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Assessment of the Danish climate crisis mitigation potential of two new straw management options

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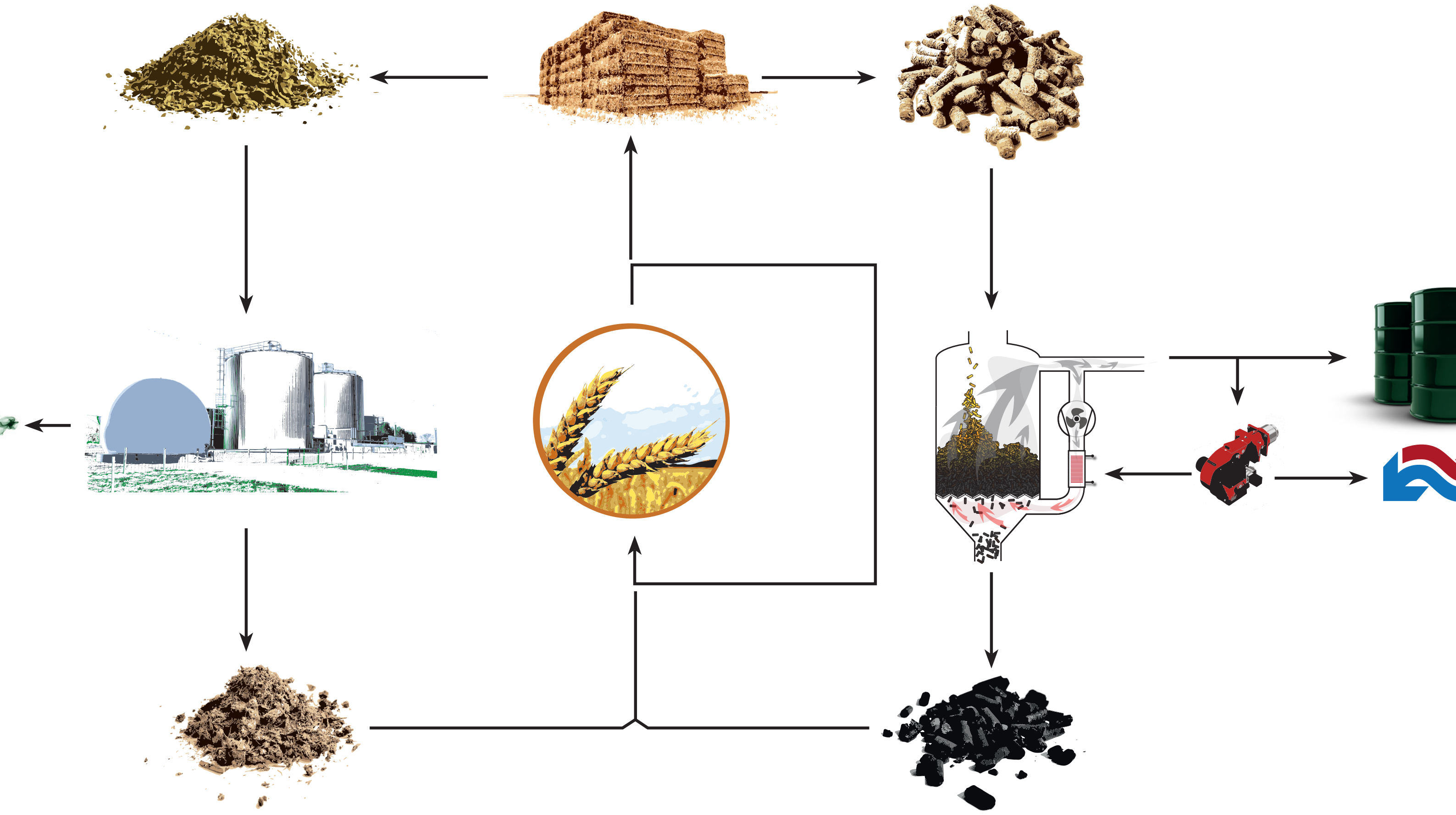

Tobias Pape Thomsen, assistant professor @ RUC IMT . September 2021

Climate Footprint Analysis of Straw Pyrolysis & Straw Biogas
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Foreword, personal interests and project contributions

This report as well as the reported Climate Footprint modelling has been conducted in full by me - assistant professor Tobias Pape Thomsen (TPT) at Roskilde University, Department of People and Technology as an academic contribution to the ongoing debate about the climate change mitigation potential of pyrolysis technology, biogas production and straw management. I have worked with bioenergy and sustainability assessment of thermal bioenergy systems – pyrolysis and thermal gasification, for more than 12 years and I have a profound, professional interest in this area. I have also worked extensively with the straw resource and with anaerobic digestion, but I am no expert in these areas. For these aspects, especially, I have received highly valuable input, questions and critique from colleagues and the expert review panel. As such, many peers have contributed – directly and indirectly, to this work e.g.:

- DTU Chemical and Biochemical Engineering (DTU KT) and Stiesdal Fuel Technologies (SFT) have contributed with invaluable, new primary data about the pyrolysis system in focus of this work. Both DTU KT and SFT develop the pyrolysis technology modelled in this work and therefore have profound professional interest in the conducted analysis.
- SFT have paid for an external review of the work at the consultancy company LCA 2.0 to quality-check and strengthen the analysis and results prior to publication.
- Armin Vauk, Magnus Bo Karlsson, Henrik Hauggaard-Nielsen and Andreas Kamp from Roskilde University have contributed with discussions, insight and data related to Danish agricultural practice and the utilization of straw and manure.
- Andreas Dyreborg Martin from RUC IMT have contributed with insight and sparring related to the biogas-oriented parts of the analysis.
- LCA 2.0 have arranged an external expert panel review of the work. The external expert review panel consisted of highly qualified experts within life cycle assessment, Easetech software, thermal bioenergy systems and biogas technology and -business. The review process has increased the quality, robustness and relevance of the work substantially. **The final review-report is enclosed as appendix 6 including a description of the panel.** The final review report was issued by the review panel after a very comprehensive review process and substantial changes to the study on the basis hereof. The impact of the panel's challenging questions, constructive criticism, competent input and assistance is now an embedded and integrated part of this study. Therefore, the large efforts of the panel in regard to the review process and this study are not expressed in the relatively short final version of the review report that is enclosed in the appendix.

Thank you all for your contributions!

Tobias Pape Thomsen, Roskilde – September 2021

Content

Central abbreviations

AFOLU: Agriculture, Forestry and Other Land Use

CCFB: Climate-Carbon Feedback

CCS: Carbon Capture and Storage

CCU: Carbon Capture and Utilization

CF: Characterization Factor

CFA: Climate Footprint Assessment

CH_4: Methane

CO_2: Carbon dioxide

DM: Dry matter

EOL: End-Of-Life

FU: Functional Unit

GWP: Global Warming Potential

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LULUCF: Land Use, Land Use Change and Forestry

N_2O: Nitrous Oxide

PyCCS: Pyrogenic Carbon Capture and Storage

QSA: Quantitative Sustainability Assessment

t: Metric tonne (metric ton), non-SI unit accepted for use with SI-units. 1 t = 1000 kg.

TS: Total solids

VS: Volatile Solids

Stakeholder abbreviations:

AU: Aarhus University

DTU KT: Technical University of Denmark, Department of Chemical and Biochemical Engineering

DTU ENV: Technical University of Denmark, Department of Environmental Engineering

RUC IMT: Roskilde University, Department of People and Technology

SFT: Stiesdal Fuel Technologies

Summary

Agricultural straw is an abundant crop residue in the current Danish agricultural system and 2-2.5 mio metric tons of straw is left uncollected in the fields every year to be amended back into the soil for soil enhancement purposes and nutrient recycling. Increased high-value straw utilization may benefit the sustainable transition of society away from fossil fuel use, but may also increase the sensitivity towards weather extremes of the socio-ecological system around straw utilization. In addition, circumventing straw management from current soil amendment practice may negatively influence soil quality and health if conducted without a proper compensation strategy. In short – we have to consider using more of the produced straw to mitigate the climate crisis, but using more straw may have unintended negative effects on soil – and the accelerating climate crisis will make us more vulnerable when doing this.

Part of the straw resource – around 1/3rd of the straw that is today amended directly back to soil, is already economically and politically bound to treatment of animal manure. Large amounts of animal manure are currently untreated. Treatment by anaerobic digestion may reduce emissions of both greenhouse gases and ammonia from this material. But to do so, a substantial amount of straw is required to boost the gas production from the manure treatment and thereby improve the process viability. The remaining 2/3^{rds} of the collectable straw, is in this study suggested to be managed in thermal pyrolysis systems to produce primarily bio-char and bio-oil. As with the use of straw for manure treatment in biogas, there is also a large political focus on the potential effects of straw pyrolysis.

This study seek to determine what level of climate change mitigation effects that may arise from increased straw utilization in a combination of 1) anaerobic co-digestion of straw and manure in biogas plants and 2) thermal pyrolysis of the remaining straw resource. The study is not a comparative assessment that seek to determine which of the suggested technologies that perform best. Instead, it is a study that acknowledge the purposefulness of having both technologies and seek to determine the climate mitigation potential of applying both in a new straw management strategy. The Climate Footprint of the proposed strategy is compared to a split reference system encompassing i) direct amendment of straw to soil and ii) simple tank-storage of animal manure. The analysis is conducted as a Climate Footprint Assessment based on LCA methodology but only encompassing a single impact indicator – influence on the global warming potential (GWP) of the modelled systems compared to the reference. The GWP impact is quantified in two different time horizons: The accumulated radiative forcing in 20 years' and 100 years' time horizon, expressed as the Global Warming Potential (GWP20 and GWP100), measured in CO_2-equivalent. The study is conducted to support technical R&D, planning and decision-making processes related to development of climate change mitigation strategies of Danish agriculture and energy production. The investigation has focus on the following main aspects:

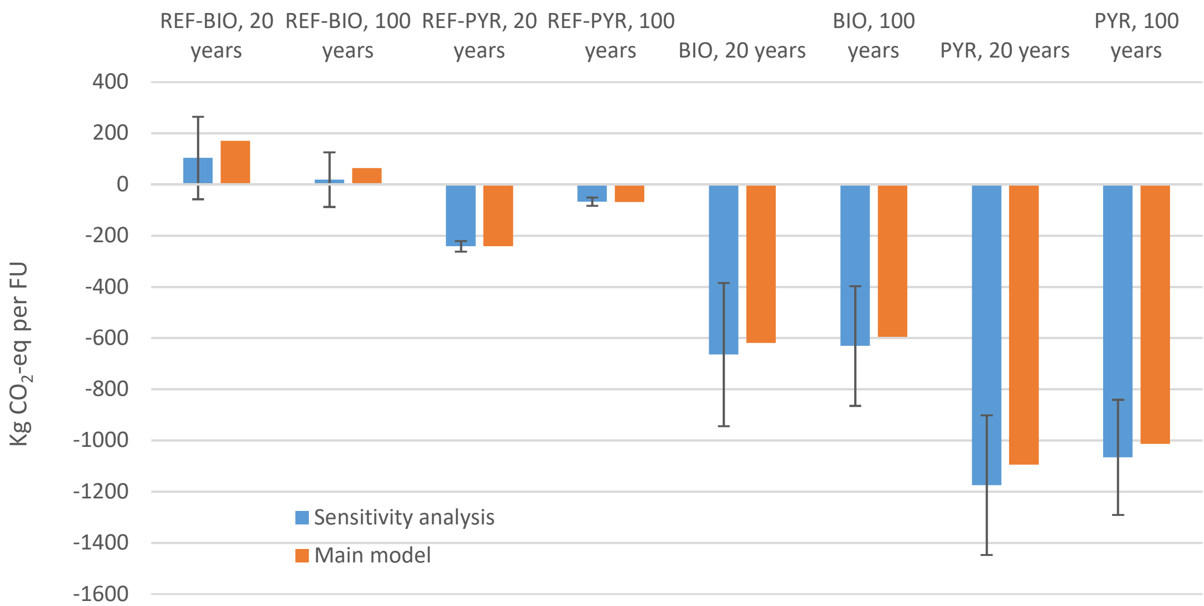
- Climate Footprint studies of established reference systems: unused straw and untreated manure.
- Climate Footprint studies of straw pyrolysis and straw-manure co-digestion in modern plants.
- Estimation of the national scale climate change mitigation potential of using the available Danish straw resource for straw-manure co-digestion and straw pyrolysis compared to current practice.
- Hotspot analysis and comprehensive sensitivity assessment to identify critical and sensitive aspects of the analysis, determine the width of the relevant impact spectrums as well as to provide insight and recommendations for further technical development and future implementation of the investigated systems
- Effect on results of modelling with a 20 year impact potential >< a 100 year impact potential related to the calculation of Global Warming Potential metrics

The functional unit of the study is based on the collectable fraction of the straw in the field that can be removed with conventional machinery in the biogas- and pyrolysis scenarios. The remaining fraction of the straw - as well as stubs, roots, husks etc., that is left on the field are not modeled. The study does not provide an assessment of Climate Footprint of wheat production, only of straw management. The study assume a straw resource potential of 2.5 mio metric ton collectable and storable, relatively dry straw per year. Wet-straw biogas processes encompassing open-air silage as pre-treatment are not included in the model.

From the main set of results, it is found that the Climate Footprints of the three systems are influenced primarily by the following aspects (an * indicate that the factor primarily influence the Climate Footprint of the system in a 20 year time horizon, order is ranked with the most influential parameters first):

- **Reference:** i) Emissions from manure storage*, ii) Soil carbon sink*, iii) Straw nutrient fertilizer effects, and iv) Field work input
- **Biogas:** i) Natural gas substitution, ii) Emissions from digestate storage*, iii) Soil carbon sink*, iv) Digestate nutrient fertilizer effects, and v) CH_4-leak from biogas plant*
- **Pyrolysis:** i) Soil carbon sink, ii) Fossil oil substitution, iii) District heating production, iv) biochar nutrient fertilizer effects and, v) Input requirements for the palletization process

Based on the results of the current study (see figure below), increased utilization of an available cereal straw resource by up-draft pyrolysis is expected to reduce the Climate Footprint of the embedding system with around 0.85 - 1 t of CO_2-equivalent per t collectable straw that is managed in this way compared to the current practice of direct amendment into soil. Using the straw for co-digestion with manure and production of upgraded biogas for the natural gas grid will reduce the Climate Footprint of the related systems with around 0.65 - 0.8 t of CO_2-equivalent per t straw compared to the present practice. The span of these results is driven by changing time horizons from 20 to 100 years. The climate related benefit of the pyrolysis scenario compared to the reference increase from 20 to 100 years while the opposite is the case for the biogas scenario.



Summary Figure: *Main results (blue) and average results from sensitivity assessment (orange). Deviation bars indicate standard deviation among all results from single-parameter variations in the sensitivity assessment.*

As there are numerous parameters, assumptions and design choices that may influence the results of a Climate Footprint assessment, a thorough sensitivity assessment has been conducted. A results chart presenting both the results from the main model as well as average values and standard deviations across all single parameter variations in the sensitivity analysis is provided below.

The original model results are very close to the average model results from all tests in the sensitivity assessment, but the standard deviation of the different data sets vary substantially. The uncertainty in the 20 year horizon assessment of both the biogas systems and the pyrolysis systems is slightly higher than in the 100 year horizon assessment. Among the main drivers for these uncertainties are energy end-use variations, aspects of methane emissions and carbon-sink effects.

The results of the sensitivity assessment were used to determine the width of the system climate impact spectrum and the risks and opportunities that made up this spectrum around the main set of results. Risks are found to relate mainly to:

- Suboptimal energy product end-use (situated)
- The marginal energy technology (generic)
- Methane leaks and emissions from digestate storage
- Stability of amended substrates and the related carbon-sink potentials

On the other hand, there seem to be large additional potentials relating to:

- Optimized energy product end-use. Preferably through direct substitution of carbon-intense fuels in industrial processes.
- CCS of biogas CO_2
- Improved stability of amended substrates and the related carbon-sink potentials
- Optimized energy product distribution in pyrolysis process
- Stabilizing digestate and reducing methane leaks

A promising alternative system configuration of the biogas scenario was found to be the development of a CCS-management option for biogas CO_2. Such an initiative would have a substantial improvement potential and could - in the investigated case, increase the climate benefit with more than 50%. Potentials may be even higher if processes for more effective digestion of the straw is developed. According to the carbon balance estimated in the study there is a lot more carbon to capture from the digestate. However, an alternative approach could be drying and pyrolysis of the digestate to make pyrogenic CCS through production and use of biochar to complement the conventional CCS on the gaseous CO_2.

An assessment has been conducted where the possible worst-case and best-case effects of reasonable combinations of these risks and potentials were determined. From these results, the following extreme end impact spectrums have been estimated when transitioning from the established reference of amending straw directly into the soil to a new management practice based on either pyrolysis or biogas with co-digestion of animal manure:

- When establishing new plants for co-digestion of straw and manure, the impact on climate change can range from a net increasing effect of around 250 kg CO_2-eq per metric ton straw to a net mitigating effect of around 2050 kg CO_2-eq per metric ton straw in a 20 year perspective. In a 100 year perspective the impact on climate change can range from a net increasing effect of 200 kg CO_2-eq per metric ton straw to a net mitigating effect of 1700 kg CO_2-eq per metric ton straw.
- When establishing new plants for pyrolysis of straw, the impact on climate change will in all cases be a net mitigating effect, but the size of the effect may vary substantially. In a 20 year time

horizon, the mitigation effect may be around 400 - 1700 kg CO_2-eq per metric ton straw. In a 100 year time horizon, the mitigation effect is found to be around 500 - 1650 kg CO_2-eq per metric ton.

More than anything else, the huge spans of results should make it clear that this type of project need to be thoroughly developed and planned to avoid sub-optimal or even problematic climate effects. On the other hand, the results also indicate that there is a huge optimization potential compared to average results and the main model.

Assuming average straw and manure compositions and system layouts as described in the present study, it is calculated how large the Climate Footprint of the different reference systems and scenarios are on a Danish, national scale.

The results indicate a beneficial climate change mitigation effect spectrum of 1-3 million metric ton CO_2-eq per year in 2030 if transitioning from direct straw amendment of 2.5 mio metric ton straw and tank storage of 4.7 mio metric ton manure to new management systems based on anaerobic co-digestion and pyrolysis. The main set of model results – excluding the impact spectrum results from the sensitivity assessment, indicate a climate change mitigation potential of 2-2.3 million metric ton CO_2-eq per year in 2030 from this system varying only with the temporal scope of the assessment. However, in extreme-end scenarios, impact potentials even higher and lower than 1-3 million metric ton CO_2-eq per year may be obtained.

These results are calculated using average values and standard deviations based on un-aggregated results from the sensitivity assessment. This means that there may be many different project configurations that will yield results outside the spectrum from 2-2.3 million metric ton CO_2-eq per year. Lower impacts – as well as substantially higher impacts, may be obtained and adopting e.g. CCS on biogas CO_2 from the proposed new biogas capacity may increase the estimated potential with 0.3 million metric ton CO_2-eq per year pushing the full system potential estimate to 2.3-2.6 million metric ton CO_2-eq per year. Based on the large span in results, it is recommended to use some of the findings in the present study and similar works to guide both development, planning and implementation of such projects. Increasing focus on some of the following parameters in future R&D efforts could increase the quality of the Climate Footprint analysis – and results, as well as increase the climate crisis mitigation potential performance of the assessed system:

- Biogas system performance is expected to benefit from an increased focus on biogas end-use value, CCS, reducing methane leakage, increasing methane yields and stabilizing the digestate, possibly through drying and pyrolysis. Methane yields could be increased by methanation of the CO_2-part of the biogas with hydrogen from electrolysis of water as an alternative to CCS.
- The Climate Footprint of the pyrolysis system could benefit from increased oil yields (through optimized product distribution and Power-to-X), increased char yields and/or increased use value of the surplus/residual gas product. Optimized climate benefit from the residual gas and/or heat production seem to be a key issue and while low temperature heat may be valuable in specific cases, the general case should be focused on other higher value use cases.

To indicate the potential influence of these risks and potentials, the impact of selected parameters have been extracted from the sensitivity assessment and provided in the table below. These impact modifications should be compared to the main results on climate change mitigation potentials of 0.85 - 1 t of CO_2-equivalent per t collectable straw that is managed in pyrolysis systems compared to the current practice 0.65 - 0.8 t of CO_2-equivalent per t straw used for co-digestion with manure and production of upgraded biogas for the natural gas grid compared to the present practice.

Summary Table: *Effect of selected high-impact parameters from the sensitivity assessment on the estimated climate change mitigation potentials of the proposed biogas- and pyrolysis based straw management system. Effects are described per metric ton of straw managed in biogas- or pyrolysis-systems.*

Impact modification	Short term effect (20 years)	Long term effect (100 years)
Reduced emissions from reference manure storage via acidification	May **reduce** the net climate benefit of manure-digestion in biogas plants with around 350 kg CO_2-eq per metric ton straw co-digested with manure	May **reduce** the net climate benefit of manure-digestion in biogas plants with around 140 kg CO_2-eq per metric ton straw co-digested with manure
Carbon Capture and Storage (CCS) systems deployed for sequestration of biogas CO_2	May **increase** the climate change mitigation effect of co-digestion of straw and manure in biogas plants with around 350 kg CO_2-eq per metric ton straw co-digested with manure	
Energy product from biogas replace coal-based process heat	May **increase** the climate change mitigation effect of co-digestion of straw and manure in biogas plants with around 940 kg CO_2-eq per metric ton straw co-digested with manure	May **increase** the climate change mitigation effect of co-digestion of straw and manure in biogas plants with around 740 kg CO_2-eq per metric ton straw co-digested with manure
Energy product from biogas replace long-term marginal district heating	May **reduce** the climate change mitigation effect of co-digestion of straw and manure in biogas plants with around 510 kg CO_2-eq per metric ton straw co-digested with manure	
Energy products from pyrolysis process replace coal-based process heat	May **increase** the climate change mitigation effect of straw pyrolysis with around 740 kg CO_2-eq per metric ton straw pyrolyzed	May **increase** the climate change mitigation effect of straw pyrolysis with around 590 kg CO_2-eq per metric ton straw pyrolyzed
Energy product from pyrolysis process replace long-term marginal district heating	May **increase** the climate change mitigation effect of straw pyrolysis with around 410 kg CO_2-eq per metric ton straw pyrolyzed	

As a single-metric study, this work alone is not sufficient to draw decisions on development and implementation of large-scale straw utilization. A more comprehensive Life Cycle Assessment that covers more/all relevant impact categories would be an obvious next-phase study. Also, the effect of increased straw utilization on the larger straw-based value network should be investigated in the light of other relevant aspects e.g. system robustness and resilience under accelerating climate change related weather extremes as discussed in the introduction. Stressing the use of the straw resource will potentially make parts of the straw based value network more sensitive to disturbances. Increased straw utilization may also deprive the soil and soil biome of valuable nutrients and carbon, needed to build and maintain robustness and productivity of the soil. There are many knowledge gaps in this part of the system. In all cases, it is essential to make sure that implementation of the desired systems is done in a way that maintain or build soil quality, -life and -productivity in the long run as the bio-based economy is fully dependent hereon.

Robustness of the socio-technical parts of the socio-ecological systems that are influenced by the proposed changes is also relevant to address. Agriculture is changing. Food habits are changing. It will not be robust to develop 2030 perspectives for technology that are only viable in the current agricultural settings. Both pyrolysis and biogas has to be applicable in the management of other biomasses than cereal straw to be robust in the long term. And the biogas process need to be adaptable to situations with lesser animal manure. Similarly, the products from the conversion have to be flexible and valuable in the long run. The climate impact of heat and power production is on a steady decline and it becomes more valuable to provide other energy products – or carbon sequestration. The combination of green methane and a national gas grid provide a broad portfolio of end-uses and potential value. The carbon sequestration value of the biochar will remain the same regardless of changes in the energy system. However, a discussion about the need for biogenic carbon in the energy- and manufacturing sectors have to be taken into account when investigating the systemic climate effect of biochar.

From this study, it is found that the climate effect of pyrolysis-based systems may be easier to predict than effects of biogas systems, but also that there are some aspects that need further validation. First and foremost, the full value of new value chains for large amount of pyrolysis bio-oil need to be developed and investigated in experimental and social R&D projects. Also, value chains for large scale production and use of both biochar and bio-oil have to be established and implemented in the market. One of the first barriers to break in this task is that several legal issues and uncertainties have to be resolved. The Climate Footprint of biogas projects may be more difficult to predict precisely as result volatility is very high and the impact spectrum very wide. However, utilization of biogas via the gas grid has the advantage of being very mature in both market and legislation and expanding activities can be enacted more or less immediately.

New/additional effects and potentials may arise from potential synergies between the three management strategies – reference, biogas and pyrolysis, which has not been included in the present work and it is recommended to investigate a more integrated approach to straw management as well.

There are parts of the relevant systems that could not be adequately modelled in the present work and the results are influenced by data-and-assumption uncertainty. It is found particularly important to refine and improve the model of system processes related to N_2O emissions and soil effects. This may require new data on soil CN-dynamics, leaching, emissions, fertilizer effects, productivity etc. Any decimal use of the quantitative results should be done with care! On the other hand, the results are largely supported by other studies, the study has undergone thorough expert review and the sensitivity related to the main set of results is found to be reasonable. Therefore, the overall conclusions and the size-range of the potential climate mitigation effect of the new straw management by biogas and pyrolysis is expected to be both relevant and valid.

The current work is an isolated assessment of Climate Footprint impact potential of a single technologically based strategy that does not in itself provide sufficient foundation for decisions within system development and implementation. Integrated system development – especially on larger scale, is complex and requires broad, interdisciplinary insight, nuances and balance among social aspects, technological aspects and ecosystem stewardship. It is important not to lose track of the climate change mitigation effects – and other environmental impact effects, when dealing with such complex projects. There are vast potentials to develop, but also large risks to avoid. Quantitative sustainability assessment type of efforts – LCA, CFA etc. should be continuously integrated in these processes on a sufficient and productive level to guide and support central decisions along the way.

1 Introduction

Agricultural straw is an abundant crop residue in the current Danish agricultural system. The majority of straw originate from cereal crops grown for fodder purposes as illustrated in Figure 1. Around 10% of the straw originate from rape seed and around 1% originate from the production of various legumes. The dotted line show the linear trend for the size of the total straw resource. It show a slight increasing trend.

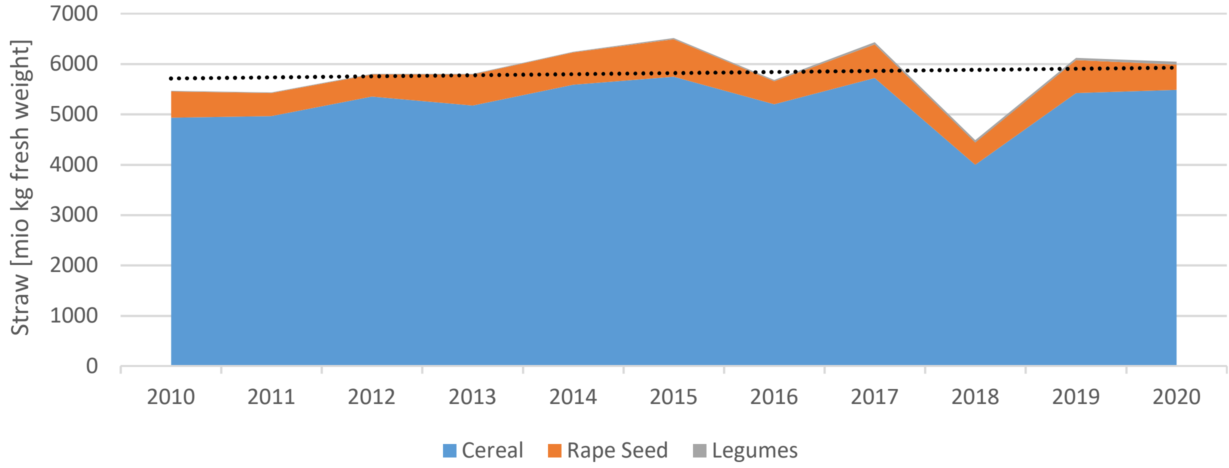


Figure 1: *Straw resource statistics, Denmark 2010-2020, total production. Dotted line is sum trend. From Statistics Denmark*[1]

There is a profound history of straw use in Denmark and straw logistics systems – procurement, transport, storage etc. are widespread. Figure 2 illustrate the main straw uses in Denmark in recent years.

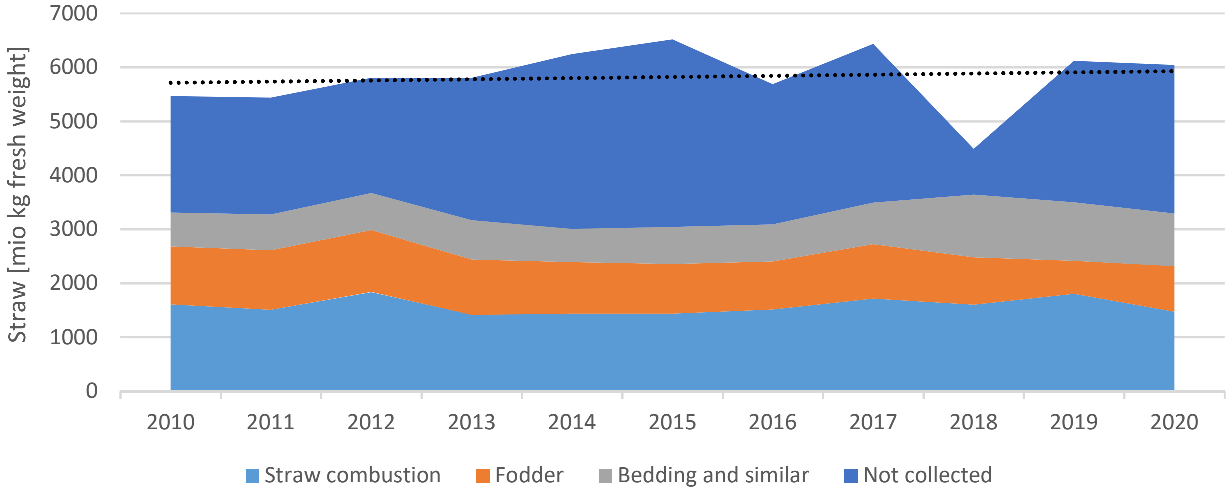


Figure 2: *Straw use statistics, Denmark 2010-2020, total production. Dotted line is sum trend. From Statistics Denmark*[1]

[1] https://www.statistikbanken.dk/statbank5a/default.asp?w=1920

The statistics show that the Danish straw resource is abundant and relatively stabile. The average total production is almost 6 million metric ton per year with a slightly increasing trend during the last decade. The general variation is around ½ million metric ton +/- from year to year. However, the major drought in 2018 reduced straw production with almost 25% compared to the average production. Development of new straw uses and the related value networks must be able to endure such events as the frequency of drought – and floods, is very likely to increase in the coming years due to the accelerating climate crisis.

With the current levels of straw production and straw utilization in Denmark, there is very little risk that high value use (energy utilization and as input for animal production) will suffer major straw shortages in the near future. The large share of straw that is not collected act as a buffer as seen in 2018 where the amount of straw used for energy production and in animals husbandry is largely unaffected by the low production, whereas the amount of straw that is not collected is reduced with more than 66%. The uncollected straw is usually amended back into the soil for replenishment of soil organic matter pools and essential nutrients. Soil quality maintenance in the current agricultural systems is an ongoing struggle where continuous losses of soil organic matter are sought balanced out by amendment of organic matter. Despite substantial efforts in this regard, the soil carbon content is on a decline in many areas [1]. Due to complex soil dynamics and high rates of annual turnover of organic material in Danish soils, it may be difficult to see the direct effects of reduced straw amendment in a single year. Therefore, the current system with the large uncollected straw buffer is quite resilient and provides a robust framework for high value use at the current level of exploitation. If the amount of uncollected straw decrease – e.g. by reduced production or increased high value use, then the robustness of the overall straw collection and use networks may be expected to decrease. This would make e.g. energy production and livestock in the system that is dependent on straw for fodder and bedding more vulnerable during periods with reduced straw availability.

On the other hand, the uncollected straw resource present a large asset in the sustainable transition towards a more biobased economy and in the efforts taken to reduce the net level of anthropogenic greenhouse gas emissions. At all Danish universities there are ongoing activities related to increased and enhanced straw utilization. Biogas, Biofuels, fibers, waxes and construction materials are some of the products in the scope of the straw value networks of the future. Many stakeholders favor the opinion that further straw use may benefit society – not only economically, but also environmentally, and that the straw resource production may even to some extent increase with increased market demand[2].

However, removing straw for industrial use instead of amending it back into the soil will drain nutrients and organic matter from the soil system and disturb the before mentioned balance that is paramount to maintain healthy and productive soils. And soils are an essential part of the foundation of a biobased economy. However, with the proper compensation it may be possible to maintain soil quality and utilize straw value at the same time. Including catch-crops and cover-crops in the crop rotation will cost the farmer time and money but will benefit the soil by building and adding organic matter, retain nutrients, reduce erosion etc. The cover- and catch crops can even supply nutrients by N-fixation or deep soil retrieval if legumes or deep-root species are grown. There will also be residues from the cereal and rapeseed crops even if straw is collected, since roots, stubs and in-field losses (husk, dust, leaves etc.) will remain for soil nourishment. The share of collection may even be modified to further improve the soil quality balance. And finally, the residues from the straw value networks may be returned to the soil as well if they are in a suitable condition to do so. The residue will change with the utilization of the straw and both quality and

[2] https://ing.dk/artikel/radnende-halm-markerne-skal-ind-energiforsyningen-238538

quantity of this residue should be prioritized when designing new straw use systems. If these compensations are all included in the system development and proper use-re-use strategies are developed that secures recirculation of non-renewable nutrients it could be possible to increase straw value network development while maintaining soil health and quality[3].

So, if more straw should be used, the next question is obviously; *how and for what*?

At the University of Southern Denmark (SDU), it is argued that using approximately 2 mio metric ton currently uncollected straw in biogas is a good solution to produce 25 PJ non-fossil natural gas substitute and high quality residues for soil amendment[4]. And model results from SDU have indicated that anaerobic digestion of the straw will only reduce long term soil carbon content marginally compared to direct straw amendment [2]. The business organization Biogas Danmark assume a potential of biogas from straw of more than 40 PJ[5], and many other stakeholders also work with straw as a substrate for anaerobic digestion. In a recent Climate Footprint Assessment study at Aarhus University (AU) [3] it was found that around 10% straw of total substrate mass (assumed technical maximum) gave highly beneficial climate impact results compared to the reference systems.

At the same time as interest in straw for biogas is growing, the total biogas capacity in Denmark is also increasing. Production has grown from 3 PJ in 2003 to 11 PJ in 2017 [4] to 13.4 PJ in 2018 [5] to more than 25 PJ in 2020 and frozen policy projections[6] by the Danish Energy Authority project as much as 50 PJ in 2030 [6]. The development is illustrated in Figure 3.

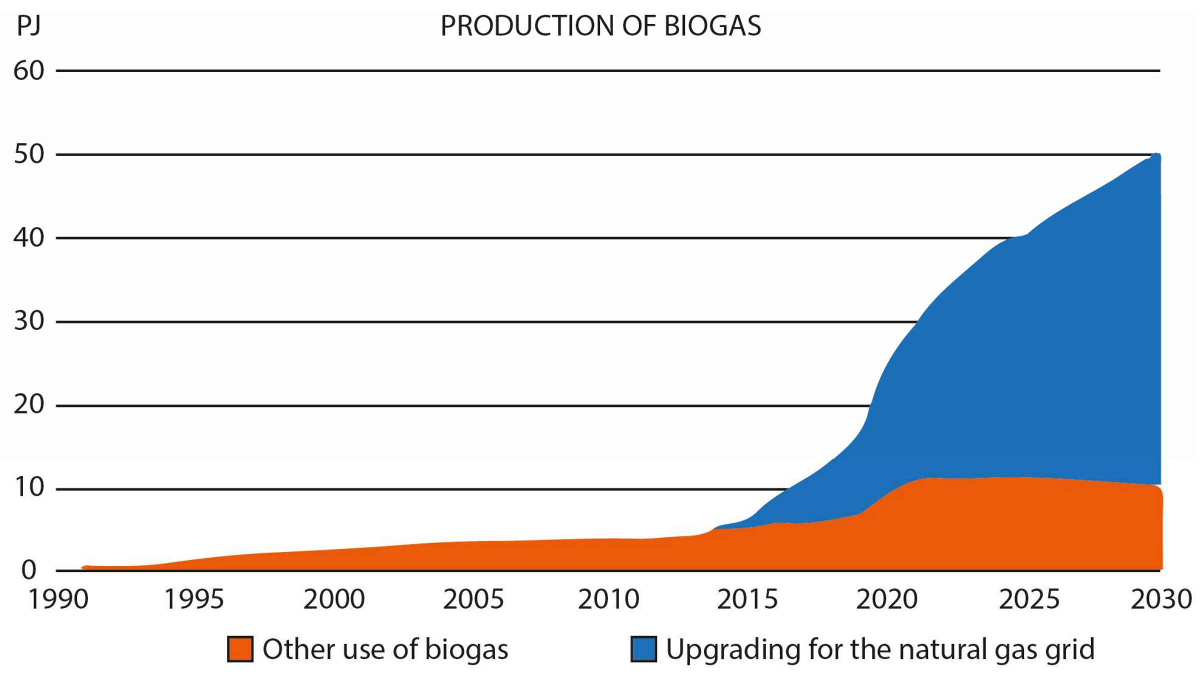


Figure 3: *Development of biogas production capacity in Denmark until 2020 + Frozen policy projections[7] towards 2030. Adapted from the publication "Klimastatus og –fremskrivning 2021" by the Danish Energy Authority* [6]

[3] https://ing.dk/artikel/forskere-mere-halm-energiforsyningen-vil-ikke-udpine-landbrugsjorden-238813
[4] https://ing.dk/artikel/radnende-halm-markerne-skal-ind-energiforsyningen-238538
[5] https://energinet.dk/-/media/1C6EE20C76C44768B91FADB3898B23D9.pdf
[6] Forecast studies that include effects of current political agreements but no further effects or projections, trends etc.

As indicated in the projections, future increases in biogas production capacity is primarily expected to be used to further replace natural gas in the natural gas grid. In 2020, 43 biogas plants supplied upgraded biogas to the natural gas grid[7] and before the end of 2021, more than 50 suppliers are expected[8]. The maximum technical capacity for supply of upgraded biogas to the Danish natural gas grid (current status of the grid) is expected to be in the range of 80 PJ annually [7].

Despite a large capacity in the natural gas grid for upgraded biogas, it is not widely believed that the Danish biogas production and injection into the natural gas grid will reach the technical limit of 80 PJ anytime soon. Instead, it is expected from both business, farmers, politicians and academics that levels around 52 PJ are both relevant and realistic. This amount relate to the fact that Danish biogas first and foremost is build and operated to manage animal manure, and manure can only be digested in an economical way by adding other biomass with a lower water content. Various types of industrial waste have been the major supplement so far, including substrates from dairies and slaughterhouses. The organic fraction of municipal household waste is a newer source, but according to the Danish Biogas business association (Biogas Danmark) these resources will only make it possible to treat 30 % of the manure in Denmark. There is a political agreement to pursue manure treatment in biogas plants much further than this and therefore maize silage and other energy crops are already added as well. However, this is only a temporary solution and will not be allowed after 2030. In a Danish context, straw is therefore more or less the only abundant substrate that may be used to facilitate increased manure treatment in biogas plants to meet political targets. According to Biogas Danmark, the Danish Parliament has granted subsidies for up to 52 PJ biogas and this can only be realized by co-digestion with around 1/3rd of the available straw resource of around 2.5 million metric ton [8].

The anaerobic digestion of manure and straw in a Danish setting, is thereby found to be mutually dependent on each other. As such, it is found reasonable to assume that 1/3rd of the available straw resource is politically and economically bound to manure treatment in biogas and therefore the climate impact of straw biogas should be included in the study. However, at the same time, the mutual dependence is also found to set a maximum limit on the expansion of economically viable straw biogas processes.

Straw biogas is a relatively new approach, and the current use of cereal straw in Danish biogas production is limited to around 0.5 PJ (2020 numbers) [3]. However, straw biogas is found to be a highly relevant new straw management technology and is included for assessment in the present work. For more information on the development and promotion of straw in biogas see is e.g. [2,3,9–13].

Another straw utilization pathway under development is thermal pyrolysis of straw for production of non-fossil energy and biochar. In Denmark, the pyrolysis based straw management platform is under rapid development by the company Stiesdal Fuel Technologies (SFT) that has provided substantial data for the present work. In addition to SFT, many other companies including AquaGreen, MASH Energy, Frichs Pyrolysis, Dall Energy and MOE are also contributing to the development of the Danish biomass pyrolysis platform. The organization Danish Agriculture and Food Council has a massive focus on the potentials of the technology and promotes SFT's SkyClean technology as a promising way to reduce the agricultural sectors Climate Footprint with as much as 50%[9]. The profound technical potential of biomass pyrolysis to mitigate

[7] https://energinet.dk/-/media/1C6EE20C76C44768B91FADB3898B23D9.pdf
[8] https://evida.dk/vvs/biogas-fylder-mere-og-mere-i-gasnettet/
[9] https://lf.dk/viden-om/klima/ny-teknologi-kan-halvere-landbrugets-klimaaftryk

climate change is supported by back-of-the-envelope type estimations from DTU[10] as well as from a wide range of scientists and researchers across multiple Danish universities[11] whereof the author of the current study is also part. In the beginning of 2021, the Danish government issued a proposal for a climate mitigation strategy plan for the Danish agricultural sector. This plan included emission abatements from pyrolysis of up to 2 mio. t CO_2-eq per year in 2030[12]. According to Stiesdal Fuel Technologies, the ambition of the company is to reach this target. Momentum is currently building fast and focus is increasing around thermal pyrolysis as a climate technology – and in Denmark, specifically around thermal pyrolysis of straw.

Like anaerobic digestion, pyrolysis is also an ancient technology known and used for thousands of years – and for many different purposes. However, until recently the commercial success and total penetration of the technology on industrial scale has been highly limited. This seem to be changing, and in Denmark – and many other countries, the awareness on biomass pyrolysis has increased substantially in the last 5 years. The potential of biomass pyrolysis as a new cross-sectorial climate mitigation initiative is heavily debated among researchers, business organizations and politicians but very few studies have conducted detailed investigations of the potential. In a Climate Footprint inspired process modelling study of Danish wheat straw pyrolysis from 2011, conducted by the same main author as the present work, it was found that the Climate Footprint varied substantially with the assumed climate benefit of the energy products but also that slow pyrolysis of cereal straw in all cases yielded carbon negative energy production. Under specific assumptions related to the energy product value, it was found possible to compare the results to a British study and under these conditions all the assessed pyrolysis processes had a negative Climate Footprint around -1 t CO_2-equivalent per t dry straw treated [14,15].

On this background, it is decided to include thermal pyrolysis of straw in the assessment alongside straw biogas and base this climate crisis oriented straw management analysis on these two technologies. The present study aim to develop new Climate Footprint models for state-of-the-art straw biogas and straw pyrolysis and use the new models to make an assessment of the combined potential for these technologies to be used in management of the available Danish straw resource and thereby thrive to determine this strategy's potential contribute to climate change mitigation.

[10] https://ing.dk/artikel/forskere-pyrolyse-biokoks-kan-halvere-udledning-landbruget-238546?utm_source=nyhedsbrev&utm_medium=email&utm_campaign=ing_daglig
[11] https://forskning.ruc.dk/da/publications/reduktion-af-landbrugets-klimaaftryk-ved-termisk-pyrolyse-af-afgr
[12] https://www.regeringen.dk/nyheder/2021/regeringen-viser-vejen-til-at-reducere-co2-udslippet-i-landbruget-med-7-1-mio-metric tons/

2 Goal and Scope

The goal of this work is to investigate the climate impact – and potential climate mitigation effect, of expanding the use of Danish straw for production of green methane for the natural gas grid, bio-oil and biochar in a near-2030 temporal setting. The focus of the study is on new utilization of straw in new state-of-the-art processing facilities, and the scope is formed – and limited, by the amount of straw that is currently plowed down directly after grain-harvest and which is therefore argued to be a potential resource for alternative uses.

The study is conducted in a Danish system context encompassing both the agricultural sector, the energy sector and the LULUCF/AFOLU[13] sector. The study is conducted to support planning processes and decision-making processes related to development of climate change mitigation strategies of Danish agriculture and energy production. The investigation will focus on the following main aspects:

- Climate Footprint studies of established reference systems: unused straw and untreated manure.
- Climate Footprint studies of straw pyrolysis and straw-manure co-digestion in modern plants.
- Estimate the Danish national scale climate change mitigation potential of using the available Danish straw resource for straw-based biogas production and straw pyrolysis compared to current soil amendment practice.
- Hotspot analysis and comprehensive sensitivity assessment to identify critical and sensitive aspects of the analysis as well as to provide insight and recommendations for further technical development and future implementation of the investigated systems
- Effect on results of modelling with a 20 year impact potential >< a 100 year impact potential related to the calculation of Global Warming Potential metrics

2.1 Scale of the assessment is guided by the straw resource

As described in the introduction, there is approximately 2.5 million metric ton of straw (mainly cereal straw) that is currently plowed directly into the soil after grain-harvest. It is this biomass resource that is investigated in the current work. As also mentioned in the introduction, the exact amount of this resource change from year to year. And so does the quality of the material. Timing of harvest, field operations and weather may influence how dry the material is and there will usually be a fraction of the material that is too wet for conventional logistics developed for dry material. This wet material is currently in focus from the expanding Danish biogas industry as it is found to be both economically viable and highly suitable for wet processes like anaerobic digestion. For use of straw in anaerobic digestion, there are substantial differences between wet and dry material [16]. The general situation may be characterized as follows:

- Dry straw is baled and stored in conventional straw logistic systems. Before digestion in the biogas plant, the materials is pre-treated in quite extensive processes primarily with mechanical cutting and grinding, but possibly also by chemical and thermochemical means [17]
- Wet straw is managed completely differently than the dry material. It is collected and cut or shredded before it is stacked in large outdoor piles. During the storage in these piles, the material degrades biologically to improve digestability in an open-air silage process. This approach has found to be effective and substantially reduce costs of pre-treatment and is therefore a highly desired option in the biogas industry.

[13] Land Use, Land Use Change and Forestry / Agriculture, Forestry and Other Land Use

Ideally, both of these processes should be included in the model. However, there is a lack of knowledge and data to model the wet system while the dry system has been described in high detail in at least two very recent studies [3,16]. The most important gaps of knowledge and data in regard to modelling the wet straw system, seem to relate to the effects of the large pile silage process on straw characteristics and the related emissions from this storage. In particular material loss/carbon loss and potential for CH_4 and N_2O emissions from these biomass stacks need to be more thoroughly analyzed before a consistent Climate Footprint analysis can be conducted. It is important to investigate this biogas straw system as soon as possible as this praxis is already developing, and the development should (also) be guided by quantitative sustainability assessment. However, procuring the required data and developing the required models is found to be outside the scope of the present work.

For remainder of the present work, the focus is therefore on relatively dry material that is handled with conventional straw logistics for baling, handling and storage, and it is assumed that the amount of this resource is approximately 2.5 million metric ton per year. This is equal to more or less the full amount of collectable straw that is currently plowed down. Achieving such high collection rates may not be possible every year, for reasons previously discussed. However, it may be expected that a steadily increased demand for dry straw towards 2030 is also going to increase the availability of it on the market.

In the present study, new management of an annual 2.5 million metric ton per year straw resource is investigated from the following strategy:

- 1/3rd of the available straw resource is used for co-digestion with manure in anaerobic digestion processes producing biogas that is upgraded for injection into the natural gas grid (see more on the amount needed for co-digestion in the introduction).
- The rest i.e. 2/3rd, of the available straw resource is converted in thermal pyrolysis systems producing primarily bio-oil and bio-char

2.2 General system boundaries of the reference and scenario systems

The study is a Climate Footprint assessment of two new straw-management systems compared to two established reference systems. The study is not a comparative study of straw biogas and straw pyrolysis, but instead a stacked analysis of the aggregated effect on implementing both technologies in future straw management. One of the main reasons why the two technologies are not directly compared is the political and economical straw-manure dependence that exist for future biogas plants but not for pyrolysis plants.

The reference for the straw biogas system include the established system for manure management as the straw biogas system is based on co-digestion with manure. The reference for the pyrolysis straw system does not include manure and manure is not included in the pyrolysis scenario either. It is technically possible to convert manure fibers in pyrolysis systems after separation and drying of the fibers. However, there are currently not sufficient knowledge and data published to model this system. The data and knowledge required for this task will be produced and published during the forthcoming years as part of the GUDP-funded research-project STABIL[14]. With the data from the STABIL-project it will be possible to make a more directly comparable assessment of anaerobic digestion and pyrolysis for management of both manure and straw, and it will also become possible to model the technical integration of the two technologies by assessing the effect of thermal pyrolysis of digestate fibers from biogas plants. However, in

[14] https://mst.dk/erhverv/groen-virksomhed/groent-udviklings-og-demonstrationsprogram-gudp/gudp-projekter/klimapuljen-2020/stabil/

the present work it is instead the aim to make a stacked assessment of the accumulated effect of straw biogas and straw pyrolysis in shared management of the straw resource. In the following, the two references and two scenarios are briefly described.

2.2.1 Straw reference for the pyrolysis scenario (REF-PYR)

The straw reference for the pyrolysis scenario (**Figure 4**) include only direct incorporation of the straw into the agricultural soil where the plants were grown. This is currently the case for a large share of the straw produced in Denmark as described in the introduction. This practice ensure a potential for a full use-re-use cycle of nutrients in the straw while supplying substantial amounts of organic matter and organic carbon to the soil microbial community. Main system input is fuel for field work.

Figure 4: *Straw reference for the pyrolysis scenario. Own work.*

2.2.2 Straw and manure reference for the biogas scenario (REF-BIO)

The straw and manure reference for the biogas scenario (**Figure 5**) also include the direct incorporation of the straw into the agricultural soil where the cereal plants were grown. However, this reference also include the common practice for manure management in a system without anaerobic digestion and production of biogas. The dominating practice is simply collection and storage of manure in tank structures until it is distributed on farm soil. As it was the case for the straw-only reference, this ensures a potential for a full use-re-use cycle of nutrients in the manure while supplying substantial amounts of organic matter and organic carbon to the soil microbial community. Main system input are also in this case fuel for fieldwork. However, tank-storage of manure lead to emissions of both ammonia and greenhouse gases, especially methane, and this is expected to have a substantial impact on the Climate Footprint of this system.

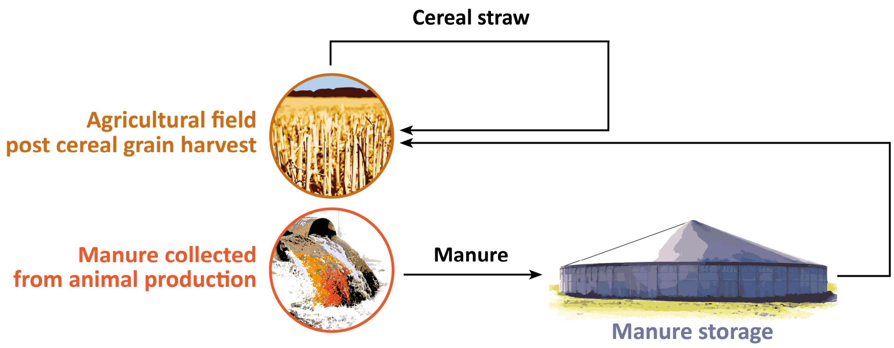


Figure 5: *Straw reference for the biogas scenario. Own work.*

2.2.3 Straw biogas scenario (BIO):

In the biogas scenario (**Figure 6**), the straw is utilized for production of green methane in a system comprising the following main elements:

- Straw baled and collected and stored
- Straw bales opened, cut and grinded
- Straw co-digested with animal manure in a state-of-the-art, industrial anaerobic digestion facility
- Biogas from digestion is upgraded to natural gas quality and injected into the gas-grid
- Digestate (residual material) from the biogas process is stored before being spread out on the same soil where the (cereal) crop was grown

There are several studies indicating that substantial pre-treatment and/or very long hydraulic retention times in the digestion tanks are required to obtain satisfactory biogas yields from straw application [17–19]. The model of the biogas system is based on a process design with a thermophilic biogas reactor, hydraulic retention times of 65+ days and gas upgrading based on amine scrubbers.

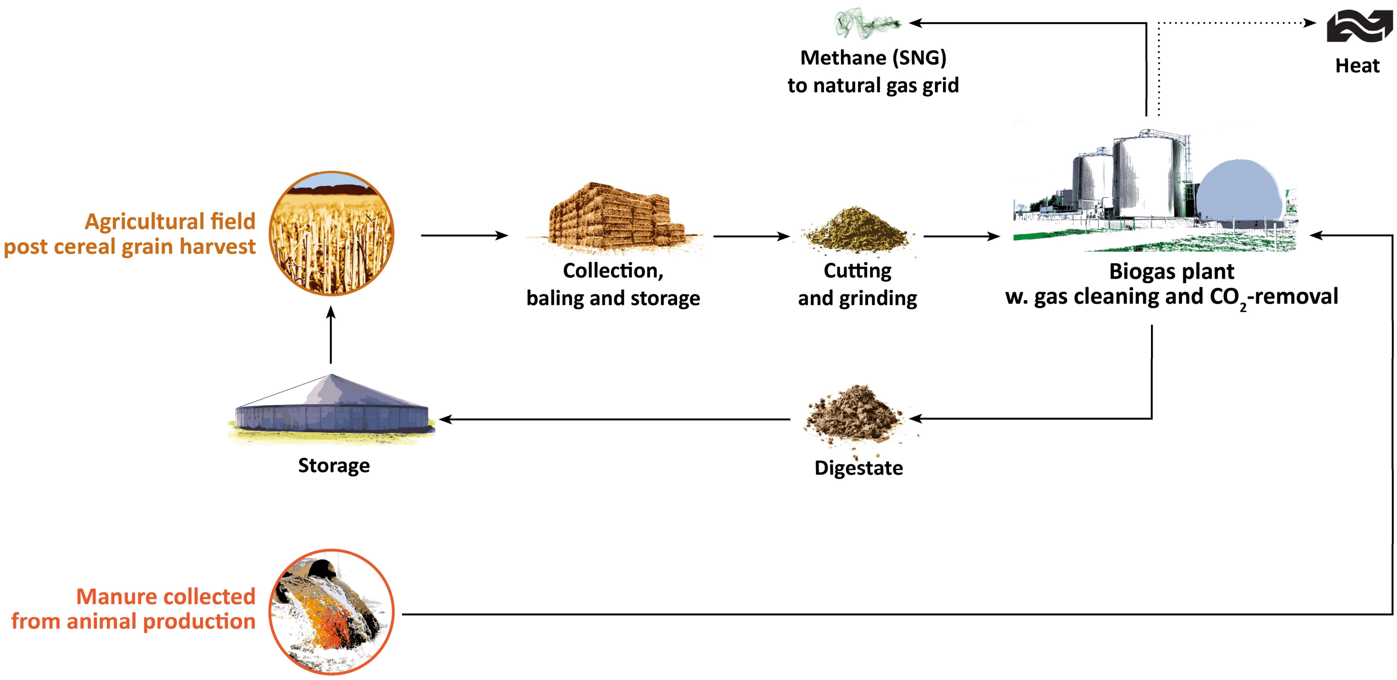


Figure 6. *Straw Biogas scenario. Own work.*

In modern, large scale biogas plants with amine scrubbers in the gas upgrading train, there may be an excess of relatively high temperature heat (120-150 °C [20]) even after heating of substrate and tank reactors. The size and value of this heat source will vary with size, configuration and climatic conditions. In the present model, an option for utilization of surplus heat for production of district heating is included. This is illustrated with the dotted line towards heat production.

2.2.4 Straw pyrolysis scenario:

In this scenario (**Figure 7**), the straw is utilized for production of biochar, bio-oil and heat is a system comprising the following main elements:

- Straw baled and collected and stored
- Straw cut and pelletized
- Straw pyrolysis in counter-current slow-pyrolysis plant at 500-600 °C
- Water-free bio-oil is collected from the pyrolysis vapors above water dew point and sold to an oil refinery or used directly to substitute heavy fuel oil in start-up or peak load application at heating plants or CHP plants.
- Residual gas is burned to produce heat for the pyrolysis process and for district heating
- Biochar is quenched with water and stored until it is being spread out on the same soil where the (cereal) crop was grown

There are currently, no full-scale commercial straw pyrolysis plants operating in Denmark or neighboring countries with the purpose to produce both bio-oil and char for soil amendment. There are however, several established commercial full-scale projects (in other countries) on straw pyrolysis for char production as well as for char and heat production combined. Generally, the mature projects on the market are relatively small scale, and most are based on screw conveyer pyrolysis technology as e.g. PyREG's different plants and BioGreen's SpiraJoule technology [21,22]. However, there are also a few examples of past projects on larger scale straw pyrolysis/ low-temperature thermal gasification for char and heat or char + combined heat and power (CHP) – as well as low temperature straw gasification for CHP. In Denmark the most well-known of these projects was Ørsted's Pyroneer project based on DTU KT/DFBT's Low-Temperature Circulating Fluidised Bed Gasification technology [23–25].

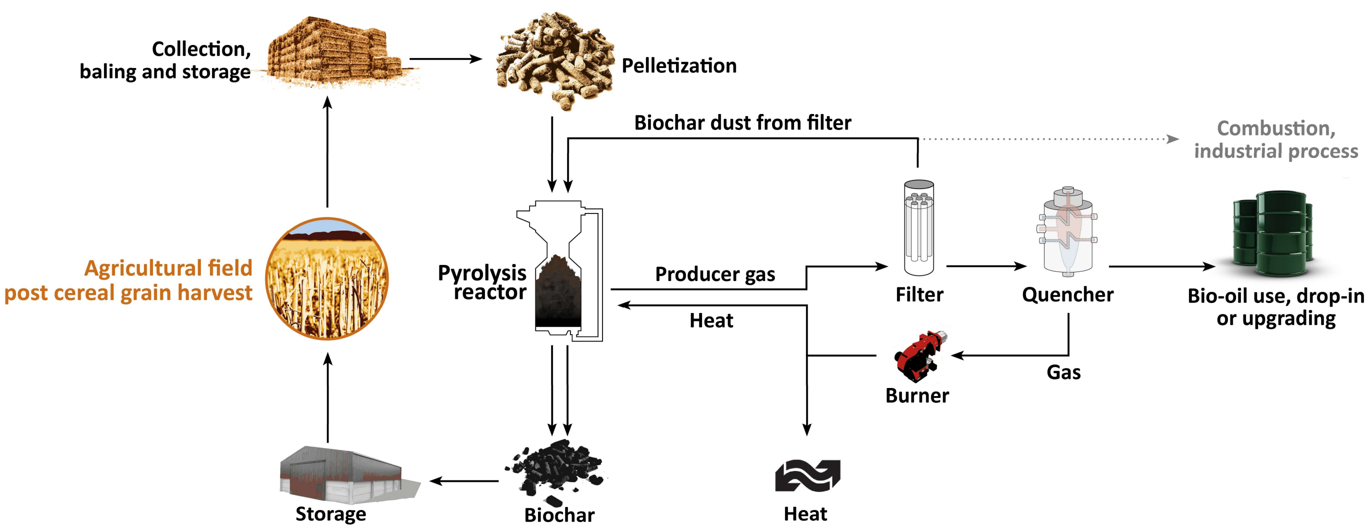


__Figure 7:__ Straw pyrolysis scenario. Own work based on input from SFT and DTU KT.

Currently, Stiesdal Fuel Technologies together with DTU Chemical Engineering, Siemens, Haldor Topsoe and a series of other stakeholders are developing and promoting a new technology for medium and large scale straw pyrolysis in a Danish context. The projects is called SkyClean and include 20 + MW pyrolysis reactors based on a counter-current slow-pyrolysis design developed by DTU KT. Two pilot-scale plants are in operation and the first full scale plant is expected in 2023 [26]. This is a technology in a very different scale than most pyrolysis plants and can be expected to profoundly change the market for biochar and pyrolysis based energy products. It is estimated - based on simple calculations and a recent biochar market survey by EBI – the European Biochar Industry Consortium, that just two of these 20 MW reactors would be able to double the total production of biochar in EU [27]. The SkyClean project and technology may therefore, quite rapidly, obtain a strong lead position on the European biomass pyrolysis and biochar market and for the purpose of this work, the assessed straw pyrolysis system is therefore based on input from SFT and DTU KT about this ongoing straw pyrolysis project.

On a national scale implementation of the technology, other end-uses than direct substitution of fuel oil for start-up and peak-load burners will be required. In larger scale application of the system, new value chains with drop-in at large oil refineries and/or centralized oil-upgrading as proposed by SFT in the SkyClean project will be required to increase demand and market size [26]. More on this issue in section 3.1.5.

As illustrated in **Figure 7**, most of the mass and energy flows of the system are unambiguous. However, for the oil there are several end-use scenarios as presented above. This is discussed further in section 3.1.5. In addition, the fate of the filter material can also vary with context/situation and characteristics of the material. The filter material from straw pyrolysis is most likely highly similar to the main biochar-product fraction and may simply be mixed into this fraction. This is the situation modelled in the present work. If the filter material contains elevated concentrations of PAHs[15] it may be reintroduced into the pyrolysis reactor for thermal degradation of the PAHs. If the material contain increased amounts of heavy metals it may be relevant to use in as fuel in industrial boilers, waste incinerators, cement kilns etc. This may be the case if the straw is mixed with sewage sludge or other material with high content of volatile heavy metals e.g. cadmium [28].

2.3 Functional unit (FU)

The analysis of the four systems is conducted based on the following, global functional unit:

> *Functional unit of study: Per metric ton of storage-dry, average composition straw collectable from a Danish agricultural field.*

All modelling is conducted based on this functional unit. For the remainder of this report, the functional unit is referred to as “per FU” or “per metric ton straw”.

The functional unit is thus based only on the collectable fraction of the straw in the field and the fraction of total straw that is removed in the biogas- and pyrolysis scenarios. The remaining fraction of the straw - as well as stubs, roots, husks etc., that is left on the field are not modeled, as they are the same in all systems. The study does not provide an assessment of Climate Footprint of grain production, only of straw management.

[15] Poly-cyclic Aromatic Hydrocarbons, a class of compounds of which several are toxic/carcinogenic

2.4 General approach, scope and global assumptions

The goal of the study is to compare the Climate Footprint of the above mentioned systems for straw management in a Danish setting. The study encompasses a life cycle oriented assessment of Global Warming Impact potential from the systems. Other environmental impacts e.g. eutrophication, toxicity impacts, resource depletion etc. are not included in the study. The study is thereby a Climate Footprint Assessment and not a full LCA. However, the study has been designed and conducted based on the guidelines in conventional Life Cycle Assessment studies as provided by ISO 14044.

The geographical boundaries of the investigated systems are set by the technical and natural systems involved in the post-harvest lifecycle of a Danish wheat straw resource as described above. The systems are developed in a Danish setting and only representative for Denmark and comparable countries with respect to climate, soil conditions, agricultural systems, energy systems etc.

The study has a near-future perspective towards 2030 where a fleet of full scale straw pyrolysis plants could be in continuous operation and anaerobic co-digestion of straw and manure has matured fully. The processes modelled in the study are modelled as state-of-the-art technology and the results are not representative for old biogas plants and pyrolysis plants. The study does not include infrastructure and end-of-life hereof is not included either. While the data used in the model only represent a relatively narrow span of technologies. the temporal scope of the work is set by the time horizon of the applied Global Warming Potential impact indicators and is thereby either 20 or 100 years. The time perspective may have a large influence on the global warming potential assessment – and thus the Climate Footprint, as all greenhouse gasses have different atmospheric lifetimes and radiative forcing intensities. The potential effect on climate change of a given green-house gas emission pulse here-and-now will thus vary with the type of gas emitted and the time horizon in which this effect is regarded. Using global warming potential as the climate metric for aggregating different greenhouse gases into CO_2-equivalent implies an assessment of the accumulated greenhouse gas effect of a given gas compared to CO_2 in the same time period. Applying only a short time perspective may underestimate the persistent nature of CO_2 which is paramount to acknowledge when aiming towards long term sustainable development. However, focusing only on the long time horizon may neglect the massive here-and-now effects of the greenhouse gas methane which may cause harmful effects on the short term as well as initiate positive feed-back loops in natural environments and push the climate closer to irreversible, self-enforcing tipping points as previously argued by – among others, the author of the present work[16].

The temporal scope also influence the carbon budget in the model – and the related impact on global warming potential of the different systems. To anchor this influence, the study include a distinction between biogenic carbon and fossil carbon. Biogenic carbon is carbon originating from CO_2 in the atmosphere that is taken up recently by the cereal plant and locked in the straw product or manure product. Uptake of carbon in this way - as well as release of this carbon back to the atmosphere as CO_2, is not included in the impact assessment. In the modelling, it is assumed that all carbon in the straw and manure products is biogenic carbon recently taken up from the atmosphere. Fossil CO_2 differs from biogenic CO_2 in this model, since the carbon stored in fossil fuels was not stored recently. Therefore, all fossil carbon emissions have impact on global warming potential and are contributing to the Climate Footprint of the relevant system.

[16] https://www.information.dk/indland/2021/04/greenpeace-husdyrproduktionens-store-klimabelastning-paa-kort-sigt-overset & https://ing.dk/artikel/kronik-vi-undervurderer-temperatur-klimaeffekter-metanudledninger-242877

Also, when biogenic carbon is emitted to the atmosphere as biogenic methane instead of CO_2 it has a substantial impact. The impact of biogenic methane is different than the impact from fossil methane as the degradation product of methane - CO_2, only has impact in the assessment if the carbon is of fossil origin. When biogenic carbon is stored beyond the temporal scope of the assessment (20 or 100 years) the carbon also has impact. In this case, the impact is negative and the carbon storage is modelled as a permanent.

As mentioned, this study does not include an assessment of the impact of the material and energy cost of infrastructure requirements. Ideally, cost of establishing and maintaining the different technological systems and buildings as well as grid infrastructure e.g. roads, district heating grids, electricity grids, natural gas grid and fuel distribution systems should be in the modelling. The main reason to omit these aspects is a lack of sufficiently high quality data combined with a limited expected impact below the threshold of the cut-off criteria of the study. In many other studies of this type, machinery and infrastructure costs are also ignored as they are often expected to have a negligible impact in the analysis of energy systems [29]. A recommendation to conduct a more thorough investigation of these aspects are, however, included in the last chapter of the report. When including infrastructure, it is important to be aware of the temporal scope of the study and the difference between long term and short term effects. Establishing new infrastructure is usually a concentrated effort with a relatively short term impact that is commonly divided out on a long horizon by cutting it up into FU-size pieces. However, if the study include also a short term impact assessment and the lifetime of the infrastructure is longer than this scope it may become relevant to scale the impact of infrastructure to the relevant scope.

System processes that are similar or assumed similar between all three systems are not modelled. This approach reduces complexity of the model development and analysis as well as the total level of data-related uncertainty.

2.4.1 Data quality requirements

Data for the study is collected from several different sources. For the data to be sufficient quality for the work it need to comply with the following:

- Experimental results or modelling results from SFT or close partners on the counter-current pyrolysis technology
- peer-reviewed scientific studies or technical expert reports on pyrolysis, biogas, straw management and manure systems preferably in a Danish context
- EcoInvent 3.7.1 data on marginal processes
- Average data from the Easetech official 2020-01 v2 database and other data-bases only for highly generic processes and background processes with low impact
- Technology related data need to be very recent – max 5 years, while data on background processes, generic processes and the established reference systems may be older

2.4.2 Cut-off criteria

Cut-off criteria are set as follows: All inputs and outputs to a (unit) process shall be included in the calculation, for which data are available. In case of insufficient input data or data gaps for a unit process, materials and processes can be omitted, if the process contributes with less than 1% to the total system climate impact, and all excluded processes of the given category do not sum up to more than 5% of total climate impact of the assessed system. For standard comparative studies, cut-off criteria have to comply on energy- and mass level as well as on impact level. However, as this is not a standard comparative study, the criteria is only set on impact level.

Negligible flows that are identified in the LCIA phase are not omitted from the results unless there are good arguments to do so within the sensitivity assessment and/or data quality analysis.

2.4.3 Data collection procedures and validation of data

Main primary sources of data for this study includes:

- Input on SFT / DTU KT 20 MW counter current straw pyrolysis plant in:
  - COWI-project report and feasibility study, autumn 2020 via DTU KT [26]
  - Socio-economic analysis by Ea Energianalyse, primo 2021 [30]
  - 20 MW plant electricity consumption by Dall Energy, primo 2021 [26]
- Input on straw pellet production from KAHL pellet factory, by Stiesdal primo 2021 [26]
- Additional information about plant inputs and emissions by Stiesdal/DTU KT, primo 2021 [26]

Main secondary data sources for this study includes:

- A study by Aarhus University on Climate Footprint of different biogas-systems [3]
- A study by the Danish Technological Institute Climate Footprint of different biogas-systems [16]
- The National Inventory Emission accounting report version 2021 [31]

Main tertiary data sources for this study includes:

- Easetech official 2020-01 v2 database [32,33]
- BioGrace II standard values database and modelling tool [34]
- Phyllis2 database [35]
- EcoInvent database 3.7.1 [36]

Data quality is primarily assessed through the sensitivity assessment while both data quality and data use procedures and calculations are indirectly validated by comparing overall results to results from other comparable studies.

2.4.4 Allocation procedures

In accordance with standard LCA recommendations, allocation procedures related to the main processes are accounted for by “avoided production” with the inherent assumption that all products and services provided out of the system will replace a broadly representative and comparative product and service somewhere else on the market and that the avoided impact from this product or service is accounted for as a benefit to the relevant system [37,38]. In the current study, this is relevant for energy products out of the system and differences in nutrient recovery rates. All substituted products as well as most background processes are modelled with data from Ecoinvent databse 3.7.1 *Substitution, consequential, long-term data*. This approach reduce the risk of inconsistent allocation procedures. However, even with this database where may be strange allocations in the background data. The significance of these processes on the overall results and the conclusions is expected to be highly limited in most cases. However, especially for the extreme-end cases on energy product use in the sensitivity assessment, the large impact of single data points may be under influence of inconsistent allocations in the background processes.

2.4.5 Life Cycle Impact Assessment using a single impact indicator

Impact assessment include only climate change modelled by Global Warming Potential characterization factors, and assessment is based on IPCC2013 Impact Assessment method with Carbon-Climate Feedback effects in a 20 years perspective as well as a 100 years perspective.

***Table 1**: Characterization factors for main greenhouse gases in the IPCC 2013 LCIA method embedded in Easetech v. 3.3.4.*

	IPCC 2013, climate change, GWP 100a with LT_with ccfb*	IPCC 2013, climate change, GWP 20a with LT_with ccfb*
Unit	kg CO_2-equ	kg CO_2-equ
Carbon dioxide, CO_2	1	1
Dinitrogen monoxide, N_2O	298	268
Methane, CH_4 (fossil / non-fossil)	34 / 28.5	86 / 83.9

* ccfb: climate-carbon feedback

The impact assessment method is integrated with the modeling software; Easetech [32] version 3.3.4 with the Easetech official 2020-01 v2 database. Easetech (http://www.easetech.dk) is a substance flow-based LCA software developed and maintained by DTU Environmental Engineering.

The study is conducted with a single impact indicator (GWP) and is as such not a full LCA of the investigated systems. The main rationale for limiting the study to global warming potential is a lack of sufficiently high quality data and in-depth knowledge related to especially soil CN dynamics, soil enhancement effects and storage emissions. It is recommended to expand the work at a later stage with additional indicators particularly eutrophication, acidification and ecotox that are highly relevant in agricultural systems and settings.

The impact assessment method *IPCC 2013, climate change, GWP100a/20a with LT_with ccfb* was selected due to its updated characterization factors for methane and nitrous oxide, inclusion of differences in impact of biogenic and fossil methane and focus on the influence of the temporal scope and the long-term effects.

2.4.6 Data quality assessment

Only the pyrolysis plant operation is modelled with primary data and the study thus has an inconsistency in the level of detail and data quality. However, the reference system is simple and well described and the biogas scenario has recently been very thoroughly described in an LCA from Aarhus University [3]. Data of all systems are representative for now-and-near-future state-of-the-art systems in a Danish context. The available data is deemed suitable to reflect the physical reality of the assessed systems to a satisfactory level related to the goal and scope of the work. The absence of certain data may be expected to increase overall uncertainty of the results and conclusions. These deficiencies were described in the previous sections and relate a lot to soil dynamics and -emissions. In addition, it is currently not decided where to locate the first SFT 20 MW straw pyrolysis plant, and the penetration of straw in biogas plants is still limited. For these reasons any assumptions on transport distances may prove to be unrepresentative for a mature system. However, as transport has been found to have a limited sensitivity in the analysis, the overall data quality of the study is found to be high and adequate for the goal and scope.

Three databases are used in the modelling:

- BioGrace II standard values database and modelling tool [34]
    - Used for alternative values on fertilizer climate impact and standard values on fuel properties
- Phyllis2 database [35]
    - Used for alternative straw composition based on average data
- Easetech official 2020-01 v2 database for the following 4 processes, all by Roberto Turconi from 2015 based on his work published in 2014 [39]:
    - *Heat from Biogas, Denmark 2010*.
    - *Heat from straw, Denmark 2010*.
    - *Combustion of natural gas, Denmark 2010*
    - *Combustion of residual oil, Denmark 2010.*
- EcoInvent 3.7.1 (Substitution, consequential, long-term) for all the remaining processes.

This use of databases is considered reasonable for the scope of the project and overall the data quality is found sufficient for the purpose of the work. The sensitivity assessment indicate large sensitivity on several parameters, but this is mainly related to assumptions and the influence of context on specific parameters and less so to data quality.

2.4.7 Analysis of material and energy flows to justify their inclusion or exclusion

An early iteration estimation of the impact of infrastructure was conducted with a generic dataset to illuminate the potential importance. The initial assessment indicated that the climate cost of infrastructure and maintenance would be very limited. All individual processes was below 1% and the total impact was found to be in the magnitude of 1-5 % of total results.

Minor chemical/material inputs related to e.g. baling (plastic string), the biogas process (pH control, anti-foaming agents), biogas upgrading (amine-substrate) or pyrolysis (catalysts for exhaust gas cleaning) have not been included in the study. The impact of such input in unresolved and it has not been possible to verify the expectation and assumption that the potential impact from these input is below the cut-off criteria.

NH3-impact omitted. A recent study from AU on sustainable Biogas found a < 15% increase in NH_3 emissions from systems with anaerobic digestion compared to systems without. NH_3 emitted to air may be converter into N_2O and thus impact Climate Footprint of the system. Data for modelling these aspects in the current work have not been available. It was therefore investigated how large the impact of NH_3 emissions were on the climate impact in the referred work from AU. By assuming 1% conversion of NH_3-N to N_2O-N it was found that the potential impact from these processes amounted to 0.2-0.8% of total impact (GWP 100 years). As this is below the cut-off criteria of the present work it was found reasonable to omit this potential impact in the biogas scenario from the study.

NO_3-leaching and NOx emissions are not included either. These emissions have no climate impact according to the applied LCIA method.

Soil enhancement effects are also not included. This is not a single effect, but many different effects that vary with the substrate, soil type, agricultural system and crop type. In addition, these effects may influence each other. Assessing these effects is beyond the scope of the present work. However, these effects may have significant impact – also on climate mitigation potential, and should be thoroughly investigated in future studies. Some of the effects will be addressed for selected substrates in the STABIL research project in the forthcoming years[17].

Finally, impact on crop-production is also not included. This has not been found possible to model in a generic Danish context, and no reasonable conservative estimate has been found relevant except for an assumption about no impact across the different systems. With the current functional unit (omitting the grain-system), crop-production is also not expected to influence CFA results directly. However, a dynamic modelling with consecutive periods and year-to-year effects could be relevant. Similarly, it could be interesting to investigate the effect of yield-influence assumptions related to the different management systems and the effect on the national scale resource (and thus potentials) if there were sufficiently robust data.

[17] https://mst.dk/erhverv/groen-virksomhed/groent-udviklings-og-demonstrationsprogram-gudp/gudp-projekter/klimapuljen-2020/stabil/

3 Development of Life Cycle Inventory (LCI)

In this section, identified assumptions and key parameters are presented. Additional data and parameters may be found in the detailed model overviews in Appendix 1 -> Appendix 3.

3.1 Main assumptions related to LCI

3.1.1 Main assumptions - Straw yield, handling and field operations

A straw yield of 4.1 t straw incl. moisture per hectare is used in the study based on an average of statistical data[18] for yield of winter wheat in Denmark from 2006 to 2019.

All processes about collection, baling, storage and transportation of straw is assumed similar for the biogas- and pyrolysis scenarios while they are not included in the reference with direct application of straw to the soil. With this approach, it is also assumed that the straw is stored in similar periods for the two scenarios which may not always be the case. The processes are assumed to take place around the same time of year.

The only effects on the collected straw from transport and storage is assumed to be a total 2% loss, averagely distributed on the mass. This loss is assumed converted to biogenic CO_2 and water without further environmental impact. Similarly, 1% of average material weight and composition is assumed lost in straw pretreatment in the biogas (cutting and grinding) and the pyrolysis (cutting, grinding and palletization) scenarios. This loss is also assumed converted to biogenic CO_2 and water without further environmental impact.

It is assumed that the soil is managed similarly – and with the same machines, in the different systems except for differences related to distribution of fertilizers and related substrates as follows:

- Pyrolysis char is distributed with a 30% moisture content, with a lime spreader and harrowed into the field before it dries up
- Straw is harrowed down directly
- Biogas digestate as well as manure is distributed as manure

The crop-production systems in which the straw management is nested are all expected to need additional nutrient supply in addition to the nutrient amended via the straw or straw-based digestate or biochar. The machine operations in the fields related to providing these extra nutrients are assumed to be comparable in all systems.

3.1.2 Main assumptions - Fertilizer value, soil enhancement effects, soil based GHG emissions and carbon sequestration

There is nutrient recovery in all modelled systems, but also differences in the recovery rates that make it important to include. In both the biogas and the pyrolysis scenario there are losses of straw and in the pyrolysis process there are also losses of substantial amounts of N and a minor fraction of P. Therefore the impact of nutrient recycling of all three macro nutrients is included in the assessment.

Recovery of fertilizer value – e.g. recovery of nitrogen by straw amendment vs. loss of nitrogen in straw pyrolysis, is included in the modelling as avoided production of new, commercial fertilizers. Avoided

[18] https://www.statistikbanken.dk/statbank5a/SelectVarVal/saveselections.asp

production of N, P and K fertilizer is modeled with marginal fertilizer values from the Ecoinvent 3.7.1 database.

P and K content in straw, digestate and biochar is assumed to replace commercial P and K fertilizer 1 : 1 while N content in straw, digestate and biochar is assumed to replace commercial N fertilizer 1 : 0.4. Current Danish legislation has a definition of utilization-percentages for nitrogen contend in different organic substrates and residues. Straw, biochar and digested straw is expected to be classified as "other organic substrate" with an N-utilization-percentage of 40[19]. In this approach is also assumed that the average farmer will try to maximize nitrogen-application to his crops within the legislative framework.

The N-utilization factor combined with losses of N in the pyrolysis process lead to differences in total quantity as well as quality of the N-sources supplied to soil in the three systems. The more N the farmer can apply as discount-N in the form of digestate, biomass or biochar, the more total-N is the farmer allowed to apply. Despite these differences among the systems, N_2O emissions from soil conversion of N to N_2O are omitted from the modelling. The two main reasons for this is; 1) the variations in N supply quantity and quality among the systems are decimal compared to total N use in modern, Danish agriculture[20] and 2) representative differences in N_2O emissions are notoriously problematic to measure and quantify due to massive variations and the substantial influence of very local effects [40]. However, this is potentially a severe assumption and simplification since the different forms of N would most likely lead to different emissions to air as well as to water compartments via leaching. The dynamics of different N sources and the related emissions to air and water bodies is a complex and highly context-depended system of effects that is not easily generalized across different soil types and agricultural practice. As there are currently no suitable data on general differences in N_2O emissions from application of nitrogen as straw >< digested straw >< mineral fertilizer + straw biochar, this is omitted from the analysis and justified with the assumptions above. However, to test the potential impact of these assumptions, the potential effect of the 40% utilization factor and the difference in total N-supply on N_2O emissions is addressed in the sensitivity assessment.

No carbon-based GHG emissions are included from the soil either. This is based on the following:

- All carbon released from the soil is assumed to be in the form of biogenic CO_2. Some emissions of CH_4 can be expected from soil amendment of biogas digestate and manure and in wet climate perhaps also from straw amendment. However, the impact on the total system results is expected to be very small.
- Potential differences in priming effect / retarding effect on soil carbon and nitrogen dynamics are not included in the assessment due to a lack of robust and consistent data
- It is assumed that mechanical soil management in all systems induce the same turnover of the residual soil carbon pool.

Biochar has in several studies been found to reduce N_2O emissions from soil [41]. However, the effect has also been found to vary heavily and depend on many parameters. To test the potential importance of this aspect a preliminary calculations has been conducted assuming a quite conservative 10% reduction in average N_2O soil emission levels from application of 15 t biochar/ha (biochar from herbaceous biomass (e.g. straw) has been found to decrease N_2O emission levels substantially with a 50% average effect across several studies [41]). Biochar from 1 metric ton straw (functional unit of this study) corresponds to 15 t/ha

[19] https://www.retsinformation.dk/eli/lta/2020/1166

[20] https://lbst.dk/fileadmin/user_upload/NaturErhverv/Filer/Landbrug/Goedningsregnskab/Vejledning_om_goedsknings-_og_harmoniregler_2020_2021.pdf

at 0.02 ha. National emission levels from N_2O are 1.5 t CO_2-equ/ha across all agricultural areas [42]. Assuming the effect last for 5 years, the accumulated effect of a 10% reduction with 15 t biochar/ha is 15 kg CO_2-equ/metric ton straw. This is expected to be decimal compared to the effect of e.g. carbon sequestration of the biochar and due to substantial uncertainties and a lack of representative data this effect is not included in the study.

Similarly, biochar have been found to have other soil enhancement effects that may indirectly influence the CFA related to e.g.

- increased water- and nutrient retention, increased soil drainage during flooding, impact on soil biota and increased cation exchange capacity that may all in some cases increase yield [43–46]
- Prolonged root growth, especially in sandy soils that may increase yield [47,48]
- Cascade use of biochar to adsorb nutrients in water purification prior to soil amendment [49]
- decreased soil density and thereby reduced drag energy requirements that may reduce field work energy input [45,50].

Similarly, there is known to be soil enhancement effects related to amendment of straw and digestate. However, as all these effects are highly context dependent and vary substantially – also between the three substrates, and no robust and representative data set has been available they are not included in this work.

Carbon persisting in the soil beyond the temporal scope of the study is considered sequestered and accounted for as a carbon sink. Data for conversion of carbon amended as straw, digestate or biochar to the soil is based on C-tool modelling and an assumption that digested straw has soil carbon dynamics comparable to manure [51]. Results for a 20 year and 100 year time horizon are presented in **Table 2**.

Table 2: *Values applied for carbon mineralization (conversion to CO_2) as a result of assessment time horizon. Developed in C-tool by Haftor Ægir Sigurjonsson* [51]

	Time horizon	Carbon mineralization
	Years	%
Biochar	100	15
	20	6
Straw	100	98
	20	87
Digestate (as manure) and manure	100	97
	20	78

3.1.3 Main assumptions – use and production of electricity and district heating

Use and avoided production of electricity and heat is included in the model. This is not simple to model. The Danish energy systems are in transition – for policy reasons. This makes it difficult to foresee how the system will change and develop. The actual consequences of using and producing electricity and heat are uncertain. The study is conducted as a consequential LCA, since the purpose of the study is to assess the consequences of a change in demand for a new straw management service. For this reason, wherever possible only marginal suppliers are considered in the system. In LCA in general, it is a recommended approach to replace the same source of energy as is used [52]. The background energy system can be expected to largely influence the carbon intensity of the electricity and heat used and produced in the different systems. As the purpose of the study is decision support related to decisions that have long-term implications, the relevant marginal supply is the long-term marginal supply, sometimes referred to as the 'build-marginal', i.e. the technology of the capacity to be installed next [53]. Build marginal technology for Danish production of electricity has been thoroughly investigated in a recent study by Muñoz and Weidema (2021) the long-term marginal for Danish electricity production including imports from neighboring countries was examined and identified [54]. This marginal is used in the present work in the form showed in **Table 3**.

A long-term marginal for district heating production is also included in the table based on recent projections from the Danish Energy Authority [55]. In a frozen policy forecast on production of district heating in Denmark in 2030, the Danish Energy authority foresee a mix dominated by 14% heat from waste incineration, 39% heat from biomass (mainly wood) and 37% heat from heat pumps. Average COP of the electric heat production is assumed to be 2550 MW/700 MW = 3.6. In addition, the heat mix will contain approximately 1% heat from natural gas, 4% from recovered industrial excess heat (mainly from cooling stations), 1% from electrical boilers, 3% from biogas and 3% heat from direct solar heat capture. Heat from waste incineration is a byproduct from waste management and this is difficult to substitute in a Danish context. Similarly, the recovery and use of residual heat from industrial cooling is also a byproduct and also not feasible to substitute on a general level. Scaling the residual heat sources to fill the gap, the long term built district heating marginal used in the study is composed as shown in **Table 3**.

Table 3: *Composition of marginal electricity production and marginal district heating production used in the study*

Electricity production incl. import		**District heating production**	
Energy source [54]	Ecoinvent 3.7.1 process model	Energy source [55]	Ecoinvent 3.7.1 process model (EI) or Easetech 2020 process model (ET)
0.4% coal	electricity, high voltage,electricity production, hard coal,RoW	46.2% Heat pumps	Marginal electricity (see column to the left)
23.6% gas	electricity, high voltage,electricity production, natural gas, combined cycle power plant,RoW	0.8% Heat boilers	Marginal electricity (see column to the left)
45.4% wind	electricity, high voltage,electricity production, wind, >3MW turbine, onshore,DK	43.6% Wood	heat, district or industrial, other than natural gas,heat production, softwood chips from forest, at furnace 5000kW, state-of-the-art 2014,RoW (EI)
20.7% biofuels	electricity, high voltage,electricity production, wood, future,GLO		
3% nuclear	electricity, high voltage,electricity production, nuclear, pressure water reactor,RoW	3.8% Biogas	Heat from biogas, DK 2010 (ET)
2.6% hydropower	electricity, high voltage,electricity production, hydro, pumped storage,RoW	0.6% Natural gas	natural gas, high pressure,market for natural gas, high pressure,DK (EI) & Combustion of natural gas, DK 2010 (ET)
4.4% photovoltaic	electricity, low voltage,electricity production, photovoltaic, 570kWp open ground installation, multi-Si,RoW	4.8% Straw	Heat from straw, DK 2010 (ET)

There are significant uncertainties related to the development of the future energy system and to the determination of the build marginal. As this may be expected to have substantial influence on the results, these aspects are included in the sensitivity analysis by comparing the near future models with models using a commonly applied marginal for present Denmark electricity and heat production – coal [56–58], as well as fully renewable heat and power production capacity based on off-shore wind and heat pumps (also modelled as off-shore wind). More information about these alternatives in section 6.1.

3.1.4 Main assumptions – Straw-manure co-digestion in Biogas

In this scenario, straw is co-digested with manure in a state-of-the-art biogas plant with amine scrubbers in the biogas upgrading train. This result in low methane losses but high process heat requirements [20].

1 metric ton of straw is co-digested with 5.64 t of manure. This amount fits the approximate 15/85 ratio for straw/manure on wet basis used in recent recommendations from Aarhus University [59]. Digestion of the manure and straw is modelled in individual models even though it in reality is a co-digestion process.

The manure modelled in this scenario is assumed to be a 50/50 mixture of cattle and pig manure. The reason behind this approach is that recent estimations about the 2030 manure resource in Denmark predict an approximate 50/50 distribution between the two manure types [59].

Manure is assumed to be transported directly from the stables to the biogas plant without intermediate storage. This is a simplification that may overestimate the climate benefit of manure digestion. However, the impact is expected to be relatively small as the retention time and temperature in the intermediate storage will be much lower than retention time and temperature in the biogas plant.

It is expected that the anaerobic digestion will make the digestate biologically active and this will lead to emissions of CO_2, CH_4 and N_2O during storage and potentially also during subsequent in-field use [3]. However, due to the assumptions described in section 3.1.2 only emissions from storage are included in the modelling. 6.02 g CH_4/kg VS is used for both straw and manure after digestion. For untreated manure, the used value is 14.91 g CH_4/kg VS for cattle manure and 40.05 g CH_4/kg VS for pig manure [16]. These emissions are expected to have significant impact on the systems Climate Footprint and is therefore investigated further in the sensitivity assessment.

The only greenhouse gas that is modelled with impact from storage of manure and digestate is methane. Previous studies have shown large variations in the emissions of N_2O and it has been found that implementing anaerobic digestion of manure may both decrease and increase the net emission of N_2O from storage and use of the digested substrate compared to the untreated material [60,61]. As previously mentioned, only storage emissions are modelled and emissions related to in-field use are omitted. In-field emissions are small and often not even included/recorded [31,61].

CO_2 is also emitted during storage, but the CO_2 is biogenic and the losses have no impact on the system Climate Footprint. However, CO_2 emissions are accounted for at losses that influence the downstream carbon flows.

No losses are accounted for during transport and distribution of digestate.

Only mechanical pretreatment – consisting of cutting and grinding, of the straw is included in the model. An average retention time of 60-65 days is assumed to yield a methane production of 286 L CH_4/kg VS from this straw, as well as 250 L CH_4/kg VS in the cattle manure and 345 L CH_4/kg VS in the pig manure [3,18]. Produced biogas is assumed to consist only of 60 vol% methane and 40 vol% CO_2.

0.5% of the produced methane is assumed lost/leaked during the digestion and the subsequent upgrading and on-site storage of the digested biomass. In a comprehensive, experimental study from 2019 it was found that there was a loss/leakage of 1.7% of production as weighted average across 13 agricultural biogas plants in Denmark with optimum performance of 0.4% for a single new, state-of-the-art plant [62]. A recent study from 2021 found an average leak of 2.5% of produced methane across a range of different biogas plants [63]. A net leak/loss of 0.5% is in this study assumed to be representative for the average new constructions towards 2030. As this is expected to be a highly influential parameter, it is also included in the sensitivity assessment where a representative future worst case with a 1% average loss/leak is modeled. 1 % total leakage is the current target of the Danish biogas industry and to avoid economical penalties, the biogas business has to comply with this target in the near future [3]. A new-plant best case model with 0.4% loss/leak is also included for assessment of the currently optimal conditions [62].

Manure energy content (higher heating value of dry matter) is assumed to be 6.2 MJ/kg TS [64].

Energy and utility input for the biogas process encompass primarily electricity for pumping, conveying, mixing etc. as well as heat for maintaining a sufficient temperature in the digestion tanks and for the amine scrubber where CO_2 is separated from CH_4. The biogas plant is assumed to have a heat exchanger that cools digestate leaving the plant while heating material going into the plant. This will also reduce the biological activity of the digestate and reduce emissions during storage.

Total power consumption is assumed to be 6.5 kWh per metric ton material treated including biogas upgrading. This is based on site data from 16 different biogas plants [3]. Same heat requirement and electricity requirement in the biogas process per metric ton of material assumed for straw and manure.

Heat requirements are in this case composed of i) energy for increasing the temperature of inlet material, ii) energy for maintaining the temperature in the tank throughout the digestion procedure and iii) process heat for amine scrubbing. Initial heating of a thermophilic process has previously been estimated to 15.4 kWh/metric ton biomass [3]. Energy required for maintaining the reactor temperature depend substantially on reactor design. In a large scale plant fed with almost 3000 metric ton of biomass per day and constructed with high, state-of-the-art insulated steel reactors and 65 days retention time, this loss has recently been estimated to be around 426 kW [65]. This corresponds roughly to 3.5 kWh per metric ton biomass. Finally, there is the process heat required for amine scrubbing. This has been estimated by DGC to be 0.55 kWh/m^3 biogas which correspond very well with the findings of Vo et al (2018) of approximately 1 kWh per m^3 methane produced [20,66]. For the present case, the amine scrubber will require approximately 225.8 kWh heat per metric ton straw and 15.5 kWh heat per metric ton manure. With 5.7 metric ton manure per metric ton straw, the total heat requirement for the amine scrubbers is estimated to 314 kWh heat per FU (1 metric ton straw and 5.6 metric ton manure) The heat for the scrubbers has to be relatively high temperatures around 120-150 C. In this study, the energy requirement for the amine scrubbing is met by converting 10% of the produced methane which is simply subtracted from production in the model. However, according to Torben Kvist (2018) around 50% of the heat supplied to the amine scrubber can be recovered and used for low temperature purposes including heating incoming biomass and maintaining tank temperature [20]. In the present work, the large production of biogas per t of straw leads to an excess of heat from the amine scrubbing of the straw-related biogas compared to the energy required to heat the material in the biogas process and maintain the temperature during the digestion. With 50% recovery of heat from the scrubbers, there is around 0.34 GJ excess low temperature heat available per metric ton straw. However, due to the low production of biogas per metric ton manure, this part of the system suffer a deficit of heat from the scrubbers. The deficit is around 0.04 GJ per metric ton manure. This deficit is covered with the excess heat from scrubbing of the straw based biogas. Based on the assumption of 5.7 t manure per metric ton straw, there is an overall excess amount of low temperature heat from the combined process of 0.11 GJ FU. This excess heat is assumed sold for district heating and substitute marginal district heating.

In the model, biogas is used to provide high temperature process heat. Under real, market conditions the grid-connected biogas plants will often use natural gas for heating instead to be able to maximize the production of biogas-based methane to the grid as this product has a higher economical value than natural gas [3]. The difference may be expected to slightly underestimate emissions from the biogas plant in the model as methane leak is modelled after subtraction of biogas for process heat. However, test-calculations indicate an impact of less than 1% of total system footprint and the approach is maintained to keep the model as simple as possible. The upgraded biogas is assumed to replace natural gas in the Danish gas grid. Potential losses from transport and storage are not accounted for. End-use of the upgraded biogas is assumed to lead to biogenic emissions without Climate Footprint impact. As losses in the Danish natural has grid are generally small and most gas is used in clean combustion processes, this is found to be reasonable.

Natural gas – and thereby upgraded biogas on the natural gas grid, has many different potential uses – from direct conversion to heat (low and high temperature) to synthesis of liquid fuels and chemicals, plastics, proteins etc.. To embrace all options on the general level is outside the scope of the present work. To span the value of biogas on the gas grid, this aspect is included in the sensitivity assessment with a worst case and a best case setting. The same worst- and best-cases are used to investigate the use value of the pyrolysis energy products.

Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU) is developing fast and there is a keen political focus on the options to mitigate climate change by capturing and storing or re-using CO_2. CO_2 from biogas plants with gas upgrading is an obvious candidate for CCS and CCU as it has already been separated out of the gas and is therefore concentrated and available compared to many other sources. CCS is not commercial and fully mature in Denmark, but the technology has appealing potentials. A preliminary investigation of input, emissions and impact of including CCS on the developed biogas scenarios is therefore included in the sensitivity assessment.

3.1.5 Main assumptions – Straw Pyrolysis

The straw pyrolysis system is based on a counter-current slow-pyrolysis design developed by DTU KT in a system as the one illustrated in Figure 8. This design requires large, well-defined particles and when considering straw as fuel, it therefore has to be pelletized. Data for the plant modeling has been provided from DTU KT based on a pilot-scale plant of 200 kW thermal capacity as well as by Stiesdal Fuel Technologies based on economic and thermodynamic modeling of plant scale-up projects in 20 MW scale.

Straw is converted in the pyrolysis plant at around 500 °C, yielding a product portfolio of biochar, bio-oil and surplus heat sold as district heating. Bio-oil is extracted at temperatures above water dew-point and all un-condensed organics plus water go with the permanent gases to a combustion chamber for heat production. In the present model, excess heat is extracted as district heating while it could also be extracted in higher temperature for industrial processes. It is assumed that the bio-oil can be transported directly to end-use as start-up fuel or peak load oil replacement or to an oil refinery capable of dropping 5-10% bio-oil directly into the process. According to SFT, the Danish company Ørsted alone could utilize up to 15.000 t bio-oil for start-up and peak-load purposes [26]. In very large scale application of biomass pyrolysis and bio-oil production, new oil value chains would have to be included in the bio-oil value network.

In a recent online seminar, Tijs Lammens, Senior Process Engineer at BTG Bioliquids showed results from successful operation of a commercial Fluid Catalytic Cracking (FCC) unit at an established oil refinery with 5% crude pyrolysis oil. BTG's R&D work had also proven operation with 10% crude pyrolysis oil in a pilot scale FCC. The co-refining process had almost no impact on FCC product yields and very high yields of gasoline were recorded in the process [67]. With the vast scale of existing oil refineries, it is found to be reasonable to assume full substitution of crude oil or heavy fuel oil even at the national scale level of production. However, modelling such value chains is beyond the scope of the present work.

Potential losses from transport and storage of the bio-oil are not accounted for and after application of the oil at the bio-refinery all subsequent process steps are assumed similar for fossil oil and the bio-boil substitute. In addition, end-use of the bio-oil and the products originating from this oil is assumed to lead to biogenic emissions without climate impact. Process input include electricity for fans, conveyers, pumps, electronics ect., water for char wetting and 0.5% of the produced oil for occasional start-up heating of the plant after maintenance shutdown. Input of N_2 for sweep and back-flush are not included as the amount is decimal.

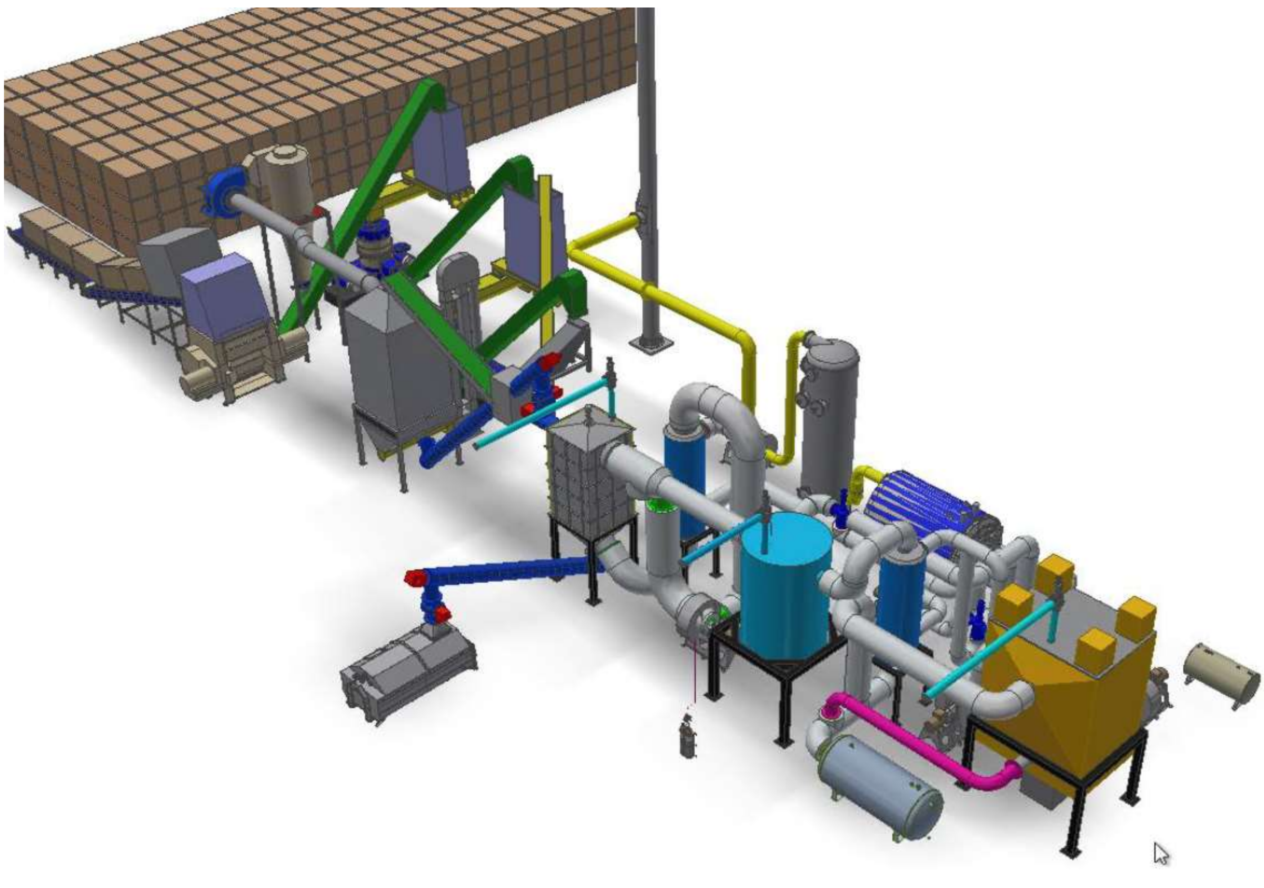


Figure 8: *Plant schematics, SkyClean 20 MW straw pellet pyrolysis plant including straw storage. Source: Stiesdal A/S.*

Potential losses from transport and storage of the produced biochar is also not accounted for. These losses are expected to be minimal due to the recalcitrant nature of the produced char. All char collected in the hot, ceramic filter is assumed to have a composition that make it reasonable to mix into the main char fraction without any significant impact on average composition.

28% of N, 70% of P and 100% of K in the straw fuel is assumed recovered in the biochar based on laboratory studies on straw pyrolysis [68]. Residual N and P is all assumed transferred to the gas phase. The final fate of these elements depend on the gas-train. But regardless of how this gas-train is configured (configuration and design of oil-extraction, gas cleaning, gas combustion etc.) these elements are not expected to influence the Climate Footprint.

The commercial break-through of Danish straw pyrolysis and the SFT technology has not yet occurred. As such, it could be expected that the technology will to improve in future optimization. However, such optimization is mainly expected to related to internal processes, cost and operational issues and not so much on input requirements, product distribution and quality. It is therefore not expected that significant changes within these aspects will occur in large scale application. It is, however, expected that new systems using pyrolysis under different circumstances will develop and that new biochar value chains will follow. However, this is outside the scope of the present work. Also, alternative pyrolysis technologies may also become relevant within straw management in the future. Such alternative technologies may yield different product distributions and products with slightly different characteristics. To investigate the potential influence of a modified product distribution, an alternative, screw-conveyer based pyrolysis technology is modeled in the sensitivity assessment.

3.1.6 Main assumptions - Transportation

All transport beyond in-field agricultural transport is modelled using the same truck model Ecoinvent 3.7.1 process *transport, freight, lorry 16-32 metric ton, EURO5,RoWTruck, 28-32t, Euro5, Highway*. This is a simplification of the real system where amounts and load characteristics may have substantial influence on transportation type. Transport of machinery between the field and machine station is not included. An overview of the total model off-field transport is provided in Table 4.

Table 4: *Assumed transport distances included in model*

From	To	Distance [km]
Field	Bale storage	10
Bale storage	Pellet mill	50
Bale storage	Biogas plant	25
Pellet mill	Pyrolysis plant	25
Biogas plant	Field (via storage)	25
Pyrolysis plant	Field (via storage)	50
Pyrolysis plant	Final oil use (via storage)	500*
Manure tank	Biogas plant	25

The distances are based on indicative assessments of potential distribution of fields, farms, pellet mills, biogas plants and pyrolysis units in a Danish setting. The transport distance for final oil use is for a large scale setting beyond the market for direct use in peak-load and start-up burners. Ideal bio-oil refinery processes with proper bio-oil cracking capabilities currently exist in Germany as well as Norway and can be reached either by a combination of naval and road transport or road alone. This example is road only to Norway. In larger scale implementation of bio-oil production capacity it may be expected that dedicated HDO[21] plants will be established in Denmark within a radius of 3-400 km. As described previously, bio-oil

[21] Hydro deoxygenation see e.g. https://www.sciencedirect.com/topics/engineering/hydrodeoxygenation

may also substitute crude or directly in conventional oil-refineries and as such the 500 km radius is found to cover the whole span of end-use scenarios.

3.2 Main material flow compositions

The straw composition used in the model is based on Easetech official 2020-01 v2 database wheat straw composition. The composition is adapted to match the straw composition used to calculate e.g. energy and mass balances on straw pyrolysis in the work by SFT, COWI and Ea Energianalyse. The applied manure is composed of 50% cattle manure and 50% pig manure also from the native Easetech official 2020-01 v2 database. The transfer functions presented in section 3.3 drive the change of composition of the straw and the manure into forms e.g. digestate, bio-oil and biochar.

Table 5: *Straw composition applied in model*

Water	TS	VS	Ash	Energy	C bio	N	P	K
%	%	%TS	%TS	MJ/kg TS	%TS	%TS	%TS	%TS
9	91	95	5	18	46	0.55	0.03	0.87

Table 6: *Manure mix composition applied in model*

Water	TS	VS	Ash	Energy	C bio	N	P	K
%	%	%TS	%TS	MJ/kg TS	%TS	%TS	%TS	%TS
93	7	80	20	16	44	2.4	1.2	4.8

Table 7: *Straw digestate composition derived by the model*

Water	TS	VS	Ash	Energy	C bio	N	P	K
%	%	%TS	%TS	MJ/kg TS	%TS	%TS	%TS	%TS
18	82	88	12	19	50	1.17	0.06	1.86

Table 8: *Manure digestate composition derived by the model*

Water	TS	VS	Ash	Energy	C bio	N	P	K
%	%	%TS	%TS	MJ/kg TS	%TS	%TS	%TS	%TS
96	4	64	36	15	44	4.3	2.2	8.6

Table 9: *Biochar composition derived by the model*

Water	TS	VS	Ash	Energy	C	N	P	K
%	%	%TS	%TS	MJ/kg TS	%TS	%TS	%TS	%TS
30	70	85	15	22	57	0.45	0.06	2.54

Table 10: *Bio-oil composition derived by the model*

Water	TS	VS	Ash	Energy	C	N	P	K
%	%	%TS	%TS	MJ/kg TS	%TS	%TS	%TS	%TS
0	100	100	0	33	70	0	0	0

3.3 Main transfer functions

Transfer functions are derived from energy and mass balances calculated with input from STF, DTU KT, Dall Energy and COWI. There are no transfer functions derived for the reference system in this study. The most essential transfer functions in the biogas scenario relate to the anaerobic digestion process and are provided in Table 11 (with references in the section on system assumptions 3.1.4) while the most essential transfer functions in the pyrolysis scenario relate to the pyrolysis process as described in Table 13. Additional parameters for all systems are provided in the detailed model flowsheets in Appendix.

Table 11: *Transfer functions (on basis of % in straw feed) of the straw biogas process applied in the model*

Material property	Gas use	CH_4 leakage	Bio-SNG	Digestate
Total Wet Weight	4.9	0.2	43.6	51.3
Water	0.0	0.0	0.0	100
VS	5.7	0.3	50.6	43.5
Ash	0.0	0.0	0.0	100
C	5.0	0.3	44.7	50.0
Energy	5.0	0.2	44.2	50.6
N	0.0	0.0	0.0	100
P	0.0	0.0	0.0	100
K	0.0	0.0	0.0	100

Table 12: *Transfer functions (on basis of % in manure feed) of the manure biogas process applied in the model*

Material property	Gas use	CH_4 leakage	Bio-SNG	Digestate
Total Wet Weight	0.3	0.0	3.0	96.7
Water	0.0	0.0	0.0	100
VS	5.9	0.3	52.6	41.2
Ash	0.0	0.0	0.0	100
C	4.6	0.2	41.0	54.2
Energy	4.8	0.2	43.2	51.7
N	0.0	0.0	0.0	100
P	0.0	0.0	0.0	100
K	0.0	0.0	0.0	100

Table 13: *Transfer functions (on basis of % in straw feed) of the pyrolysis process applied in the model*

Material property	Exhaust gas and heat losses	Excess heat for District heating	Bio-oil	Biochar
Total Wet Weight	56	0	14	30
Water	100	0	0	0
VS	54	0	16	30
Ash	5.0	0	0	95
C	34	0	23	42
Energy	10	21	28	41
N	72	0	0	28
P	30	0	0	70
K	0	0	0	100

3.4 Main energy, carbon and total mass flows

A set of mass and energy flow Sankey diagrams have been derived from the main models to illustrate flows in the Pyrolysis and Biogas scenarios. These diagrams are provided in **Figure 9** and **Figure 10**.

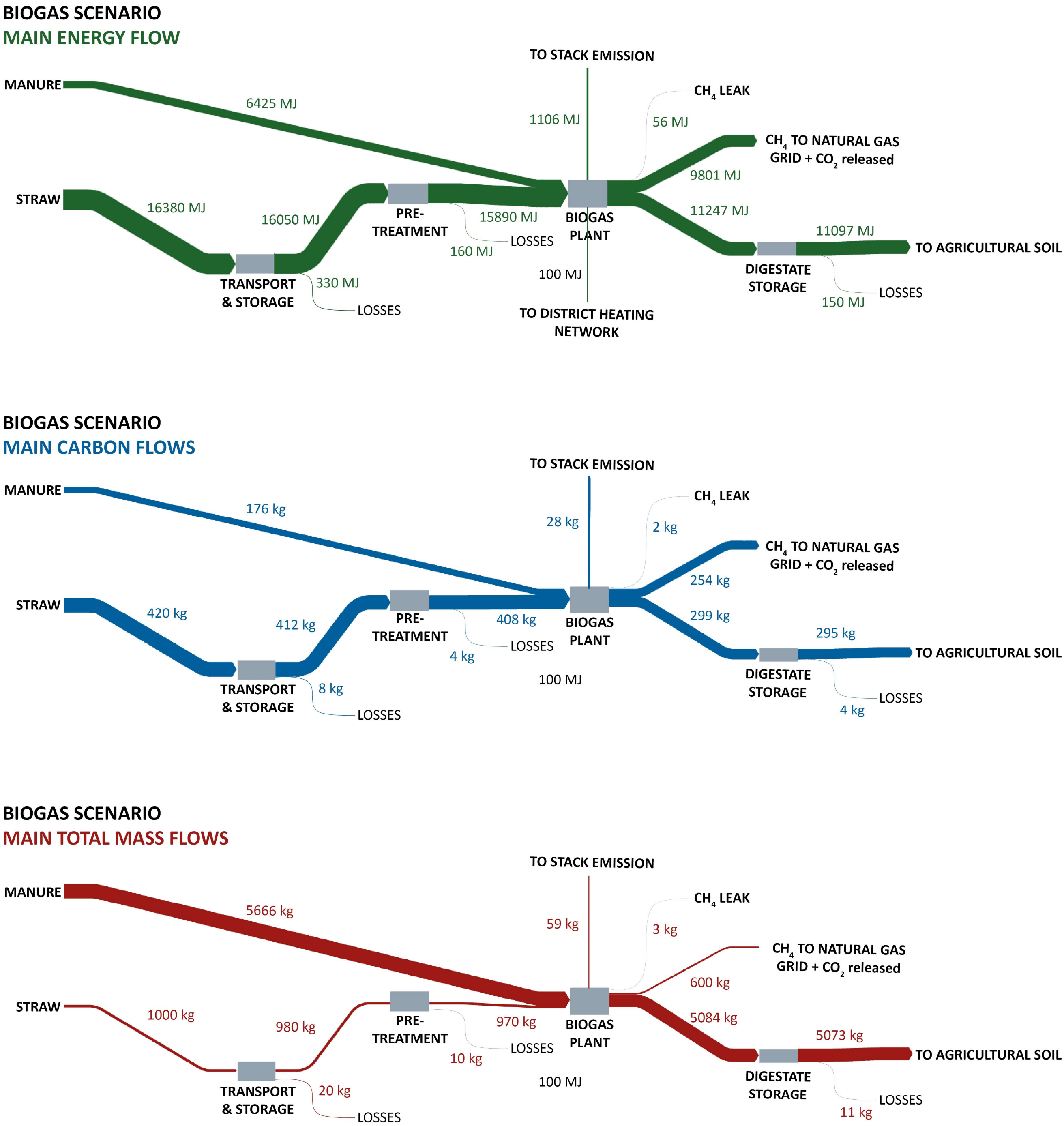


Figure 9: *Energy-, carbon- and mass flow diagrams for the Biogas scenario*

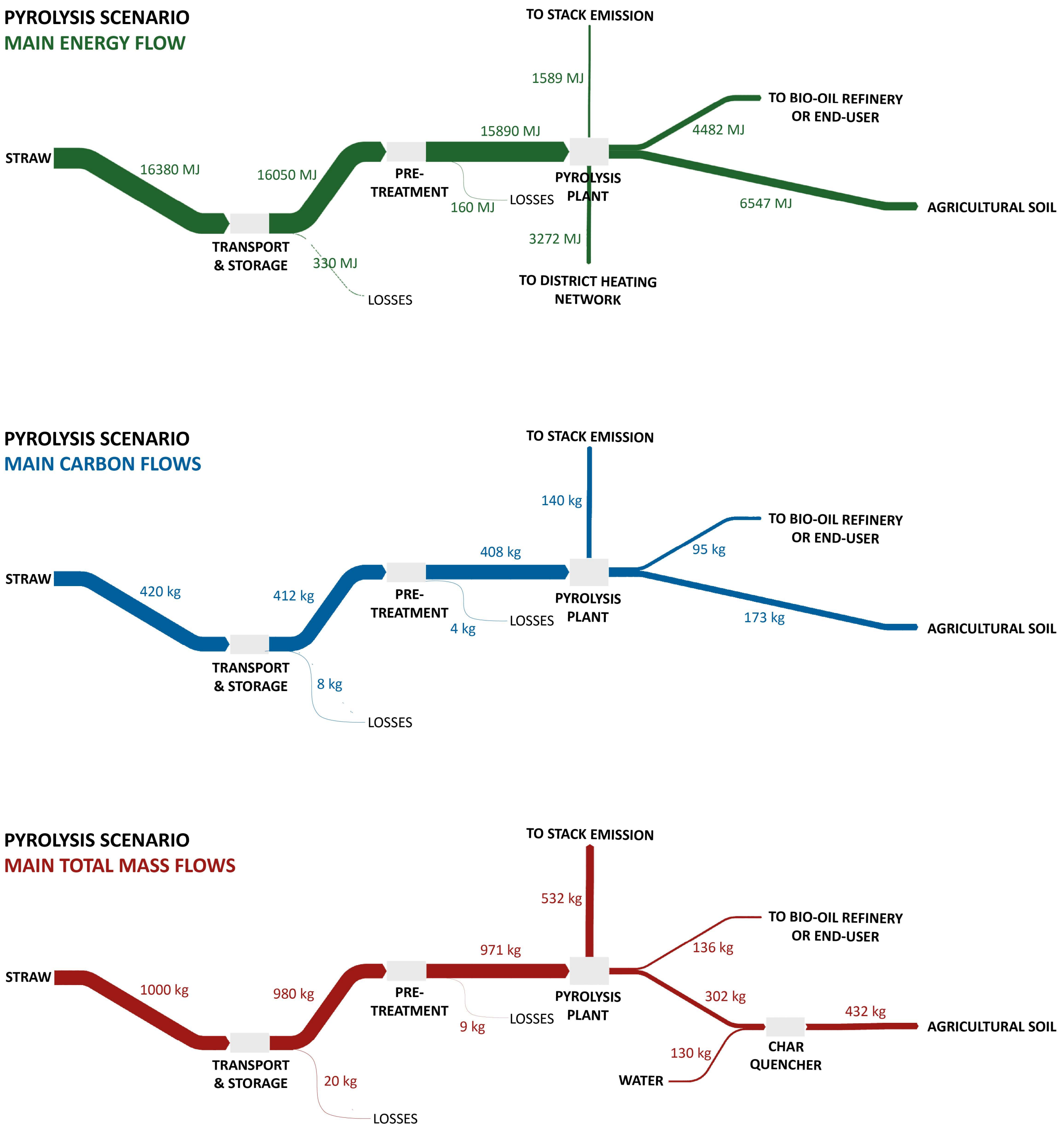


Figure 10: *Energy-, carbon and mass flow diagrams for the Pyrolysis scenario*

4 Life Cycle Impact Assessment (LCIA) results

4.1 System impact - categorized and detailed

In the following, the results from the LCIA step of the assessment are provided. Initially the 4 systems are analysed in a 20 and 100 year time frame where the different input and emission impacts are categorized across all system. Subsequently, the four systems are shown individually in larger detail. The Climate Footprint of the two references cannot be directly compared and neither can the Climate Footprint of the two scenarios. The difference between reference + relevant scenario, describe the potential climate mitigation effect of transition from the established reference to the proposed scenario.

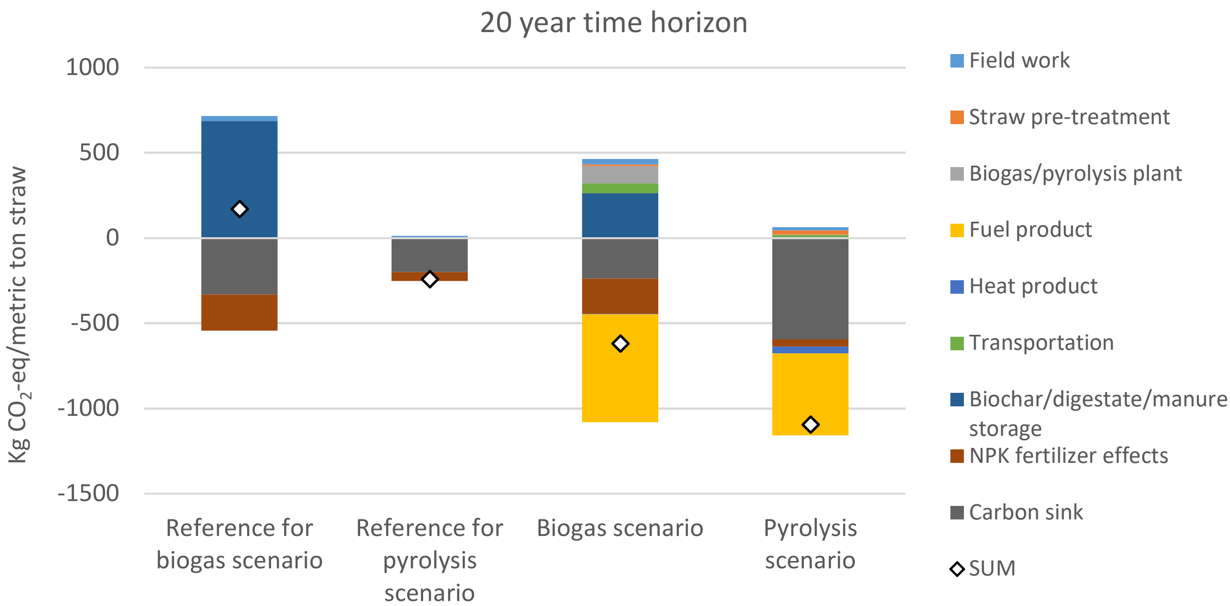


Figure 11: *Climate Footprint of two straw management systems and references with a 20 year time horizon.*

Table 14: *Climate Footprint of two straw management systems and references with a 20 year time horizon.*

20 year time horizon [kg CO_2-equ/metric ton straw]	Reference for biogas scenario	Reference for pyrolysis scenario	Biogas scenario	Pyrolysis scenario
Field work	29	11	32	19
Straw pre-treatment	0	0	8	24
Biogas/pyrolysis plant	0	0	101	1
Fuel product	0	0	-634	-480
Heat product	0	0	-1	-40
Transportation	0	0	59	18
Biochar/digestate storage	685	0	262	0
NPK fertilizer effects	-211	-53	-209	-43
Carbon sink	-332	-200	-238	-596
SUM	171	-242	-620	-1095

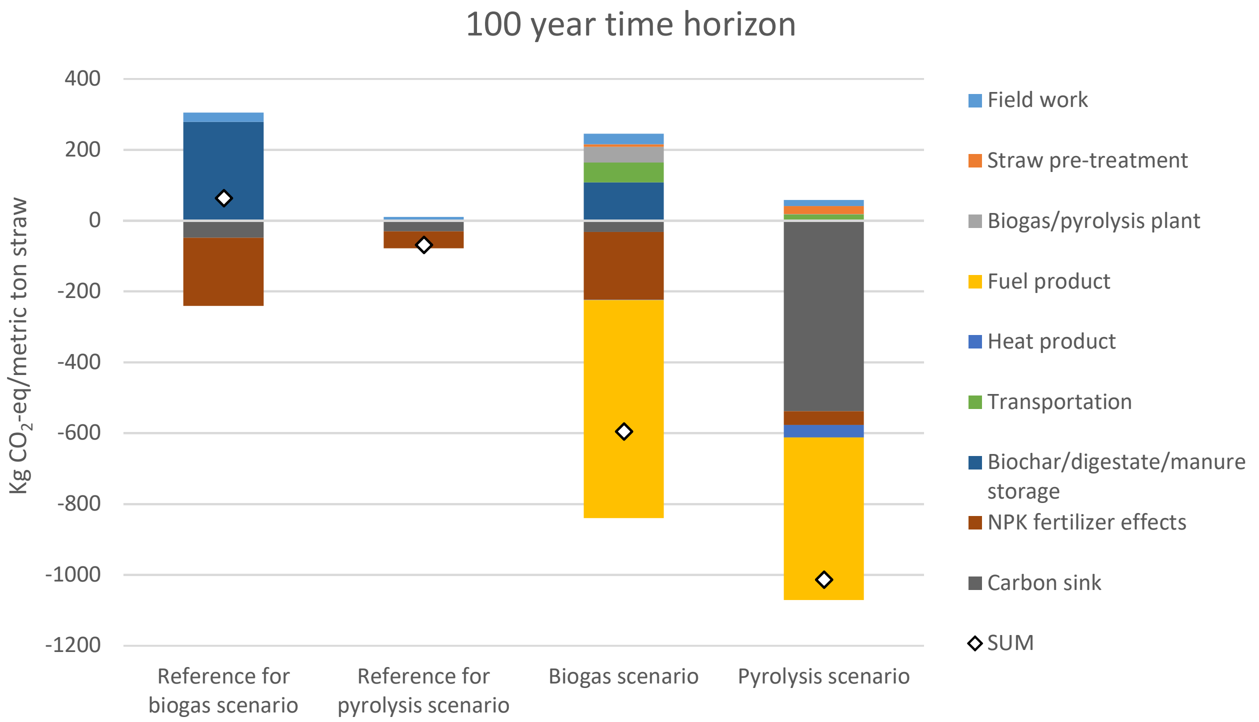


Figure 12: *Climate Footprint of two straw management systems and references with a 100 year time horizon.*

Table 15: *Climate Footprint of two straw management systems and references with a 100 year time horizon.*

100 year time horizon [kg CO_2-equ/metric ton straw]	Reference for biogas scenario	Reference for pyrolysis scenario	Biogas scenario	Pyrolysis scenario
Field work	27	10	29	17
Straw pre-treatment	0	0	7	22
Biogas/pyrolysis plant	0	0	44	1
Fuel product	0	0	-615	-459
Heat product	0	0	-1	-35
Transportation	0	0	57	17
Biochar/digestate storage	278	0	107	0
NPK fertilizer effects	-193	-48	-191	-39
Carbon sink	-49	-31	-32	-539
SUM	63	-69	-596	-1014

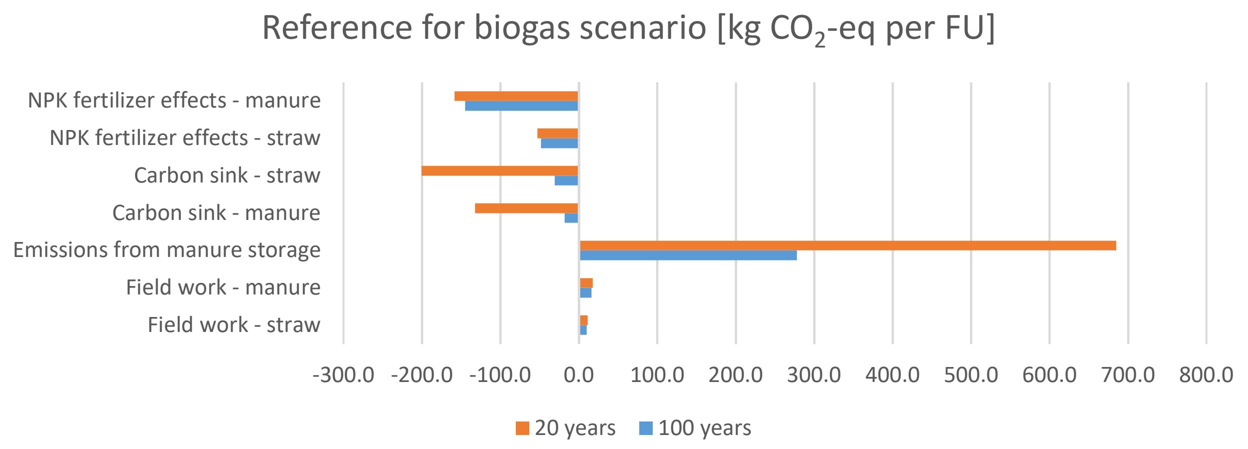


Figure 13: *Climate Footprint hotspot analysis of the reference system for the biogas scenario in a 20 year and 100 year time horizon. A table with numerical results can be found in Appendix 4.*

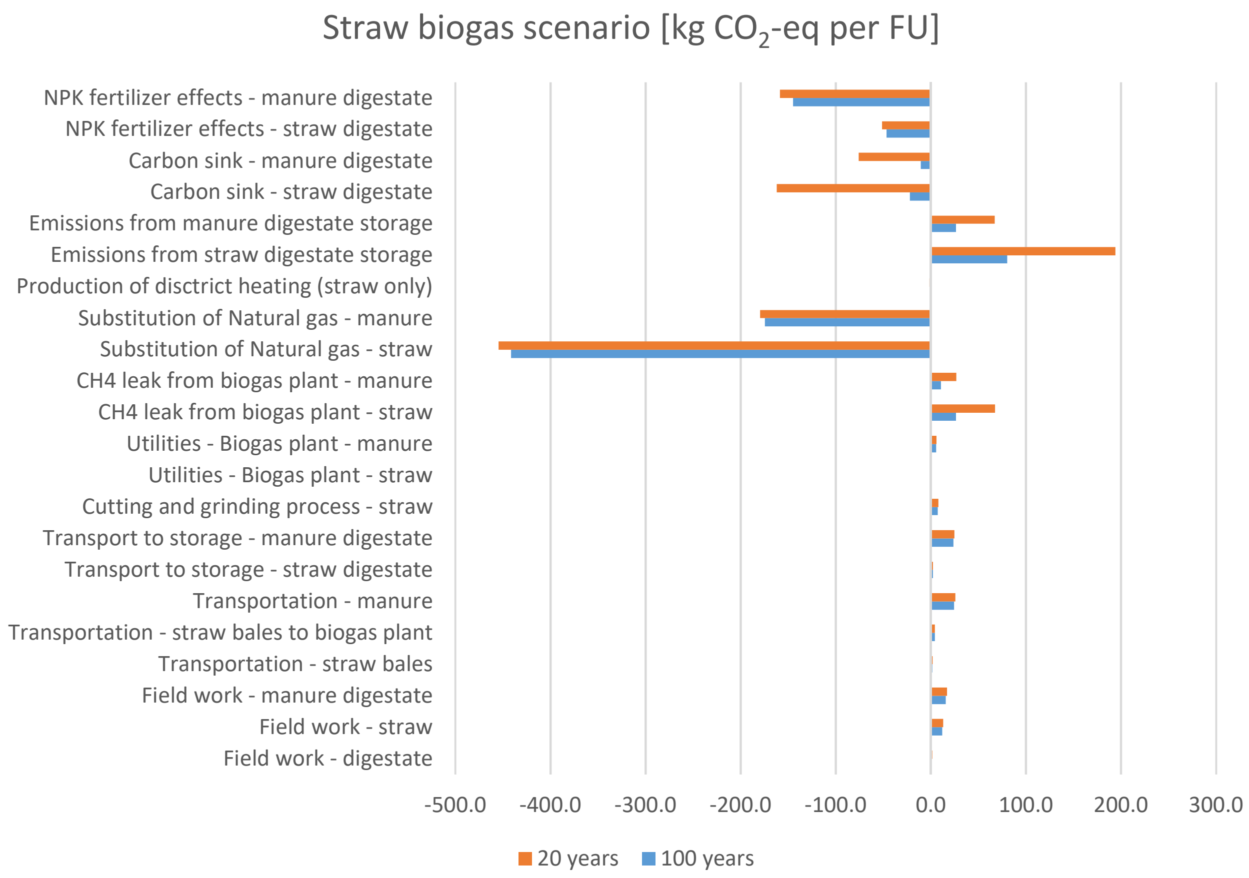


Figure 14: *Climate Footprint hotspot analysis of the straw biogas scenario in a 20 year and 100 year time horizon. A table with numerical results can be found in Appendix 4.*

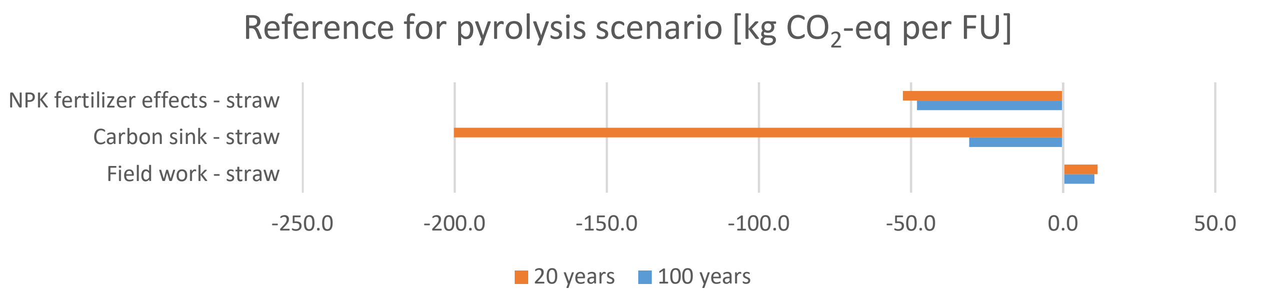


Figure 15: *Climate Footprint hotspot analysis of reference system for the pyrolysis scenario in a 20 year and 100 year time horizon. A table with numerical results can be found in Appendix 4.*

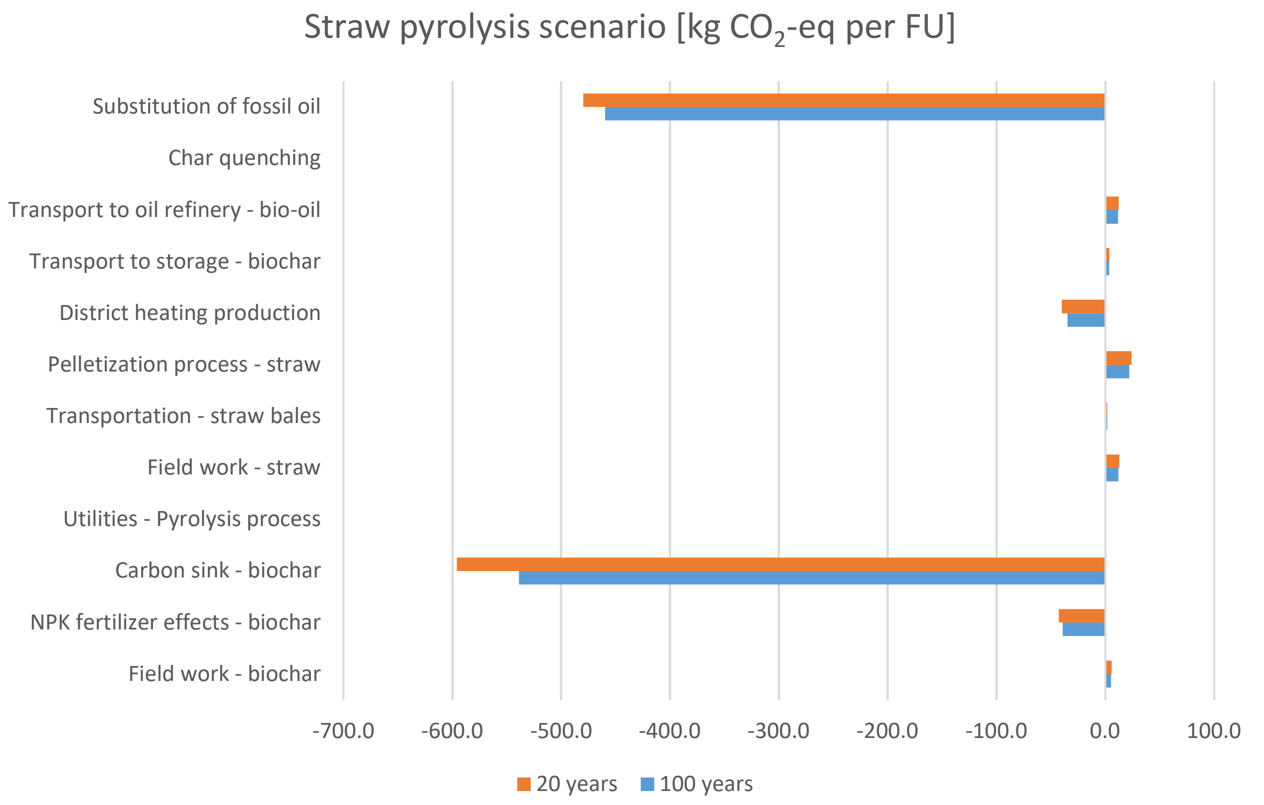


Figure 16: *Climate Footprint hotspot analysis of straw pyrolysis system in a 20 year and 100 year time horizon. A table with numerical results can be found in Appendix 4.*

5 Interpretation and validation of the main results

From the results in Figure 11, it is found that three of the four investigated systems have substantial negative footprints in the 20 year horizon. These range from around -240 kg CO_2-equ/metric ton straw in the reference system with direct amendment of the straw into soil to around -620 kg CO_2-equ/metric ton straw in the biogas system and onwards to almost -1100 kg CO_2-equ/metric ton straw in the straw pyrolysis system. The fourth system – the reference for the biogas scenario, encompassing established reference management of both straw and manure, yielded a substantial positive footprint of 170 kg CO_2-equ/metric ton straw.

The most significant net changes from the 20 year perspective to the 100 year perspective are a 100 kg CO_2-equ/metric ton straw decrease in the Climate Footprint of the reference for the biogas scenarios as well as 80 kg CO_2-equ/metric ton straw increase in the Climate Footprint of the pyrolysis scenario and 170 kg CO_2-equ/metric ton straw increase in the Climate Footprint of the reference for the pyrolysis scenario. These changes influence the apparent climate mitigation potential of transitioning from the established reference to the proposed scenarios on the short and long term.

On the short term, adopting straw pyrolysis may contribute to mitigation of climate change with approximately 850 kg CO_2-equ/metric ton straw while this effect on the longer term may increase to around 1000 kg CO_2-equ/metric ton straw. On the short term, adopting more co-digestion of straw with animal manure may contribute to mitigation of climate change with approximately 800 kg CO_2-equ/metric ton straw while this effect on the longer term has been found to decrease to potentials around 650 kg CO_2-equ/metric ton straw.

Overall, the parameters benefiting Climate Footprints of the different systems are primary:

- carbon sink in the soil
- substitution of the fossil energy products
- stabilization of animal manure

The performance of the biogas system is dominated by natural gas substitution and stabilization of animal manure but is hampered somewhat by methane emissions from the from the digestate storage and to a smaller extent directly from methane leaks at the biogas plant. The negative emissions in the pyrolysis system is almost divided 50/50 between carbon sequestration and fossil fuel substitution. Neither transport, field work, fertilizer effects or use and production of electricity and heat has any substantial influence on the overall results. From these results – and with a Climate Footprint perspective only, it is found relevant to circumvent use of excess heat from the pyrolysis from the general case of district heating substitution to more carbon intense heat use application. Most of the excess heat from pyrolysis can be extracted at temperatures high enough for e.g. high quality steam production and the heat could thereby substitute e.g. coal or natural gas in high temperature industrial use. In later stage development, perhaps even higher value (climate/economic) use of the excess gas could be developed. This is investigated further in the sensitivity analysis. Similarly, the end-use of the upgraded biogas may also obtain a higher climate effect by situated transition from coal to green methane from upgraded biogas in industrial processes with e.g. cement production or sugar production. This is also investigated further in the sensitivity assessment.

From the results in Figure 12, it can be seen how a shift in time horizon from 20 to 100 years, almost completely remove the carbon sink effect in the two reference systems and the biogas system. As a result, the modelling indicate that while straw – and digestate, amendment may have a substantial beneficial climate effect in the first years this is not very significant in the long run. The effect may be long enough to accumulate year by year where straw and digestate is added. However, with time the accumulation will approach an equilibrium and stabilize at an unknown maximum level. after around 100+ identical years. This modelled effect is – unfortunately, more theoretical than empirical and for many reasons not a reasonable representation of reality. The expected soil carbon increase, is not evident in empirical studies of soil carbon levels in Danish agriculture despite vast efforts to amend carbon via straw, manure, compost etc. On the contrary, Danish soil carbon has been decreasing on average 0.2 metric ton C/ha/year at least from 1986 to 2009 where substantial experimental work has been carried out on this matter [1]. To reach higher total soil carbon levels – and also perhaps to do it more quickly than with traditional strategies, it seems that application of biochar or co-application of biochar and biomass may be a relevant alternative. From the 20 to the 100 year perspective there is almost no loss of carbon from the biochar amended to soil. Obviously, this is a simplified representation as well, and more thorough experimental and praxis oriented investigations are required to validate this. The potential priming-effect, effects of co-amendment, combinations with various fertilizers, cover crops, agricultural practice and crop rotations need to be taken into consideration to determine more precisely the sequestration potentials of biochar in a Danish setting.

The net differences from a 20 to 100 years horizon of the pyrolysis and biogas systems are relative small, indicating a change of less than 10% in both cases. However, for the biogas system there are large underlying differences related to methane emissions and carbon sequestration. While carbon sequestration decrease to almost nothing from 20 to 100 years, so does the GWP of methane. In the end, the biogas footprint in the 100 year horizon is completely dominated by the value of natural gas substitution with only minor opposite effects of methane leaks and emissions. There is also an effect of nutrient-recovery, but it is important to notice that this effect is slightly smaller to the effect of nutrient-recovery in the relevant reference.

The main results of the Climate Footprint analysis of the straw pyrolysis system are very much in agreement with two previous studies – a British study and a Danish study, from 2009 and 2011. In the present work, impact potentials of -850 to -950 CO_2-equ per metric ton straw are determined in the main model. The variation is the temporal scope related to soil carbon-sink and GWP. Thomsen et al found a net effect of straw pyrolysis of -800 to -900 kg CO_2-equ per metric ton dry straw and Brownsort et al identified a potential of -900 to -1200 kg CO_2-equ per metric ton dry straw [14,15]. Results from both studies varied with different types and configurations of pyrolysis plants. Recalculation of the results from the present work into “per metric ton of dry straw” instead of “per metric ton of straw” would yield impact potentials of approximately -950 to -1050 CO_2-equ per metric ton straw which is directly situated between the findings of Thomsen et al and Brownsort et al.

The results of the present work on the co-digestion of straw and manure have been compared to a Climate Footprint assessment study on biogas that was recently published at Aarhus University (AU) [3]as well as a comparable study published by the Danish Technological Institute(TI) [16].The main differences from the present study to these two are co-digestion ratio. In the AU study, a 10/90 mixture of straw and manure on wet basis is examined. In the present work, the ratio was 15/85 and in the TI study the ratio was 25/75. In addition, the TI study was made on the wet straw system with silage (see the discussion in goal and scope), but without emissions from the silage process. There was also a dry-straw scenario in the TI study, but in this study the established reference included incineration of straw making it incomparable to the present work. Another aspect that differ among the studies is the temporal scope. Both the AU study and the TI study use a mixed scope with assessment of carbon-sink effects in the soil in a 20 year perspective and assessment of GWP impact in a 100 year perspective. In the present study it is attempted to make consistent temporal scope in both a 20 year (Bio, 20) and a 100 year (Bio, 100) time horizon. The results from the comparison between the three studies are provided in Figure 17.

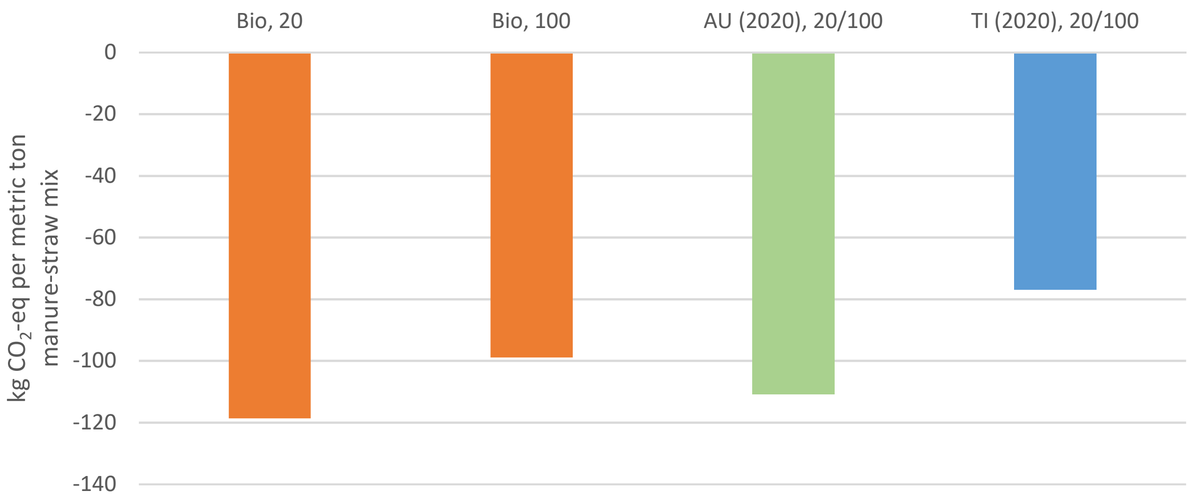


Figure 17: *Comparing Climate impact potentials of straw-manure co-digestion across three different studies. Bio 20 & 100 are results from the present work in a 20 and 100 year perspective. AU (2020) are results from a recent study from Aarhus University* [3]. *TI (2020) is a recent study from the Danish Technological Institute* [16]. *Both the AU and TI study work with a mixed temporal scope where soil sink potential is assessed in a 20 year horizon while a 100 year perspective on GWP is applied.*

The three studies on co-digestion of straw and manure are very much in agreement about the climate change mitigation potential of transitioning from the established reference to the proposed scenarios. Especially the AU study and the present work are highly aligned. The impact potential of the TI study is somewhat smaller than the others owing mainly to the high ratio of straw in the co-digestion which reduce the benefit from manure management.

From the detailed results in Figure 13 to Figure 16, it is evident that the (up to five) most influential parts of the models are (ranked with the most influential parameters first):

- **Reference:** i) Emissions from manure storage, ii) Soil carbon sink, iii) Straw nutrient fertilizer effects, and iv) Field work input
- **Biogas:** i) Natural gas substitution, ii) Emissions from digestate storage, iii) Soil carbon sink, iv) Digestate nutrient fertilizer effects, and v) CH_4-leak from biogas plant
- **Pyrolysis:** i) Soil carbon sink, ii) Fossil oil substitution, iii) District heating production, iv) biochar nutrient fertilizer effects and, v) Input requirements for the palletization process

The potential uncertainty of the sensitive factors identified above is addressed in the sensitivity assessment in chapter 6 together with the assessment of other relevant aspects of overall results uncertainty and the related impact spectrum.

6 Sensitivity assessment

A wide selection of parameters are investigated in this chapter for their influence on the model results. All parameters are evaluated in both the 20 and the 100 year time horizon models. The effect of the various parameters on the modeling results are investigated individually and the potential effect of stacking them in reasonable clusters is discussed. The parameters that are included in the sensitivity assessment have been identified by different means:

- Parameters related to system/model aspects with large influence on results have been included. These have been identified in the first iteration set of results.
- Parameters with high uncertainty and large or medium influence on the results have been included. These have been identified in a combination of result-analysis, expert review comments and discussions and the research of background literature and data.
- A few parameters that was found in literature to be highly uncertain and was not included in the main model was investigated for their potential impact on the results.
- Indicative modelling of more comprehensive system variations that encompass changes with high political interest and/or potential influence on the results have also been included. This relate to the assessment of e.g. acidification of manure and biogas digestate as well as CCS based management of the CO_2 by-product from the biogas process.
- Finally, it was decided after the expert review to include an assessment of the use-value of biogas and bio-oil that was consistent across the two scenarios.

6.1 Sensitivity of selected Global parameters and settings

From the work with Goal and Scope, LCI and results interpretation, the following parameters have been selected for sensitivity assessment in all scenarios:

- **Glo 1: Coal marginal:** An extreme-end scenario where the influence of applying coal based electricity and district heating as marginal energy production is investigated [56–58]. The following EcoInvent 3.7.1 processes are used:
    - Per kWh electricity: 1 kWh *Electricity, high voltage, electricity production, hard coal, RoW*
    - Per MJ heat: 1 MJ *Heat, district or industrial, other than natural gas, heat production, at hard coal industrial furnace 1-10MW, RoW*
- **Glo 2: Renewable energy marginal:** Another extreme-end scenario where the influence of applying very low-impact renewable energy sources for production of electricity and district heating as marginal is investigated. Ecoinvent 3.7.1 data for wind power production is assumed to supply the vast majority of this energy – directly as electricity and through COP 5 heat pumps for household room heating. The following EcoInvent 3.7.1 processes are used:
    - Per kWh electricity: 1 kWh *electricity, high voltage,electricity production, wind, >3MW turbine, onshore,DK*
    - Per MJ heat: 1/(3.6 kWh/MJ * 5 MJ heat/ MJ electricity) kWh *electricity, high voltage,electricity production, wind, >3MW turbine, onshore,DK*
- **Glo 3: Alternative Straw:** Alternative straw composition – content of carbon, nutrients and energy potential in the straw resources is tested in all scenarios. An average straw composition from ECN's Phyllis 2 database is used based on 73 wheat straw samples [35]
- **Glo 4: Alternative Fertilizers:** Influence of using BioGrace II database fertilizer footprint data instead of Ecoinvent 3.7.1 processes. CFA of fertilizers in BioGrace II standard values:

- 3.47 kg CO_2-equ per kg N replaces 5.04 (20 years) and 5.57 (100 years) kg CO_2-equ per kg N
- 0.54 kg CO_2-equ per kg P_2O_5 replaces 2.96 (20 years) and 3.24 (100 years) kg CO_2-equ per kg P_2O_5
- 0.70 kg CO_2-equ per kg K_2O replaces 3.75 (20 years) and 4.10 (100 years) kg CO_2-equ per kg K_2O

  All replaced values from default impact assessment method; *IPCC 2013, climate change, GWP 20a with LT_with ccfb and IPCC 2013, climate change, GWP 100a with LT_with ccfb* on Ecoinvent 3.7.1 processes *inorganic nitrogen fertiliser, as N,market for inorganic nitrogen fertiliser, as N,DK, inorganic phosphorus fertiliser, as P2O5,market for inorganic phosphorus fertiliser, as P2O5,DK and inorganic potassium fertiliser, as K2O,market for inorganic potassium fertiliser, as K2O,DK*

- **Glo 5: 100% N utilization factor:** Influence of 100% substitution efficiency (following a 100% utilization factor of N in straw, digestate and biochar).
- **Glo 6: Alternative LCIA method:** Alternative LCIA method tested without long-term effects. Used *ReCiPe v.1.11 Midpoint (H) w/o LT, climate change w/o LT, GWP100 w/o LT*. This method assume zero impact of methane in a 100 year perspective. Only applicable in 100 year perspective.

6.1.1 Results from sensitivity assessment of global parameters

The results from the assessment of sensitivity on the global parameters GLO 1-6 are presented in absolute values in Figure 18 and as a relative impact on the system Climate Footprint in Figure 19. As the main goal of this study is to investigate the difference between the established reference systems and the proposed scenarios, an assessment of the impact of the global parameters on these differences is provided in Figure 20 and Figure 21. Numerical results from the models investigated in the sensitivity assessment are provided in Appendix 5.

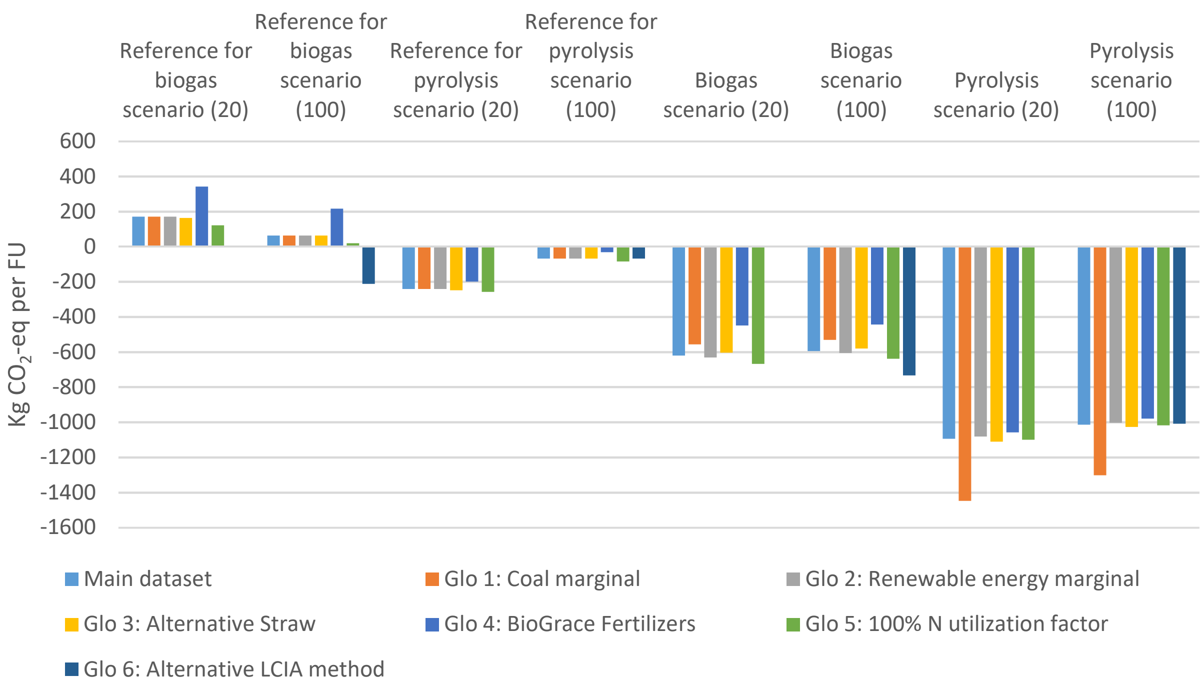


Figure 18: *Sensitivity analysis – absolute results of systems with alternative global parameters*

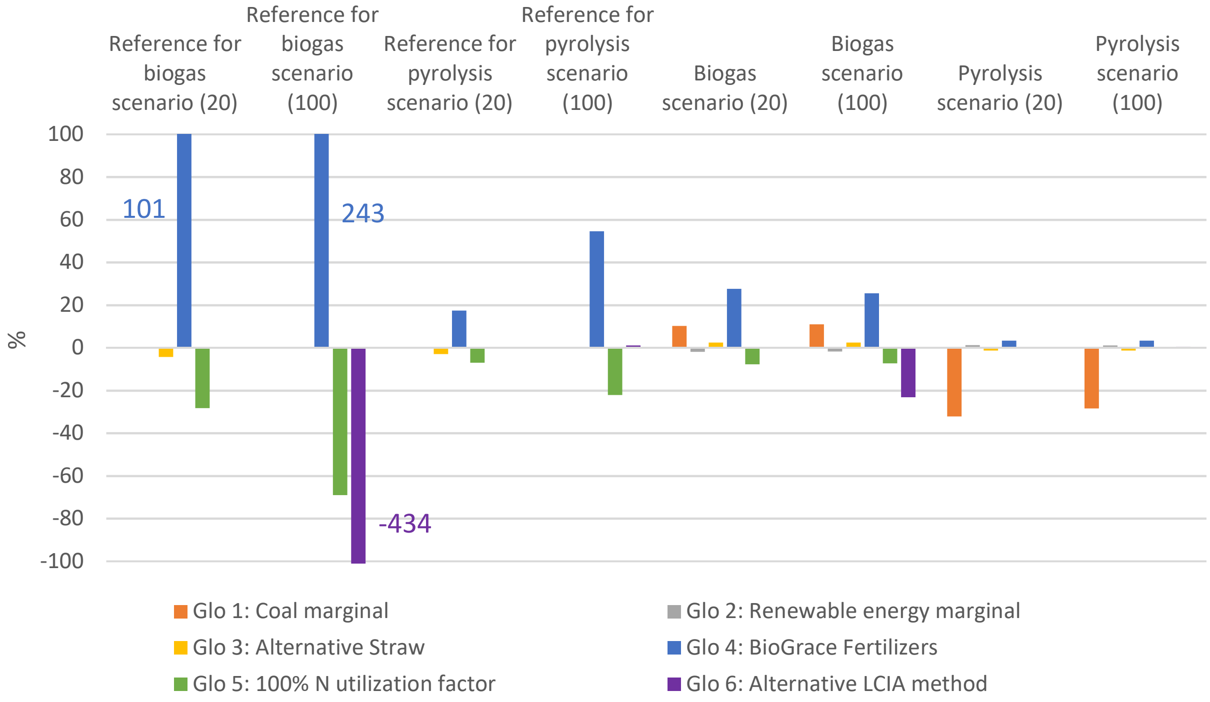


Figure 19: *Sensitivity analysis - relative impact of the global parameters investigated on reference- and scenario systems. A positive result implies that the modified parameter increase the Climate Footprint of the system with the percentage shown relative to the size of the footprint of that system (positive or negative) calculated with the main dataset.*

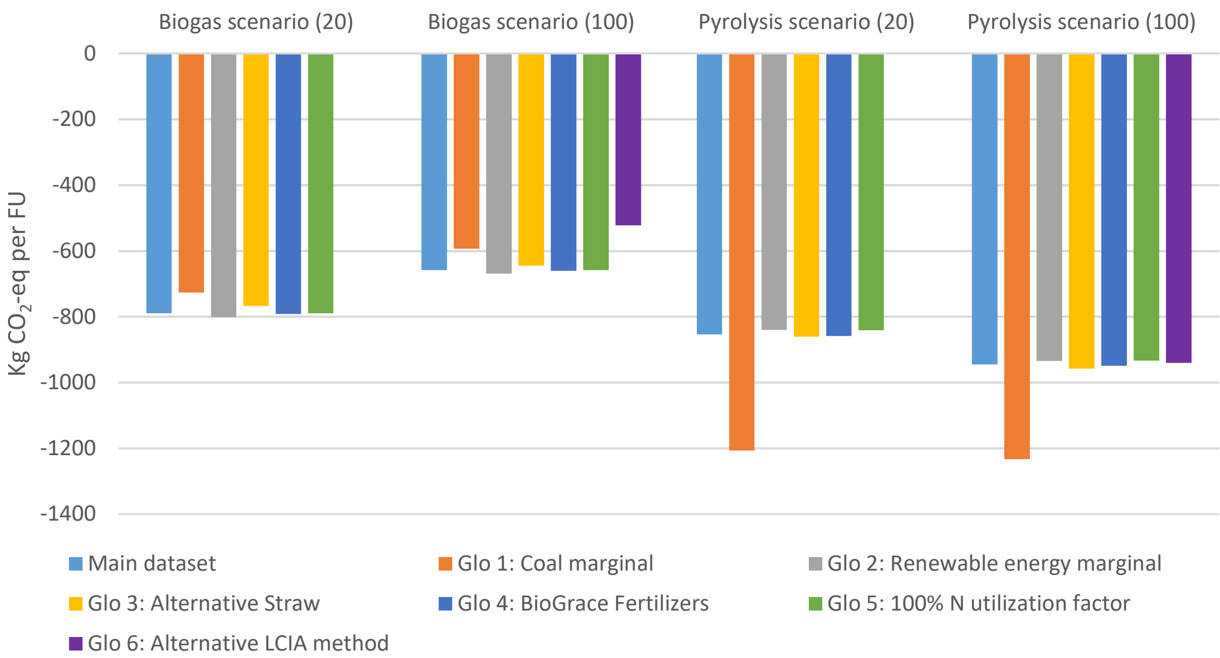


Figure 20: *Sensitivity analysis – impact of global parameters on the absolute difference between the Climate Footprint of an established reference and the related scenario.*

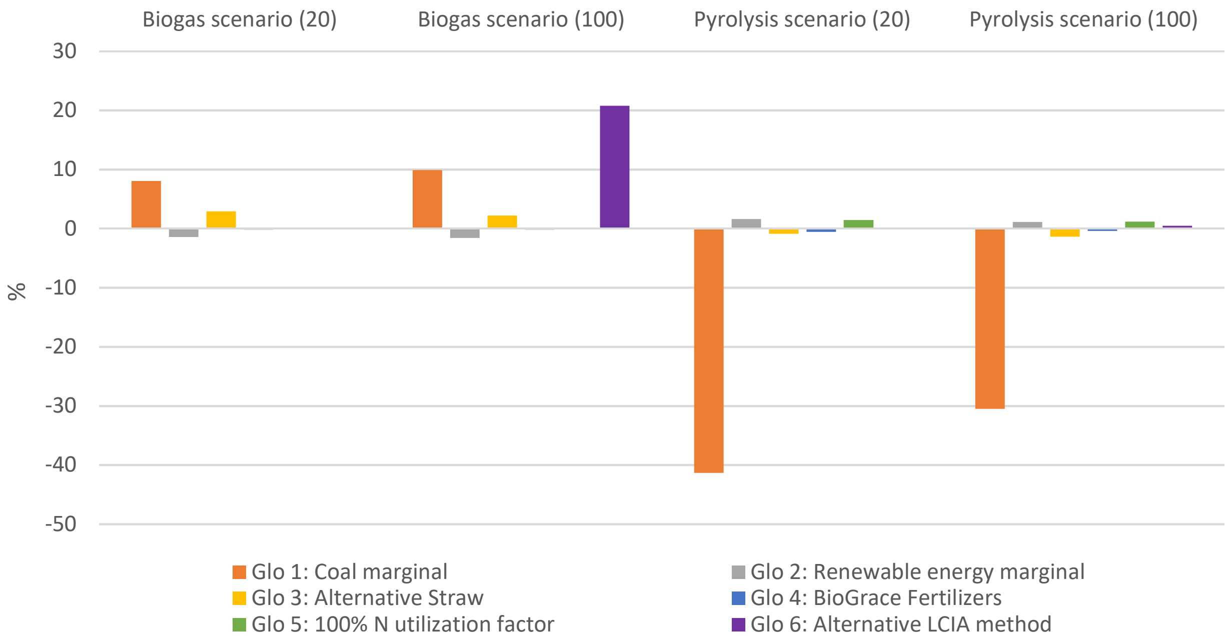


Figure 21: *Sensitivity analysis - relative impact of the global parameters investigated on the difference between reference and scenario. A positive result implies a reduced climate benefit when transforming from the established reference to the relevant scenario.*

The investigation of the global parameters indicate that the most sensitive parameters relate to:

- Fertilizer production cost and substitution value
- Electricity and heat production cost and substitution value
- Choice of LCIA method

The investigation of the global parameters do not change the overall pattern of results in any of the addresses cases.

The impact found from using the RED II (EU's Renewable Energy Directive II) compliant BioGrace II database for fertilizer production footprints instead of the marginal production cost of the Ecoinvent 3.7.1 database are very large in the system-specific accountings. The assumed substitution value of the nutrients decrease substantially with the alternative dataset and the specific impact of fertilizer-related parameters is important on all systems. However, when assessing the difference between reference and scenario, it is hardly detectable. There is only a small loss of nutrients in these systems except for loss of nitrogen in the pyrolysis scenario. And the amount of nitrogen in the pyrolysis scenario is very low (straw only) and the same is the impact from nutrient recovery.

The sensitivity of the impact potentials when transitioning from the established reference to the proposed scenarios are dominated by the effect of the coal marginal and – in the case of the biogas system in a 100 year perspective, the LCIA method. The reduced footprint related to the LCIA originate from the fact that in contrast to the IPCC method with long term effects, the alternative method - ReCipe 2016 without long term effects, accounts no impact of methane in a 100 year perspective. This is important to be aware of when modelling biological systems with unstable organic fractions. It is recommended to include long-term effects, but at the same time to acknowledge the short and intense greenhouse gas effect of methane by also including a short-perspective assessment e.g. 20 years or towards 2050.

The shift to a coal marginal electricity influence especially the impact of straw pretreatment. However, this is only detectable in the biogas scenario as the increase in the pyrolysis scenario is cancelled out by an increased benefit from heat production.

In sum, of all the global parameters investigated, it is only the energy marginal and the LCIA method that influence the impact potential (difference between reference and scenario) with more than 10% and from these results alone, the system footprint seem quite robust. However, there may be substantial sensitivity related to system-specific parameters that cannot be investigated across all systems. This is the focus of the following section of the report.

6.2 Sensitivity of selected Scenario-specific parameters and settings

From the work with Goal and Scope, LCI research, results interpretation from early iterations and external review process, the following parameters have been selected for sensitivity assessment in specific scenarios:

Reference:

- **Ref 1: C-sink:** Influence of using an alternative setup of the C-tool model predicting higher carbon sequestration effects from soil amendment of straw and manure. In the alternative dataset, a 100 year sink of 3.9% (straw) and 7.9% (manure) of amended C and a 20 year sink of 15.6% (straw) and 30.5% (manure) of amended C is estimated which is significantly higher than the original sink levels applied in the current work of around 2 and 3% (100 years) and 13 and 22% (20 years) [2,51].
- **Ref 2: Field work:** Influence of changing input-data between different straw amendment techniques and the related fuel consumption from minimum at 7 L/ha (rotor harrow) to maximum at 13 L/ha (2x plate harrow) [69].
- **Ref 3: Alternative manure reference system – acidification (Biogas reference only):** In this work, straw and manure in anaerobic digestion are modelled as mutually dependent (economically/ politically) with a reference for the manure management of simple tank storage of the manure. However, there are alternative manure management options and these may change the impact of the reference and thereby the potential climate benefit of the scenario in a near-future setting. These alternatives include acidification, separation, cooling and potentially a combination of separation and drying and pyrolysis of the fiber fraction [68,70]. Acidification of manure is already on the list of Best Available Technology in EU [71] for reduction of NH_3 emissions and expected to be a relatively simple approach with a substantial potential. For these reasons, a simplified estimation of the impact of this alternative is included in the sensitivity assessment with the following assumptions and key parameters:
    - Only tank-acidification is modelled, as this is widely applicable and does not have influence up-stream of the set system boundaries. Stable-acidification (not modelled) may be expected to yield a more profound effect on total emissions, since a large share of methane (and NH_3) emissions originate from stable floors, floor trenches etc. However, stable-acidification is not as straight forward to retrofit on existing infrastructure as tank acidification [72].

  - Only the effect on methane is included. Several studies have also shown effect on N_2O from tank storage as well as subsequent field application. However, the effect on N_2O has been shown to vary a lot (even all the way from positive to negative net effect) and be highly volatile. As the effect on methane is much more robust, only this effect is included in the current work [72,73].
  - 50% reduction in methane emissions from storage is included as an approximate average of 32% (7-49%) from Wesnæs et al (2009) [73] and 74 (52-96%) from Saue & Tamm (2018) [72]
  - Input for the acidification is modeled as 5.5 kg H_2SO_4 + 2 kWh electricity per metric ton manure (50/50 dairy and pig manure) from Wesnæs et al (2009) Appendix 2, table B4 [73]
- **Ref 4: Alternative manure storage emission factor (Biogas reference only):** To test the influence of the methane emission factor from the manure storage in a system without acidification, an alternative factor is applied in the reference for the biogas scenario. Original factors: 14.91 g CH_4/kg VS for cattle manure and 40.05 g CH_4/kg VS for pig manure [16] are therefore replaced with a set of alternative factors of 9.25 g CH_4/kg VS for cattle manure and 13.9 CH_4/kg VS for pig manure from The Danish National Emission Inventory 2021, Table 3D-26a *Emission estimates for cattle slurry inside the barns and not digested stored liquid manure* and *Table 3D-26b Emission estimates for swine slurry inside the barns and not digested stored liquid manure,* Page 864 [31]. This change the transfer of carbon from manure to methane from 2.0 / 5.4 / 3.4% (cattle / pig / average mix) to just 1.2 / 1.9 / 1.5%.
- **Ref 5: Field N_2O (Pyrolysis reference only):** The main model does not take differences in N_2O emissions into account as the same amount of total N is applied. This approach has been common practice in several Tier 1 model approaches. However, there might be a substantial impact related to the Danish regulation on use of organic N-fertilizers. When applying 1 kg N as manure or digestate – or biochar, there is a utilization factor in the regulation of 40% meaning that only 0.4 kg N is accounted for in the farmer's N-accountings. With the global assumption that the average Danish farmer will always maximize his allowed N-use, application of more "discount-N" will lead to application of more total N. In the pyrolysis scenario, some of the potential discounted N is lost to the gas phase compared to the reference. A potential effect of increased N_2O emissions from increased total N-supply in the reference for the pyrolysis scenario is therefore included. However, as there are no difference between the biogas scenario and biogas reference in this regard, this effect is not investigated in this part of the study. Emissions of N_2O from conversion of 1% N to N_2O-N after distribution onto the field is assumed [3] from additional 2.2 kg N supplied in the straw reference compared to the pyrolysis scenario (see section 3.1.2).

Biogas:

- **Bio 1 & Bio 2: Energy product use:** Upgraded biogas on the natural gas grid is a versatile energy carrier that may be used for many different end-use purposes. The substitution value of the upgraded biogas may vary with these different end-uses. Therefore, two alternatives to direct substitution of natural gas are investigated for use of the upgraded biogas. The alternative energy end-use scenarios are developed so they cover a worst-case and best-case extreme-end of a large spectrum. The same alternatives are applied for energy end-use from the pyrolysis scenario. There may be value chains within production of e.g. chemicals, plastics or even higher value products that may yield better "best cases", but this is outside the scope of the present work to pursue.
  - **Bio 1: Energy product use - Best case:** In this alternative system design, the upgraded biogas is converted in an industrial facility to produce high temperature process heat and

this process heat substitute the use of coal. This could be e.g. Cement production or sugar factory. 7024 MJ upgraded biogas from the digestion of straw and 2776 MJ of upgraded biogas from the digestion of manure substitute coal. In the main model, the gas substitute natural gas modeled with Easetech official 2020-01 v2 database process *Combustion of natural gas, DK 2010* [39] *(1 MJ per MJ upgraded biogas)* and EcoInvent 3.7.1 *natural gas, high pressure,market for natural gas, high pressure,DK* (0.32·1.552 m^3 per kg total wet weight where 32% of biogas mass is CH_4 and 1.522 is the inverse density of methane in m^3 CH_4/kg CH_4). In the alternative model, the 7024+2776 MJ substitute *Heat, district or industrial, other than natural gas, heat production, at hard coal industrial furnace 1-10MW, RoW* (1 MJ per MJ upgraded biogas) from EcoInvent 3.7.1.

  - **Bio 2: Energy product use - Worst case:** In this system, the upgraded biogas is converted in district heating boilers or house-hold gas boilers producing a room heating service in both cases. The produced heat substitute the long-term district heating marginal of the study. This may be an economically viable setup in some cases, but the potential for climate change mitigation is expected to suffer substantially as the district heating marginal has a very low climate impact. See more information about the marginal in section 3.1.3.

- **Bio 3 & Bio 4: Upgraded biogas production +/- 10% from digestion of straw:** Influence of + 10% (Bio 3) and -10% (Bio 4) production of upgraded biogas from digestion of straw tested. Include mainly increase/decrease in natural gas substitution and increase/decrease in the amount of carbon left in the digestate which influence methane emissions from storage. This parameter may also be regarded as an investigation into the biogas plant's use of gas to produce heat for the amine scrubbers.
- **Bio 5 and Bio 6: Straw digestate storage methane emissions:** Digestate storage emissions of especially methane have been found to be substantial. Two alternative datasets are used which present lower and higher emissions than the data applied in the main model. Only effect on emissions from the straw digestate is investigated, not the emissions from the manure digestate.
  - **Bio 5: Lower emissions (generic data):** The first alternative data set is comprised of highly generic data with accumulated storage emissions of 1.76 g CH_4 per kg stored VS (from Danish National Emission Inventory, *Table 3D-26c Emission estimates for digested biomass*, page 864) [31]. This correspond to 0.24 % of C in straw digestate and is substantially lower than the parameters used in the main dataset; 6.02 g CH_4 per kg stored VS and 0.81% of C in straw digestate converted to methane.
  - **Bio 6: Higher emissions (study with straw focus):** The second alternative dataset is comprised of more specific data on digestate methane potential measurements with digestate from 5 Danish biogas plants digesting straw or straw-like biomasses with retention times of 50-96 (up to 150) days [16]. Methane production in the biogas reactors were around 220 nm^3 CH_4/metric ton VS, which is quite close to the data used in the current work. The residual methane potential in the digestate was found to be up to 100 nm^3 CH_4/metric ton VS – and still on the increase after 100 + days of measurements. As a worst-case scenario, ultimate methane potentials of 120 nm^3 CH_4/metric ton VS is assumed based on the above. In calculations on methane emissions, the methane potential has to be combined with a Methane Conversion Factor (MCF) which is highly dependent on type of storage, digestate characteristics and temperature. The specific values for digested straw fibers are not available, and therefore an average of the following identified MFC-factors are applied:

- For digested manure from pig and cattle, a set of MFC values were proposed by AU in 2016 of 10.5 and 2.9% [74].
- Møller and Moset (2015) determined MCF values for cattle manure up to 8% [75].
- 10-17% have even been applied previously based on IPCC recommendations.

In this study, an average across all five identified MCF values of 9.7% is applied. This correspond to 8.1 kg CH_4/metric ton VS which is 35% higher than the main dataset (6.02 kg CH_4/metric ton VS) that is currently used and a factor of almost 4.5 higher than the data from the National Inventory report. 8.1 kg CH_4/metric ton VS correspond to 1.1% of C in straw digestate.

- **Bio 7: Digestate acidification:** The emissions from digestate storage may be reduced by several different means e.g. cooling, acidification or a combination of separation and drying and pyrolysis of the fiber fraction. In this study, an indicative estimation of the effect of simple tank-acidification is conducted using the same assumptions and parameters as used the indicative estimation of the effect of manure tank acidification (Ref 3 above).
- **Bio 8 and Bio 9: CH_4-leak best case and worst case:** Current methane leak emissions from Danish biogas plants are substantial despite a yearlong focus on the issue. A recent study has shown average methane leaks of 2.5 % on a range of tested biogas plants [63]. This is substantially higher than the 0.5% applied in the main scenario in this study. However, this difference is to a large extent due to the fact that the recent leak survey was made for a variety of plant types, sizes and ages. Generally, there are higher leak emissions from older plants, and sludge plants while newer plants generally have much lower losses.
  - **Bio 8: Biogas business leak target – worst case:** It is investigated how a representative near-future worst case with a 1% average loss/leak will influence the climate impact of the straw biogas model. 1% is the current target of the Danish biogas industry for average CH_4 leak emissions [3].
  - **Bio 9: Optimal technology – best case:** It is investigated how best-case, state-of-the-art leak emission levels of just 0.4% will influence the results. This is assumed to be the currently optimal conditions [62].
- **Bio 10: Carbon sink:** Influence of using an alternative setup of the C-tool model predicting higher carbon sequestration effects from soil amendment of biogas digestate. In the alternative dataset a 100 year sink of 7.9% of amended C and a 20 year sink of 30.5% of amended C is estimated which is significantly higher than the sink levels applied in the main model of around 3 and 22% [2,51].
- **Bio 11: CCS:** A preliminary investigation of the potential impact of adopting CCS in the biogas scenario is conducted as described below based on an IEA study on CO_2 transportation [76]. It may be that the CO_2-by-product may obtain even higher value in various CCU systems than for CCS, but modelling such systems is outside the scope of the present work.
  - Step 1: Liquefaction: Power demand: 123 kWh/metric ton CO_2 (Electrical) and heat for drying the CO_2: 24 MJ/metric ton CO_2 (electrical = 7 kWh) sum = 130 kWh/metric ton
  - Step 2: Transport by truck from biogas plant to harbor, assumed 200 km using Ecoinvent 3.7.1 transport process *transport, freight, lorry 16-32 metric ton, EURO5,RoW*
  - Step 3: Storage: Including a loss from storage boil-off: 1% of CO_2

- Step 4: Transport by ship 750 km (distance based on Esbjerg to Øygarden ca 750 km by ship where the Northern Lights CO_2 injection terminal will be located[22]. Include a ship boil-off up to 1000 km of 0.6% of CO_2
- The climate impact of the total CCS logistics chain has been validated by matching it to recent estimates by Rambøll, Denmark [77].
- The CCS procurement and processing steps are included identically on CO2 from the straw-digestion and the manure-digestion.

Pyrolysis:

Pyr 1 & Pyr 2: Energy product use: As for the biogas scenario, the same two alternative energy end-use scenarios are investigated for production and use of energy from the pyrolysis process. The energy-use spectrum of the two technologies are not alike, but there are many overlapping options, and the two extreme-end scenarios may be relevant for both technologies. See more above on Bio 1 and Bio 2.

- **Pyr 1: Energy product use - Best case:** The pyrolysis plant is placed in close proximity of an industrial facility where it is assumed that high temperature process heat can be produced from all high temperature surplus energy from the pyrolysis process and that this process heat substitute the use of coal. This could be e.g. Cement production or sugar factory as in the biogas scenario. 3274 MJ heat previously sold as marginal district heating & 4482 MJ (135.5 kg) substitution of oil modeled with Easetech official 2020-01 v2 database *Combustion of residual oil, DK 2010* (1 MJ per MJ bio-oil) and Ecoinvent 3.7.1 process *heavy fuel oil,market for heavy fuel oil,RoW* (1 kg per kg total wet weight) is replaced with 7756 MJ *Heat, district or industrial, other than natural gas, heat production, at hard coal industrial furnace 1-10MW, RoW* from EcoInvent 3.7.1.
- **Pyr 2: Energy product use - Worst case:** Both the condensable and un-condensable parts of the pyrolysis gas is burned directly to drive the pyrolysis process and produce low-temperature heat for district heating thus substituting the long-term marginal of the study. This may be an economically viable setup in some cases, but the potential for climate change mitigation is expected to suffer substantially as the district heating marginal has a very low climate impact. 4482 MJ (135.5 kg) substitution of oil modeled with Easetech official 2020-01 v2 database *Combustion of residual oil, DK 2010* (1 MJ per MJ bio-oil) and Ecoinvent 3.7.1 process *heavy fuel oil,market for heavy fuel oil,RoW* (1 kg per kg total wet weight) is replaced with 4482 MJ substitution of the long-term district heating marginal applied in the study (see section 3.1.3).

- **Pyr 3: Pyrolysis products:** In this alternative setup of the main transfer functions of the pyrolysis scenario, and alternative distribution between oil, char and gas products. Yields from a slow pyrolysis process kinetic model operated at 500 C with 30 minutes retention time is used. This model predict: 350 kg oil, 280 kg biochar, 240 kg gas and 130 kg water in the gas phase [14] per metric ton straw. The alternative process produce 210 kg more oil, 20 kg less char and 190 kg less wet gas than the counter current pyrolysis model from SFT. Oil C content assumed to be 50% with a correlated higher heating value of 20 MJ/kg [14]. This is substantially lower than the 70% C applied in the main model. Remaining part of oil is mainly H & O.
- **Pyr 4: C-sink:** Biochar carbon stability is a significant factor in the Climate Footprint assessment. Tested by modelling a mean residence time (MRT) of 556 years for the recalcitrant pool of carbon

[22] https://northernlightsccs.com/what-we-do/

in the char (97%) and an MRT of 108 days for the labile fraction of carbon in the char (3%). These are average values from a large meta study on char stability [78]. Assuming a near-linear loss rate for the first 100 years after the labile burn off, approximately 21% of biochar carbon would be mineralized after 100 years and 7% after 20 years. These values indicate a slightly lower carbon stability than the primary dataset where 15% is mineralized in 100 years and 6% during the first 6 years.

- **Pyr 5: Pellet production:** Alternative estimation of the production input requirements of pellet production is obtained from DONG (now Ørsted) and Vattenfall[23]. Energy input requirements correspond to approximately 4% of biomass energy potential and the energy is in the form of steam and electricity. Assuming steam produced from natural gas. Alternative input requirements of 0.00833 kWh electricity (3% of straw HHV) and 0.01 MJ natural gas (1% of straw HHV) per MJ of straw pelletized.

6.2.1 Results from sensitivity assessment of scenario specific parameters for the reference systems

The results from the assessment of sensitivity of the scenario-specific parameters for the reference systems are presented in absolute values as well as with relative impacts compared to the main model results. Results are presented alongside the impact from the global parameters. Numerical results from the models investigated in the sensitivity assessment are provided in Appendix 5.

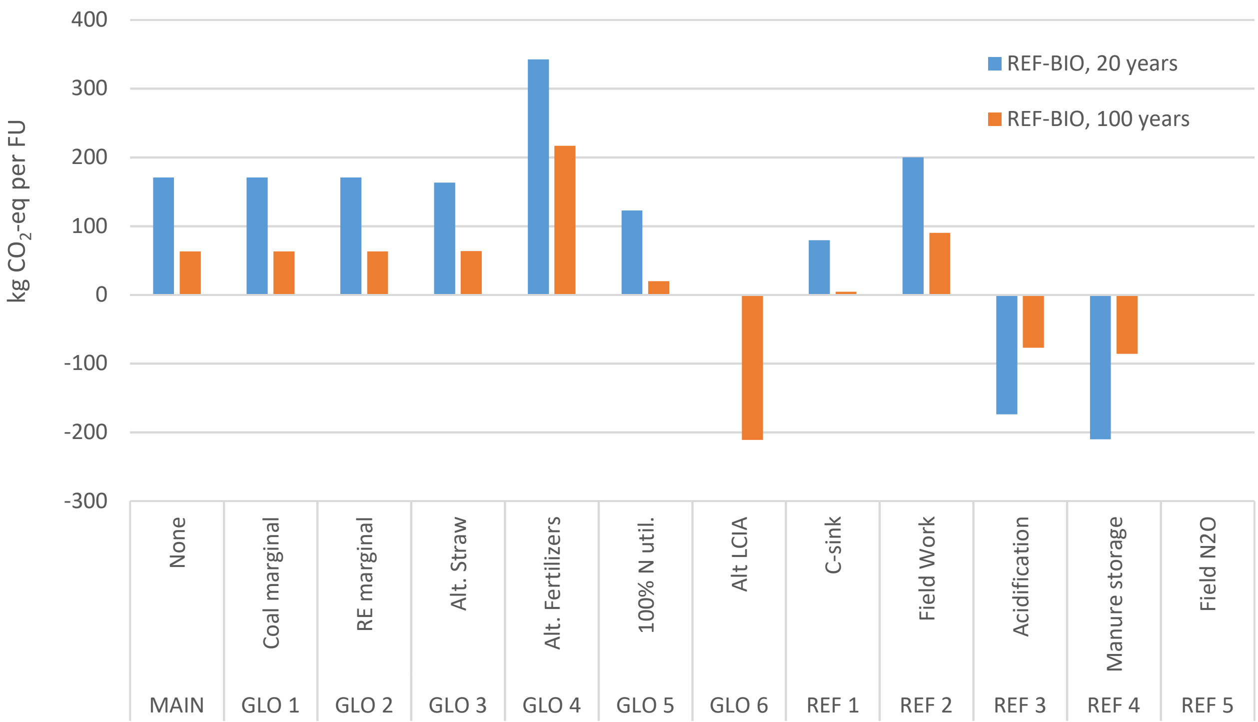


Figure 22: *Absolute results of reference system for the biogas scenario with influence of all tested parameters. REF 5 is not relevant for the reference for the biogas scenario, and GLO 6 is only applicable in a 100 year perspective.*

[23] https://www.experimentarium.dk/klima/biobraendsler-til-kraftvarmevaerker/

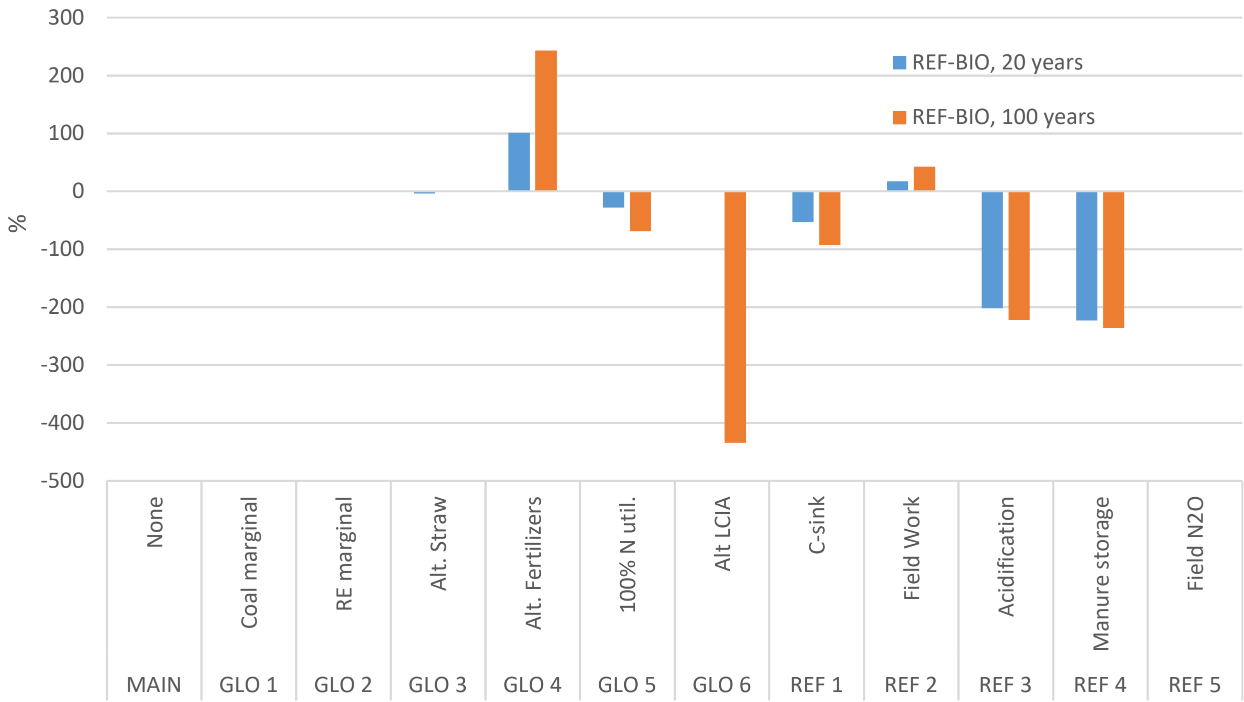


Figure 23: *Relative difference of <u>reference system for the biogas scenario</u> under influence of all tested parameters and compared to the main model results. A positive result implies an increased Climate Footprint of the system compared to the main model results. REF 5 is not relevant for the reference for the biogas scenario, and GLO 6 is only applicable in a 100 year perspective.*

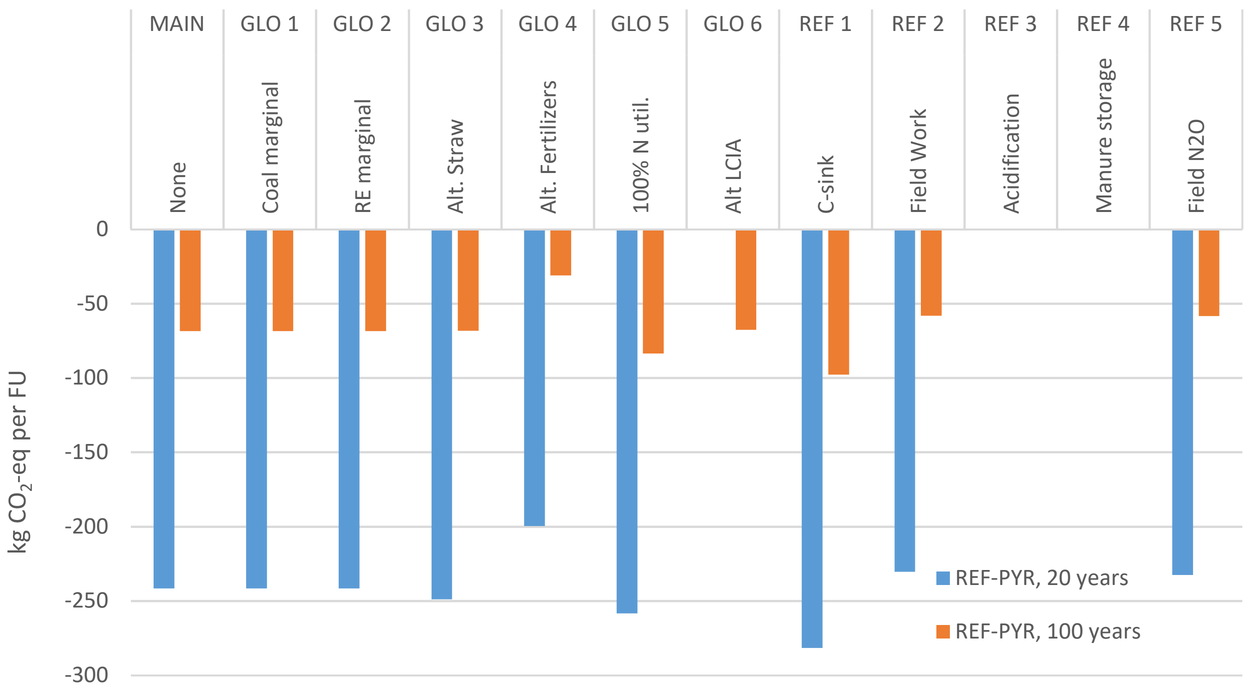


Figure 24: *Absolute results of <u>reference system for the pyrolysis scenario</u> with influence of all tested parameters. REF 3 & 4 are not relevant for the reference for the pyrolysis scenario, and GLO 6 is only applicable in a 100 year perspective.*

Figure 25: *Relative difference of reference system for the pyrolysis scenario under influence of all tested parameters and compared to the main model results. A positive result implies an increased Climate Footprint of the system compared to the main model results. REF 3 & 4 are not relevant for the reference for the pyrolysis scenario, and GLO 6 is only applicable in a 100 year perspective.*

The system-specific parameters tested for the reference of the biogas system, generally have high sensitivity. This is especially prominent in a 20 year perspective and less so in 100 years. The most sensitive parameters are the manure storage emission factors and the potential effect of manure acidification. The sensitivity of the carbon-sink parameters is also substantial in both the 20 and 100 year perspective.

In general, the tested parameters for the pyrolysis reference systems are much less sensitive than the parameters tested on the reference for the biogas scenario. Fertilizer production cost and substitution value is still the most sensitive part of the system followed by carbon-sink potentials.

6.2.2 Results from sensitivity assessment of scenario specific parameters for the biogas systems

The results from the assessment of sensitivity of the scenario-specific parameters for the biogas system are presented in absolute values as well as with relative impacts compared to the main model results. Results are presented alongside the impact from the global parameters. Numerical results from the models investigated in the sensitivity assessment are provided in Appendix 5.

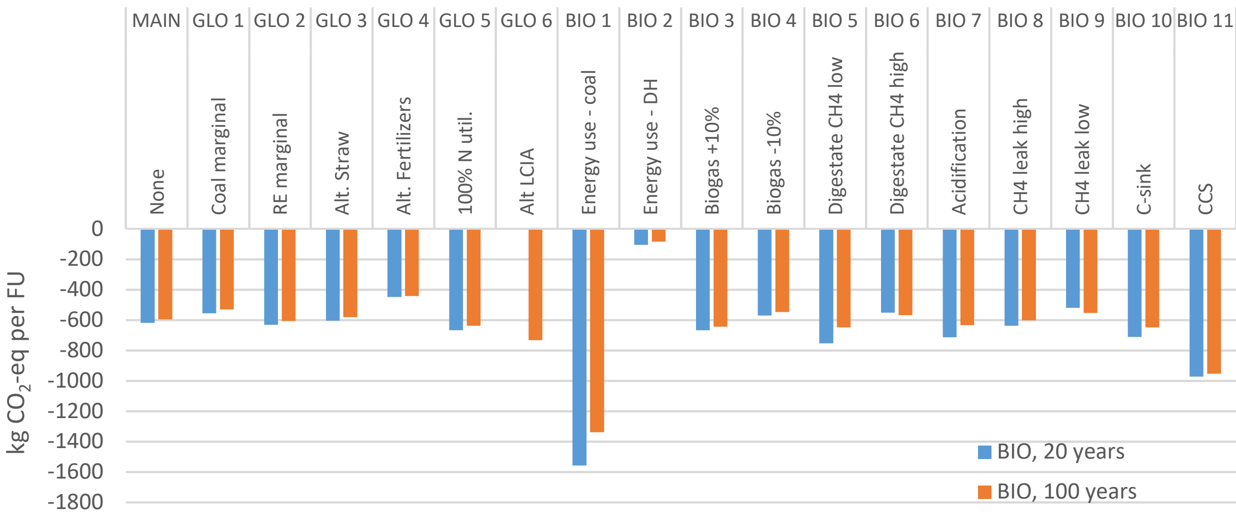


Figure 26: *Absolute results of the biogas scenario with influence of all tested parameters. GLO 6 only in a 100 year perspective.*

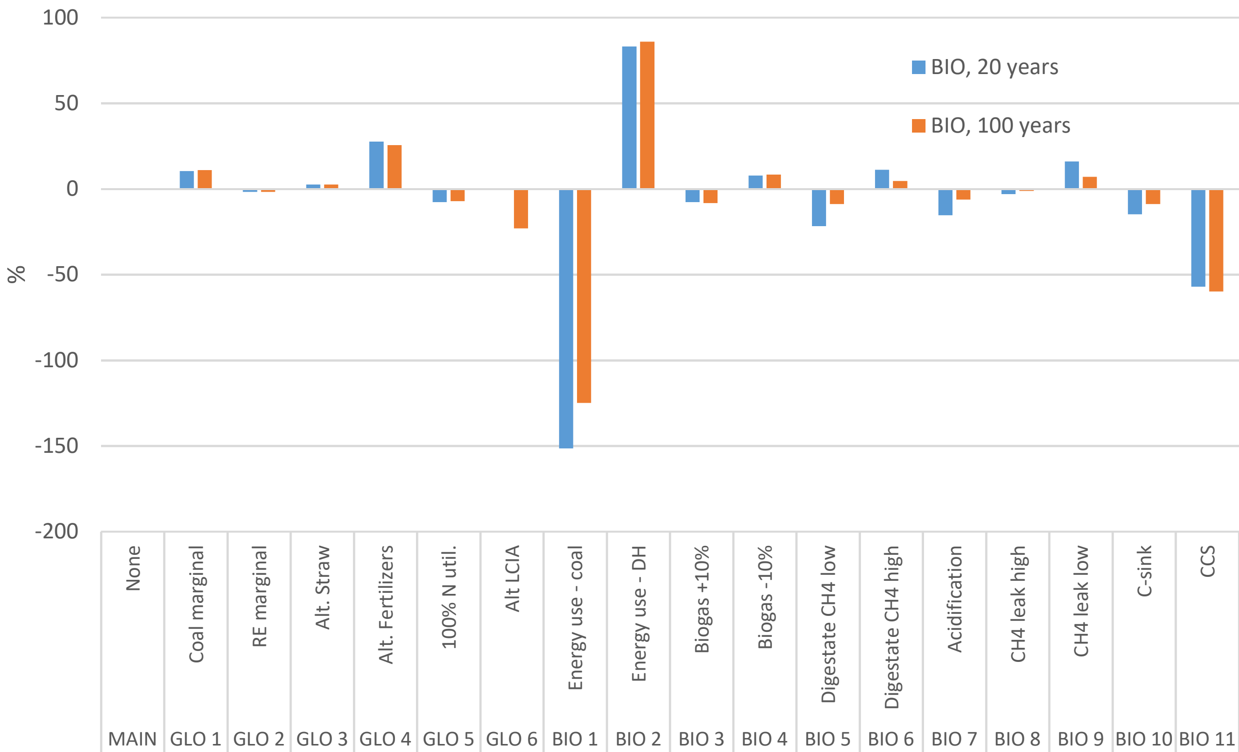


Figure 27: *Relative difference of the biogas scenario under influence of all tested parameters and compared to the main model results. A positive result implies an increased Climate Footprint of the system compared to the main model results. GLO 6 is only applicable in a 100 year perspective.*

The most sensitive parameter in both the 20 and 100 year modeling of the biogas straw system is energy product end-use. Both the worst-case and best-case alternatives substantially influence the overall scenario result – in both the short and long time horizon. The third most influential alternative was found to be the development of a CCS-management option for biogas CO_2. Such an initiative would have a substantial improvement potential and increase the climate benefit with more than 50%. Potentials may be even higher if processes for more effective digestion of the straw is developed. According to the carbon balance estimated in Figure 9 there is a lot more carbon to capture from the digestate. An alternative approach could be drying and pyrolysis of the digestate to make pyrogenic CCS through production and use of biochar to complement the conventional CCS. Following the impact of energy end-use and CCS, the categories of the next-most sensitive parameters are i) Fertilizer production cost and substitution value, ii) methane emissions from leak and digestate incl. potential effect of acidification methane leak from the biogas plant, iii) Carbon-sink, and iv) biogas production/use.

6.2.3 Results from sensitivity assessment of scenario specific parameters for the pyrolysis systems

The results from the assessment of sensitivity of the scenario-specific parameters for the pyrolysis systems are presented in absolute values as well as with relative impacts compared to the main model results. Results are presented alongside the impact from the global parameters. Numerical results from the models investigated in the sensitivity assessment are provided in Appendix 5.

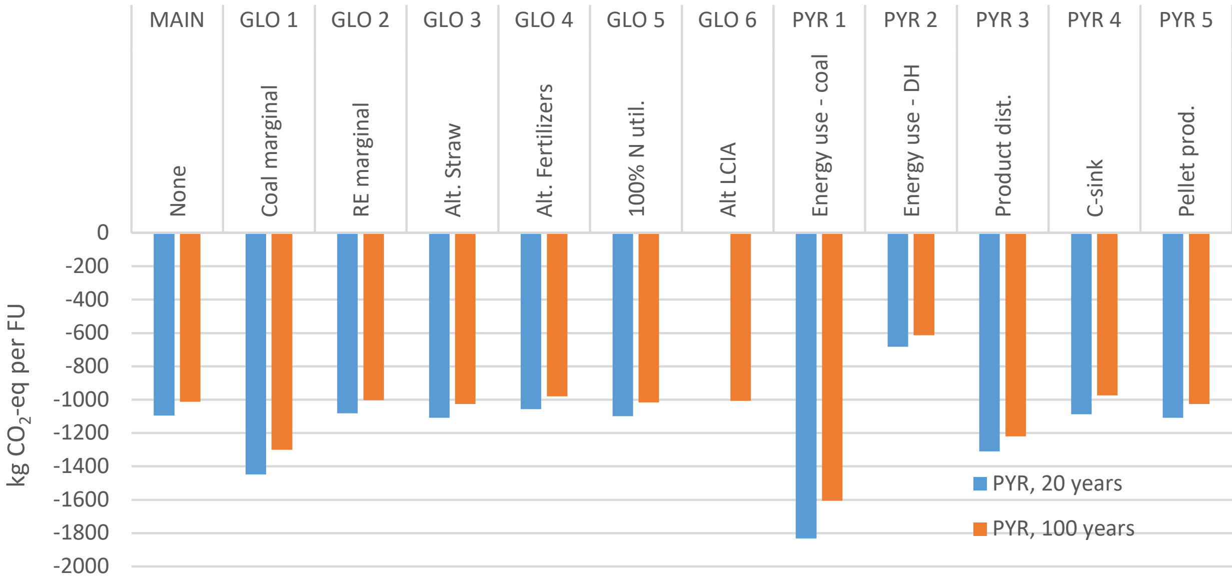


Figure 28: *Absolute results of* *<u>the pyrolysis scenario</u>* *with influence of all tested parameters. GLO 6 is only applicable in a 100 year perspective.*

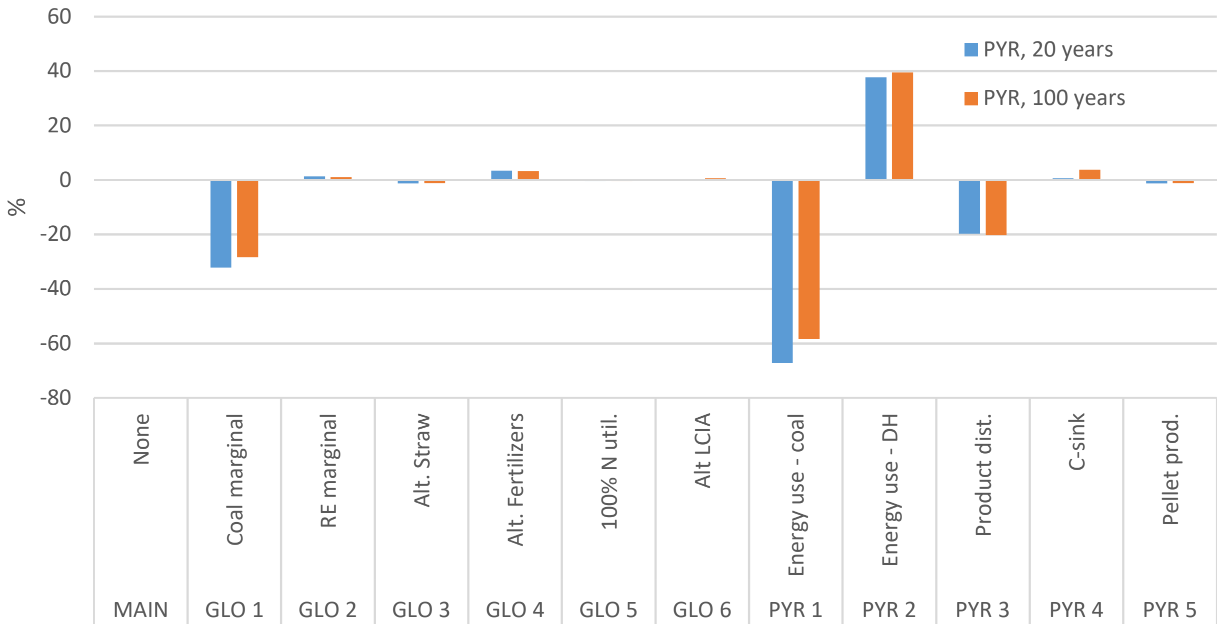


Figure 29: *Relative difference of* *<u>the pyrolysis scenario</u>* *under influence of all tested parameters and compared to the main model results. A positive result implies an increased Climate Footprint of the system compared to the main model results. GLO 6 is only applicable in a 100 year perspective.*

As with the biogas scenario, the most sensitive part of the pyrolysis system is also the energy product end-use. The best-case scenario indicate a substantial optimization potential from improved value end-use while the worst-case show a slightly smaller impact on results. This is due to the fact that a substantial part of the energy in the main model is already applied for marginal district heating which is equal to the worst-case scenario.

The distribution of the pyrolysis products – and especially the size of the condensable organic fraction >< the incondensable organic fraction in the gas, also has a substantial impact on the Climate Footprint of this system. The main driver behind this effect is the substantial substitution value of the bio-oil product from the pyrolysis compared to almost no substitution value of the heat product generated from the non-condensable fraction of the gas. This emphasize the importance of substitution value for the produced energy products. In cases where heat from the pyrolysis may abate emissions from e.g. natural gas based heat, then a large heat production may still prove highly valuable. However, when the built marginal is considered then the heat contributes with very little benefit and alternative uses of the gas should be investigated. There are several alternatives and some of them have been investigated for years. Two such alternatives are part of next-phase development of the SFT pyrolysis and are presented briefly in the final chapter 8 with “Suggestions for further work”. The carbon intensity of electricity and heat used and produced – and to a smaller extent, the biochar carbon-sink potential, are also significant. Sensitivities related to fertilizer substitution value (due to low biochar N content), straw composition, pellet process energy requirements, field N_2O emissions and alternative LCIA method are insignificant.

6.3 Overall, average results and indications of result uncertainty based on sensitivity assessment

Results from the sensitivity assessment are summarized in Figure 30 as overall average results with indication of uncertainty based on standard deviations of the impacts of the tested parameters. A category variation is included as “Excl. Energy SA” where energy-use-and-production related variations of the Sensitivity Assessment are excluded. The average results and standard deviations of this special category is thus produced without influence of the variations of GLO 1&2, BIO 1&2 and PYR 1&2.

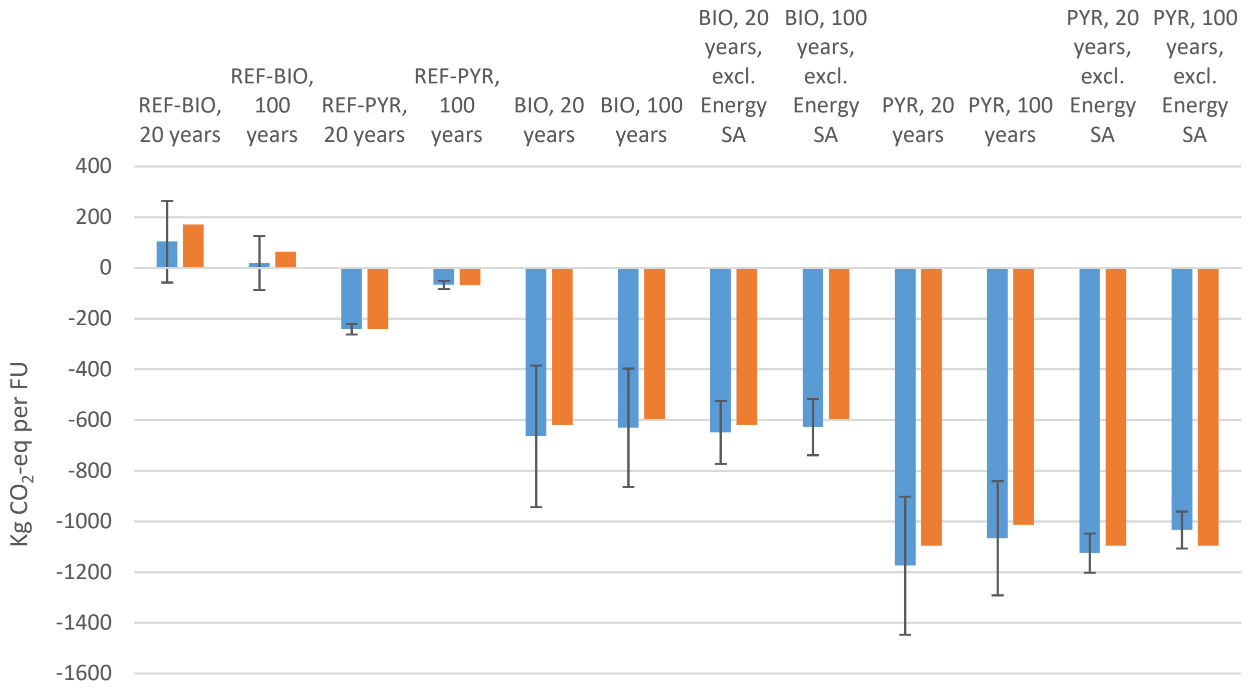


Figure 30: *Main results (orange) and average results from sensitivity assessment (blue). Deviation bars indicate standard deviation among the results from sensitivity assessment. Data from “Excl. Energy SA” exclude the energy-use-and-production related variations as investigated under GLO 1&2, BIO 1&2 and PYR 1&2.*

The results indicate that i) the manure part of the reference severely influence the uncertainty of the reference Climate Footprint, and ii) the energy-production-and-use aspects of the two scenarios also substantially increase uncertainty related to the Climate Footprint of these systems compared to the other assessed factors.

The original model results are very close to the average model results from all tests in the sensitivity assessment, but the standard deviation of the different data sets vary substantially. The uncertainty in the 20 year horizon assessment of both the biogas systems and the pyrolysis systems is slightly higher than in the 100 year horizon assessment. And the uncertainty of the biogas results without energy-aspects is slightly higher than for the pyrolysis scenario results.

The uncertainty remaining after removing energy-related aspects is quite low and the volatility in the remaining biogas results originate from uncertainty related to emissions from digestate storage and methane leak from the biogas plant as well as the potential effect of digestate acidification and carbon capture and storage. The reference for the pyrolysis scenario (REF-PYR) contain neither manure-related processes nor energy related processes and the results have a very narrow impact spectrum and very limited uncertainty. The reference for the biogas scenario may have Climate Footprints from the positive to the negative. The majority of the results indicate that the current practice for combined management of unused straw and manure induce climate change while certain configurations of this system may contribute to mitigate climate change. As was found previously, these beneficial configurations include manure tank acidification or similar stabilization of the manure. The Climate Footprint of the reference systems severely influence the potential climate benefit of transitioning to the relevant scenarios and the uncertainty of the Climate Footprint of the reference for the biogas scenario is substantial.

The potential climate impacts of transitioning from the established references to the suggested scenarios are thus influence by uncertainty and possibilities in both the reference system and the scenario. The calculated size of the potential climate impact – and the related uncertainty, of transitioning from each of the established references to the relevant scenario is illustrated in Figure 31.

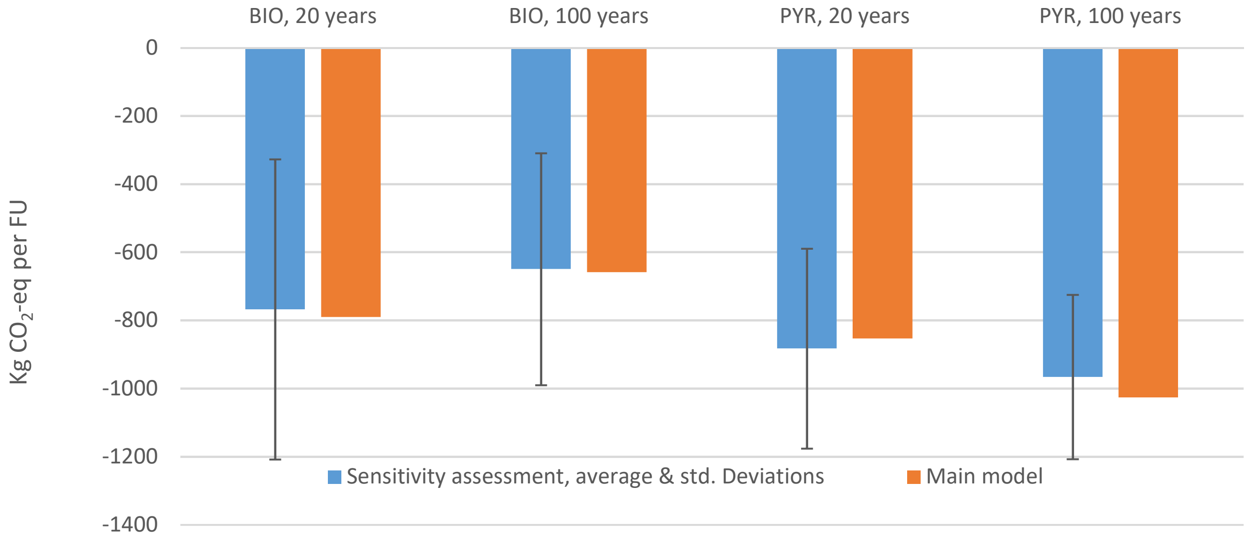


Figure 31: *Potential climate impact – and the related uncertainty, of transitioning from each of the two established references (the reference for the biogas scenario BIO and the reference for the pyrolysis scenario PYR) to their relevant scenarios. Blue bar show average impact from all results of the sensitivity assessment combined with the sum of standard deviations from reference and scenario assessment. Orange bar show results from main model.*

From these results it seem highly relevant to investigate the risks and potentials related to potential transition from the established reference systems to the proposed scenarios. The results indicate large uncertainty and/or climate impact spectrums. Risks are found to relate mainly to:

- Suboptimal energy product end-use (situated)
- The marginal energy technology (generic)
- Methane leaks and emissions
- Stability of amended substrates and the related carbon-sink potentials

On the other hand, there seem to be large additional potentials relating to:

- Optimized energy product end-use. Preferably through direct substitution of carbon-intense fuels in industrial processes.
- CCS on biogas CO_2
- Improved stability of amended substrates and the related carbon-sink potentials
- Optimized energy product distribution in pyrolysis process
- Stabilizing digestate and reducing methane leaks

The indicated span of results is calculated as the standard deviation on the results from the sensitivity assessment. The total span of the assessed parameters may be even larger. However, it is assumed that the provided results will the most relevant for scaling of the results in a general setting while situated, context embedded projects may have both higher and lower climate impacts than these spans indicate.

In addition, the results in Figure 31 are based on maximum and minimum single parameter spans. In actual implementation, the Climate Footprint of such projects may deviate from the main model results by an aggregated or stacked set of a number of these alternative parameters. The full range of the derived impact spectrums with aggregated impacts is provided in Figure 32.

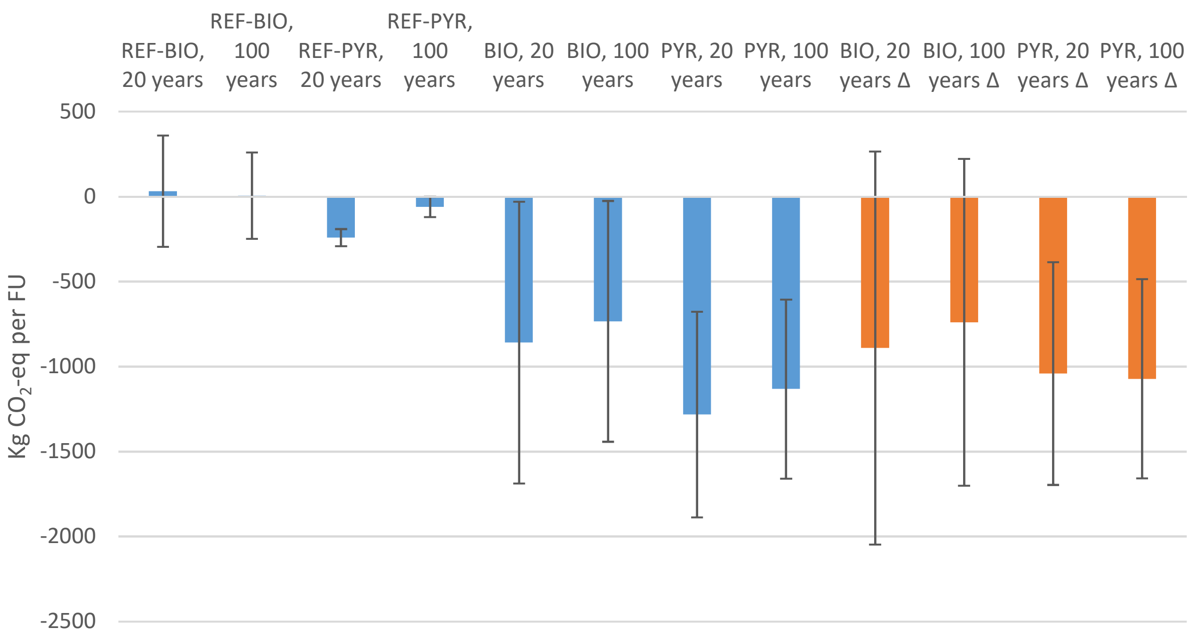


Figure 32: *Stacked variation of results from sensitivity assessment. All results included except for the alternative LCIA method. Blue bars are Climate Footprint of references and scenarios determined as average of the stacked best-case and stacked worst-case and with indications of the full span of results. Orange bars are the equivalent worst- and best-case climate change mitigation potential when transitioning from the established reference to the relevant scenario.*

From these results, the following extreme end impact spectrums have been estimated when transitioning from the established reference of amending straw directly into the soil to a new management practice based on either biogas or pyrolysis:

- When establishing new plants for co-digestion of straw and manure, the impact on climate change can range from a net climate change increasing effect of around 250 kg CO_2-equ per metric ton straw to a net climate change mitigating effect of around 2050 kg CO_2-equ per metric ton straw in a 20 year perspective. In a 100 year perspective the impact on climate change can range from a net climate change increasing effect of 200 kg CO_2-equ per metric ton straw to a net climate change mitigating effect of 1700 kg CO_2-equ per metric ton straw.
- When establishing new plants for pyrolysis of straw the impact on climate change there will in all cases be a net climate change mitigating effect, but the size of the effect may vary substantially. In a 20 year time horizon, the climate change mitigation effect may be around 400 - 1700 kg CO_2-equ per metric ton straw. In a 100 year time horizon, the climate change mitigation effect is found to be around 500 - 1650 kg CO_2-equ per metric ton straw.

More than anything else, the huge spans of results should make it clear that this type of project need to be thoroughly developed and planned to avoid sub-optimal or even problematic climate effects. On the other hand, the results also indicate that there is a huge optimization potential compared to average results and the main model. New technical R&D combined with improved project planning strategies encompassing quantitative sustainability assessment should be considered as a way to investigate – and perhaps even release, these additional climate change mitigation potentials from increased straw utilization.

7 National scale climate impact potential of biogas- and pyrolysis based straw management

In the introduction it was described how much uncollected straw there is produced in Denmark. On average this amounts to around 2.5 million metric ton straw per year during 2010-2020. In the present study it is investigated how large the Climate Footprint of the current management of this straw compared to the proposed management in biogas- and pyrolysis systems. Approximately 1/3rd of the straw is assumed used in biogas plants for co-digestion of animal manure. The remaining 2/3^{rds} of the straw is assumed converted in pyrolysis systems. The established reference of manure management has to be taken into account when assessing the potential impact of the biogas process as the straw will facilitate increased manure treatment and thus avoid greenhouse gasses from conventional tank storage.

Assuming average straw and manure compositions and system layouts as described in the present study, it is calculated how large the Climate Footprint of the different reference systems and scenarios are on a Danish, national scale. Main data used for the calculations are provided in **Table 16** and **Table 17** below in 20 and 100 year time perspectives. Results are calculated both on basis of the main set of model results and the spans identified in the sensitivity assessment. The applied ranges are not from the aggregated assessment of the full extreme end impact spectrum, but instead made from the full range of single-parameters results from the sensitivity assessment except for the results with alternative LCIA method.

***Table 16**: Main parameters for calculation of Climate Footprint Assessment results & climate change mitigation potentials of straw management, 20 year perspective*

	Specific Climate Footprint [Kg CO_2-equ per metric ton straw]		Straw and manure treated in new system
	Main model results	Average + Span from sensitivity assessment (not aggregated)	Mio metric ton, wet weight
REF-PYR: Straw reference	-242	-242 ± 21	
REF-BIO: Straw + manure reference	171	104 ± 161	
BIO: Anaerobic co-digestion of straw and manure	-620	-664 ± 279	0.83 mio t straw & 4.7 mio t manure
PYR: Straw pyrolysis	-1095	-1174 ± 273	1.67 mio t straw

***Table 17:** Main parameters for calculation of Climate Footprint Assessment results & climate change mitigation potentials of straw management, 100 year perspective*

	Specific Climate Footprint [Kg CO_2-equ per metric ton straw]		Straw/ manure treated in new system
	Main model results	Average + Span from sensitivity assessment (not aggregated)	Mio metric ton, wet weight
REF-PYR: Straw reference	-69	-67 ± 16	
REF-BIO: Straw + manure reference	63	19 ± 107	
BIO: Anaerobic co-digestion of straw and manure	-596	-630 ± 234	0.83 mio t straw & 4.7 mio t manure
PYR: Straw pyrolysis	-1013	-1066 ± 225	1.67 mio t straw

Based on these parameters, the potential climate mitigation effect of transitioning from the established reference for management of 2.5 mio metric ton straw and 4.7 mio metric ton manure to the suggested new system comprised of biogas and pyrolysis is calculated. The results are provided in **Table 18**.

***Table 18:** Danish, national scale calculations of the potential climate mitigation effect of transitioning from the established reference for management of 2.5 mio metric ton straw and 4.7 mio metric ton manure to the suggested new system comprised of biogas and pyrolysis*

[All results in million metric ton CO_2-equ]	Main model results		Results based on sensitivity assessment averages and standard deviation spans	
	20 years	100 years	20 years	100 years
Deployment of new straw biogas facilities for co-digestion of 0.83 mio metric ton straw and 4.7 metric ton animal manure	0.66	0.55	0.64 ± 0.37	0.54 ± 0.28
Deployment of new straw pyrolysis facilities to convert 1.67 mio metric ton straw	1.42	1.71	1.47 ± 0.49	1.61 ± 0.40
Total climate change mitigation potential	2.1	2.3	2.1 ± 0.9	2.1 ± 0.7

The results indicate a beneficial climate change mitigation effect of 2-2.3 million metric ton CO_2-equ per year in 2030 if transitioning from direct straw amendment of 2.5 mio metric ton straw and tank storage of 4.7 mio metric ton manure to new management systems based on new biogas plants and new pyrolysis technology. As mentioned, these results are calculated with average and variation values based on un-aggregated results from the sensitivity assessment. This means that there may be many different project configurations that will yield results outside the spectrum from 2-2.3 million metric ton CO_2-equ per year. Lower impacts – as well as substantially higher impacts, may be obtained, and it is the therefore recommended to use some of the findings in the present study and similar works to guide both development, planning and implementation of such projects.

One particular initiative that may increase climate mitigation potential substantially is the deployment of CCS on biogas CO_2. The potential effect of CCS as determined in the sensitivity assessment is highly diluted in the calculations based on average values and standard deviations. Including the potential effect of biogas CCS directly on the main results indicate an increased potential of 57 and 60 kg CO_2-equ per FU in a 20 and 100 year perspective (see Appendix 5). Complete implementation on a Danish national scale would then increase the climate change mitigation potential of the biogas based straw management from 0.66 / 0.55 million metric ton CO2-equ per year to 0.95 / 0.85 million metric ton CO2-equ per year (20 year perspective / 100 year perspective). The total system climate change mitigation potential increase similarly with around 0.3 million metric ton CO2-equ per year.

In spring 2021, the Danish government issued a proposal for a climate mitigation strategy plan for the Danish agricultural sector. This plan included emission abatements from pyrolysis of up to approximately 2 mio metric ton CO_2-equ per year in 2030[24]. From the current Climate Footprint analysis it is argued that comprehensive pyrolysis of unused straw alone may not be sufficient to meet this target as a substantial share of the straw resource is needed for co-digestion with manure. However, together the two technologies can reach the 2 million metric ton target and with proper implementation and support mechanisms the investigated utilization of the straw resource may yield even higher mitigation effect.

7.1 Additional and alternative biomass resources for biogas and pyrolysis

For both the biogas and perhaps especially the pyrolysis technology, it may be relevant to investigate additional straw resource potentials as well as alternatives to straw. Total biogas capacity may be limited by the amount required for manure treatment while pyrolysis does not have this apparent limitation. On top of the 2.5 mio metric ton straw, there is a potential additional straw resource in the approximately 1.5 mio metric ton that is already used for energy purposes mainly through various combustion processes producing heat and power. Some of this capacity could be replaced with pyrolysis, or the boilers could have a pyrolysis "pre-treatment" stage where after the gas is burned in the existing boiler and the char extracted as biochar. However, as found in the sensitivity assessment, production of heat – and power as well, will not contribute much to the climate change impact of the project. This is also expected to be the case if straw is allocated from incineration to biogas production and use of the biogas to produce heat and power.

However, the potential of the biogas and pyrolysis technologies go beyond that of available straw. According to a study 2016 from KU by Morten Gylling et al., the current amount of available biomass can be profoundly increased with a series of different initiatives, including new species, new production systems etc. [79]. The results are presented in the figure below.

From the biomass resource projections above it is evident that in addition to straw and hay, the main biomass resources in 2016 were wood and manure. The situation changes significantly in the "Biomass" and "Environment" scenarios, mainly from a drastic increase in grass and beet biomass of 4-5 mio metric ton extra. Grass or grass pulp from grass refineries as well as beet or beet residues are also relevant for pyrolysis and already in the scope of the technological development at SFT as well as at AquaGreen. These biomasses may also be relevant in biogas, and may in some cases even be preferable to dry straw. All-in-all there is a vast biomass potential now and in the near future for expanded pyrolysis and biogas employment, the climate mitigation potential that can be expected from such activities may be in the scale of several mio metric ton CO_2-equivalent.

[24] https://www.regeringen.dk/nyheder/2021/regeringen-viser-vejen-til-at-reducere-co2-udslippet-i-landbruget-med-7-1-mio-metric tons/

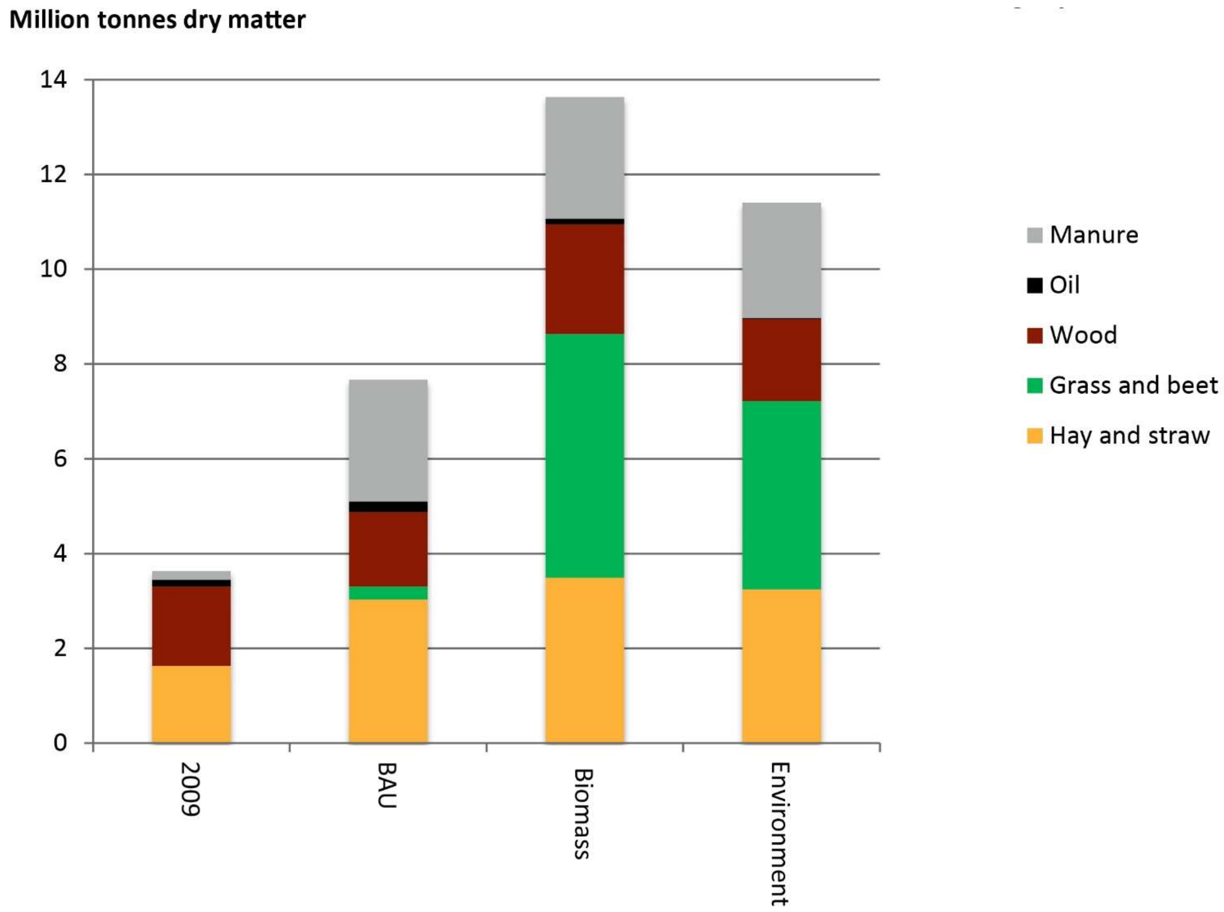


Figure 33: *Biomass ressource potential estimations in the "+10 million metric ton" study. From Gylling et al (2016) The + 10 million metric tonnes study: increasing the sustainable production of biomass for biorefineries* [79]

8 Conclusions and recommendations

The findings of the current study indicate a potential climate change mitigation effect of 2-2.3 million metric ton CO_2-equ per year in 2030 if transitioning from direct straw amendment of 2.5 mio metric ton straw and conventional tank storage of 4.7 mio metric ton manure to new management systems based on co-digestion of straw and manure in new biogas plants and establishment of new pyrolysis plants to convert straw into biochar and bio-oil. The suggested impact spectrum covers both a short time horizon of 20 years and a longer time horizon of 100 years. However, the full spectrum of potential Climate Footprint effects of the proposed straw management strategy was found to be substantially larger and the results of this study indicate that that there may be many different project configurations that will yield results outside the spectrum from 2-2.3 million metric ton CO_2-equ per year. Lower impacts – as well as substantially higher impacts, may be obtained, and it is therefore recommended to use some of the findings in the present study and similar works to guide both development, planning and implementation of such projects. Across all systems, the main dominating factors driving the results were:

- energy product end-use and fossil fuel substitution
- carbon-sink effects through amendment of organic material, biochar use and Carbon Capture and Storage (CCS) project options on biogas plants
- methane leaks and losses – and the related options for stabilization

A shift in the applied time horizon from 20 to 100 years, was found to substantially reduce the positive effect of manure stabilization and almost completely remove the carbon sink effect in the two reference systems and the biogas system. As a result, the modelling indicate that while straw – and digestate, amendment may have a substantial beneficial climate effect in the first years this is not very significant in the long run. The situation is different in the pyrolysis scenario where the carbon-sink effect related to biochar use is found to be both stabile, robust and very substantial covering around 50% of the total climate benefit of the system in both a short time and long term perspective.

The net differences from a 20 to 100 years horizon of the pyrolysis and biogas systems are found to be relative small, indicating a change of less than 10% in both cases. However, for the biogas system there are large underlying differences related to methane emissions and carbon sequestration. While carbon sequestration decrease to almost nothing from 20 to 100 years, so does the GWP of methane. In the end, the biogas footprint in the 100 year horizon is completely dominated by the value of natural gas substitution with only minor opposite effects of methane leaks and emissions.

For both the biogas and the pyrolysis parts of the system, it is found to be essential for the Climate Footprint to use energy products in an optimal way and secure carbon sequestration. Production of district heating yield almost no benefit in the general case. However, there may be situated projects where heat production may improve the Climate Footprint. This goes for both district heating projects and perhaps especially industrial process heat. Both the pyrolysis and biogas scenario may benefit from such heat application. However, the main model with substitution of natural gas in the biogas scenario and crude oil or heavy fuel oil in the pyrolysis scenario also give large and important contributions to the Climate Footprint. The large impact of carbon sequestration in the pyrolysis system render the technology capable of providing emission-reductions beyond the non-fossil society. And the most robust effect of the investigated systems across system variations and a changing temporal scope was found to be the carbon-sink effect of biochar amendment to soil. However, the biogas scenario may obtain a similar potential effect by one or both of the following routes:

- CCS of biogas CO_2 which may increase the climate benefit of the straw-manure co-digestion with as much as 50% compared to the main set of results.
- Separation of biogas digestate and drying and pyrolysis of the solid fraction

In addition, it was found that the biogas system benefit substantially from the treatment of manure during co-digestion of straw and manure. This is also an effect that may go beyond changes in the energy system. Without allocation of straw for manure treatment – and unless current manure management practice change drastically in other ways, the emissions from animal manure will persist and hamper the Climate Footprint of the full system. The benefit of co-digestion of animal manure with straw are especially prominent in the short time horizon. While stabilizing manure, it is important to be aware of the risk that this effect is somewhat reversed in the straw-part of the proposed management system where inherently dry and stabile straw biomass risk being rendered wet and biologically active in the biogas process. In the current study, digestate acidification was briefly assessed, but it is expected that thorough separation of the digestate and subsequent drying and pyrolysis of the fiber fraction may yield even more superior climate change mitigation potentials. Investigating this system is now under way in the GUDP-funded R&D project STABIL.

Scaling of the main model results indicate that a combined system with straw-manure co-digestion and straw pyrolysis of currently unused straw in the current agricultural system, may provide climate change mitigation potentials of 2-2.3 mio metric ton CO_2-equ compared to the current practice of direct soil amendment of the straw in both a long and short time horizon. The findings in the sensitivity assessment indicate several risks and further potentials that may both increase and decrease this impact potential substantially and a large scale impact spectrum of 1-3 mio metric ton CO_2-equ is proposed based on these results. In addition, the driving resource potential may be further expanded by several ways e.g. i) reallocating straw currently combusted in heat and power systems, ii) including pyrolysis treatment of manure or digestate fibers, iii) including marginal wood resources or iv) expanding the use and production of e.g. grass, grass pulp and beet derived biomass.

Overall, it is found that the applied method can be used to determine the climate impact potential of the assessed systems. However, a more integrated analysis with the aim to identify potential synergies between the three management strategies (reference, biogas and pyrolysis) is also recommended. Further work is also required to validate, enhance and expand the current work as proposed in chapter 9. New variations and synergies should be investigated and a broader selection of environmental impact categories should be addressed. In addition, the effect of increased straw utilization on the larger straw-based value network should be investigated in the light of system robustness and resilience under accelerating climate change related weather extremes as discussed in the introduction. Agriculture is changing. Food habits are changing. It will not be robust to develop 2030 perspectives for technology that are only viable in the current agricultural settings. Similarly, the products from the conversion also have to be flexible and valuable in the long run. Finally, it is essential to make sure that implementation of the desired systems are done in a way that maintain or build soil quality, soil life and soil productivity as the bio-based economy is fully dependent hereon. This may require in-depth analysis and substantial R&D on many aspects from practitioners level to the system level.

Under consideration of the described uncertainties and the impact spectrums identified in this study, the main results are found to be both relevant and useful to guide further efforts within technical R&D, planning and implementation of new straw management in a Danish context.

9 Suggestions for further work

As this study is a first-of-its kind and thus an initial assessment of a novel system, there are numerous ways to improve, validate, expand and elaborate on the study setup, the modeling, the sensitivity assessment and the interpretation of results.

Bringing in more agricultural expertise could shed lights on aspects related to the assumptions on fertilizer use and avoided emissions. Are there differences in the way that the 3 substrates would lead to avoided production of N, P and K fertilizer under the current – and near future, regulatory framework? Does the Danish case differ from the general case in this regard?

Going into more detail on the technical aspects of biogas production as well as on various agricultural aspects would also be relevant in regard to the scaling and expected implementation potential of the pyrolysis- and biogas technologies. A relevant discussion in this regard relates to determining thresholds and optimum strategies for amending straw >< digestate >< straw biochar to soil with regard to soil life requirements for organic material and labile carbon fractions. This relate again to soil type, crop rotation, use of cover crops and other aspects of the agricultural practice.

Investigating and modeling new value chains for large-scale use of bio-oil is very relevant to validate or challenge the scaled results on the pyrolysis scenario.

In addition, it would be highly relevant to elaborate on emissions and effects after soil amendment of straw, digestate and biochar. This should include a detailed assessment of especially nitrogen and carbon related emissions including emissions of NH_3, N_2O, NO_2^-, NO_3^- and CH_4 and focusing on emissions to air as well as to water bodies. Main task in this regard may be to include relevant differences in N_2O emissions from systems with application of nitrogen as straw-N >< digested straw-N >< and mineral fertilizer-N together with biochar.

Better N_2O data, especially related to soil emissions and storage of manure and digestate will be relevant for further assessments. Can be both better global/generic values for the average Danish case and more precise and more representative measurements for a situated context. The recent GUDP project STABIL will provide data and knowledge about two key aspects in regard to potential expansion of the current work:

- The STABIL project will provide data and models for assessment of pyrolysis of digestate fibers. In relation to the current work it would be highly relevant to consider integration of the two technologies to avoid emissions from digestate fibers, use pyrolysis heat to substitute natural gas used at the biogas plant and increase total system production of biochar.
- New data for a consistent comparison between pyrolysis and anaerobic digestion on management of straw as well as manure. In the current work, these two technologies are not obvious alternatives but instead regarded as supplementary. However, as it is both technically and commercially feasible to pyrolyse manure fibers it could be relevant to make a comparison of the two technologies on both manure and straw+manure.

In connection to these new potential studies, it could also become highly relevant to make a new assessment of biogas systems operating on the wet fraction of the straw resource, and in this regard conduct measurements on emissions from the open air silage process as well as the CN balance across this pretreatment method.

In general, all the sensitive parameters could be both interesting and relevant to investigate further. This include e.g.:

- Energy product substitution values and the wide variety of end-use options for upgraded biogas, pyrolysis oil, biogas-CO_2 etc.
- Carbon-sink effects of organic materials and biochar
- Emissions from digestate storage and manure storage
- Methane leak from biogas plant

Several additional/modified straw-use systems could also be relevant to include in next-phase assessment. This could involve e.g. Straw incineration for production of heat or combined heat and power and/or straw biogas followed by digestate pyrolysis. Straw incineration is currently a central straw use strategy in a Danish context, while the combination of anaerobic digestion and pyrolysis is an upcoming system design that may prove to have several synergetic benefits in specific cases. A study encompassing more comprehensive integrative efforts between e.g. direct biomass amendment + wet resource digestion with biogas production + pyrolysis of dry material fractions and dried residual fibers is also found to be both interesting and relevant.

As part of expanding the work in this regard, it is relevant to include next-phase SkyClean technology with production of methanol and/or CH_4 + bio-oil as illustrated in Figure 34 and Figure 35.

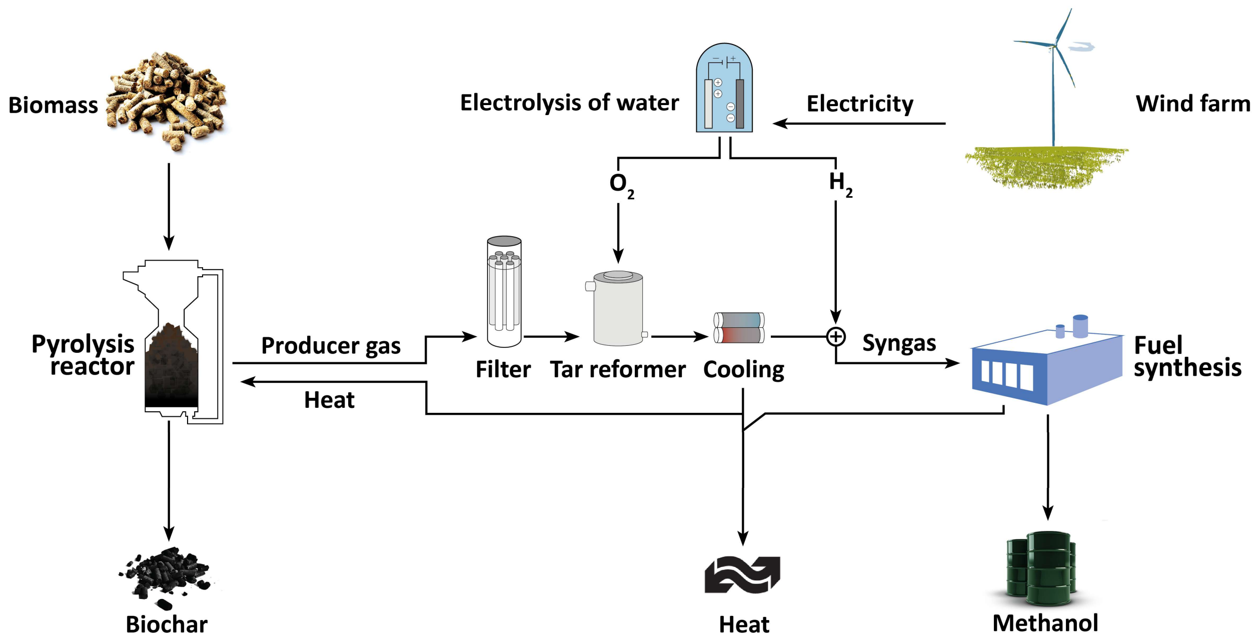


Figure 34: *SFT SkyClean phase 2 system with production of methanol*

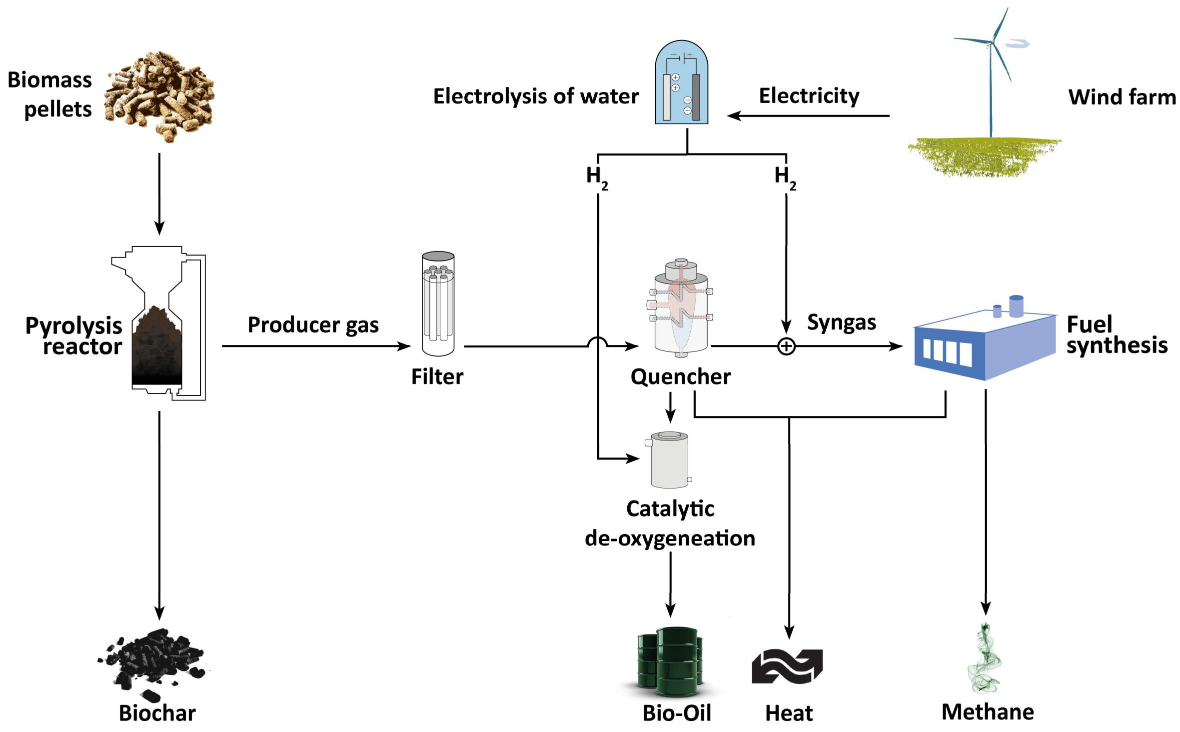


Figure 35: *SFT SkyClean phase 2 system with production of methane and bio-oil*

Similarly, increasing biogas yield using e.g. green hydrogen for methanisation of the CO_2 content in the biogas would also be relevant to model and compare with.

Finally, it is also suggested to expand the study with the following relevant additions:

- Include the effect of infrastructure and maintenance of e.g. pyrolysis plant, biogas upgrading and transport vehicles (cargo trucks)
- Include a detailed assessment of the indirect emission impacts of using biochar including:
    - Potential effects on N_2O emission reductions
    - Potential effects on water- and nutrient retention in the soil
    - Potential effects on soil drainage during flooding of farm soil
    - Potential effects on soil biota and the circumstances for soil life
    - Potential effects of increased cation exchange capacity
    - Potential effects of prolonged root growth, especially in sandy soils
    - Potential effects of new biochar value chains with cascade use of biochar prior to soil amendment
    - Potential effects of decreased soil density and thereby reduced drag energy requirements in the field
- Expand the CFA to a full Life Cycle Assessment (LCA) with multiple environmental impact categories relevant for the investigated systems e.g.
    - Eutrophication potential
    - Toxicity potentials
    - Air pollution potentials
    - Soil life potentials
    - Resource depletion potentials

    - Odor potentials

  Expanding the work into a full LCA (of for example the suggested impact categories) will make it possible to use the study to identify the straw management option that is the environmentally preferable alternative of the assessed systems.
- Expand with Social impact categories and economical Life Cycle Cost assessment

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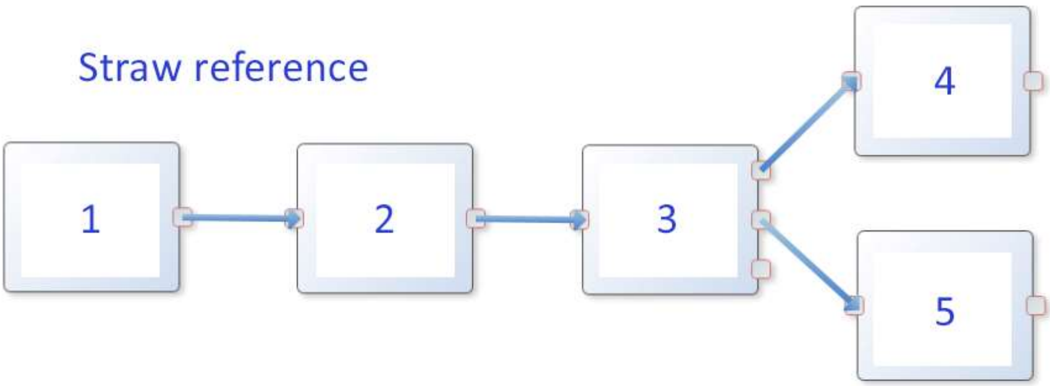
Appendix

Appendix 1: Straw reference flowsheet with input description

Reference for the pyrolysis scenario:



1: Material generation:

- 1 metric ton of case wheat straw generated

2: Field work:

- Use of machinery for straw harrowing: 0.0018 L diesel combusted per kg total wet weight
    - Ecoinvent 3.7.1 process *diesel, burned in agricultural machinery,GLO*

3: Soil effects:

- Separation into carbon (4) and fertilizer nutrients NPK (5)

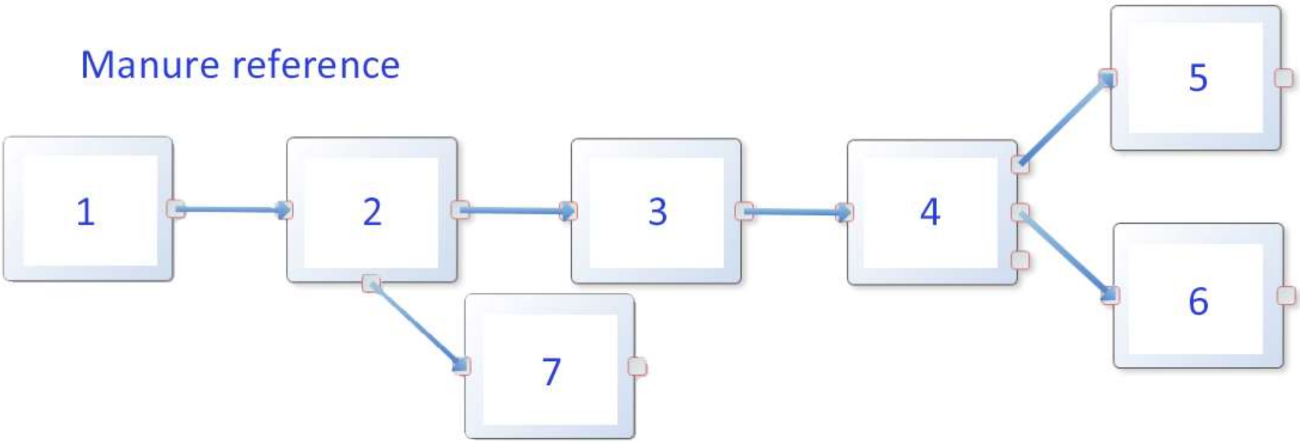
4: Carbon related soil effects:

- 13% of carbon persisting (sink) after 20 years
- 2% of carbon persisting (sink) after 100 years

5: NPK-related soil effects:

- P fertilizer: Ecoinvent 3.7.1 process *inorganic phosphorus fertiliser, as P2O5,market for inorganic phosphorus fertiliser, as P2O5,DK* (100% substitution efficiency)
- K fertilizer: Ecoinvent 3.7.1 process *inorganic potassium fertiliser, as K2O,market for inorganic potassium fertiliser, as K2O,DK* (100% substitution efficiency)
- N fertilizer: Ecoinvent 3.7.1 *inorganic nitrogen fertiliser, as N,market for inorganic nitrogen fertiliser, as N,DK* (40% substitution efficiency)

Reference for the biogas scenario: This reference include both the straw conversion described above as well as the manure treatment described below:



1: Material generation:

- 5666 kg of case mixed animal manure generated. 50% cattle manure & 50% pig manure.

2: Manure storage:

- 2x 3.36% of carbon to Emissions (7)
- 0.25% of nitrogen to Emissions (7)

3: Field work:

- Use of machinery for manure spreading: 0.0005 L diesel combusted per kg total wet weight
    - Ecoinvent 3.7.1 process *diesel, burned in agricultural machinery,GLO*

4: Soil effects:

- Separation into carbon (4) and fertilizer nutrients NPK (5)

5: Carbon related soil effects:

- 22% of carbon persisting (sink) after 20 years
- 3% of carbon persisting (sink) after 100 years

6: NPK-related soil effects:

- P fertilizer: Ecoinvent 3.7.1 process *inorganic phosphorus fertiliser, as P2O5,market for inorganic phosphorus fertiliser, as P2O5,DK* (100% substitution efficiency)
- K fertilizer: Ecoinvent 3.7.1 process *inorganic potassium fertiliser, as K2O,market for inorganic potassium fertiliser, as K2O,DK* (100% substitution efficiency)
- N fertilizer: Ecoinvent 3.7.1 *inorganic nitrogen fertiliser, as N,market for inorganic nitrogen fertiliser, as N,DK* (40% substitution efficiency)

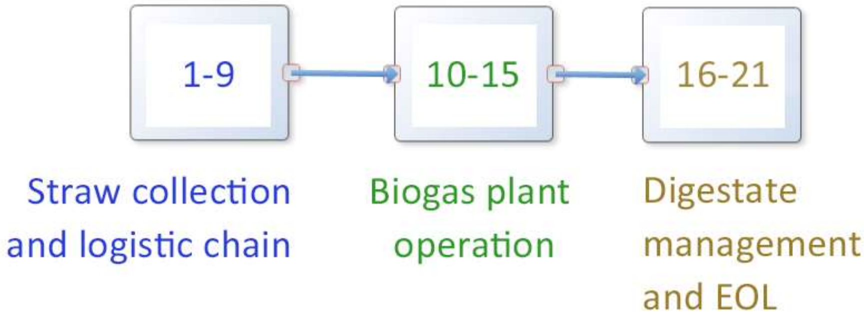
7: Emissions from manure storage

- All N transformed to N_2O with a conversion factor (weight) of 1 : 1.6
- 50% of C transformed to biogenic CH_4 with a conversion factor (weight) of 1 : 1.33
- 50% of C transformed to biogenic CO_2 with a conversion factor (weight) of 1 : 3.7

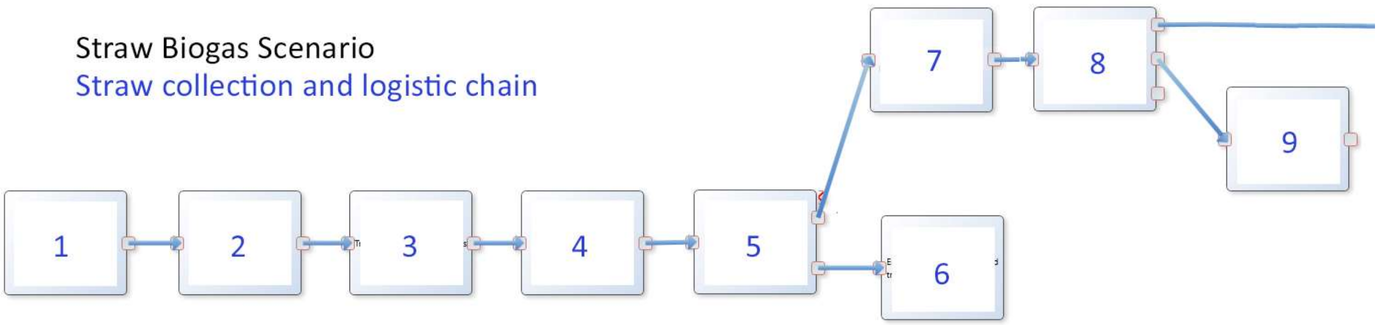
Appendix 2: Straw Biogas system flowsheet with input description

Biogas system consist of 2 parts – 1 system for straw digestion and 1 system for manure digestion.

Straw digestion system of biogas scenario:



Detailed descriptions below



1: Material generation:

- 1 metric ton of case wheat straw generated

2: Field work:

- Use of machinery for baling and handling straw: 0.0021 L diesel combusted per kg total wet weight
    - Ecoinvent 3.7.1 process *diesel, burned in agricultural machinery,GLO*

3: Transportation, straw bales from field to barn

- Ecoinvent 3.7.1 process *transport, freight, lorry 16-32 metric ton, EURO5,RoWTruck, 28-32t, Euro5, Highway*: 10 kg-km per kg total wet weight

4: Straw storage, 1 season

- No impact

5: Losses from storage and transportation

- 2% material losses of average properties and characteristics

6: Emissions from storage and transportation losses

- Only biogenic CO_2 emitted, no impact on Climate Footprint

3: Transportation, straw bales from barn to biogas plant

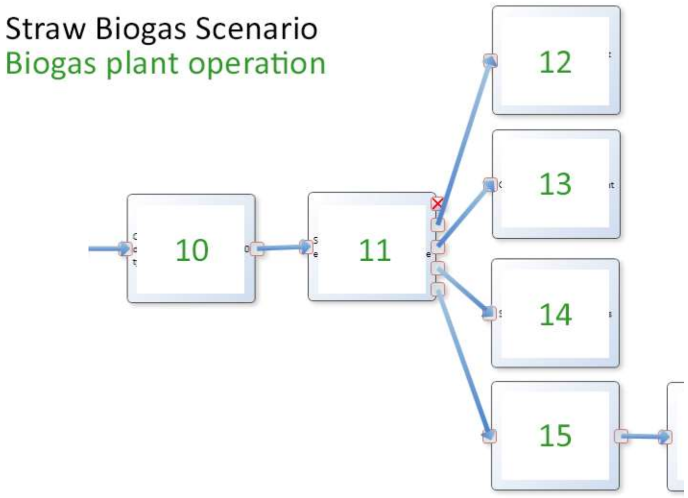
- Ecoinvent 3.7.1 process *transport, freight, lorry 16-32 metric ton, EURO5,RoWTruck, 28-32t, Euro5, Highway*: 25 kg-km per kg total wet weight

7: Straw pre-treatment (losses and input for cutting and grinding)

- Electricity for cutting and grinding; 0.05 kWh per kg straw (KAHL plant for straw cutting and grinding, information from Stiesdal A/S)
- Marginal electricity used, see section 3.1.3
- 1% material loss, average characteristics

8: Emissions from straw pre-treatment

- No direct emissions from pre-treatment processes



10: Utility use at Biogas plant

- Electricity for pumping, stirring etc. incl gas upgrading; 0.0065 kWh per kg TS
- Marginal electricity used, see section 3.1.3
- Heat requirements not included here as the heat energy requirements are deducted from production of biogas. See section 3.1.4

11: Anaerobic digestion of straw

- Material and energy transfer function as described in section 3.3 and section 3.4

12: Emissions from on-site heat production and production of district heating

- Only emissions of biogenic CO_2 i.e. no impact on Climate Footprint
- Marginal heat process used

13: Methane leak from digestion and gas upgrading

- 0.5 % of total biogas production assumed lost
- 57.8 wt% of biogas C is methane C

14: Substitution of natural gas

- Avoided production of 0.32 kg natural gas per kg biogas (CH_4 mass content)
- Natural gas modelled with Ecoinvent 3.7.1 process *natural gas, high pressure,market for natural gas, high pressure,DK*
- Avoided combustion of 1 MJ natural gas per MJ biogas
- Combustion of natural gas modelled with Easetech official 2020-01 v2 database process "Combustion of natural gas, DK 2010"

15: Transportation of digestate to de-central storage at farmer

- Ecoinvent 3.7.1 process *transport, freight, lorry 16-32 metric ton, EURO5,RoWTruck, 28-32t, Euro5, Highway*: 25 kg-km per kg total wet weight

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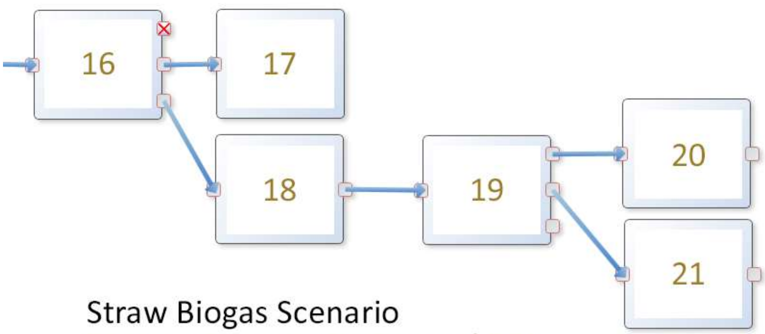


Straw Biogas Scenario
Digestate management and EOL

16: Digestate storage

- Mass transfer:
    - 2x 0.81% of total carbon and 0.25% of total nitrogen to "17 – greenhouse gas emissions from digestate storage"
    - The rest to "18 – field work, digestate"

17: Greenhouse gas emissions from digestate storage

- All N transformed to N_2O with a conversion factor (weight) of 1 : 1.6
- 50% of C transformed to biogenic CH_4 with a conversion factor (weight) of 1 : 1.33
- 50% of C transformed to biogenic CO_2 with a conversion factor (weight) of 1 : 3.7

18: Field work – digestate

- Distribution of digestate in field: 0.0005 L diesel per kg total wet weight distributed
    - Ecoinvent 3.7.1 process *diesel, burned in agricultural machinery,GLO*

19: Soil effects:

- Separation into carbon (20) and fertilizer nutrients NPK (21)

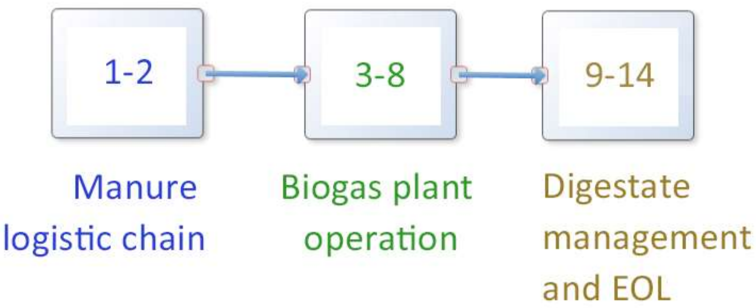
20: Carbon related soil effects:

- 22% of carbon persisting (sink) after 20 years
- 3% of carbon persisting (sink) after 100 years

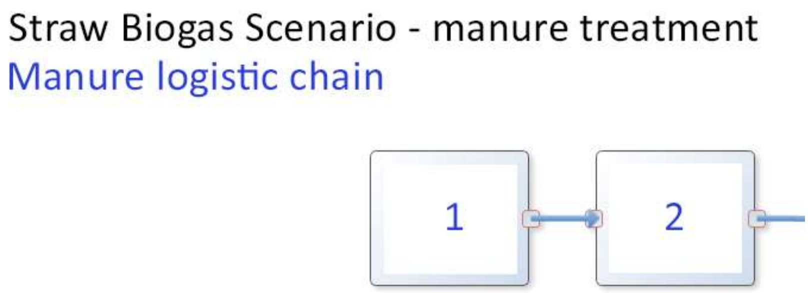
21: NPK-related soil effects:

- P fertilizer: Ecoinvent 3.7.1 process *inorganic phosphorus fertiliser, as P2O5,market for inorganic phosphorus fertiliser, as P2O5,DK* (100% substitution efficiency)
- K fertilizer: Ecoinvent 3.7.1 process *inorganic potassium fertiliser, as K2O,market for inorganic potassium fertiliser, as K2O,DK* (100% substitution efficiency)
- N fertilizer: Ecoinvent 3.7.1 *inorganic nitrogen fertiliser, as N,market for inorganic nitrogen fertiliser, as N,DK* (40% substitution efficiency)

Manure digestion system of biogas scenario:



Detailed descriptions below



1: Material generation:

- 5666 kg of case mixed animal manure generated. 50% cattle manure & 50% pig manure.

3: Transportation, manure from farm to biogas plant

- Ecoinvent 3.7.1 process *transport, freight, lorry 16-32 metric ton, EURO5,RoWTruck, 28-32t, Euro5, Highway*: 25 kg-km per kg total wet weight

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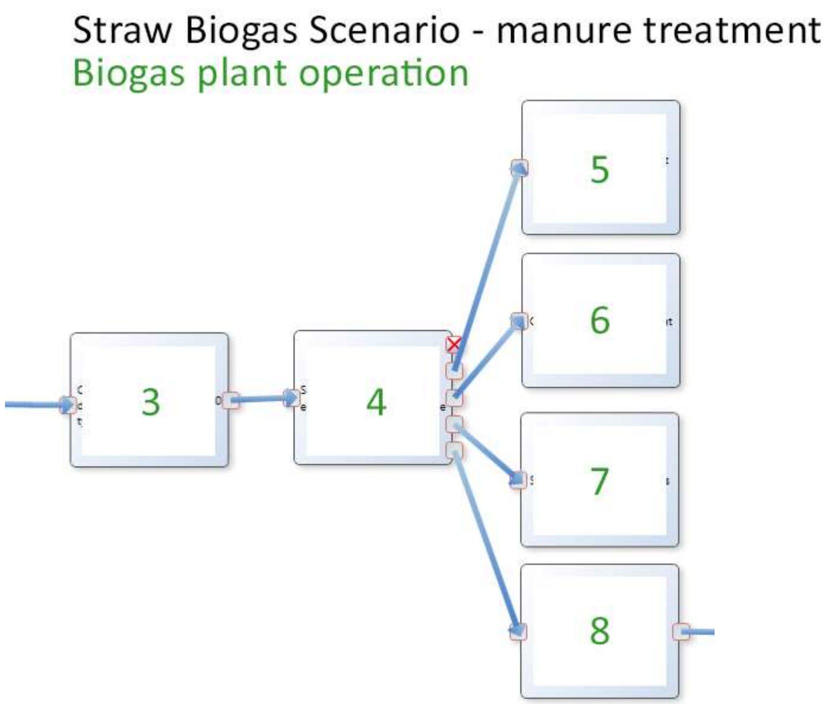

3: Utility use at Biogas plant

- Electricity for pumping, stirring etc. incl gas upgrading; 0.0065 kWh per kg TS
- Marginal electricity used, see section 3.1.3
- Heat requirements not included here as the heat energy requirements are deducted from production of biogas. See section 3.1.4

4: Anaerobic digestion of manure

- Material and energy transfer function as described in section 3.3 and section 3.4

5: Emissions from on-site heat production

- Only emissions of biogenic CO_2 i.e. no impact on Climate Footprint

6: Methane leak from digestion and gas upgrading

- 0.5 % of total biogas production assumed lost
- 57.8 wt% of biogas C is methane C

7: Substitution of natural gas

- Avoided production of 0.32 kg natural gas per kg biogas (CH_4 mass content)
- Natural gas modelled with Ecoinvent 3.7.1 process *natural gas, high pressure,market for natural gas, high pressure,DK*
- Avoided production and combustion of 1 MJ natural gas per MJ biogas
- Combustion of natural gas modelled with Easetech official 2020-01 v2 database process "Combustion of natural gas, DK 2010"

8: Transportation of digestate to de-central storage at farmer

- Ecoinvent 3.7.1 process *transport, freight, lorry 16-32 metric ton, EURO5,RoWTruck, 28-32t, Euro5, Highway*: 25 kg-km per kg total wet weight

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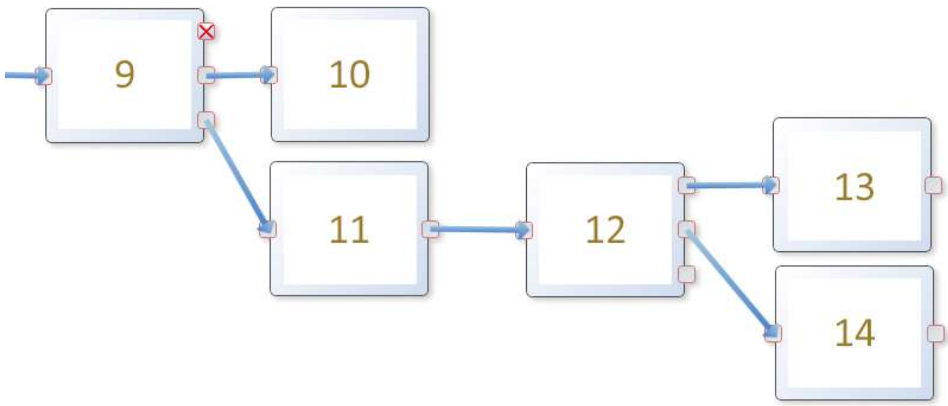


Straw Biogas Scenario - manure treatment
Digestate management and EOL

16: Digestate storage

- Mass transfer:
  - 2x 0.62% of total carbon and 0.25% of total nitrogen to "10 – greenhouse gas emissions from digestate storage"
  - The rest to "11 – field work, digestate"

17: Greenhouse gas emissions from digestate storage

- All N transformed to N_2O with a conversion factor (weight) of 1 : 1.6
- 50% of C transformed to biogenic CH_4 with a conversion factor (weight) of 1 : 1.33
- 50% of C transformed to biogenic CO_2 with a conversion factor (weight) of 1 : 3.7

18: Field work – digestate

- Distribution of digestate in field: 0.0005 L diesel per kg total wet weight distributed
  - Ecoinvent 3.7.1 process *diesel, burned in agricultural machinery,GLO*

19: Soil effects:

- Separation into carbon (20) and fertilizer nutrients NPK (21)

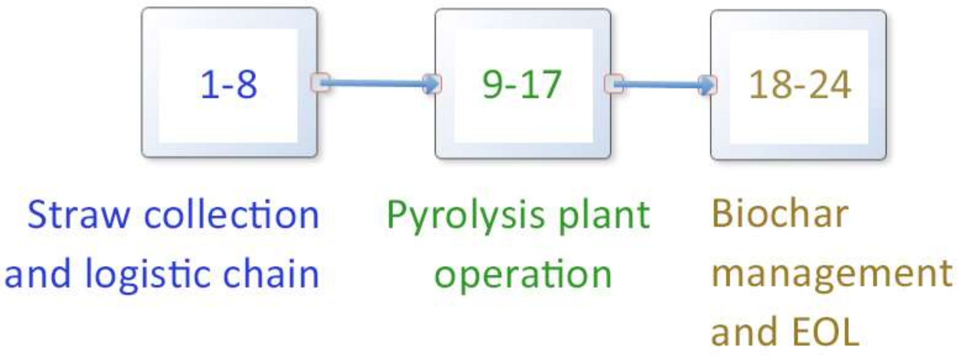
20: Carbon related soil effects:

- 22% of carbon persisting (sink) after 20 years
- 3% of carbon persisting (sink) after 100 years

21: NPK-related soil effects:

- P fertilizer: Ecoinvent 3.7.1 process *inorganic phosphorus fertiliser, as P2O5,market for inorganic phosphorus fertiliser, as P2O5,DK* (100% substitution efficiency)
- K fertilizer: Ecoinvent 3.7.1 process *inorganic potassium fertiliser, as K2O,market for inorganic potassium fertiliser, as K2O,DK* (100% substitution efficiency)
- N fertilizer: Ecoinvent 3.7.1 *inorganic nitrogen fertiliser, as N,market for inorganic nitrogen fertiliser, as N,DK* (40% substitution efficiency)

Appendix 3: Straw pyrolysis system flowsheet with input description



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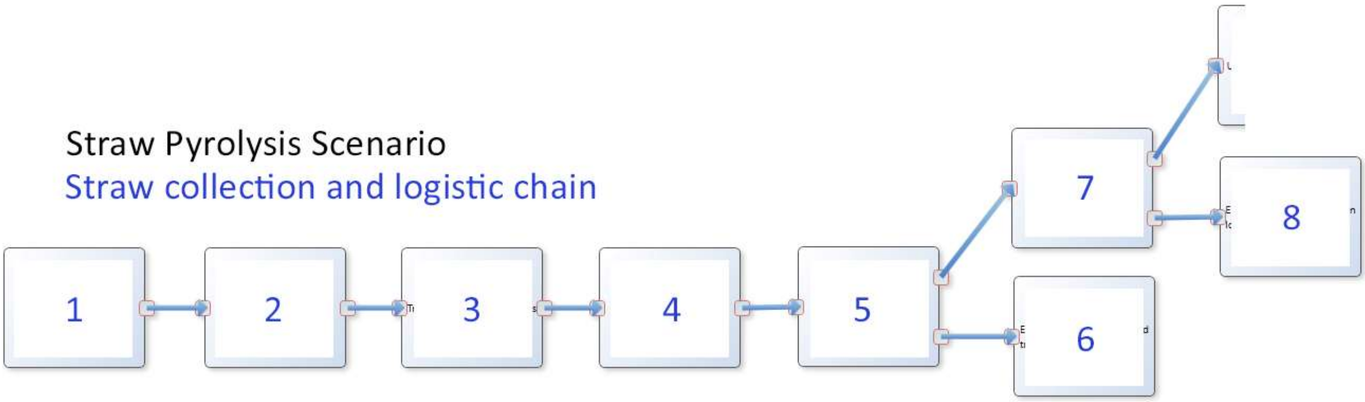


1: Material generation:

- 1 metric ton of case wheat straw generated

2: Field work:

- Use of machinery for baling and handling straw: 0.0021 L diesel combusted per kg total wet weight
  - Ecoinvent 3.7.1 process *diesel, burned in agricultural machinery,GLO*

3: Transportation, straw bales from field to barn

- Ecoinvent 3.7.1 process *transport, freight, lorry 16-32 metric ton, EURO5,RoWTruck, 28-32t, Euro5, Highway*: 10 kg-km per kg total wet weight

4: Straw storage, 1 season

- No impact

5: Losses from storage and transportation

- 2% material losses of average properties and characteristics

6: Emissions from storage and transportation losses

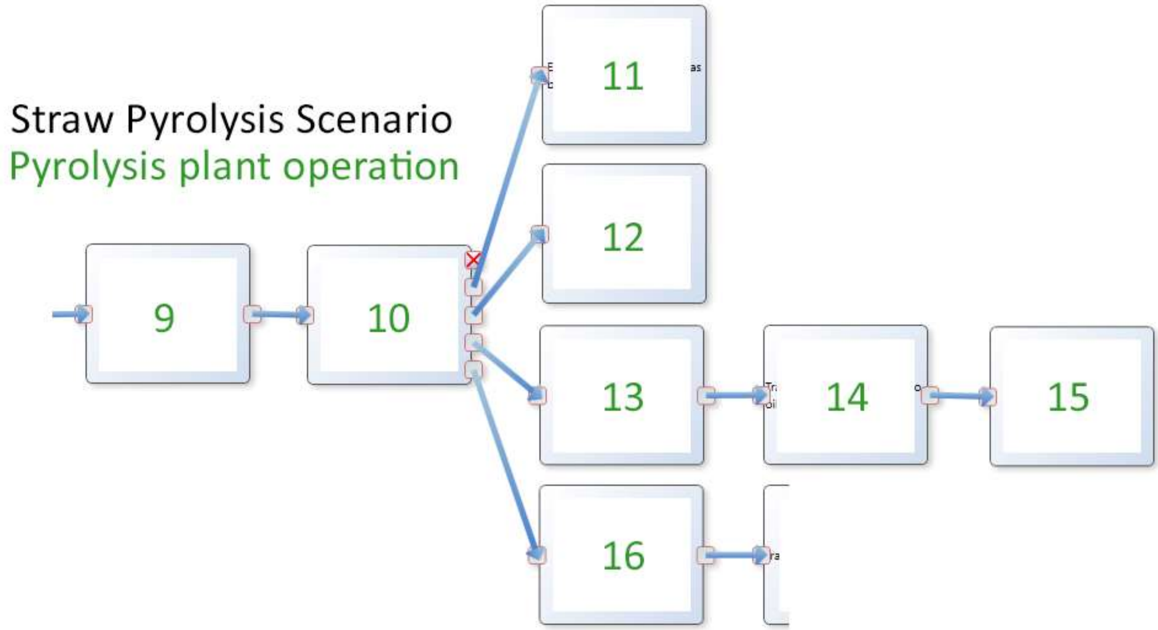
- Only biogenic CO_2 emitted, no impact on Climate Footprint

7: Straw pre-treatment (material loss and input for cutting, grinding and pelletization)

- Electricity for cutting, grinding and pressing; 0.15 kWh per kg straw (KAHL plant for straw cutting, grinding and pelletization, information from Stiesdal A/S)
- Marginal electricity used, see section 3.1.3
- 1% material loss, average characteristics

8: Emissions from straw pre-treatment

- No emissions with impact from pre-treatment processes



9: Utility use at Pyrolysis plant

- Electricity for conveyers, fans, control system etc.: 27.9 kW in 20 MW plant (Dall Energy calculation)
- Electricity for conveyers, fans, control system etc.: 0.006 kWh per kg TS
- Marginal electricity used, see section 3.1.3

10: Straw pyrolysis incl. heat integration

- Material and energy transfer function as described in section 3.3 and section 3.4

11: Emissions from pyrolysis gas burner

- Only greenhouse gas is biogenic CO_2 with no impact

12: Excess heat to district heating

- Substitution of district heating from combined heat pumps and wood biomass boilers, see section 3.1.3.
    - Substituting marginal heat

13: Storage and on-site use of Bio-oil

- 0.5% of the produced oil is used for occasional start-up heating of the plant after maintenance shut-down
- Only greenhouse gas emitted during oil combustion is biogenic CO_2 with no climate impact
- Storage heated with heat loss from pyrolysis plant
- No input or emissions associated with storage of the bio-oil

14: Transport to oil-refinery (bio-oil)

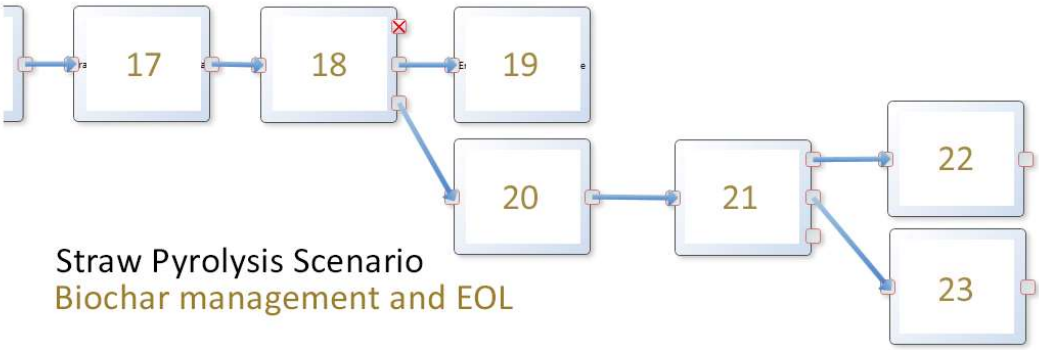
- Ecoinvent 3.7.1 process *transport, freight, lorry 16-32 metric ton, EURO5,RoWTruck, 28-32t, Euro5, Highway*: 500 kg-km per kg total wet weight

15: Substitution of fossil oil

- Avoided production and combustion of 1 MJ heavy fuel oil per MJ bio-oil
- Natural gas modelled with Ecoinvent 3.7.1 process *heavy fuel oil,market for heavy fuel oil,RoW*
- Combustion of natural gas modelled with Easetech official 2020-01 v2 database process "Combustion of residual oil, DK 2010"

16: Char quenching

- Add water to 30% of total wet weight
- Modelled with Ecoinvent 3.7.1 process *tap water,tap water production, underground water without treatment,Europe without Switzerland*



17: Transportation of biochar to de-central storage at farmer

- Ecoinvent 3.7.1 process *transport, freight, lorry 16-32 metric ton, EURO5,RoWTruck, 28-32t, Euro5, Highway*: 500 kg-km per kg total wet weight

18: Biochar storage, 3 months

- No emissions, no impact

19: Greenhouse gas emissions from biochar storage

- No emissions of greenhouse gasses with impact expected

20: Field work – Biochar

- Distribution of Biochar in field and subsequent harrowing: 0.00216 L diesel per kg total wet weight distributed
    - Ecoinvent 3.7.1 process *diesel, burned in agricultural machinery,GLO*

21: Soil effects:

- Separation into carbon (24) and fertilizer nutrients NPK (25)

22: Carbon related soil effects:

- 94% of carbon persisting (sink) after 20 years
- 85% of carbon persisting (sink) after 100 years

23: NPK-related soil effects:

- P fertilizer: Ecoinvent 3.7.1 process *inorganic phosphorus fertiliser, as P2O5,market for inorganic phosphorus fertiliser, as P2O5,DK* (100% substitution efficiency)
- K fertilizer: Ecoinvent 3.7.1 process *inorganic potassium fertiliser, as K2O,market for inorganic potassium fertiliser, as K2O,DK* (100% substitution efficiency)
- N fertilizer: Ecoinvent 3.7.1 *inorganic nitrogen fertiliser, as N,market for inorganic nitrogen fertiliser, as N,DK* (40% substitution efficiency)

Appendix 4: Numerical results from modelling of main systems

Main results with impact from modelling of reference system for biogas scenario [kg CO_2-eq per FU]:

REFERENCE FOR BIOGAS SCENARIO	100 years	20 years
Field work - straw	10.4	11.3
Field work - manure	16.3	17.8
Emissions from manure storage	278.0	684.9
Carbon sink - manure	-18.0	-132.0
Carbon sink - straw	-30.8	-200.3
NPK fertilizer effects - straw	-48.0	-52.6
NPK fertilizer effects - manure	-144.6	-158.4

Main results with impact from modelling of biogas scenario [kg CO_2-eq per FU]:

BIOGAS SCENARIO	100 years	20 years
Field work - digestate	1.4	1.6
Field work - straw	12.1	13.2
Field work - manure digestate	15.8	17.2
Transportation - straw bales	1.7	1.8
Transportation - straw bales to biogas plant	4.3	4.5
Transportation - manure	24.6	25.8
Transport to storage - straw digestate	2.2	2.3
Transport to storage - manure digestate	23.9	25.0
Cutting and grinding process - straw	7.4	8.1
Utilities - Biogas plant - straw	1.0	1.0
Utilities - Biogas plant - manure	5.6	6.1
CH_4 leak from biogas plant - straw	26.7	67.6
CH_4 leak from biogas plant - manure	10.6	26.8
Substitution of Natural gas - straw	-441.2	-454.4
Substitution of Natural gas - manure	-174.3	-179.5
Production of disctrict heating (straw only)	-1.1	-1.3
Emissions from straw digestate storage	80.6	194.3
Emissions from manure digestate storage	26.7	67.4
Carbon sink - straw digestate	-22.1	-161.9
Carbon sink - manure digestate	-10.3	-75.7
NPK fertilizer effects - straw digestate	-46.6	-51.0
NPK fertilizer effects - manure digestate	-144.6	-158.4

Main results with impact from modelling of reference system for pyrolysis scenario [kg CO_2-eq per FU]:

REFERENCE FOR PYROLYSIS SCENARIO	100 years	20 years
Field work - straw	10.4	11.3
Carbon sink - straw	-30.8	-200.3
NPK fertilizer effects - straw	-48.0	-52.6

Main results with impact from modelling of pyrolysis scenario [kg CO_2-eq per FU]:

PYROLYSIS SCENARIO	100 years	20 years
Field work - biochar	5.4	5.9
NPK fertilizer effects - biochar	-38.9	-42.5
Carbon sink - biochar	-538.6	-595.7
Utilities - Pyrolysis process	0.9	1.0
Field work - straw	12.1	13.2
Transportation - straw bales	1.7	1.8
Straw storage - 1 season	0.0	0.0
Pelletization process - straw	22.3	24.3
District heating production	-34.6	-40.0
Transport to storage - biochar	3.8	3.9
Transport to oil refinery - bio-oil	11.8	12.3
Char quenching	0.0	0.0
Substitution of fossil oil	-459.4	-479.7

Appendix 5: Numerical results from modelling of system alternatives in Sensitivity Assessment efforts

REF-BIO, 20 years

Name	MAIN	GLO 1	GLO 2	GLO 3	GLO 4	GLO 5	GLO 6	REF 1	REF 2	REF 3	REF 4	REF 5
Unit	None	Coal marginal	RE marginal	Alt. Straw	Alt. Fer-tilizers	100% N util.	Alt LCIA	C-sink	Field Work	Acidi-fication	Manure storage	Field N2O
Sum	170.6	170.6	170.6	163.4	342.6	122.4		79.6	199.8	-174.1	-210.2	
Field work	11.3	11.3	11.3	11.3	11.3	11.3		11.3	22.6	11.3	11.3	
Carbon-related effects	-200.3	-200.3	-200.3	-209.2	-200.3	-200.3		-240.3	-200.3	-200.3	-200.3	
Field work - manure	17.8	17.8	17.8	17.8	17.8	17.8		17.8	35.6	17.8	17.8	
Carbon-related effects - manure	-132.0	-132.0	-132.0	-132.0	-132.0	-132.0		-183.0	-132.0	-132.0	-137.3	
Emissions from manure storage	684.9	684.9	684.9	684.9	684.9	684.9		684.9	684.9	347.5	309.3	
NPK fertilizer effects	-52.6	-52.6	-52.6	-50.9	-10.7	-69.4		-52.6	-52.6	-52.6	-52.6	
NPK fertilizer effects - manure	-158.4	-158.4	-158.4	-158.4	-28.4	-189.9		-158.4	-158.4	-158.4	-158.4	

REF-BIO, 100 years

Name	MAIN	GLO 1	GLO 2	GLO 3	GLO 4	GLO 5	GLO 6	REF 1	REF 2	REF 3	REF 4	REF 5
Unit	None	Coal marginal	RE marginal	Alt. Straw	Alt. Fer-tilizers	100% N util.	Alt LCIA	C-sink	Field Work	Acidi-fication	Manure storage	Field N2O
Sum	63.2	63.2	63.2	63.4	216.7	19.5	-211.2	4.5	89.9	-77.1	-86.0	
Field work	10.4	10.4	10.4	10.4	10.4	10.4	10.1	10.4	20.7	10.4	10.4	
Carbon-related effects	-30.8	-30.8	-30.8	-32.2	-30.8	-30.8	-30.8	-60.1	-30.8	-30.8	-30.8	
Field work - manure	16.3	16.3	16.3	16.3	16.3	16.3	15.9	16.3	32.6	16.3	16.3	
Carbon-related effects - manure	-18.0	-18.0	-18.0	-18.0	-18.0	-18.0	-18.0	-47.4	-18.0	-18.0	-18.7	
Emissions from manure storage	278.0	278.0	278.0	278.0	278.0	278.0	0.0	278.0	278.0	144.6	129.6	
NPK fertilizer effects	-48.0	-48.0	-48.0	-46.5	-10.7	-63.2	-47.0	-48.0	-48.0	-48.0	-48.0	
NPK fertilizer effects - manure	-144.6	-144.6	-144.6	-144.6	-28.4	-173.1	-141.4	-144.6	-144.6	-144.6	-144.6	

REF-PYR, 20 years

Name	MAIN	GLO 1	GLO 2	GLO 3	GLO 4	GLO 5	GLO 6	REF 1	REF 2	REF 3	REF 4	REF 5
Unit	None	Coal marginal	RE marginal	Alt. Straw	Alt. Fer-tilizers	100% N util.	Alt LCIA	C-sink	Field Work	Acidi-fication	Manure storage	Field N2O
Sum	-241.6	-241.6	-241.6	-248.9	-199.6	-258.3		-281.6	-230.3			-232.5
Field work	11.3	11.3	11.3	11.3	11.3	11.3		11.3	22.6			11.3
Carbon-related effects	-200.3	-200.3	-200.3	-209.2	-200.3	-200.3		-240.3	-200.3			-200.3
NPK fertilizer effects	-52.6	-52.6	-52.6	-50.9	-10.7	-69.4		-52.6	-52.6			-43.6

REF-PYR, 100 years

Name	MAIN	GLO 1	GLO 2	GLO 3	GLO 4	GLO 5	GLO 6	REF 1	REF 2	REF 3	REF 4	REF 5
Unit	None	Coal marginal	RE marginal	Alt. Straw	Alt. Fer-tilizers	100% N util.	Alt LCIA	C-sink	Field Work	Acidi-fication	Manure storage	Field N2O
Sum	-68.5	-68.5	-68.5	-68.3	-31.2	-83.6	-67.7	-97.8	-58.1			-58.4
Field work	10.4	10.4	10.4	10.4	10.4	10.4	10.1	10.4	20.7			10.4
Carbon-related effects	-30.8	-30.8	-30.8	-32.2	-30.8	-30.8	-30.8	-60.1	-30.8			-30.8
NPK fertilizer effects	-48.0	-48.0	-48.0	-46.5	-10.7	-63.2	-47.0	-48.0	-48.0			-38.0

BIO, 20 years										
Name	MAIN	GLO 1	GLO 2	GLO 3	GLO 4	GLO 5	GLO 6	BIO 1	BIO 2	BIO 3
Unit	None	Coal marginal	RE marginal	Alt. Straw	Alt. Fertilizers	100% N util.	Alt LCIA	Energy use - coal	Energy use - DH	Biogas +10%
Sum	-619.6	-555.8	-631.0	-604.0	-448.9	-667.3		-1558.3	-105.3	-667.8
Field work - digestate	1.6	1.6	1.6	1.6	1.6	1.6		1.6	1.6	1.4
Carbon-related effects	-161.9	-161.9	-161.9	-169.2	-161.9	-161.9		-161.9	-161.9	-147.4
Utilities - Biogas plant	1.0	6.5	0.2	1.0	1.0	1.0		1.0	1.0	1.0
Field work - straw	13.2	13.2	13.2	13.2	13.2	13.2		13.2	13.2	13.2
Transportation - straw bales	1.8	1.8	1.8	1.8	1.8	1.8		1.8	1.8	1.8
Cutting and grinding process	8.1	50.5	1.4	8.1	8.1	8.1		8.1	8.1	8.1
CH4 leak from biogas plant	67.6	67.6	67.6	70.6	67.6	67.6		67.6	67.6	67.6
Transport to storage - digestate	2.3	2.3	2.3	2.3	2.3	2.3		2.3	2.3	2.1
Emissions from digestate storage	194.3	194.3	194.3	202.4	194.3	194.3		194.3	194.3	177.5
Substitution of Natural gas	-454.4	-454.4	-454.4	-444.3	-454.4	-454.4		-1127.2	-85.7	-499.8
Field work - manure digestate	17.2	17.2	17.2	17.2	17.2	17.2		17.2	17.2	17.2
Carbon-related effects - manure digestate	-75.7	-75.7	-75.7	-75.7	-75.7	-75.7		-75.7	-75.7	-75.7
Utilities - Biogas plant - manure	6.1	38.0	1.1	6.1	6.1	6.1		6.1	6.1	6.1
Transportation - manure	25.8	25.8	25.8	25.8	25.8	25.8		25.8	25.8	25.8
CH4 leak from biogas plant - manure	26.8	26.8	26.8	26.8	26.8	26.8		26.8	26.8	26.8
Transport to storage - manure digestate	25.0	25.0	25.0	25.0	25.0	25.0		25.0	25.0	25.0
Emissions from manure digestate storage	67.4	67.4	67.4	67.4	67.4	67.4		67.4	67.4	67.4
Substitution of Natural gas - manure	-179.5	-179.5	-179.5	-179.5	-179.5	-179.5		-445.4	-33.9	-179.5
Transportation - straw bales to biogas plant	4.5	4.5	4.5	4.5	4.5	4.5		4.5	4.5	4.5
Production of disctrict heating	-1.3	-17.3	-0.2	-1.3	-1.3	-1.3		-1.3	-1.3	-1.3
NPK fertilizer effects	-51.0	-51.0	-51.0	-49.4	-10.4	-67.2		-51.0	-51.0	-51.0
NPK fertilizer effects - Manure digestate	-158.4	-158.4	-158.4	-158.4	-28.4	-189.9		-158.4	-158.4	-158.4
Liquefaction – straw CO2	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	0.0
Road transport and storage boil-off – straw CO2	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	0.0
Ship transport and CO2-injection – straw CO2	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	0.0
Liquefaction – manure CO2	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	0.0
Road transport and storage boil-off – manure CO2	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	0.0
Ship transport and CO2-injection – manure CO2	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	0.0

BIO, 20 years - continued									
Name	MAIN	BIO 4	BIO 5	BIO 6	BIO 7	BIO 8	BIO 9	BIO 10	BIO 11
Unit	None	Biogas -10%	Digestate CH4 low	Digestate CH4 high	Acidification	CH4 leak high	CH4 leak low	C-sink	CCS
Sum	-619.6	-571.4	-754.6	-550.9	-714.8	-638.9	-521.0	-711.4	-973.3
Field work - digestate	1.6	1.7	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Carbon-related effects	-161.9	-176.4	-163.8	-160.9	-161.9	-162.1	-161.7	-224.5	-161.9
Utilities - Biogas plant	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Field work - straw	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
Transportation - straw bales	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Cutting and grinding process	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1
CH4 leak from biogas plant	67.6	67.6	67.6	67.6	67.6	54.1	135.2	67.6	67.6
Transport to storage - digestate	2.3	2.5	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Emissions from digestate storage	194.3	211.2	61.2	262.1	99.8	194.5	194.2	194.3	194.3
Substitution of Natural gas	-454.4	-408.9	-454.4	-454.4	-454.4	-454.4	-451.3	-454.4	-458.0
Field work - manure digestate	17.2	17.2	17.2	17.2	17.2	17.2	17.2	17.2	17.2
Carbon-related effects - manure digestate	-75.7	-75.7	-75.7	-75.7	-75.7	-75.8	-75.7	-105.0	-75.7
Utilities - Biogas plant - manure	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Transportation - manure	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8
CH4 leak from biogas plant - manure	26.8	26.8	26.8	26.8	26.8	20.9	53.5	26.8	26.8
Transport to storage - manure digestate	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Emissions from manure digestate storage	67.4	67.4	67.4	67.4	67.4	67.5	67.4	67.4	67.4
Substitution of Natural gas - manure	-179.5	-179.5	-179.5	-179.5	-179.5	-179.5	-178.3	-179.5	-167.2
Transportation - straw bales to biogas plant	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Production of disctrict heating	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3
NPK fertilizer effects	-51.0	-51.0	-51.0	-51.0	-51.0	-51.0	-51.0	-51.0	-51.0
NPK fertilizer effects - Manure digestate	-158.4	-158.4	-158.4	-158.4	-158.4	-158.4	-158.4	-158.4	-158.4
Liquefaction – straw CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.1
Road transport and storage boil-off – straw CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.3
Ship transport and CO2-injection – straw CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-276.1
Liquefaction – manure CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4
Road transport and storage boil-off – manure CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.1
Ship transport and CO2-injection – manure CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-109.0

BIO, 100 years										
Name	MAIN	GLO 1	GLO 2	GLO 3	GLO 4	GLO 5	GLO 6	BIO 1	BIO 2	BIO 3
Unit	None	Coal marginal	RE marginal	Alt. Straw	Alt. Fertilizers	100% N util.	Alt LCIA	Energy use - coal	Energy use - DH	Biogas +10%
Sum	-595.7	-530.6	-606.4	-581.2	-443.3	-638.9	-733.5	-1339.8	-83.9	-644.9
Field work - digestate	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.3
Carbon-related effects	-22.1	-22.1	-22.1	-23.1	-22.1	-22.1	-22.1	-22.1	-22.1	-20.1
Utilities - Biogas plant	1.0	6.4	0.2	1.0	1.0	1.0	0.9	1.0	1.0	1.0
Field work - straw	12.1	12.1	12.1	12.1	12.1	12.1	11.8	12.1	12.1	12.1
Transportation - straw bales	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Cutting and grinding process	7.4	49.4	1.2	7.4	7.4	7.4	7.3	7.4	7.4	7.4
CH4 leak from biogas plant	26.7	26.7	26.7	27.9	26.7	26.7	0.0	26.7	26.7	26.7
Transport to storage - digestate	2.2	2.2	2.2	2.2	2.2	2.2	2.1	2.2	2.2	2.0
Emissions from digestate storage	80.6	80.6	80.6	83.5	80.6	80.6	0.0	80.6	80.6	73.9
Substitution of Natural gas	-441.2	-441.2	-441.2	-431.3	-441.2	-441.2	-438.0	-974.5	-74.3	-485.3
Field work - manure digestate	15.8	15.8	15.8	15.8	15.8	15.8	15.4	15.8	15.8	15.8
Carbon-related effects - manure digestate	-10.3	-10.3	-10.3	-10.3	-10.3	-10.3	-10.3	-10.3	-10.3	-10.3
Utilities - Biogas plant - manure	5.6	37.2	0.9	5.6	5.6	5.6	5.5	5.6	5.6	5.6
Transportation - manure	24.6	24.6	24.6	24.6	24.6	24.6	24.3	24.6	24.6	24.6
CH4 leak from biogas plant - manure	10.6	10.6	10.6	10.6	10.6	10.6	0.0	10.6	10.6	10.6
Transport to storage - manure digestate	23.9	23.9	23.9	23.9	23.9	23.9	23.5	23.9	23.9	23.9
Emissions from manure digestate storage	26.7	26.7	26.7	26.7	26.7	26.7	0.0	26.7	26.7	26.7
Substitution of Natural gas - manure	-174.3	-174.3	-174.3	-174.3	-174.3	-174.3	-173.1	-385.1	-29.3	-174.3
Transportation - straw bales to biogas plant	4.3	4.3	4.3	4.3	4.3	4.3	4.2	4.3	4.3	4.3
Production of disctrict heating	-1.1	-15.0	-0.2	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1
NPK fertilizer effects	-46.6	-46.6	-46.6	-45.1	-10.4	-61.2	-45.5	-46.6	-46.6	-46.6
NPK fertilizer effects - Manure digestate	-144.6	-144.6	-144.6	-144.6	-28.4	-173.1	-141.4	-144.6	-144.6	-144.6
Liquefaction – straw CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Road transport and storage boil-off – straw CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ship transport and CO2-injection – straw CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Liquefaction – manure CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Road transport and storage boil-off – manure CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ship transport and CO2-injection – manure CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

BIO, 100 years - continued									
Name	MAIN	BIO 4	BIO 5	BIO 6	BIO 7	BIO 8	BIO 9	BIO 10	Bio 11
Unit	None	Biogas -10%	Digestate CH4 low	Digestate CH4 high	Acidification	CH4 leak high	CH4 leak low	C-sink	CCS
Sum	-595.7	-546.6	-648.6	-568.8	-633.1	-603.3	-554.4	-648.7	-953.0
Field work - digestate	1.4	1.6	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Carbon-related effects	-22.1	-24.0	-22.3	-21.9	-22.1	-22.1	-22.1	-58.1	-22.1
Utilities - Biogas plant	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Field work - straw	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1
Transportation - straw bales	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Cutting and grinding process	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
CH4 leak from biogas plant	26.7	26.7	26.7	26.7	26.7	21.4	53.4	26.7	26.7
Transport to storage - digestate	2.2	2.3	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Emissions from digestate storage	80.6	87.2	27.9	107.3	43.2	80.6	80.5	80.6	80.6
Substitution of Natural gas	-441.2	-397.0	-441.2	-441.2	-441.2	-441.2	-438.2	-441.2	-443.9
Field work - manure digestate	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8
Carbon-related effects - manure digestate	-10.3	-10.3	-10.3	-10.3	-10.3	-10.3	-10.3	-27.2	-10.3
Utilities - Biogas plant - manure	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
Transportation - manure	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6
CH4 leak from biogas plant - manure	10.6	10.6	10.6	10.6	10.6	8.3	21.2	10.6	10.6
Transport to storage - manure digestate	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9
Emissions from manure digestate storage	26.7	26.7	26.7	26.7	26.7	26.7	26.6	26.7	26.7
Substitution of Natural gas - manure	-174.3	-174.3	-174.3	-174.3	-174.3	-174.3	-173.1	-174.3	-165.0
Transportation - straw bales to biogas plant	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3
Production of disctrict heating	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1
NPK fertilizer effects	-46.6	-46.6	-46.6	-46.6	-46.6	-46.6	-46.6	-46.6	-46.6
NPK fertilizer effects - Manure digestate	-144.6	-144.6	-144.6	-144.6	-144.6	-144.6	-144.6	-144.6	-144.6
Liquefaction – straw CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6
Road transport and storage boil-off – straw CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.8
Ship transport and CO2-injection – straw CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-276.2
Liquefaction – manure CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2
Road transport and storage boil-off – manure CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9
Ship transport and CO2-injection – manure CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-109.0

PYR, 20 years

Name	MAIN	GLO 1	GLO 2	GLO 3	GLO 4	GLO 5	GLO 6	PYR 1	PYR 2	PYR 3	PYR 4	PYR 5
Unit	None	Coal marginal	RE marginal	Alt. Straw	Alt. Fertilizers	100% N util.	Alt LCIA	Energy use - coal	Energy use - DH	Product dist.	C-sink	Pellet prod.
Sum	-1095.4	-1448.5	-1081.6	-1110.1	-1058.3	-1100.0		-1832.6	-682.8	-1311.6	-1089.1	-1109.3
Field work - char	5.9	5.9	5.9	5.7	5.9	5.9		5.9	5.9	4.8	5.9	5.9
NPK fertilizer effects	-42.5	-42.5	-42.5	-41.5	-5.4	-47.1		-42.5	-42.5	-42.5	-42.5	-42.5
Carbon-related effects	-595.7	-595.7	-595.7	-622.4	-595.7	-595.7		-595.7	-595.7	-554.9	-589.3	-595.7
Utilities - Pyrolysis process	1.0	6.0	0.2	1.0	1.0	1.0		1.0	1.0	1.0	1.0	1.0
Field work - straw	13.2	13.2	13.2	13.2	13.2	13.2		13.2	13.2	13.2	13.2	13.2
Transportation - straw bales	1.8	1.8	1.8	1.8	1.8	1.8		1.8	1.8	1.8	1.8	1.8
Pelletization process	24.3	151.6	4.3	24.3	24.3	24.3		24.3	24.3	24.3	24.3	10.4
Heat to grid	-40.0	-525.3	-5.4	-39.0	-40.0	-40.0		-525.3	-40.0	-16.9	-40.0	-40.0
Transport to storage - biochar	3.9	3.9	3.9	3.8	3.9	3.9		3.9	3.9	3.2	3.9	3.9
Transport to oil refinery - bio-oil	12.3	12.3	12.3	12.2	12.3	12.3		0.0	0.0	28.0	12.3	12.3
Substitution of fossil oil / Energy product use	-479.7	-479.7	-479.7	-469.2	-479.7	-479.7		-719.1	-54.7	-773.6	-479.7	-479.7
Char quenching	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0

PYR, 100 years

Name	MAIN	GLO 1	GLO 2	GLO 3	GLO 4	GLO 5	GLO 6	PYR 1	PYR 2	PYR 3	PYR 4	PYR 5
Unit	None	Coal marginal	RE marginal	Alt. Straw	Alt. Fertilizers	100% N util.	Alt LCIA	Energy use - coal	Energy use - DH	Product dist.	C-sink	Pellet prod.
Sum	-1013.6	-1302.2	-1003.0	-1026.4	-980.2	-1017.7	-1008.3	-1607.2	-613.4	-1220.0	-975.6	-1025.8
Field work - char	5.4	5.4	5.4	5.2	5.4	5.4	5.2	5.4	5.4	4.4	5.4	5.4
NPK fertilizer effects	-38.9	-38.9	-38.9	-37.9	-5.4	-43.0	-38.0	-38.9	-38.9	-38.9	-38.9	-38.9
Carbon-related effects	-538.6	-538.6	-538.6	-562.8	-538.6	-538.6	-538.6	-538.6	-538.6	-501.8	-500.6	-538.6
Utilities - Pyrolysis process	0.9	5.9	0.1	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Field work - straw	12.1	12.1	12.1	12.1	12.1	12.1	11.8	12.1	12.1	12.1	12.1	12.1
Transportation - straw bales	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Pelletization process	22.3	148.3	3.7	22.3	22.3	22.3	21.8	22.3	22.3	22.3	22.3	10.1
Heat to grid	-34.6	-454.2	-4.6	-33.8	-34.6	-34.6	-33.2	-454.2	-34.6	-14.6	-34.6	-34.6
Transport to storage - biochar	3.8	3.8	3.8	3.6	3.8	3.8	3.7	3.8	3.8	3.1	3.8	3.8
Transport to oil refinery - bio-oil	11.8	11.8	11.8	11.6	11.8	11.8	11.6	0.0	0.0	26.8	11.8	11.8
Substitution of fossil oil / Energy product use	-459.4	-459.4	-459.4	-449.3	-459.4	-459.4	-455.1	-621.7	-47.4	-735.9	-459.4	-459.4
Char quenching	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Appendix 6: Final expert panel review report & author's note

Summary review statement

This study illustrates that the use of straw from Danish cereal fields in pyrolysis and biogas production brings significant climate benefits, compared to leaving the straw in the field. A panel of four external experts reviewed the study based on the international standards for LCA. Overall, the review panel finds that the study is well conducted. We find it meets the requirements of ISO 14040 and 14044. It is scientifically and technically valid. The input data are appropriate. A systematic assessment of key uncertainties is made. The interpretation of the results reflects the goal and limitations of the study, and the conclusions are sound. Since the study is consequential, they are relevant for decision-making aiming to reduce the climate impact of society. The numerical results, however, should be used with care, remembering that the study is not designed to be a comparison between pyrolysis and biogas production.

The study is well presented. It meets the many reporting requirements posed by ISO 14044 on a comparative assertion disclosed to the public. The report also includes much useful information about the systems investigated. It is largely consistent and transparent.

Introduction

The study

The study compares the climate impacts (detrimental and beneficial) of anaerobic digestion and pyrolysis of collectible straw from cereal fields in Denmark, compared to leaving the straw in the field for soil enhancement and nutrient recycling. It is conducted at Roskilde University by assistant professor Tobias Pape Thomsen – expert in sustainability assessments of thermochemical bioenergy, in particular gasification and pyrolysis – with some support from developers of pyrolysis technology at Technical University of Denmark and Stiesdal Fuel Technologies.

Prof. Thomsen aims for the study to adhere to the international standard for life cycle assessment (LCA), except for the limitation that this study cover climate impacts only.

The review

This critical review was based on the international standards for LCA: ISO 14040 and 14044. There is a specific international standard for carbon footprint (ISO 14067), which includes requirements not included in 14040 and 14044. However, these additional requirements are not found to be important for this report. The study is consequential (see Section 3.1.3), and we applied a consequential interpretation of ISO 14044 where, for example, system expansion is interpreted to imply substitution and accounting for the associated avoided environmental burdens.

Since the study is a comparative assertion disclosed to the public, the review was conducted by an external panel:

- Tomas Ekvall, adjunct professor in Environmental Systems Analysis at Chalmers University of Technology, and consultant in Tomas Ekvall Research Review & Assessment (chair),
- Bo Weidema, professor at the Danish Center for Environmental Assessment, Aalborg University, and senior consultant at 2.-0 LCA Consultants,

- Concetta Lodato, postdoc researcher in Circularity & Environmental Impact at the Technical University of Denmark, and
- Frank Rosager, head of Biogas Denmark

Tomas Ekvall and Bo Weidema are internationally recognized LCA experts, each with 30 years of experience. Concetta Lodato is an expert on process and life cycle modelling of biowaste treatment and bioenergy supply. She is also an expert on Easetech, the modeling software used in the study. Frank Rosager is an expert on anaerobic digestion, which complements the expertise on pyrolysis that contributed to the study.

The purpose of the review is to ensure that the methods used are consistent with the standard and scientifically and technically valid, that the input data are appropriate, that the interpretations reflect the goal and limitations of the study, and that the report is transparent and consistent.

The review panel compiled a list of review comments on a draft version of the report and discussed these with the author. The report was then significantly revised before this final review report was written. For example, the study initially compared pyrolysis and anaerobic digestion as two competing options for straw utilization, but now assesses pyrolysis and digestion as two complementary technologies. The revision meant most of the original comments were dealt with before the report was finalized.

Comments

Despite our overall positive review statement, the review panel still has a few pointers. These are listed below.

The aim of the study

The only diagram in the Summary presents the climate impact per tonne straw for different options of straw and manure management. This diagram and the associated text can easily be misinterpreted as a comparison between biogas production and pyrolysis. However, the study is not designed for such a comparison. Instead, the stated aim is to assess the combination of the two technologies (Section 2.2).

Calculations

In the final report, we found no errors in the models or calculations. However, the input data and method used for calculating or estimating the standard deviation in the sensitivity assessment is not transparent. A standard deviation is typically difficult to estimate in LCA, due to lack of sufficient data.

Results and their uncertainty

The report states that the results indicate a climate benefit of 2-2.3 Mtonne CO_2-eq per year for the combination of biogas production and pyrolysis. It also states that the actual climate benefit might be lower or higher than this range. In fact, the results of the sensitivity analysis, as presented in Table 18, indicate that the estimated climate benefit is in the range of 1-3 Mtonne CO_2-eq per year, which better reflects the uncertainty that can be expected from this kind of systems analysis.

Note that this assessment of the uncertainty is not based on extreme values but on estimates of the standard deviation.

Conclusions

A sentence at the middle of Page 71 repeats the numerical results 2-2.3 Mtonnes CO_2-eq from the 1st paragraph of the chapter, but assigns the full climate benefit to the pyrolysis only. This appears to be a mistake.

The report

The Summary should be self-explaining, but the bar diagram is difficult to understand without further explanations. These can be found in Chapter 6 on sensitivity assessments.

Author's note to final review-report

A minor revision of the report has been conducted after obtaining the final review-report. This revision included:

- Several text and grammar oriented changes related to a list of comments of editorial nature from the review panel
- Smaller changes in the formulation of a part of the conclusion and summary related to the two comments in the final review-report under "Results and their uncertainty" and "Conclusions".