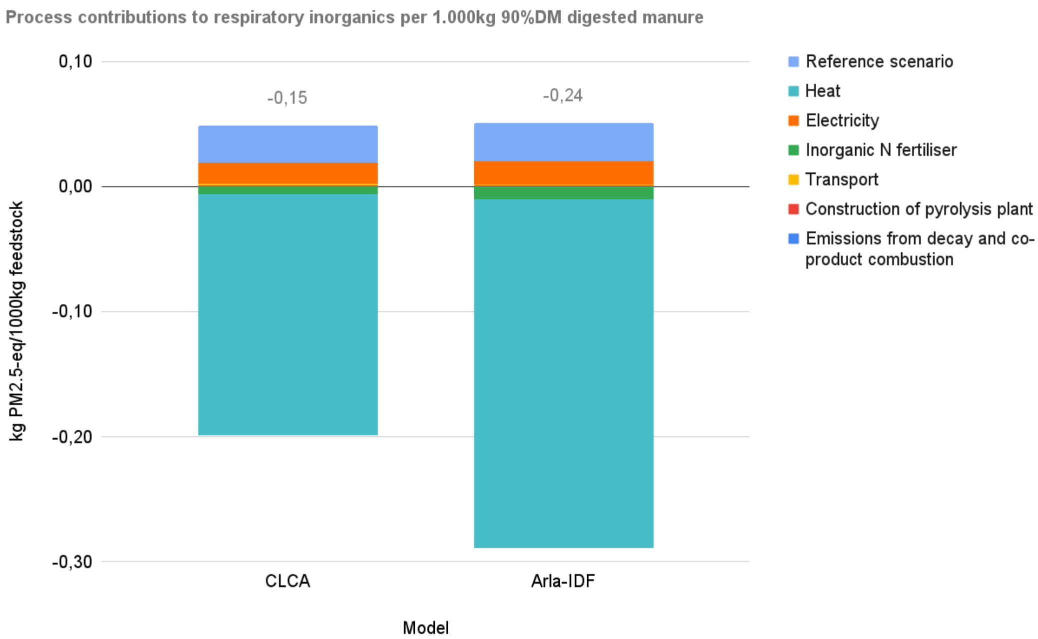

Figure 6.3. LCIA results for respiratory inorganics per 1.000kg 90%DM digested manure feedstock for both modelling approaches. Method: Stepwise.

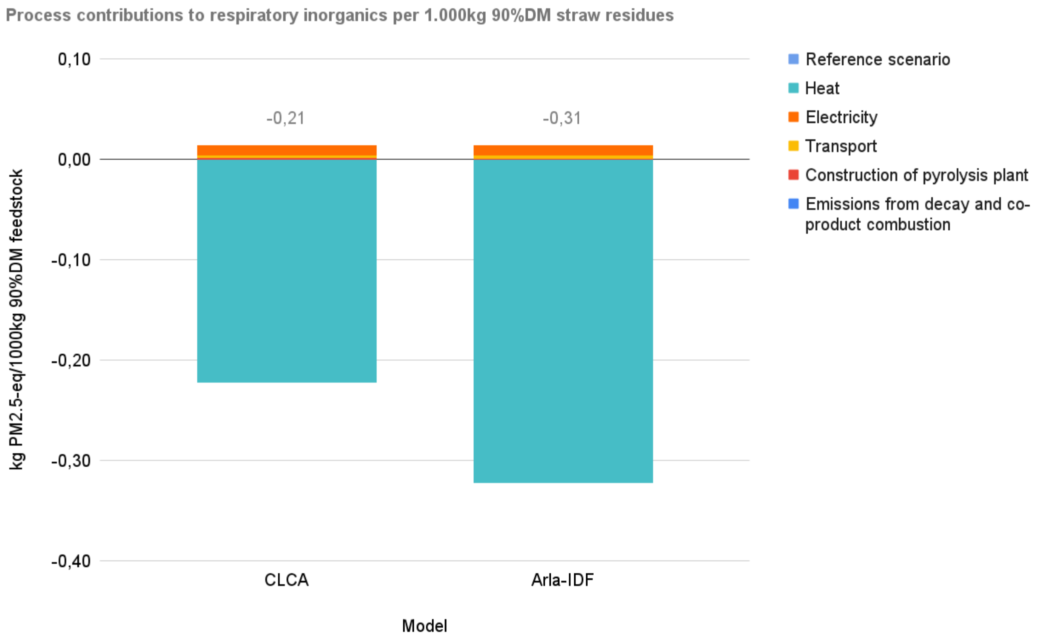

Figure 6.4. LCIA results for respiratory inorganics per 1.000kg 90%DM straw residue feedstock and modelling approaches. Method: Stepwise.

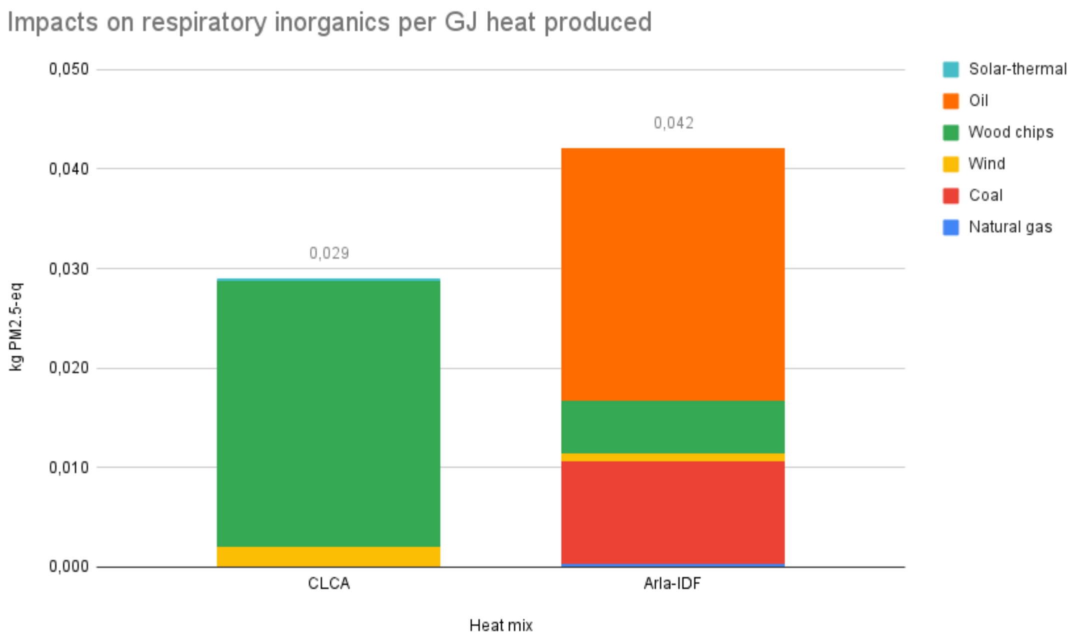

Figure 6.5. LCIA results for respiratory inorganics per 1GJ heat produced. Method: Stepwise.

Summary

The LCIA results show that the environmental impacts from pyrolysis are dependent on which heat mix is modelled to be avoided from the combustion of the syn-gas and bio-oil co-products. On Figure 6.5 it can be derived that environmental impacts are not only caused by fossil heat sources, but wood chips and wind power also caused potential environmental impacts.

The overall conclusion of this LCIA section is that electricity consumption and the respective energy mix play an important role in both impact categories, and it is therefore important how it has been modelled. Additionally, for the digested manure models, the extra need for inorganic N fertiliser also contributes to impacts.

6.3 Relating impact assessment to the dairy farm

In this chapter, the results of the impact assessment are interpreted in order to properly assess the potential impacts of biochar production and carbon sequestration for Danish dairy farmers.

When looking at the impacts of pyrolysis on global warming, digested manure gives a reduction of 650,15kg CO_2eq for the CLCA model or 795,88kg CO_2eq for the Arla-IDF model per 1.000kg 90%DM feedstock that is treated. For straw residues, the reduction is 533,26kg CO_2eq (CLCA) or 722,69kg CO_2eq (Arla-IDF) per functional unit.

In the description of the case farm, it was described how the annual emissions from the FPCM production were 13.194.894,75kg CO_2eq in the consequential approach and 17.157.365,67kg CO_2eq in the Arla-IDF approach. It was also described how the farmer has 5894ton 90%DM manure and slurry to deliver for biogas production and pyrolysis annually. That gives a potential total annual reduction from pyrolysis of 3.831.984,1kg CO_2eq in the consequential modelling, and 4.690.916,72kg CO_2eq in the Arla-IDF modelling when using the farmer's own biomass. When compared to the total emissions from the farm's milk production, pyrolysis can result in a 29% reduction in the consequential model and 27% in the Arla-IDF model.

Therefore, pyrolysis of digested manure can contribute substantially to reducing the emissions of the dairy farm.

6.4 Sensitivity analysis

This section presents three sensitivity analyses in order to assess how sensitive the models are to changes in assumptions. The modelled heat mixes, the carbon decay rates of biochar and biomass, and finally the utilisation rate of nitrogen in biochar are subject to sensitivity analysis.

6.4.1 Sensitivity of heat mixes

In the description of the Arla FarmTool, it is stated that substituted heat sources are the 'actual sources', instead of substituting natural gas and coal, which the 2015 IDF carbon footprint standard said should be modelled (International Dairy Federation, 2015; Schmidt & Dalgaard, 2021). This has since been removed from the IDF guidelines (International Dairy Federation, 2022a). However, as the LCIA results showed that the substituted heat mix is important for this study's findings, this modelling assumption is tested in the sensitivity analysis, to see how the LCA reacts to being based on heat production from natural gas and coal instead (See Figure 6.6). This sensitivity analysis is therefore made to show how basing LCAs on normative rules can skew results. Furthermore, it was identified in the state-of-the-art and in the LCIA chapter that the heat mix plays an important role in the results of biochar LCA's (Azzi et al., 2021, 2022; Brassard et al., 2021a; Matuštík et al., 2022; Oldfield et al., 2018; Tisserant et al., 2022), which further substantiates the need for a sensitivity analysis on heat mix.

In Figures 6.6 and 6.7, the sensitivity analysis of each feedstock and modelling choice can be seen beside the original LCIA results from this study. It can be derived from the figures, that the modelled heat mix changes the impacts on both impact categories to varying degrees, where the impact reduction on global warming is more than doubled for the consequential models and almost doubled in the Arla-IDF models when coal and natural gas are modelled as avoided production. This highlights why it is important to base LCA models on solid and transparent methodology in order to not overestimate climate impacts. This could also lead to decision-makers overestimating the benefits gained from combusting the biomass and thus resulting in a smaller production of biochar in order to increase the production of the co-products, syngas and bio-oil.

For respiratory inorganics, impacts are also reduced more when using the natural gas and coal mix compared to the original model.

The results of this sensitivity analysis show that the heat mix has a great impact on results, and it is therefore important to base the analysis of the heat market on a valid methodology, instead of modelling the same heat mix (e.g. natural gas and coal) irrespective of context.

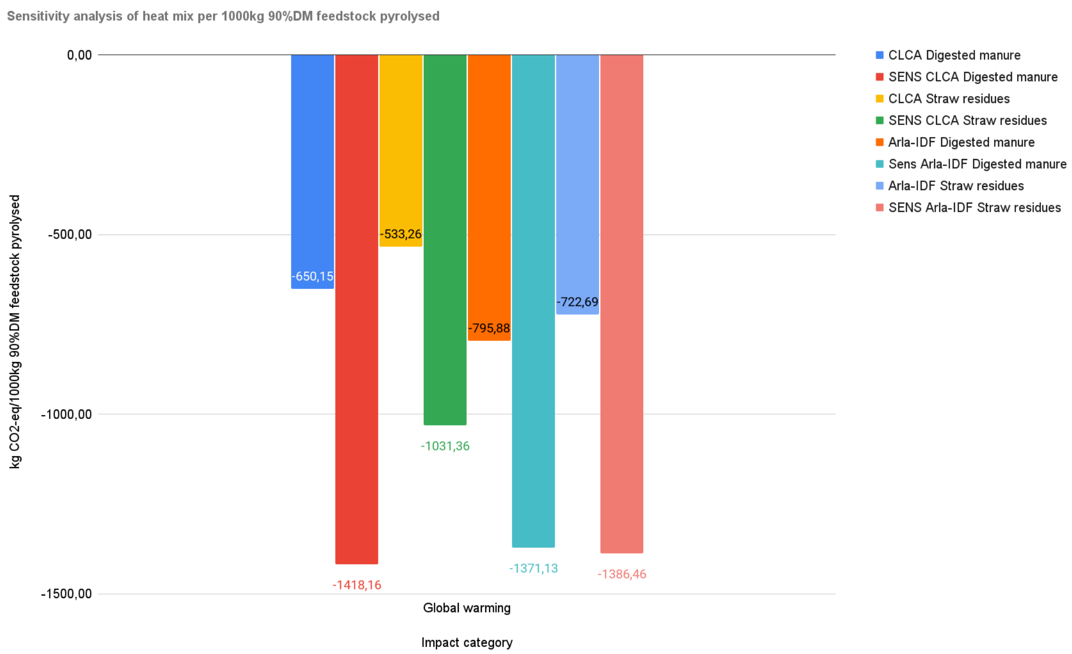

Figure 6.6. Results from sensitivity analysis on global warming impacts comparing the original heat mixes with a 50/50 mix of hard coal briquettes and natural gas based on International Dairy Federation, 2015's guidelines.

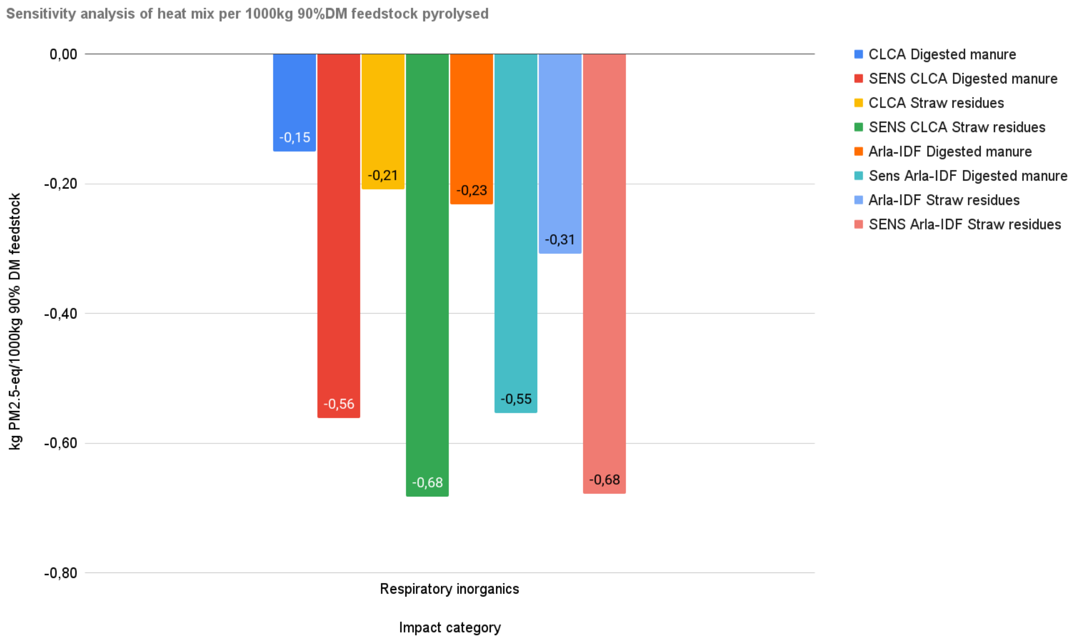

Figure 6.7. Results from sensitivity analysis on respiratory inorganics impact comparing the original heat mixes with a 50/50 mix of hard coal briquettes and natural gas based on International Dairy Federation, 2015's guidelines.

6.4.2 Sensitivity of carbon decay rates

The carbon decay rates of biochar and biomass were based on available data, but this data was estimations and based on 1-2 data points (remaining C stock at time X). Furthermore, Elsgaard et al., 2022 argues that there's a lack of data on emissions from separated digestate (ie. digested manure). Therefore, the carbon decay rates will also be subject to a sensitivity analysis, in order to analyse how this has affected the results (Figure 6.8).

Elsgaard et al., 2022 also write that the remaining carbon in biochar after 100 years is 62,7% and for digested manure is it 10%. This is based on a H/C ratio of the biochar of 0,7 instead of 0,3, which lab results found for the biochar produced by Stiesdal (H. N. Pedersen, 2023a). The same decay rates have been applied to straw residues.

In Figure 6.8 it can be seen that the changed carbon decay rates lead to an increase in impacts on global warming, which is caused by the non-pyrolysed biomass being modelled as more stable, and the biochar as less stable. Overall, the pyrolysis of biomass still leads to reduced impacts on global warming, when compared to the reference scenario of land application, even though the impact reductions are smaller. The carbon decay rates did not influence results for respiratory inorganics.

This sensitivity analysis shows the importance of gaining more solid data for the carbon decay rates, both for biomasses and for biochar. It also shows how it should be sought to minimise the H/C ratio of the biochar in order to gain as stable a material as possible in order to increase global warming impact reductions. It is furthermore important to gain context-specific data for the pyrolysis process, as the H/C ratio is a result of this process and is a main indicator for the stability of the biochar (Elsgaard et al., 2022). The decay rates used in the original models were deemed more valid and were therefore chosen over the decay rates used in the sensitivity analysis.

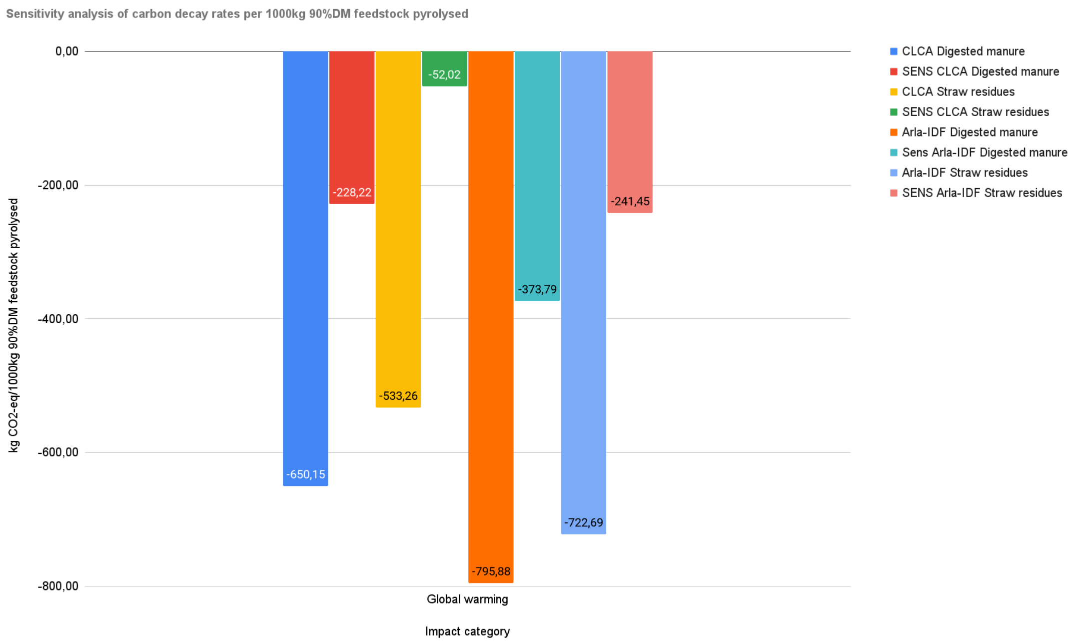

Figure 6.8. Sensitivity analysis on the carbon decay rates of biochar and digested manure per 1.000kg digested manure treated in pyrolysis plant.

6.4.3 Sensitivity of nitrogen utilisation of biochar

In the LCA, an N utilisation rate of 40% biochar N was used. However, this is not a definite N utilisation rate, as the practice of applying biochar to agricultural land is still novel and so is the research on N plant availability from biochar. Studies have shown both an increase and decrease of N availability when biochar is applied to soil (Elsgaard et al., 2022), and since the carbon in biochar is stable, the same stability might apply to the nitrogen contents of biochar. Therefore, a sensitivity analysis of the N utilisation rate of biochar nitrogen has been made, where the utilisation rate has been set to 0% (See Figures 6.9 and 6.10).

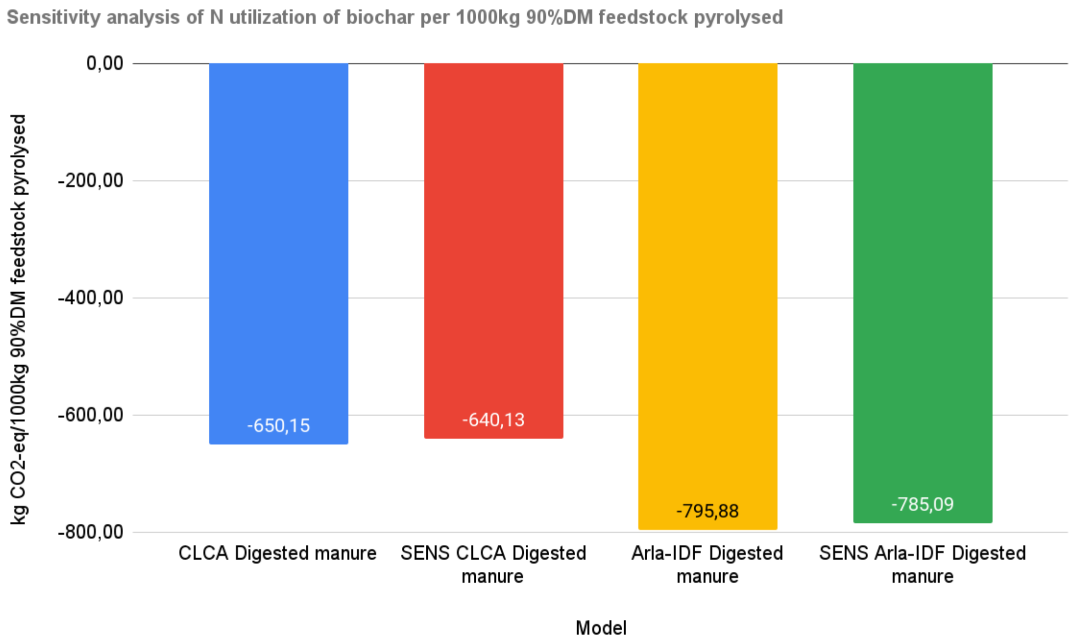

Figure 6.9. Sensitivity analysis on the N utilisation rate of biochar per 1.000kg digested manure treated in pyrolysis plant.

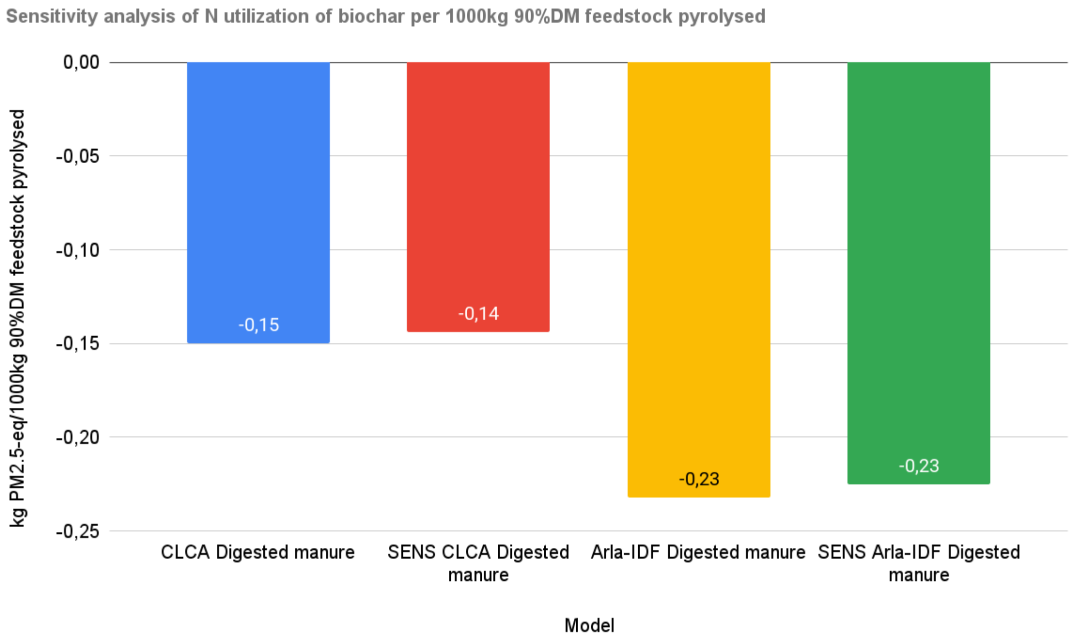

Figure 6.10. Sensitivity analysis on the N utilisation rate of biochar per 1.000kg digested manure treated in pyrolysis plant.

The above graphs show that the impacts increase in both impact categories since the avoided production of mineral N fertiliser in the pyrolysis scenario has been removed. However, compared to the other two sensitivity analyses the change in impact is smaller.

Overall, for all three sensitivity analyses, the pyrolysis of straw and digested manure still result in net impact reductions for all four impact categories for both modelling types.

7 Interpretation & Discussion

In this chapter, the results of the LCIA are interpreted in relation to how the Danish dairy sector can utilise pyrolysis and a methodological discussion of the LCA and carbon stock accounting in LCA.

7.1 Biochar's potential for reducing impacts of milk production

In this section, it is explored how biochar can be utilised by Danish dairy farmers in order to reduce the emissions of their milk production when dairy farmers' biomass is limited mostly to manure and slurry. Furthermore, to answer the second sub-research question: *"What is the potential for Danish dairy farmers to utilise pyrolysis to reduce the climate impacts of their milk production? "*, it is investigated how dairy farmers can utilise straw residues for pyrolysis instead of digested manure. This can for instance help the case farm produce net zero CO_2 emissions milk if offsetting through biomass sourced outside the dairy farm is possible. Since straw residues are the only other feedstock modelled in this study, these calculations will be based on straw residue for pyrolysis. However, other feedstocks such as wood chips could also be utilised in reality.

From the results in Section 6 and 6.3 it is possible to calculate the amount of biomass required to offset the emissions from the farmer's FPCM production. By dividing the total amount of GHG emissions from the case farm (incl. the farmer's own biomass already delivered to biogas and pyrolysis) by the amount of CO_2eq emission reductions from utilising straw residues in biochar production, the total amount of biomass can be calculated:

For the CLCA approach: First, the total CO_2eq reduction from pyrolysis of the farmer's available biomass is subtracted from the total emissions of his FPCM production:

$$13.194.894{,}75\text{kg CO}_2\text{eq} - 3.831.984{,}1\text{kg CO}_2\text{eq} = 9.362.910{,}65\text{kg CO}_2\text{eq}$$

Hereafter the total amount of excess straw residues can be derived by using the 533,26kg CO_2eq reduction from pyrolysis of straw residues:

$$\frac{9.362.910,65 kgCO_2eq/year}{533,26 kgCO_2eq/t_{straw}} = 17.558\text{t straw}$$

17.558t straw residues treated in pyrolysis plant/year is required for the case farm to reach net zero CO_2 emissions. If this is divided out per 1kg FPCM from this farm, 1,3kg of straw residue pyrolysis would be needed.

For the Arla-IDF:

$$17.157.365{,}67\text{kg } CO_2\text{eq} - 4.690.916{,}72\text{kg } CO_2\text{eq} = 12.466.448{,}95\text{kg } CO_2\text{eq}$$

Hereafter the total amount of excess straw residues can be derived by using the 722,69kg CO_2eq reduction from pyrolysis of straw residues:

$$\frac{12.466.448,95kgCO_2eq/year}{722,69kgCO_2eq/t_{straw}} = 17.250\text{t straw}$$

17.250t straw residues treated in pyrolysis plant/year is required. If this is divided out per 1kg of FPCM from this farm, 1,3kg of straw residue pyrolysis would also be needed.

To put this into a national context, Danish dairy farmers produced 5.741,26 million kg milk in 2022, with an average fat percentage of 4,3% and a protein percentage of 3,6% (Danmarks Statistik, 2022b) This equals 6.124,72 million kg FPCM (See equation 5.3 on page 42). This means Danish dairy farmers need 10.766.342,87 tons of straw residues to reach carbon net zero for the entire dairy sector's FPCM production, assuming the same CO_2eq emissions per kg FPCM as the farm is used in this report. For the Arla-IDF approach, 8.474.892,4 ton straw residues are required to make the Danish dairy sector reach net zero CO_2 emissions, again assuming every dairy farmer has the same emissions per kg FPCM as the case farm. In 2022, 6.364.900 tons of straw was available in Denmark, which is not enough to reach net zero emissions. Furthermore, straw is also demanded for other purposes. In 2022 the total amount of straw was used for; 27% combustion, 12% for feeding, 17% for bedding, and 44% was not collected from the cropland (Danmarks Statistik, 2022a). The uncollected straw can be utilised for pyrolysis as well as the straw used for bedding after use, which equals 3.888.700 tons of straw residues available, assuming the feeding and combustion purposes remain the same. One way for dairy farmers to reduce their impacts even further by using pyrolysis could be by investing in a pyrolysis plant and thereby offset their emissions by both buying other types of biomass and selling bio-oil and syngas as the by-product of biochar production. However, as these pyrolysis plants can be expensive to invest in several dairy farmers could be initiating cooperatives to overcome an investment of at least 150 mio DKK, as H. N. Pedersen, 2023b suggested during one interview:

> *"(...) Cooperative association could create a structure where farmers can come in and gain ownership and at the same time have the opportunity to raise financing for such a pyrolysis plant, which, as I said, costs DKK 150 million."*
> - (H. N. Pedersen, 2023b, line 700, own translation)

According to Hedeselskabet, n.d., a Danish environmental consultancy and communicator, pyrolysis plants are facing a few challenges before they can be implemented in the Danish landscape. One of the barriers is the need for risk-taking investors, who would invest in the construction of the new pyrolysis plants. Here dairy farmers can gain a valuable position by starting cooperative associations of becoming pyrolysis plant owners, buying biomass for biochar production and thereby offsetting their emissions, Furthermore, biogas production in Denmark is facing regulations which aim to restrict the usage of energy crops as they in some cases emit the same GHG emissions as fossil fuels (Energistyrelsen, 2021). Instead, it should be sought to utilise the biomass resources in cascades, where residues from e.g. food production are used for biogas production and pyrolysis to help produce more energy whilst also being a carbon storage technology. H. N. Pedersen, 2023b argues that it is important that the resources are utilised before being delivered for pyrolysis:

> *"You could discuss whether it [taking the biomass directly as an input for pyrolysis] is the right thing to do. It should be allowed to pass through a cow (...) or a 'cow made from concrete', ie. a biogas plant, in order to utilise the resource in cascades. That is something we must make sure happens. And there isn't that much of it [biomass]. There are scenarios describing how biomass replaces fossil carbon, right? And these scenarios actually say that there isn't enough (...)"*
> - (H. N. Pedersen, 2023b, line 75, own translation)

To give an example of this, Rasmussen et al., 2022 made a review of studies of how the Danish energy system can become fully based on renewables, and the review found that it is not possible to fully meet the future demand for non-fossil resources without negatively impacting biodiversity and nature. This is the case both for Denmark and internationally.

Therefore pyrolysis of biomasses which have also been utilised for other purposes should be preferable to the reference scenario, as it means that biomass resources are utilised for several different purposes. As shown in the LCIA, pyrolysis of the biomass leads to reduced impacts compared to direct land application. Growing crops directly for energy production (including biogas and pyrolysis) can result in no impact reductions, and the competition for arable land means that the cultivation of energy crops displaces food production.

7.2 Methodological assessment

This section of the discussion is an assessment of the methodology used in the report. This includes a discussion of the methodological choices made in the report and the quality and validity of the data used for the LCA. Furthermore, the use of responsibility windows in Cseq accounting is discussed.

7.2.1 Data evaluation

As mentioned earlier, the data used for calculating the carbon decay of biochar and the two feedstocks are based on one or two data points in time, and especially data for carbon sequestration of digested manure is lacking (Elsgaard et al., 2022). Having data from several different points in time would make the decay function more robust, as this would make the extrapolation of the function more valid. This was sought to be analysed through a sensitivity analysis, where another decay rate was modelled for both feedstocks and biochar.

The bio-oil co-product from pyrolysis will not necessarily be combusted for heat production, as it has the potential to be upgraded into fuel for the shipping industry. Including the processes needed for this might be a better representation of the flows that are going to take place in future full-scale pyrolysis plants, but at the time of writing, it was not deemed that there was enough data to support modelling this.

Overall, as there's no full-scale pyrolysis plant up and running in Denmark at the time of writing and biochar is only yet being tested in pilot projects for field application, most data is based on best estimations and assumptions. For example, it is unsure what the nutrient value of biochar is in reality. In the LCA, a 40% N utilisation was modelled, but it is not known whether the nitrogen in biochar will even be available for plant uptake and therefore the N utilisation might be 0% (Elsgaard et al., 2022; Thomsen, 2023). However, the sensitivity analysis showed minimal impacts on the results when 0% N utilisation was modelled. One of the weaknesses when studying a technology that is not yet fully implemented is that data can be lacking, and therefore the data is subject to change as more data is produced over time.

7.2.2 LCA modelling approaches

The sensitivity analysis of the heat mix showed how different modelling assumptions for energy mix can impact the results of the LCIA. Therefore, transparency has been sought in describing how the energy mixes have been modelled, in order to allow for replication and tweaking of this study. This is mainly based on how consequential and attributional LCA methodology deals with modelling. The consequential LCA methodology seeks to model how the market will respond to a change in demand and is thereby based on assumptions on the cause-effect relationships of the market. As it cannot be 100% precisely predicted how the energy mix of the future will look, it is especially important to be transparent in describing how the energy mix is modelled. The consequential heat mix was based on the development of heat supply from all sources based on the years 2015 and 2021, where only heat sources that had grown in supply were included. More data points could have been used, as well as analysing planned energy production projects for Denmark in order to model the heat mix, e.g. Energistyrelsen, 2023. Since two different years are used to model the development of heat production in Denmark, the mix can be influenced by other factors which impact the heat production from a specific source in the given years, which reduces the validity of the model. For the Arla-IDF model, a backwards-looking approach was used, where the energy mix is based on the energy supply of the most recent year available (2021). However, this does not account for how the market will change in the near future and how it will react to a change in energy demand, e.g. from new pyrolysis plants. Fewer assumptions are needed for this type of modelling as you just account for how energy has been produced recently, but it is deemed to be less valid, as you should not exclude cause-effect relationships of implementing a new energy-demanding technology. For example, heat sources like oil and coal are being phased out, and therefore impacts from these are not as relevant to look at when studying the impacts of future biochar production. As seen in the sensitivity analysis, the results of the LCA are impacted greatly when switching heat production, and therefore the modelling of this is important. Not accounting for cause-effect relationships can skew results, and make them less valid. The modelling of heat mix is used as an example in this discussion, but it is a main difference between consequential and attributional LCA modelling.

Matuštík et al., 2020 argues that even though the differences in contexts for different biochar LCAs make direct comparisons difficult, efforts should be made to improve consolidation of the methodology when performing LCAs, especially with regards to the choice of functional unit and system boundary. As can be derived from the state of the art (see Appendix A) the functional units and system boundaries in the articles are varied. However, as mentioned in Section 1.3.1, all the LCAs concluded that biochar could lead to reduced environmental impacts compared to the reference scenarios.

7.2.3 Accounting for soil carbon stock

In this part of the discussion, methodologies for carbon sequestration accounting are compared, where International Dairy Federation, 2022b's method is compared to a consequential accounting approach.

The global warming impacts from the decay of biochar/biomass are time-dependent due to the different decay rates of different types of biomass. Therefore, International Dairy Federation, 2022b proposes using a responsibility window to credit farmers for storing carbon in their soils in order to encourage change in management practices. They suggest that the characterization factor for CO_2eq sequestered should align with the IPCC's GWP100, meaning that the 'neutralization benefit'[1] of applying e.g. biochar is divided over 100 years (-0,01kg CO_2eq/year per 1kg of CO_2eq sequestered).

This neutralization benefit should be adjusted to fit a relevant responsibility window, e.g. if a 20 year responsibility window is chosen instead of a 100 year responsibility window, the yearly neutralization benefit is multiplied by 5 in order to achieve the full benefit over 20 years instead of 100 years. It should be noted that the guidelines state, that for long-term carbon storage like biochar, it is unsure whether to credit all of the benefits to one year or over several years (International Dairy Federation, 2022b).

If using the IDF's 20 year responsibility window as an example, taking point of departure in the 200kg C in the biochar produced from 1.000kg 90%DM digested manure, each year the farmer receives a credit of $200kgC/20years = 10kgC/year$ for 20 years from that biochar (simplified example, as the decay would also have to be taken into account). As can be seen in Figure 7.1, this leads to a cap of credits being reached after 20 years of continuous biochar soil application, as the biochar applied in year 1 is no longer accounted for in year 21. This results in a maximum credit of -200kg carbon/year per functional unit even if the farmer has continued the practice of applying biochar for longer. If another responsibility window was used, e.g. 100 years, a cap would also be reached, albeit it would take more time to be reached. This is especially relevant to discuss for biochar application, as it has the ability to build up carbon stock for more than 100 years and beyond the equilibrium that non-pyrolysed biomass eventually reaches (Elsgaard et al., 2022).

[1] *"The "cancelling out" of a CO_2 emission by removing carbon from the atmosphere (for a sufficient amount of time)" - (International Dairy Federation, 2022b, p. J)*

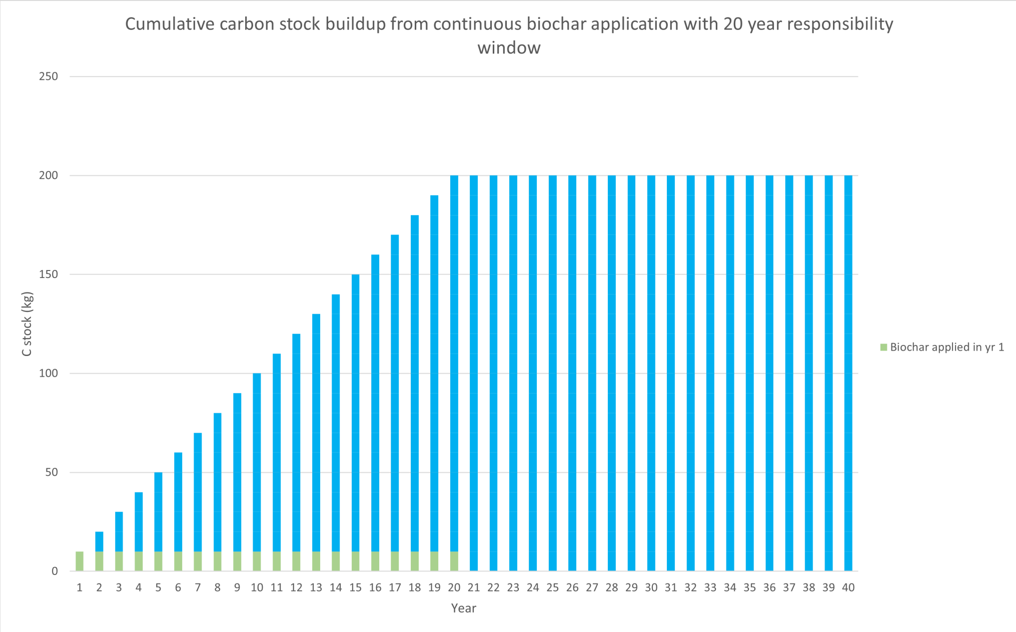

Figure 7.1. Cumulative carbon stock buildup when modelling a 20 year responsibility window. A maximum is reached after 20 years, as the input will be equal to the carbon that 'leaves' the carbon stock accounting every year afterwards. The green column represents the biochar that is applied to soil in year 1 and the blue bars are biochar added in the other years.

Figure 7.2 shows how the carbon stock build-up for the biochar produced from 1000kg 90%DM digested manure would look in reality, and it can be seen that continuous biochar application results in carbon stock build-up well beyond 20 years, as 84,7% of the carbon is still remaining in biochar applied in the first year after 100 years.

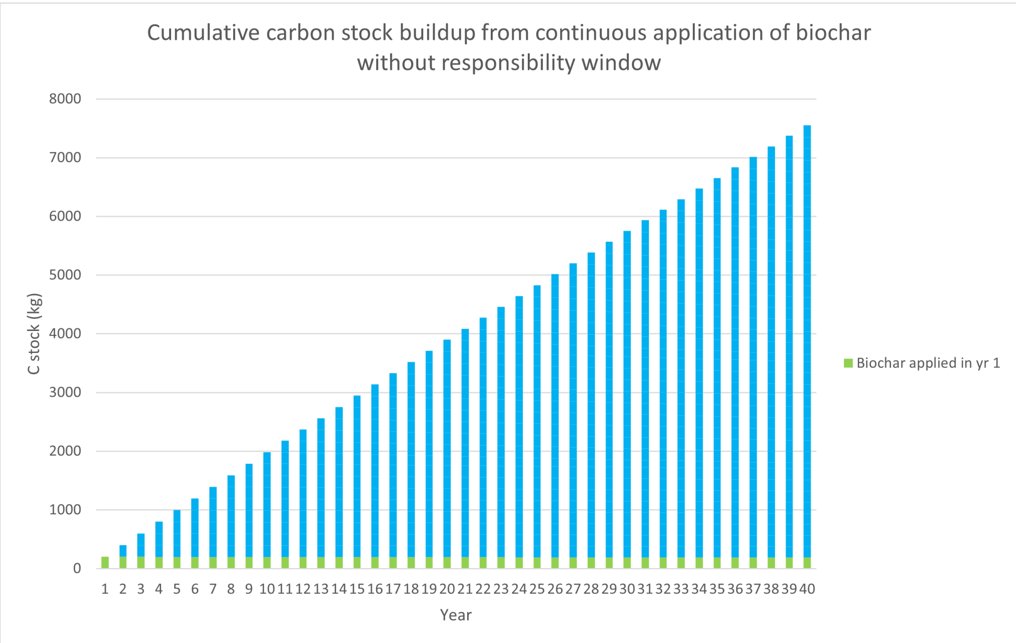

Figure 7.2. The cumulative buildup of carbon stock based on calculations of biochar C contents and decay rate. 200kg C is added every year. The green column represents the biochar that is applied to soil in year 1, and the blue bars are biochar added in the other years.

In a comment to a draft of these guidelines, Schmidt, 2020 questions whether to use a responsibility window because farmers will not get credit for managing the carbon stock in their soils beyond the responsibility window. He instead suggests not implementing a cut-off with a responsibility window in order to allow farmers to be continuously credited for maintaining good practices. When using the IDF Guidelines' approach, the credit will be given to farmers who begin managing land which has previously been poorly managed, but not to farmers who continuously had good management practices of their soils for >20 years. This means that farmers are not credited for how well they have managed the carbon stock of their soils, but for how well they perform compared to how that soil was managed 20 years ago. On the contrary, Schmidt, 2020's suggestion will give credits for maintaining good practices beyond any chosen historical cut-offs.

For example, if the farmer applies biochar instead of biomass, the difference between these two scenarios should be the base for giving any credits. The graph of the carbon decay rate of biochar, digested manure, and straw residues (Figure 5.1 on page 32) shows the effect of applying 1kg C from these different types of biomass on soils. If looking at the C stock buildup from continuous biochar land application compared to the reference scenario of applying biomass on the agricultural soil (See Figure 7.3), it can be seen that the graph for biochar carbon stock buildup rises almost linearly, whilst the graphs for the feedstocks curve off, as the equilibrium, where the input rate equals the decomposition rate of the biomass, is reached, as stated in Section 1.3. Therefore, the time it takes to reach a 'carbon effect' where biochar sequesters more carbon than the non-pyrolysed feedstock depends on the previous soil management practice of the farmer. It can be seen that in the first years after soil application, the carbon stock from applying digested manure is higher, which is due to 50% of the carbon contents of the feedstock being converted to syngas and bio-oil during the pyrolysis process.

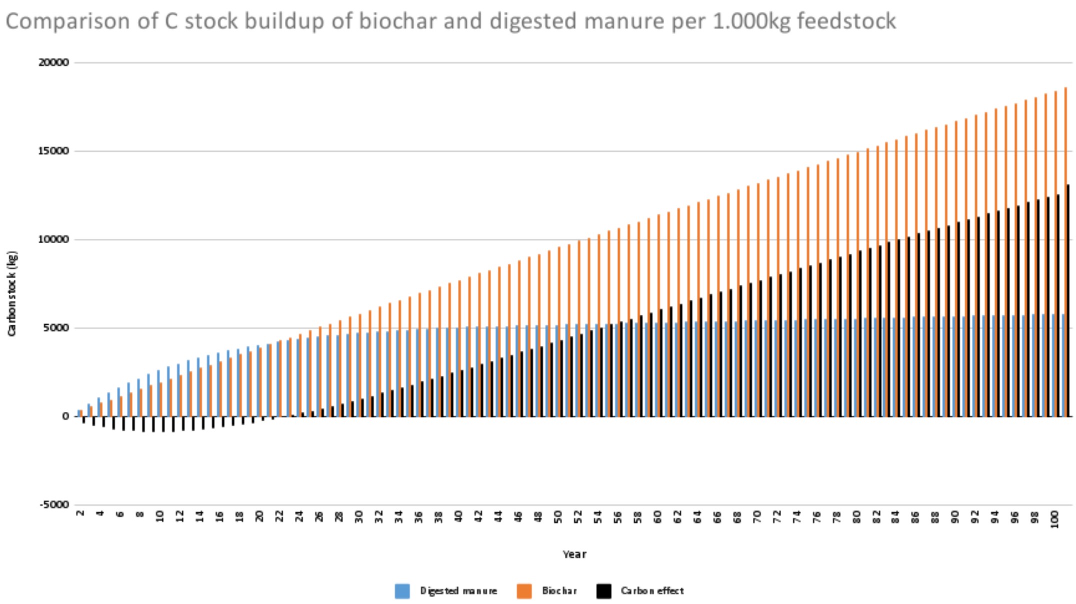

Figure 7.3. Comparison of carbon stock buildup from a constant annual application of 392kg C from 1000kg digested manure and 200kg C from biochar produced from the same amount of biomass. 'Carbon effect' shows the difference between the two practices.

Note that these two figures take point of departure in a carbon stock of 0. In reality, the soil will already have a stock of carbon, and therefore the equilibrium will be reached faster, or it may already have been reached. In that case, the carbon effect will become positive sooner, or even from year 1. Data for soil organic carbon content of the farmer's soil is needed to make a more precise analysis of the carbon effect of biochar soil application.

If farmers are only rewarded for how the carbon stock of their soil compares to the carbon stock of the soil a certain number of years ago, the farmer is not credited correctly for the carbon storage in his soils. As Thomsen, 2023 said during the interview, when discussing the use of responsibility windows, the farmers who have been early starters of building up carbon stocks can end up being miscredited for their good soil management:

> *"No, it is definitely a barrier (...) It is from now that we set the baseline, and only those who improve from now on get credit. You really should be praising people who have been quick to get started and done something so 'the hole' isn't deeper today, but we are not quite there yet."*
> - Thomsen, 2023, line 450-470, own translation

Therefore, farmers who have had continuous carbon stock build-up for many years should not be credited less than a farmer who buys poorly managed soil and starts building up the carbon stock, just because one farmer started this practice more than 20 years ago. Using International Dairy Federation, 2022b's retrospective accounting for carbon storage is not recommended, since the soil carbon management of today cannot change how the soil was managed 20 years ago.

Conclusion 8

To conclude and wrap up the main findings of this study and in order to properly answer the research question, the two sub-research questions shall be outlined and answered:

How do different LCA modelling assumptions affect the LCIA results of soil carbon sequestration, and what are the implications of these differences?

The project analysed two modelling approaches for the LCA of biochar. The main differences were found in how the heat mix was modelled, as the consequential model used a backcasting method to model the future heat supply sources, whereas the Arla-IDF model was based on an attributional approach, where the heat mix from 2021 was modelled, thus assuming no change in the heat mix. The Arla-IDF mix contained natural gas, coal, wind, wood chips and oil, and due to the fossil heat sources, larger impact reductions were gained for global warming and respiratory inorganics when this mix was avoided due to combustion of syngas and bio-oil. However, this heat mix was based on being the same as in 2021 and not accounting for cause-effect relationships. The implication of basing the heat mix on different assumptions is that the environmental impact reductions from avoided heat can be overestimated, which could lead to decisions being made on the wrong data foundation. It is deemed to be preferential to maximize the proportion of biochar produced compared to the co-products, in order to utilise biomass resources as much as possible, and it is important to gain valid results for the impact reductions from the avoided heat production. Furthermore, the state of the art revealed that the choice of functional units and system boundaries varies between different LCA studies of biochar, which makes a comparison of results difficult.

The use of responsibility windows in carbon stock accounting showed that using a responsibility window means there is a risk of incorrectly crediting farmers. Instead, using a consequential accounting method where farmers are credited for how their soil management practices are today, will lead to more correct crediting, as credits cannot change how the farmer's soil was treated in the past anyway.

What is the potential for Danish dairy farmers to utilise pyrolysis to reduce the climate impacts of their milk production?

Based on the results of the LCIA and with the data available from a Danish dairy farm it was possible to gain insight into the potential effects for dairy farmers to utilise biochar as a means of climate mitigation. A CO_2eq emission reduction of 27% for the Arla-IDF modelling and 29% for the consequential modelling was found. This means that dairy farmers have the potential to reduce emissions from their farm activities by supplying their biomass for pyrolysis (and prior biogas production as well). However, offsetting all their emissions from pyrolysis would require vast amounts of biomass resources which are also needed for other purposes, and therefore pyrolysis should be seen as one of several technologies for Arla to reach their climate goals.

Finally, an answer is provided for the main research question:

What are the potential environmental impacts of soil carbon sequestration through biochar for Danish dairy farmers?

The LCA showed potential impact reductions for global warming and respiratory inorganics when pyrolysing the biomass compared to applying it directly to cropland. This was the case for both biomass feedstocks and modelling approaches, and the sensitivity analyses also showed that the pyrolysis scenario still reduced impacts in both categories when some assumptions were changed. If the biomass is already being delivered for biogas production, the synergies between the production of biomass, biogas and biochar should be pursued in order to maximise utilisation of the resource's impact reduction potential. However, data is still lacking with regards to how soil and crops react to biochar application, as well as for commercial scale pyrolysis, and therefore the results of the LCA should be taken with caution with regards to findings of future research.

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State of the art, detailed table A

Table A.1: Main findings from state-of-art literature

LCA articles					
Main Findings	**Feedstock**	FU	**System Boundary**	**Impact categories**	**Ref.**
Comparative LCA of utilising either willow or maize as a feedstock for biomethane production. Willow-based pyrolysis is significantly better at carbon sequestration in the scenarios.	Willow and maize	(1) Area of land use (ha) and (2) Energy content of biomethane (GJ)	ALCA, Agricultural practices, transportation of biomass to plant, handling and transportation of by-products	GWP(100)	Ahmadi Moghaddam et al., 2019

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Table A.1: Main findings from state-of-art literature (Continued)

Utilizing primary forest residues for biochar has better environmental performance in 10/16 impact categories. Trade-offs in the remaining 6 impact categories are due to electricity production	Primary forest residues	1000kg dry biomass	CLCA, *"the biomass supply chain (harvest, chipping, transport), the conditioning of biomass (e.g. storage, grinding, drying), the pyrolysis plant construction and operation (including the fractional condensation of pyrolysis gases) and the use of the pyrolysis co-products"*	Environmental Footprint Method 2.0 (16 categories)	Brassard et al., 2021a
If biochar production has to be up-scaled as a solution for mitigating CO_2 emissions, a comprehensive LCIA should be obligatory to prevent environmental risks and concerns.	Waste single-use wood pallets	(1) 1t of biochar, (2) 1MWh of electricity, (3) 1MWh of heating, (4) 1t of waste pallets	ALCA Pallet collection and transportation to pyrolysis plant, shredding and drying, pyrolysis process, and distribution of biochar CLCA Same boundaries as ALCA but extended with the production of electricity, avoiding other electricity processes. Extended CLCA Same boundaries as the CLCA but extended with the production of pallets	ReCiPe 2016 (H)	Matuštík et al., 2022

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Table A.1: Main findings from state-of-art literature (Continued)

-1,4 to -0,11t CO_2e/t biochar in a decarbonised energy system (Uppsala, Sweden). Impacts on resource use, human toxicity and ecotoxicity varies depending on feedstock	Urban garden waste, wood pellets, logging residues, willow woodchips	Sensitivity analysis: *1m^3 or ton biochar (cradle-to-gate). Environmental hotspot identification: 1 unit of product. Benchmarking biochar applications: 1t biochar produced and used. Uppsala case: Amount of products needed to build and maintain new district from 2025-2100.*	*"production and supply of biochar, production and supply of other materials, manufacture of the biochar product, and its use and disposal"*	Climate change impact, resource use, human toxicity, ecotoxicity	Azzi et al., 2022
Norwegian life cycle assessment of four scenarios of utilizing biochar application to managed soils, from wood residues. The study argues that biochar cannot be assessed by itself, but the whole value chain is needed to understand the potential of carbon sequestration.	forest residues (Wood chips)	kg barley (ref) kg biochar kg feedstock	Four scenarios where all include the production of wood to residues from handling the tree/wood. Scenario 1: Only apply biochar to soil, 2. Mix biochar with fertilizer and apply it into the soil, 3. Mix biochar and fertilizer into the soil + CHP energy and electricity from pyrolysis, and 4. mix of biochar and fertilizer into the soil and production of bio-oil from pyrolysis.	Climate Change; Ozone dep.; Ozone form., human health; Fine PM; Terr. acidification; Marine eutrophication Terrestrial ecotoxicity.	Tisserant et al., 2022

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Table A.1: Main findings from state-of-art literature (Continued)

Lower environmental impacts than reference scenario (mineral fertiliser). Biochar-compost combination provided similar crop yields as mineral fertiliser	Urban and farm organic waste	1kg product (grape, leek, and olives)	ALCA Transportation of feedstock to processing facility to production of farm product. Excludes upstream impacts	Global warming, acidification, eutrophication	Oldfield et al., 2018
A study from Finland argues that willow production, pyrolysis and biochar application can compensate Finnish farmers 7.7% of their overall GHG emissions if marginal land is used for growing willow.	Willow	1t dry biochar stored in soil for 100 years	Not specified (but substitution is used to avoid allocation)Cultivation of willow, drying, chipping, transport to pyrolysis plant, more drying, pyrolysis process with district heating, and transport biochar, soil application	Climate Change	Leppäkoski (2021)
Comparative life cycle assessment of using wood chips in either pyrolysis or combustion for heating and electricity production. Pyrolysis has a great possibility for carbon mitigation and production of energy, but it can be complex to build a pyrolysis plant for this sole purpose.	Wood chips	1t wood chips (dry weight)	Not specified but mentions marginal supply and substitution comparison of different scenarios, woodchip from the global market and then used in pyrolysis (including biochar used in animal feeding and application to soils) or a CHP.	Climate Change (GWP100)	Azzi et al., 2019

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Table A.1: Main findings from state-of-art literature (Continued)

-1,43t CO_2e/t dry matter feedstock compared to reference scenario of landfilling. Pyrolysis had lower impacts on eutrophication and terrestrial ecotoxicity than incineration and hydrothermal carbonization	Pulp and paper mill biosludge	1t dry matter feedstock	Biosludge collection and preprocessing to application in soil	Climate change (GWP100), acidification potential, eutrophication potential, terrestrial ecotoxicity	Mohammadi et al., 2019
Danish context of using rapeseed production for pyrolysis. A substantial reduction of GHG emissions was recognized and the CO_2 captured was between 71.5% and 86.7% between the scenarios.	Winter oil seed rape (WOSR)	1Mg dry seed WOSR	Cultivation and production of rape seed, usage of straw in pyrolysis and avoiding electricity, and biochar application to soils. (cradle to grave)	Climate Change (GWP100)	Thers et al., 2019
Net CO_2 removal, lower impacts on ozone layer depletion, but increased impacts on land use and health respiratory effects	Wood pellets	Heating for 1 year	Upstream and use phase emissions + estimation of biochar C sequestration. No agricultural benefits from biochar assumed	Climate change, land use, ozone layer depletion, health respiratory tory effects	Azzi et al., 2021

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Table A.1: Main findings from state-of-art literature (Continued)

Pyrolysis system with soil application removed the largest part of CO_2 from the atmosphere (compared to direct combustion of feedstock). Results are dependent on the energy system, e.g. direct combustion is best if replacing coal or natural gas	Short-rotation coppice willow	1ha willow cultivation for the area, 1kWh electricity and 1MJ heat for energy services	Willow cultivation to delivery of electricity and heat	Climate impact (time-dependent)	Ericsson et al., 2017
Neutralizing global warming impacts of crop production using biochar from side flows and buffer zones: A case study of oat production in the boreal climate zone	Side flows from oat flake production (small oat and husks)	1t oat flakes	Not specified (uses system expansion to avoid allocation)Cradle to gate	Climate Change (GWP)	Uusitalo and Leino, 2019
Using broiler manure in a pyrolysis plant can in some cases better or have the same low emissions compared to using broiler manure in a biogas plant. However, the carbon stability in biochar is a significant benefit.	Broiler manure	1 metric ton broiler manure	From broiler farm-gate (exit)	GHG emissions	Kreidenweis et al., 2021
Non-LCA articles					

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Table A.1: Main findings from state-of-art literature (Continued)

Main findings	Ref.
LCA review found emissions ranging from 0,04t to -1,67t CO_2e per ton feedstock. Trade-offs for particulate matter, acidification and eutrophication depend on background energy system. Biochar has low risk of negative impacts in soils and can improve soil conditions.	Tisserant and Cherubini, 2019
Comprehensive review article analysing the potential development of biochar production by using crop residues in a pyrolysis process. Using a variety of tools to assess the potential feedstocks and pyrolysis plant potential.	Li et al., 2023
Review on synergies between pyrolysis and anaerobic digestion of organic waste. Clear evidence of benefits on energy recovery and efficiency through coupling of AD and pyrolysis, e.g. through valorization of solid digestate by pyrolysis, and through the use of biochar in the AD process. More data is needed on the 'technico-economic' benefits.	Tayibi et al., 2021
Review of LCAs on CDRs, e.g. biochar. More comprehensive LCAs are needed. LCAs need to take account for multiple impact categories, the temporal aspect of emissions, transparency, environmental side-effects, and it is important to distinguish between avoided emissions and negative emissions, as only negative emissions is equal to permanent C sequestration.	Terlouw et al., 2021
Review of negative emission technologies (NETs), e.g. biochar. Biochar soil incorporation has greatest potential of reviewed NETs, but results 'vary widely' between studies. Biochar can also lead to net savings in fossil depletion, acidification, and human toxicity due to co-products. Recommended that studies on NETs consider mass of CO_2e removed as functional unit. Need for consensus on considerations of non-permanent sequestration and delayed emissions.	Jeswani et al., 2022
Applying biochar to soils contaminated with heavy metals could help remediate soils and reduce plant uptake of cadmium, lead, and zink, thus reducing their toxicity. Only assesses biochar from sugarcane-straw.	Puga et al., 2015
Carbon sequestration through biochar is essential in improving the carbon footprint of bioenergy, especially when using biomass with a longer rotation length.	Fan et al., 2021

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Table A.1: Main findings from state-of-art literature (Continued)

A review paper discussing the valorization of digestate from anaerobic digestion plants. The paper aims to analyse the different alternatives for digestate and the authors believe a liquid digestate can be used for microalgae culture and solid digestate can be converted to energy.	Monlau et al., 2015
A review of different LCA articles which has to assess biochar/pyrolysis and analyse the different methods behind the articles assessments.	Zhu et al., 2022
A review of how biochar can be used as a climate mitigation tool. The authors take crop growth, soil health and the usage of biochar into account. There can be great potential depending on the local context and how the biochar is applied to the cropland instead of combustion.	Lehmann et al., 2021

LCIA, all impact categories B

Impact category	Unit	CLCA Digested manure	CLCA Straw	Arla-IDF Digested manure	Arla-IDF Straw
Human toxicity, carcinogens	kg C2H3Cl-eq	-1,22	-2,48	-1,21	-2,42
Human toxicity, non-carc.	kg C2H3Cl-eq	-17,62	-22,70	-5,58	-7,98
Respiratory inorganics	kg PM2.5-eq	-0,15	-0,21	-0,23	-0,31
Ionizing radiation	Bq C-14-eq	-26,88	-147,65	444,16	-426,30
Ozone layer depletion	kg CFC-11-eq	0,00	0,00	0,00	0,00
Ecotoxicity, aquatic	kg TEG-eq w	-11609,97	-14732,54	-3081,63	-4802,79
Ecotoxicity, terrestrial	kg TEG-eq s	-2968,49	-3667,56	-1263,77	-1635,15
Nature occupation	PDF*m2a	-0,04	0,03	0,01	0,10
Global warming, non-fossil	kg CO2-eq	-1,44	-1,52	-55,67	-71,03
Global warming, fossil	kg CO2-eq	-650,15	-533,26	-795,88	-722,69
Acidification	m2 UES	-7,64	-12,02	-33,18	-43,11
Eutrophication, aquatic	kg NO3-eq	-0,07	-0,16	0,01	-0,07
Eutrophication, terrestrial	m2 UES	-36,52	-54,84	-14,42	-28,81
Respiratory organics	pers*ppm*h	-0,38	-0,22	-0,52	-0,38
Photochemical ozone, vegetat.	m2*ppm*hours	-3588,92	-2438,13	-4575,14	-3583,30
Non-renewable energy	MJ primary	266,10	-415,07	-1497,91	-2827,88
Mineral extraction	MJ extra	0,46	-3,03	0,95	-2,25

Figure B.1. Characterized results for all impact categories per 1.000kg 90% DM feedstock treated in pyrolysis plant. Method: Stepwise 2006, version 1.7.

Impact category	Unit	CLCA Digested manure	CLCA Straw	Arla-IDF Digested manure	Arla-IDF Straw
Total	EUR2003	-74,52	-71,08	-87,25	-87,55
Human toxicity, carcinogens	EUR2003	-0,32	-0,65	-0,32	-0,64
Human toxicity, non-carc.	EUR2003	-4,78	-6,16	-1,51	-2,16
Respiratory inorganics	EUR2003	-10,14	-14,09	-15,69	-20,79
Ionizing radiation	EUR2003	0,00	0,00	0,01	-0,01
Ozone layer depletion	EUR2003	0,00	0,00	0,00	0,00
Ecotoxicity, aquatic	EUR2003	-0,09	-0,11	-0,02	-0,04
Ecotoxicity, terrestrial	EUR2003	-3,28	-4,05	-1,40	-1,81
Nature occupation	EUR2003	-0,01	0,00	0,00	0,01
Global warming, fossil	EUR2003	-53,96	-44,26	-66,06	-59,98
Acidification	EUR2003	-0,06	-0,09	-0,26	-0,33
Eutrophication, aquatic	EUR2003	-0,01	-0,02	0,00	-0,01
Eutrophication, terrestrial	EUR2003	-0,45	-0,68	-0,18	-0,36
Respiratory organics	EUR2003	-0,10	-0,06	-0,13	-0,10
Photochemical ozone, vegetat.	EUR2003	-1,33	-0,91	-1,70	-1,33
Mineral extraction	EUR2003	0,00	-0,01	0,00	-0,01

Figure B.2. EUR2003 impact results for all impact categories per 1.000kg 90% DM feedstock treated in pyrolysis plant. Method: Stepwise 2006, version 1.7.