MARCH 2014

Carbon footprint of bioenergy pathways for the future Danish energy system

MAIN REPORT

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Acknowledgement

An essential part of the project was the identification of candidates for marginal woody biomass supplies at a global scale. For this purpose, the partial equilibrium econometric model GLOBIOM was applied with great support from the developers of the model at International Institute for Applied System Analysis, IIASA, dr. Michael Obersteiner and dr. Petr Havlik. Runs of the GLOBIOM model under selected boundary conditions were used to identify probable origins of biomass supplies at varying market conditions. We truly appreciate the great support on this part.

During the project period, several three stakeholder workshops were carried out, and many valuable inputs were received. We hope, we have managed to pay all of them due respect.

We extend our appreciation to the critical review panel, with thanks for valuable input and many good references, and not least for critical inputs and insight into global biomass aspects. We learned a lot during this project, and we hope that we have been able to find our balance through this quite complex field.

Finally, we appreciate the opportunity given to us by the Danish Energy Agency by financing this study and for a good dialogue during the project including valuable contribution to prioritizing the effort.

Summary

Goal and scope

The overall goal of the project has been to quantify the greenhouse gas (GHG) consequences of alternative bioenergy pathways in the Danish energy system using a life cycle perspective. The life cycle methodology (LCA) is therefore at the core of this study. Focusing on GHG emissions alone, the study is a so-called Carbon Footprint assessment.

The project time frame is 2013 to 2050 and the timeline is broken down into four time periods in accordance with the key milestones of Danish energy policy, i.e. 2013-2020, 2020-2035, 2035-2050 and 2050+. These key milestones comprise that wind power makes up 50% of electricity consumption in 2020. In 2030, coal is completely phased out and so are oil boilers for heat. In 2035, all heat and power is renewable and in 2050 all energy and fuel supply for both the energy and transport sectors is fully renewable.

Geographical and technical scopes are defined by both the global market, the Danish context, and assumptions regarding potential biomass conversion pathways – biomass types and origin, conversion technologies, and types of energy supply.

To address the goal of the project and provide support for decisions on the strategy for developing the Danish energy system, the modeling is performed and carbon footprint results are considered at four modelling levels taking an increasingly systemic approach.

In all, 16 biomass conversion pathways were assessed representing the key conversion technologies today as well as some of the promising emerging technologies for a future renewable energy system. Each pathway was assessed in the four different time periods and on the background of each of the identified biomass marginal supplies, including 8 types of woody biomass as well as domestic manure and straw. All are assessed in a 20 year time horizon as well as a 100 year time horizon, and all are assessed at different system modelling levels. Moreover, 15 whole-system designs, comprising combinations of pathways, have been developed and assessed, all being 100 percent renewable based.

Results and interpretation

In conclusion, the carbon footprint of bioenergy per functional output is found to vary greatly. At one end, woody biomass from deforestation may under certain conditions emit more GHG per delivered MJ than the relevant fossil fuel comparator, whereas some pathways assuming plantation on low-carbon land may result in net removal of GHG from the atmosphere.

The main determinants of the footprint have been found to be:

- the nature and origin of the marginal biomass supply which in turn is judged to depend on background conditions, such as the global scale of biomass demand and the type and enforcement of land governance and GHG emission governance, and

- the nature and composition of the energy system in which the biomass conversion pathway is applied

As a result of these contextual dependencies, the footprints also vary over time, as e.g. the energy system develops and changes. A pathway and biomass type attractive in the near future may therefore very well become less attractive at a later point in time within the studied time frame.

Summarizing key aspects of the scope and assumptions of the study

It is part of the goal definition of the study to assess the carbon footprint of the various bioenergy pathways as applied in the changing Danish energy system as defined by the aforementioned milestones in the Danish energy policy. This development of the energy system is, thus, a key assumption in the study, and it is essential to the results.

The global-scale bioenergy demand has been assumed to develop towards a demand range of 100 – 200 EJ/year or more by 2050, corresponding to around 10 – 20 GJ/person/year with an estimate of above 9 billion people on Earth by 2050. This development of the global demand represents a background scenario with increasing global interest in bioenergy, assuming the world adapting a climate agenda aiming to stay below 2 degree C temperature increase and/or assuming increasing cost of fossil fuels rendering bioenergy more attractive. Against this scenario, the per capita Danish biomass demand for a fully renewable energy system will be comparatively higher, i.e. 45 – 120 GJ/person/year, and to depend on the degree of sophistication of the energy and transport system infrastructure as follows:

- 120 GJ/person/year in a renewable energy system of a ‘conventional’ infrastructure, i.e. in a system without significant electricity storage or electrochemical electricity conversion and without significant electrification of heat and transport infrastructure, and in which biomass is used for heat and power (in boilers and conventional combustion CHP and PP plants) and in transport (conventional biofuels, i.e. 1G biodiesel and 1G ethanol)

- 90 GJ/person/year in a more advanced system involving a maximum degree of electrification of transport (electric trains and battery cars for short distance person transport on road) and heat (heat pumps for almost all individual heating and district heating), as the electrification allows a higher share of wind and other renewable power production in the system. Biomass is in this system used in power production (conventional combustion CHP and PP plants) and transport (conventional biofuels)

- 60 GJ/person/year in the even more advanced system, in which hydrogen is used as a system integrator in power-to-gas or power-to-liquid-fuel scenarios through electrolysis. The reduced biomass demand in this system is due to a high degree of synergy in using excess fluctuating power for electrolysis, using the produced hydrogen to upgrade bio-carbon to energy dense fuels like methane or methanol, and using the waste heat of electrolysis, of biomass-to-fuel conversion (like thermal gasification) and of bio-C hydrogenation for heating purposes. Biomass is in this system prioritized for biogas fermentation and thermal gasification, and biogas and syngas are upgraded by hydrogen to methane or liquid fuels for transport. Very little biomass for combustion CHP, PP and boilers.

- 45 GJ/person/year in the most advanced system design, in which bio-C is further captured (as CO_2) from stationary facilities like fuel cells for flexible power production and hydrogenated again to methane or liquid fuels, thereby recycling part of the bio-C. Biomass is also in this system prioritized for biogas fermentation and thermal gasification, and biogas and syngas are upgraded by hydrogen to methane or liquid fuels for transport. Very little biomass for combustion CHP, PP and boilers. This system implies a demand for hydrogen as high as 20 GJ H_2/person/year.

These acknowledgements of the scale of biomass demand in design of a Danish renewable energy system are in line with the findings of a range of similar studies carried out by the Danish Energy Agency, the Danish electricity transmission system operator (energinet.dk), the Danish Climate Commission and a consortium of leading Danish universities in renewable energy system solutions (Lund et al., 2011).

Interpretation related to each main biomass category

The key biomass resources for a Danish renewable energy strategy, assessed in this study, are domestic agricultural residues of manure and straw, and domestic and imported woody biomass:

Manure conversion pathways (biogas)

The GHG emissions from using manure for energy through biogas conversion are net negative or close to zero throughout all time periods and irrespective of the dependencies on the energy system. The reason for this is that emissions of methane from storage and N_2O from storage and field application are larger for raw manure than from biogas digestate. From a carbon footprint perspective, therefore, using manure for biogas is attractive, and as the results of this study show, manure biogas conversion pathways in all cases come out with a carbon footprint in the lowest end compared to all other alternatives. This conclusion is found to be robust, but it should be noted that the benefit may decrease somewhat, as GHG emissions from both raw manure and digestate management may decrease in the future due to cleaner technology and better emission control from both storage and field application.

The carbon footprint of manure biogas does depend on the nature of the energy system and the global woody biomass marginal, as it is evident that it becomes less beneficial – for GHG reduction – to produce electricity and heat from biogas on a continuous basis as the wind power share of electricity increases. At some point, the benefit of converting biogas to pure methane as SNG, either by removing or hydrogenating CO_2 and storing it for the use in flexible power production or transport becomes very significant. Assuming the Danish energy policy milestone plan, this will be the case already after 2020. The reason for this is two-fold: firstly due to the *decreasing* GHG benefit of avoiding continuous power production compared to avoiding flexible power production or transport fuel, secondly due to the *increasing* GHG benefit of flexible power consumption by electrolysis, as this can derive increasingly from wind power.

A total of 1 % emission of produced methane throughout all conversion processes including fermentation and upgrading or CHP production has been assumed in the analysis. This emission can, however, at present reach levels around 2 % being reported as average (Nielsen et al., 2007) and up to 4 % in worst case, and this will significantly increase the carbon footprint from biogas conversion. It is, however, assumed that by future emission control and reduction from biogas reactors and of engines and fuel cells, total process emissions can be kept at levels of 1 % or below.

Straw conversion pathways

When straw residues are ploughed down, a part of the carbon stays in the soil, i.e. around 10-15% in a long term perspective. Incorporating straw carbon into the soil is the marginal alternative to using it for energy, which is reflected in the carbon footprint of straw, calculated at 24 g CO_2-eq./MJ in the 20 year horizon and 11 g CO_2-eq./MJ in the 100 year horizon. It is, however, important to note that this is very significantly reduced when the straw is used in a fermentation pathway that allows the hard bio-degradable part of the straw carbon to go back to the soil – as it does in case of using straw in biogas conversion e.g. as co-digestion with manure. Around 75% of the soil carbon will, in this case, be maintained compared to ploughing down the raw straw. This is a significant difference from using the straw in combustion or gasification pathways in which no carbon goes back to soil. In the whole-system designs, it is assumed that the functional output of the whole system includes maintaining a constant (and sufficient) soil carbon level. This approach renders the available straw potential (for energy purposes) a function of the conversion pathway. The straw available for energy in Denmark was, thus, found to vary significantly: when using the straw in biogas conversion, the Danish potential available for energy was around 50 PJ/year, whereas the potential was only 12.5 PJ/year when taking straw through combustion for CHP – as the balance of 37.5 PJ/year would have to be ploughed down directly in the CHP scenarios in order to maintain the same soil carbon level as in the biogas scenarios.

Comparing the use of straw for biogas and 2G ethanol, indicates the carbon footprint of the biogas co-digestion with manure pathways to be lower than the 2G ethanol pathway. The reason for this is two-fold. One reason is that the use of straw to add more carbon to the very dilute manure in practice makes it possible to get more manure into biogas, i.e. the conventional storage and field application of manure is assumed as an avoided marginal of using straw in biogas co-digestion with manure. Another reason is that the ethanol pathway has a somewhat lower fermentation yield plus a use of thermal energy for distillation, compared to biogas for which the gas escapes the liquor without any energy demand. Moreover, the manure-straw biogas pathways inherently ensures that the digestate, including the non-degraded straw, goes back to soil, which is possible but not equally likely in the case of the 2G ethanol pathway. It should be noted, however, that 2G ethanol & biogas combination with manure-straw co-fermentation is also an option (under implementation in Denmark, 2014). This pathway was not included in the study.

Prioritizing straw conversion pathways, there is a significant dependency on the nature and composition of the energy system in which the pathway is applied. As long as the district heating marginal and continuous power marginal are mainly based on fossil fuels, there is still a large GHG benefit of using straw in boilers and conventional combustion CHP and PP plants. But this benefit largely falls away, when the system marginals for heat and continuous power become increasingly based on wind power.

Wood conversion pathways

A relatively large potential, compared to today's scale of global, commercial bioenergy demand, exist for optimizing forestry for multiple outputs, i.e. increasing the biomass yield and using more thinnings and other biomass co-products from higher value timber production. Except for boreal forest thinnings in the 20 year horizon, thinning residues has a carbon footprint close to zero, and if forest intensification can become part of the response to a Danish biomass demand, the carbon footprint from this part becomes even negative.

Based on the scale of biomass harvest from forestry for timber, however, the limits of the scale at which thinnings and yield intensification of multi-output forestry can be the marginal biomass supply for bioenergy is judged to be around 5-10 EJ/year. Beyond this scale, increased biomass demand is judged more likely to derive from single-output short-rotation plantations, because the markets for the higher value products from multi-output forestry will, then, be saturated.

Developing an increasing market for wood pellets or chips, however, also call for caution, if it is to be avoided that woody biomass of other origin with higher carbon footprint enter the market, such as plantation on agricultural cropland or harvest from existing forest.

Plantation on cropland has become part of the marginal biomass supply for bioenergy policies already, e.g. in the case of biogas policies in both Denmark and Germany. In these policies, energy crops are allowed as part of the input – at a scale implying that the majority of the produced biogas may derive from the crop. If there is no regulation preventing this from happening, a similar situation may arise also for woody biomass, i.e. that woody energy crops from agriculture to some extent enter the wood pellet or wood chip market. On the other hand, a conscious policy of increasing the agricultural carbon stock by planting carbon rich, above and below ground, woody energy crops (e.g. miscanthus) at the expense of lower carbon stock/lower yield food or feed crops (e.g. barley) may result in a relatively small carbon footprint even including an ILUC factor. There is, however, still a large uncertainty involved in the estimation of such ILUC effects.

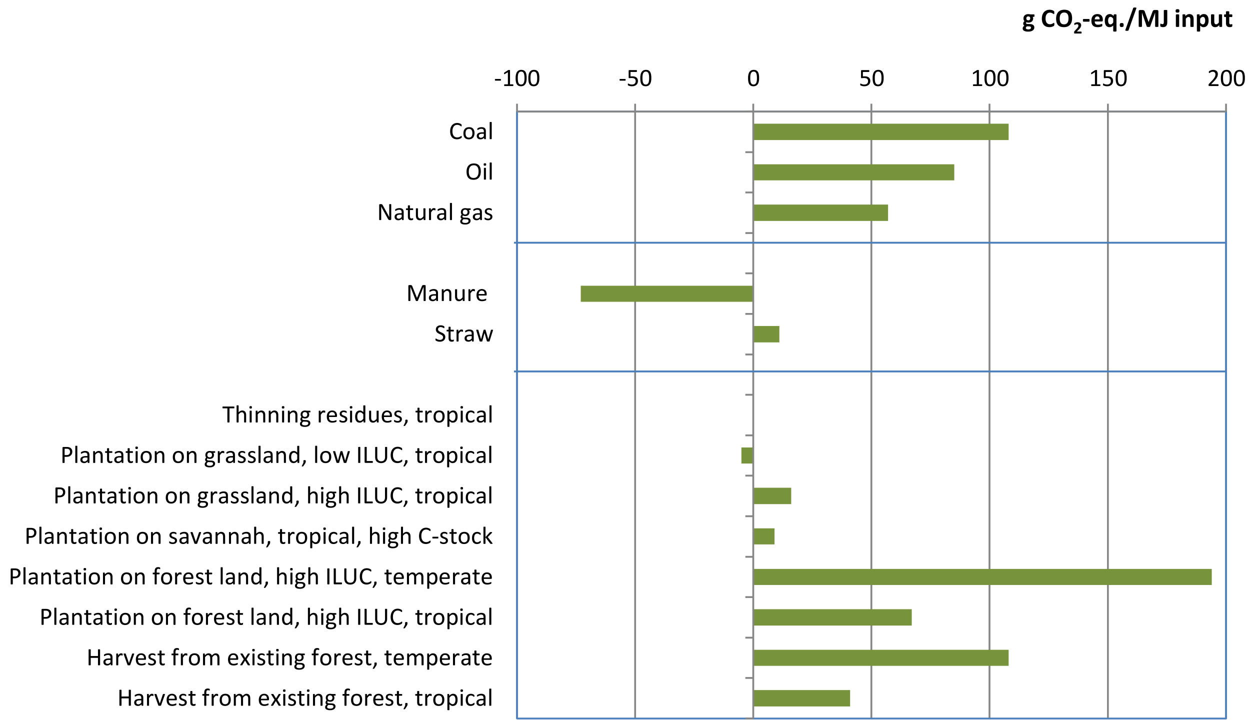
Regarding roundwood harvest from existing forest, statistics show that a minor but not negligible share finds use for energy purposes either directly as fuel wood in a household boiler, as chips or at wood pellet plants, predominantly when traded locally. This cannot be explained from a long term economic optimization perspective of a well-managed forest, as the profit margin of the higher value roundwood production for timber is much larger than for wood fuel, and it thus indicates that shorter term or private economy considerations, inheritance or self-dependency may guide management and harvest decisions for some forest owners. It also indicates that the price signal on a global international market may not direct local or informal wood markets in certain locations. As a result, this biomass may find its way to the global market, implying in this case a high carbon footprint, and that this implication should be given attention when discussing wood conversion pathways.

Balancing the findings, thinning and harvesting residues together with forest intensification are found to be able to constitute the predominant biomass supply on the shorter term up to a scale of 5-10 EJ/year of commercial global bioenergy demand, when supported by a conscious policy and governance for ensuring it. Also above 5-10 EJ/year of global biomass demand for bioenergy, there are still options for biomass supply hand-in-hand with increasing carbon stocks. Plantations on low carbon grassland, or intensifying grass yields, are such options likely to be candidates for a marginal biomass supply. Together with a policy of intensifying animal production and including ILUC from displaced animal grazing, it is found that the carbon footprint of supplying biomass from such plantation can be quite low, even though there is a risk of a high carbon footprint if displacing future high yielding tropical grasslands. Looking at the simulation results of the partial equilibrium econometric model, GLOBIOM, it is found that framework conditions of CO_2 price from 0 to 50 US$/ton and biomass prices from 1.5 to 5 US$/GJ from an economic perspective will limit the supply of biomass from plantation on grassland to something between 10 and below 40 EJ/year (on top of the supply of thinning and harvesting residues). Further, in a gradual development towards a global commercial biomass demand of just above 100 EJ/year in 2050, this limit will be reached somewhere between 2020 and 2030.

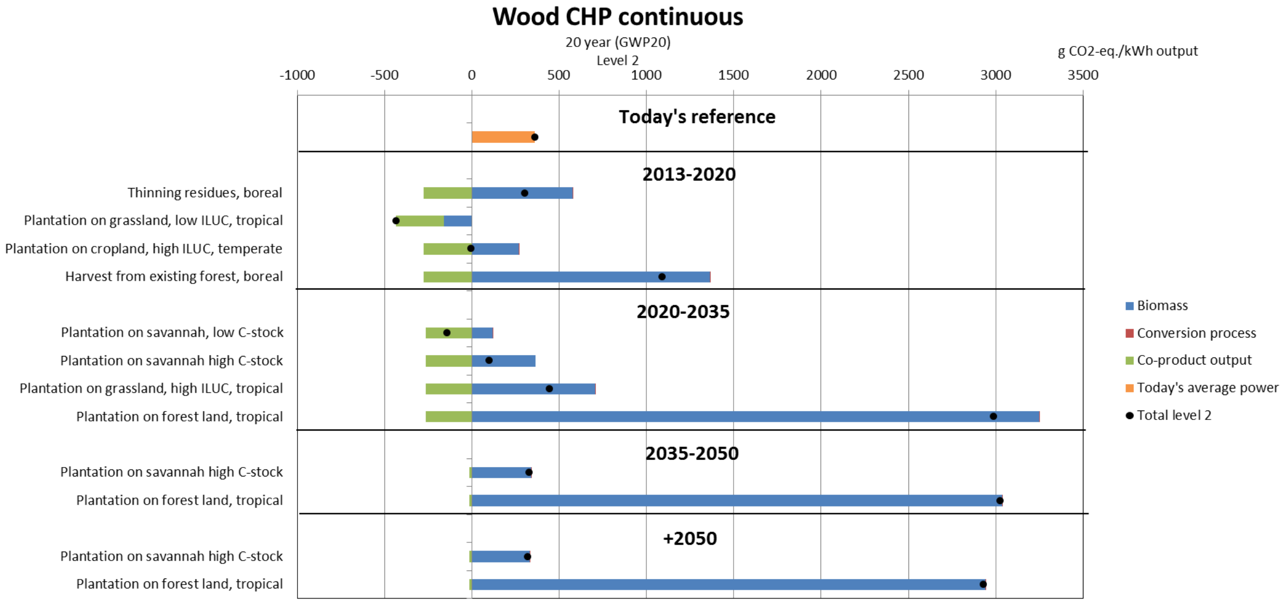
Therefore, at a scale of global commercial biomass demand for bioenergy of 50 EJ/year and beyond, plantation on other land like savannah is a more likely candidate for being the biomass marginal supply. The carbon footprint of biomass from plantation on savannah is found to be between 3 and 9 g CO_2-eq./MJ in the 100 year horizon and between 14 and 43 g CO_2-eq./MJ in the 20 year horizon. This is still significantly lower than the carbon footprint of fossil fuels and increasingly so when looking at even longer time horizons than 100 years. However, in this context, the carbon footprint is not necessarily the most decisive concern – compared to other issues like biodiversity. Also, at this large scale of biomass supply, aspects of supply security become a concern. At even higher scales of 100

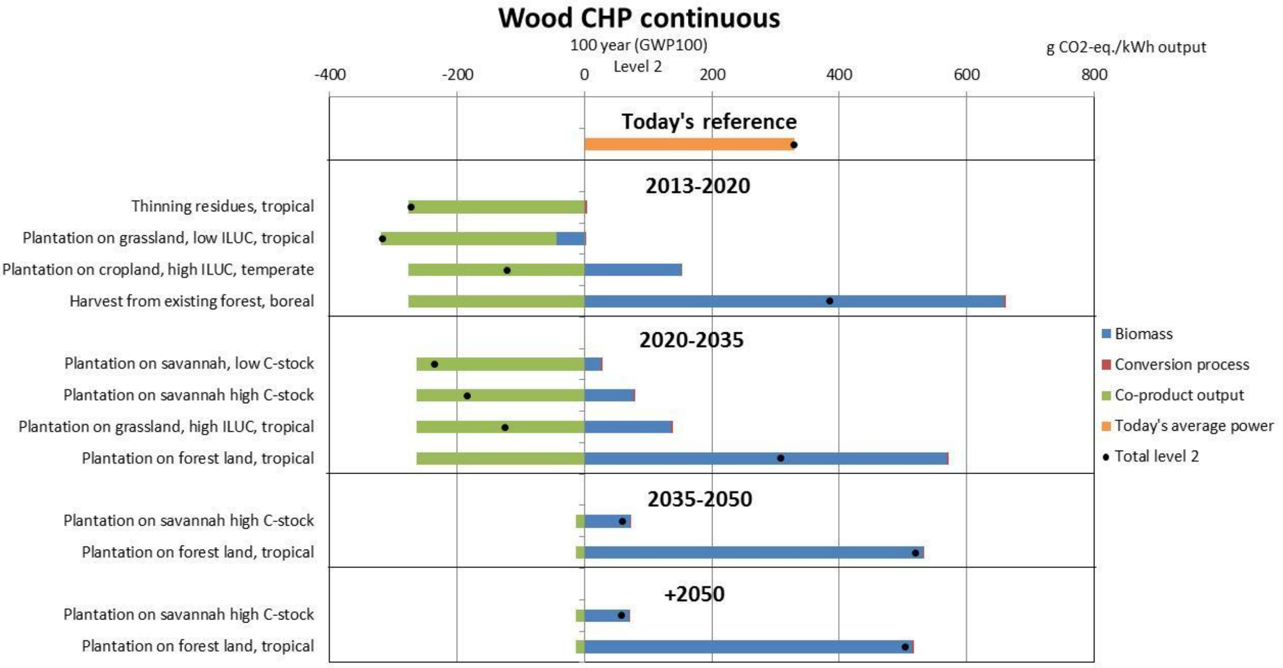
– 200 EJ/year, the probability that wood derives from conversion of natural/high standing forests into plantations or from harvesting in existing forest increases, which in turn can lead to very high carbon footprints.

Prioritizing wood conversion pathways, there is a significant dependency on the nature and composition of the energy system in which the pathway is applied. As long as the district heating marginal and continuous power marginal are mainly based on fossil fuels, there is still a large benefit of using wood in boilers and conventional combustion CHP and PP plants. But as for straw conversion pathways, this benefit largely falls away when the system marginal for heat and continuous power become increasingly based on wind power.

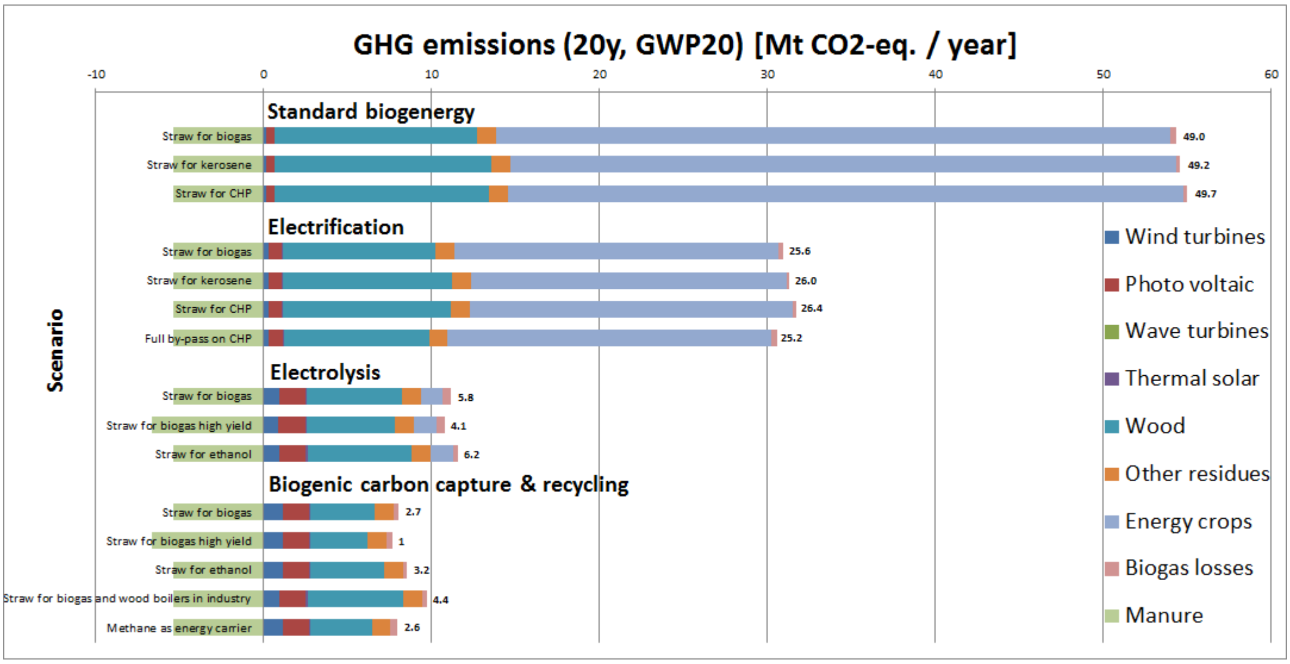


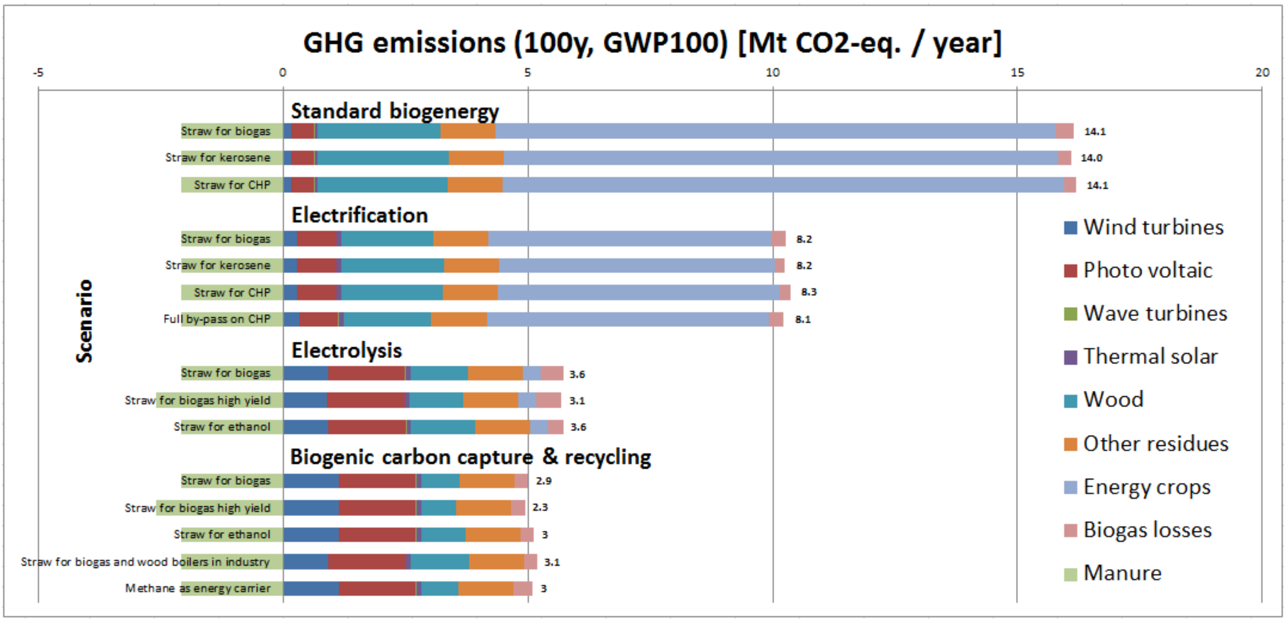
Carbon footprint of various fossil fuels and biomasses of various types and origin from cradle-to-gate including the combustion of the fuel/biomass in a 100 year time horizon.





The carbon footprint of a wood CHP continuous power production at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph).





Carbon footprint assessment of the renewable energy system designs for the Danish energy system 2050. Wood marginal assumed to be plantation on savannah with a high carbon stock.

Road map considerations

For some years ahead, there is judged to be a large potential for supplying a Danish biomass demand with biomass having a low or even negative carbon footprint, given good forest governance and optimized management. Moreover, as long as the Danish energy system allows the displacement of fossil fuels in continuous (base load) electricity production as well as heat supply, biomass including imported wood can be used in both conventional combustion CHP and PP plants and boilers. Already in 2020, however, wind power will supply 50 percent of electricity and using biomass for continuous power production becomes less attractive for GHG emission reduction. Biomass for heat still has the potential, although decreasingly, to substitute fossil based heat until 2035, but beyond that heat is assumed to be supplied by renewable energy and increasingly wind power via electric boilers and heat pumps. There is known to be economic and technological incentives for using woody biomass in boilers and combustion CHP and PP plants, and up to 2020 and also some years towards 2030, the carbon footprint of doing so appears to be low, when supported by governance to ensure the aforementioned origin of wood from pre-commercial thinnings and harvesting residues.

Manure biogas is an attractive way of ensuring GHG reduction throughout all periods of time, and prioritizing this to the extent economy allows seems recommendable. Time will show at which point an upgrading of the biogas to SNG is attractive, thereby being able to store the gas for flexible power or transport fuels, but it is judged to be within the next 5-10 years given the assumed development of the Danish energy system. With respect to prioritizing the use of straw, there are high incentives for manure-straw biogas co-digestion allowing both an increased use of manure biogas as such, and ensuring a sustainable soil carbon quality. Converting the easily bio-degradable carbon of the straw – that would have degraded in the soil anyway – to biogas is a very efficient way of using biogenic carbon in the systems perspective. This may also be an option for combinations of 2G ethanol and biogas, but the concrete carbon footprint aspects of this have not been analyzed in this study. Should such 2G bioethanol pathways at a later stage become attractive, it should be ensured that ethanol as transport fuel does not compete with electric transportation, but is targeted towards long distance transport substituting other carbon based fuels.

At the larger scale of global biomass demand, it becomes less certain if a low carbon footprint of wood can be ensured. Moreover, from concerns for biodiversity and from a supply security point of view, it does not seem recommendable to aim for large scale bioenergy dependency of much above 40 GJ/person/year equivalent to around 200 PJ/year. To keep biomass demand at a realistic scale, moreover, a gradual introduction of hydrogen as system integrator seems to be a possible solution. This involves prioritizing biomass conversion pathways that support an assimilation of hydrogen in the system, and biogas pathways as well as thermal gasification pathways can be such pathways. Also ethanol fermentation allows for capturing CO_2 for further hydrogenation.

An important acknowledgement of this study is this shift in prioritizing biomass supply and conversion pathways at some point in time in the development of the system. From larger scale combustion based CHP, PP and boilers being attractive in the first coming years, a development towards a full renewable energy strategy seem to involve a shift towards limiting biomass demand and prioritizing it for biogas fermentation (of manure and straw) and thermal gasification (of woody biomass) pathways at a later point in time. To manage this shift, special attention is required in order to create the necessary incentives and regulatory framework and to avoid technology lock-in into biomass combustion pathways.

Statement of the Critical Review Panel and Authors' response

Statement of the Critical Review Panel

1. Introduction
A critical review of the study "Carbon footprint of bioenergy pathways for the future Danish energy system" carried out by COWI and the University of Southern Denmark (Further partners in the study were IIASA and Joanneum Research) for the Danish Energy Agency has been performed by a panel consisting of

- Göran Berndes, Chalmers University
- Bart Dehue, NUON/Vattenfall
- Uwe R. Fritsche, IINAS (Chair)
- Luisa Marelli, JRC Ispra
- Jannick Schmidt, 2.-0 LCA consultants.

2. Review process
The Review Panel organized its work with regard to the ISO 14040ff recommendations (The review used the panel method (see ISO 14044, section 6.3, at least three reviewers including the chair)), but without formally adopting all respective requirements, as the Review Panel only provided limited guidance on the analytical scope and procedures used, and overall selection of data sources.

The review process focused on discussing the overall study approach and scope, and provided oral and written comments on (preliminary) study results and drafts. The review process included three meetings and several interactions by email. Some of the study team partners were available only through telephone during the meetings, which restricted possible interaction.

The review was carried out "a posteriori", i.e. draft reports (or sections of those) were made available and the Review Panel suggested improvements, most of which were taken into account. Also, various LCI datasets and results were provided to which the Review Panel made some comments. The resources available to the Panel only allowed for very limited plausibility checks of some of the LCI data and modelling developed in the study.

Due to significant **delays** in study execution, the timeline for review agreed upon during the kickoff meeting in February 2013 could not be followed, which led to some restrictions on planned interaction with the study team, and time available for the review of the final report which was submitted to the Review Panel via email in January 2014.

3. Review issues
The Review Panel underlines that the study focused on GHG emissions as the only environmental indicator, thus deviating from the original plan of work due to time restrictions. This constrains the interpretation of results significantly, although this change was made in agreement with the Danish Energy Agency (See **Recommendation 2** in Section 4 of this Review Report).

Key methodological issues are discussed under the "Scope" section of the final report, especially in sub-sections 3.6 - 3.11, and would have been positioned more clearly in an own section. Reflections on methods and results of other studies are limited, but an extensive list of literature is provided in Appendix M.

The scientific validity of methods used can be confirmed with some restrictions regarding the scope, as several Panel Members see a need for a broader approach, especially towards woody bioenergy (See **Recommendation 3** in Section 4 of this Review Report). The methods used in data collection and modelling are described, although only a very restricted LCI data review was possible due to limited transparency of used data and calculations (See **Recommendation 1** in Section 4 of this Review Report). Several conversions technologies seem to be missing in the Appendix, e.g. bioethanol. The types of conversion technologies in Appendix H are different from the list given in the report.

It is not fully clear from the description of emissions from land conversion (Appendix A to E), how data are normalized and expressed per functional output, and the description of the forest marginal is mainly qualitative. Still, the approach is valid. It would also help to replicate the approach for the time accounting at the beginning of Appendix. It remains difficult to follow in some parts how results were produced, especially for "systems design" level 4 for which the methodological documentation and sources for LCI data could be improved.

Furthermore, a concise discussion of the uncertainty range of the LCI data is lacking, although some reference to this important issue is made in the "results" section with regard to the pathways analyzed.

The final report would have benefited from a more suitable presentation of the large number of results - some of them only in the Appendix - using a more structured approach which relates different modeling levels to final outcomes. In this, the role of the modeling results from IIASA and Joanneum Research and respective data backgrounds could be presented more clearly.

With regard to the study goal to inform policy makers, it lacks a “Conclusion” section, though respective information is presented somewhat scattered.

Last but not least, the final report would have benefited from a Glossary and more detailed tables in the “Definition” section.

4. Summary and recommendations
According to ISO 14040, a critical review is meant to ensure that

- methods used to carry out the LCA are consistent with ISO 14040ff;
- methods used to carry out the LCA are scientifically and technically valid;
- data used are appropriate and reasonable in relation to the study goal;
- interpretations reflect limitations identified and the study goal;
- the study report is transparent and consistent.

These points can to some extent be **confirmed**, but a number of restrictions discussed previously should be noted.

With regard the broader context of future Danish energy policy and the role bioenergy could play in this, it is recommended to **consider follow-up** work

1. to prepare an **in-depth review** of the developed LCI data, carbon balances and calculations, explicitly taking into account both uncertainty levels and learning curves, and to better document the LCI data and calculations to improve transparency and reproducibility;
2. to **extend** the impact categories from purely GHG emissions to the **broader scope of environmental indicators** (acidification, biodiversity, particulates, land and resource use), as originally planned for the study;
3. **to expand** the scope to a **“global view”** in which the Danish energy system is not the starting point of the analysis with strict boundaries but part of an interrelated system **which evolves** towards a 2 °C world, and which explores the dynamic **transition** of bioenergy **-** especially from solid biomass **-** to a global commodity serving a significant share of the global energy demand;
4. to analyze scenarios for **changes in the Danish land use**, both for agricultural and forest land, with regard to different production levels and production mixes driven by e.g. different dietary developments, and changes in export-import relations for food and feed. This work should consider also “global view” system boundaries (see above no. 3), extend the scope from **bioenergy to biomass** in general, and reflect on possible benefits from building blocks of a **bioeconomy** such as biorefineries, and cascading use systems.

February 2014

for the Review Panel **Uwe R. Fritsche**

Scientific Director, IINAS

Authors' response to Statement of the Critical Review Panel

Key properties of the study
During the study, two key determinants for the carbon footprint of bioenergy pathways were identified, i.e. the assumptions on:

- the origin of the biomass;
- the nature of the energy system within which the bioenergy pathway is applied.

Compared to the assumptions made on these system elements, it was found that other variables and assumptions mean relatively little, a single and specific exemption being the emissions of methane and nitrous oxide from biogas and manure processes. For the same reason, the main effort was placed on creating a transparent overview of how carbon footprints depend on the assumptions regarding these two categories of system boundary conditions.

An implication of the above mentioned acknowledgement is, further, that a determining carbon footprint property of a bioenergy conversion pathway is how well it *integrates* into the energy system in which it is applied. It was found to be decisive:

- which alternative energy system services that are displaced by the main product and the co-products from the bioenergy conversion pathway;
- what the overall systemic effect of the conversion pathways is on the total biomass demand by the whole system.

The system integration properties of a bioenergy conversion pathway implies that some pathways will lead to higher overall system biomass requirements than other pathways, and as the total system biomass demand and the origin of this biomass are decisive factors, so is of course the system integration properties of the biomass conversion pathway. In practice, the ability of a biomass conversion pathway to sustain the overall performance of a system with high penetration of fluctuating wind power and high integration of electrolysis and hydrogen was found to be a decisive property in many system designs.

As a consequence of these acknowledgements, and in an effort to create clarity on the dependency of the carbon footprint on these decisive system assumptions, bioenergy pathway models were created at several levels taking an increasingly systemic approach. In this way, each bioenergy conversion pathway was modelled and its carbon footprint assessed for 48 different framework conditions leading to a total of 768 models and carbon footprint calculations of the 16 bioenergy pathways assessed.

This elaborated systemic approach to the conducted bioenergy carbon footprint assessments is a key feature of this study. With respect to this feature, the study is innovative and original, and we judge it to provide an unprecedented transparency of key dependencies and robustness of the interpretation of results.

It is our pre-amble to the reader and user of the study to acknowledge these key characteristics of it, and from this platform, we will also respond to the critical review statement.

Response to the Statement

We will address selected key points made in the review statement one by one. The statement, to which we respond, is first repeated here in italics, followed then by our response. We address them in the sequence in which they come in the statement.

Review statement: *The resources available to the Panel only allowed for very limited plausibility checks of some of the LCI data and modelling developed in the study.*

Response: We acknowledge that delays and time constraints have been a constraint on the ability for the reviewers to verify calculations. All calculations were, however, made available in the spreadsheet in which they were performed, and they will still be available to the user of the study.

Review statement: *The Review Panel underlines that the study focused on GHG emissions as the only environmental indicator, thus deviating from the original plan of work due to time restrictions. This constrains the interpretation of results significantly, although this change was made in agreement with the Danish Energy Agency.*

Response: At a point in time during the project, it was decided to delimit the study to a carbon footprint assessment, as this was judged (by the Danish Energy Agency and the project team) to be the best priority of the available time and budget. The study does not pretend to be other than a carbon footprint assessment, and it is true to this scope throughout its title, goal definition, scope definition, results and interpretation. We find the interpretation to respect the limitations of this scope of impact assessment.

Review statement: *Key methodological issues are discussed under the "Scope" section of the final report, especially in sub-sections 3.6 - 3.11, and would have been positioned more clearly in an own section.*

Response: we believe it to be conventional to have the methodological approach described as part of the scope definition, because the scope and approach to the system modelling and the impact assessment is a natural part of defining the scope of the study.

Review statement: *Reflections on methods and results of other studies are limited, but an extensive list of literature is provided in Appendix M.*

Response: The innovative and original character of the study, i.e. the multi-level and increasingly systemic approach, implies that it was necessary to create new system models. Even though many hundred bioenergy LCAs can be found in literature, therefore, none of them could be directly used. Requirements for consistency and comparability implied that all 768 models had to be created under the same conceptual approach and framework conditions. This limited our possibility to make use of historic bioenergy LCAs found in literature. Further, many of the existing bioenergy policy studies use another perspective than the one of the carbon footprint assessment at hand, as they most often apply a policy perspective addressing the supply side of biomass production from e.g. forestry. We have, therefore, tried to make the best use of such policy studies where applicable in the context of this carbon footprint assessment. Please refer also to the section on goal definition in the report on this issue. With respect to the key data on carbon balances of the various biomass supplies and land use change (LUC models), we have used a more than 50 references on woody biomass supplies, around 20 references in the development of our ILUC models and 30 references on our straw and manure models. These references and how they are used in the modelling are found in Appendices A-G. References on inventory data are, likewise, found in Appendix H comprising the inventory data sheets. The long literature list in Appendix M also comprises literature that is not referenced.

Review statement: *The scientific validity of methods used can be confirmed with some restrictions regarding the scope, as several Panel Members see a need for a broader approach, especially towards woody bioenergy.*

Response: We appreciate the review panel's acknowledgement of the scientific validity of the applied methods. We will address any restrictions on this validity, as they are perceived and presented by the review panel, in the following.

Review statement: *It is not fully clear from the description of emissions from land conversion (Appendix A to E), how data are normalized and expressed per functional output, and the description of the forest marginal is mainly qualitative. Still, the approach is valid.*

Response I: The appendices A-E provides the time profiles of emissions and uptake of CO_2 from the various land use changes and woody biomass supplies, but do not attempt to normalize these to the functional output. But it is explained in the main report in the chapter on 'Definitions', the section on 'Carbon Footprint' as well as in the report section 5.9, how this is done. The explanation is straight forward, i.e. <u>we sum up all CO_2 emissions and uptakes into a total net emission/uptake and divide them by the total harvested biomass in 20 and 100 years respectively in order to express emissions per MJ biomass harvested.</u> This brief explanation is now also inserted in section 3.3 on carbon footprint approach in the main report.

Response II: It is clear in the report that we only address the so-called 'stand-level' in terms of data quantification. The 'landscape' level, we address more qualitatively in the main report in the section, where we discuss the potential role and scale that forest intensification and the use of thinning residues can play (i.e. the 'up to 5-10 EJ/year'), and we say that biomass from thinnings and forest intensification are potential marginals below this scale of global biomass demand.

In the terminology used in the report, the point of increasing biomass yields on the landscape level, when forestry responds to increasing biomass demands, is, thus, expressed as the marginal being ‘yield intensification’ – as this is the way we express it in the cLCA terminology. We include the point also in the summary section on ‘wood conversion pathways’, where we write: “A relatively large potential, compared to today’s scale of global, commercial bioenergy demand, exists for optimizing forestry for multiple outputs, i.e. increasing the biomass yield and using more thinnings and other biomass co-products from higher value timber production. Except for boreal forest thinnings in the 20 year horizon, thinning residues has a carbon footprint close to zero, and if forest intensification can become part of the response to a Danish biomass demand, the carbon footprint from this part becomes even negative.”

We do, thus, include the point of increasing carbon stock at landscape level, and identify this as a candidate for being the biomass marginal – together with woody biomass from pre-commercial thinning residues – up to a scale of global biomass demand of 5-10 EJ/year.

Review statement: *It remains difficult to follow in some parts how results were produced, especially for “systems design” level 4 for which the methodological documentation and sources for LCI data could be improved.*

Response: The many process flow diagrams provided in Appendix J of the level 4 scenarios do contain the quantities of the flows and conversion technologies in the systems and are, thus, a quantified specification of the scenarios. Further, any emissions factors from the various types of biomasses and technologies are given in relation to the carbon footprint assessment of each individual biomass conversion technology, plus supplemented by some technologies that are only applied in the level 4 models – in this case provided in section 4.2. All necessary information should, thus, be given, and one can check the calculations of GHG emissions from all level 4 scenarios based on this.

Review statement: *Furthermore, a concise discussion of the uncertainty range of the LCI data is lacking, although some reference to this important issue is made in the “results” section with regard to the pathways analyzed.*

Response: This comment should be put into context with respect to the substance of the uncertainty/ dependency/sensitivity matter, which is that the previously mentioned two main issues completely determines the results and that other aspects of uncertainty are very insignificant compared to these:

› the origins of the biomass, i.e. the biomass marginal;
› the nature of energy system marginals.

The thoroughness, exhaustiveness and degree of detail in our use of a variety of biomass marginals and energy system marginals, i.e. ending up in the aforementioned total of 768 Carbon Footprints of the 16 pathways all together, represents a robust and transparent revealing of the crucial uncertainties, dependencies and sensitivities. In this light, the core inventory data of the conversion technologies themselves, i.e. the energy conversion efficiencies etc., are quite insignificant. The only exemption, as mentioned, being the GHG emissions from biogas operations, and as we have also elaborated on in the report.

Review statement: *The final report would have benefited from a more suitable presentation of the large number of results - some of them only in the Appendix - using a more structured approach which relates different modeling levels to final outcomes.*

Response: The results are structured in presentations of carbon footprint first at level 2, then level 3 and then level 4. Moreover, results are first presented for each individual conversion pathway in a holistic overview of the differences over the four time periods covered by the assessment, and subsequently in comparative overviews, first at level 2 comparing pathways for each type of functional output (heat, power and fuels), secondly at level 3 comparing pathways using wood and straw respectively. Finally, in the interpretation section, the findings are extracted across the different modelling levels. As we see it, this was the best way we could do it.

Review statement: *In this, the role of the modeling results from IIASA and Joanneum Research and respective data backgrounds could be presented more clearly.*

Response: In order to avoid any misinterpretation of this, we would like to make clear that all modelling results from GLOBIOM (IIASA) and Joanneum Research have been directly and transparently used.

Review statement: *With regard to the study goal to inform policy makers, it lacks a "Conclusion" section, though respective information is presented* somewhat *scattered.*

Response: We have gathered the 'conclusive' key findings in one section, which we have deliberately and in agreement with the Danish Energy Agency chosen to entitle 'Interpretation'. This choice of term is due to the fact that the study is explorative by nature and shows results conditional to a set of assumptions at many levels. The quality of the study is the transparency of results and their dependency on assumptions, it provides – and the cross cutting interpretation that can be extracted being robust to the range of results and their dependencies. We find that we have succeeded in identifying many robust interpretations – but we have chosen to use the word 'interpretation' as it reflects the character of the study best. In any case, this is just semantics, the quality of how the findings from the study is extracted and presented should be judged by the text in the section on Interpretation – including the summary section.

Recommendations from the review panel:

Review statement: *The review panel recommends to prepare an* ***in-depth review*** *of the developed LCI data, carbon balances and calculations, explicitly taking into account both uncertainty levels and learning curves, and to better document the LCI data and calculations to improve transparency and reproducibility;*

Response: Please see the response to the same point above.

Review statement: *The review panel recommends to* ***extend*** *the impact categories from purely GHG emissions to the* ***broader scope of environmental indicators*** *(acidification, biodiversity, particulates, land and resource use), as originally planned for the study.*

Response: Please see the above comments that this study is a carbon footprint study and that it does not pretend to be otherwise. Please also note our remarks to this delimitation of impact assessment in the report, section 5.9.

Review statement: *The review panel recommends* ***to expand*** *the scope to a* ***"global view"*** *in which the Danish energy system is not the starting point of the analysis with strict boundaries but part of an interrelated system* ***which evolves*** *towards a 2 °C world, and which explores the dynamic* ***transition*** *of bioenergy - especially from solid biomass - to a global commodity serving a significant share of the global energy demand.*

Response: As stated in the goal definition of this study, section 2.1 on 'Decision support', the aim of the study is to support Danish energy system decision makers, especially the Danish Energy Agency and parties of the Parliament energy agreement of March 2012, in decisions on the design of the Danish energy system. It is the effect of such decisions on GHG emissions that the study aims to assess. Other studies aim to look at international policy making addressing GHG effects of biomass supply globally, or e.g. at country-wise policy making for forest management. There is a difference in the scope of such studies. In our case, biomass supply deriving from imported woody biomass is to a wide extent part of the background system, i.e. the decision makers targeted by the study, do not have the full power to determine the origin of such supply neither to influence indirect market effects of the studied demand increase. In an international policy making situation, the scope of decision making is broader, and accordingly the scope of the study can be broader. Please also refer to section 2.1 of the report.

Note also, that the study does in fact assume a background scenario within which the world develops towards a 2 °C world in a dynamic transition, and that this is the framework conditions for identifying the biomass marginal on the longer term. Our conclusion is that the study in fact does what is asked for here, only it does so from the perspective of decision making by Danish energy system decision makers.

Review statement: *The review panel recommends to analyze scenarios for* ***changes in the Danish land use****, both for agricultural and forest land, with regard to different production levels and production mixes driven by e.g. different dietary developments, and changes in export-import relations for food and feed.*
This work should consider also "global view" system boundaries (see above no. 3), extend the scope from ***bioenergy to biomass*** *in general, and reflect on possible benefits from building blocks of a* ***bioeconomy*** *such as biorefineries, and cascading use systems.*

Response: The study does include changes in Danish land use in both agriculture and forestry, cf. the biomass scenarios of woody plantation on temperate agricultural land and temperate forest land. In doing so, we also include the ILUC related to changes in import-export. So in this respect, we are not sure what the review panel further wishes. We could, of course, include many more variants of crops and land use changes, which we would happily do had the time and budget been larger. With respect to the point of integrating scenarios with scenarios for dietary changes – this would in the consequential LCA perspective just be a framework condition influencing how much biomass would be available. It would be relevant to do, but another type of study than the one in question.

Definitions

Definitions applied are in accordance with IPCC's definitions as far as these are available.

Balancing or flexible power/reserves: Due to instantaneous and short-term fluctuations in electric loads and uncertain availability of power plants there is a constant need for spinning and quick-start generators that balance demand and supply at the imposed quality levels for frequency and voltage.

Bioenergy: Energy derived from any form of biomass.

Biofuel: Any liquid, gaseous or solid fuel produced from biomass, for example, soybean oil, alcohol from fermented sugar, black liquor from the paper manufacturing process, wood as fuel, etc. Traditional biofuels include wood, dung, grass and agricultural residues. ***First-generation manufactured biofuel*** is derived from grains, oilseeds, animal fats and waste vegetable oils with mature conversion technologies. ***Second-generation biofuel*** uses non-traditional biochemical and thermochemical conversion processes and feedstock mostly derived from the lignocellulosic fractions of, for example, agricultural and forestry residues, municipal solid waste, etc. ***Third-generation biofuel*** would be derived from feedstocks like algae and energy crops by advanced processes still under development. These second- and third-generation biofuels produced through new processes are also referred to as next-generation or advanced biofuels or advanced biofuel technologies.

Biomass: Material of biological origin (plants or animal matter), excluding material embedded in geological formations and transformed to fossil fuels or peat.

Carbon dioxide capture and storage (CCS): CO_2 from industrial and energy-related sources is separated, compressed and transported to a storage location for long-term isolation from the atmosphere.

Carbon Footprint: The impact indicator used to quantify the releases of greenhouse gases from the studied pathway or system into a unit of CO_2-equivalents. In the applied method for calculating this indicator, biogenic CO_2 emissions are annualized in both a 20 year and a 100 year time perspective. It means that any CO_2 emission from the provision and use of biomass, including all resulting differences in up-take, release, and carbon stock above and below ground are accounted for and normalised by the harvested and used biomass during the same time period. Emissions of other greenhouse gases are expressed as CO_2-equivalents using the conventional GWP20 and GWP100 approach.

CO_2-equivalent emission (CO_2eq): The amount of CO_2 emission that would cause the same radiative forcing as an emitted amount of a greenhouse gas or of a mixture of greenhouse gases, all multiplied by their respective global warming potentials, which take into account the differing times they remain in the atmosphere.

Continuous power: The power which is produced with instant and continuous output based on the input. Examples are wind energy which is produced when the wind is blowing. Continuous power cannot be regulated to reflect the actual energy need at the current moment in time.

Conversion: Energy shows itself in numerous ways, with transformations from one type to another called energy conversions. A **conversion technology** is the equipment used to realize the conversion. A biomass **conversion pathway** is the full life cycle of a biomass type from producing biomass to obtaining a functional energy output.

Global warming potential (GWP): GWP is an index, based upon radiative properties of well-mixed greenhouse gases, measuring the radiative forcing of a unit mass of a given well-mixed greenhouse gas in today's atmosphere integrated over a chosen time horizon, relative to that of CO_2. The GWP represents the combined effect of the differing lengths of time that these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. The Kyoto Protocol ranks greenhouse gases on the basis of GWPs from single pulse emissions over subsequent 100-year time frames. See also climate change and CO_2-equivalent emission.

Greenhouse gases (GHGs): Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Besides CO_2, N_2O and CH_4 , the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Land use (change; direct and indirect): The total of arrangements, activities and inputs undertaken in a certain land cover type. The social and economic purposes for which land is managed (e.g., grazing, timber extraction and conservation). ***Land use change*** occurs whenever land is transformed from one use to another, for example, from forest to agricultural land or to urban areas. Since different land types have different carbon storage potential (e.g., higher for forests than for agricultural or urban areas), land use changes may lead to net emissions or to carbon uptake. ***Indirect land use change*** refers to market-mediated or policy driven shifts in land use that cannot be directly attributed to land use management decisions of individuals or groups. For example, if agricultural land is diverted to fuel production, forest clearance may occur elsewhere to replace the former agricultural production. See also afforestation, deforestation and reforestation.

Life cycle assessment (LCA): Life Cycle Assessment is a methodology for the assessment of environmental impacts associated with all the stages of a product's life from-cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling).

Marginal energy/biomass types: The marginal energy or biomass type is the chosen type describing the consequences of a change. Thus it is the energy or biomass type that is actually affected by a change in demand.

List of abbreviations/acronyms

BEV	Battery Electric Vehicle
CHP	Combined Heat and Power
DEA	Danish Energy Agency
DM	Dry Matter
DME	Di Methyl Ether
DEV	Directly Electrified Vehicle
DLUC	Direct Land Use Change
GWP20	Global Warming Potential – in 20 year period
HANNP	Human Appropriation of Net Primary Products
ILUC	Indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LHV	Lower Heat Value
PHEV	Plug in Hybrid Electric Vehicle
PP	Power Plant
RCP	Representative Concentration Pathways
SNG	Synthetic Natural Gas
SOFC	Solid Oxide Fuel Cell
SSP	Shared Socioeconomic Pathways
VOC	Volatile Organic Compound

1 Background and introduction to the project

1.1 The political context

By 2050 EU – and Denmark – aims at having reduced greenhouse gas emission by 80-95 % compared to 1990. Over the same period, the Danish Government intends to gradually phase out fossil fuels in transport and energy sectors. The 2013 climate plan further sets out that already by 2035 power and heat should be entirely produced from renewable sources. These ambitions require transforming the existing Danish energy system into one that incorporates a range of renewable energy sources. Biomass is foreseen to play an important role in the transformation, alongside wind and solar.

The Danish energy agreement, concluded by a parliamentary majority in March 2012, stipulates a number of initiatives to be implemented before 2020 to facilitate this transformation, one of which is an analysis of the potential role of biomass in the development of the Danish energy system towards 2050.

1.2 General project description

General objectives

The project is about the use of bioenergy in the Danish energy system and focus has come to be on framework conditions for a Greenhouse Gas use of biomass in the future energy supply. Project objective is been for the time period 2013 to 2050 to assess consequences of alternative bioenergy pathways using a life cycle perspective.

This project is one out of a series of interrelated projects made to support political decisions and designing the future energy Danish system. Publications within the project framework are:

› ”Imported wood fuels, A regionalised review of potential sourcing and sustainability challenges (Bentsen og Stubak, Københavns Universitet, 2013).

- “Analysis of biomass prices, Future Danish Prices for straw, wood chips and wood pellets” (Bang et al, EA Energianalyse, 2013).

- “Technology data for advanced bioenergy fuels” (Evald et al, Force Technology, 2013).

Tender, project partners, and stakeholder involvement

The Danish Energy Agency (DEA) tendered the project in December 2012. In February 2013 COWI as main contractor, together with University of Southern Denmark, International Institute for Applied Systems Analysis (IIASA), and Joanneum Research Resources were selected as the consultants for the project.

With regard to the process and the project outcome emphasis has been on a transparent presentation of general assumptions, methodological approach and results. The project has faced a research area being highly complex, methodologically very specialized, and, therefore to some extend expert judgements has been necessary. Further, the results feed into an ongoing political debate and thus Danish key stakeholders (NGOs, business, academia, and public institutions) have been involved in the process.

Review panel

Considering these characteristics, the importance of engaging peers was clear from the very beginning and it was decided to set up a review panel of internationally acknowledged scientists.

Review Panel:

- Uwe Fritsche, IINAS

- Jannick Schmidt, 2.0 LCA consultants

- Göran Berndes, Chalmers University

- Luisa Marelli, Joint Research Centre

- Bart Dehue, Nuon/Vattenfall

Review Panel had the role of being a resource to the project and being critical reviewers (see the review statement above). Three review meetings were held in the project period. Discussions dealt with the general project setup - scope of work, and methodological approach – as well as the relevance of different biomass types and origins, size of future biomass potential, key literature and application of models to be considered.

Engaging stakeholders more broadly

Considering the overall objective of supporting political decision making, and considering the intense debate on how to most appropriately apply biomass in energy systems, engaging various stakeholders has been crucial to the project. Two stakeholder workshops were set up. Attendees were green NGOs, business associations, private companies, universities, ministries, public agencies etc. The workshops were very well attended and provided valuable input for the project team as well as for DEA directly. At the workshops project scope and overall approach was presented and discussed. Further, focus for discussions was on the importance of assumptions made. The complexity of the project and the lack of a complete overview at the point in time when the last workshop was held made it difficult to discuss concrete results. A number of issues were further discussed bilaterally after the workshops.

Altogether the process influenced the approach to meeting challenges in the project, although outcomes of workshops have not been explicitly referred to in the report.

Project development

The project tender by the Danish Energy Agency initially included all environmental impacts of the use of biomass for energy to be assessed in the study, and at the same time did not include analysis of the importance of developments in the Danish energy system up to 2050. However in the initial phase it the consortium and DEA decided to reframe the scope to focus on GHG and include developments in the energy systems. As a result environmental impacts related to e.g. emissions of SO_X, biodiversity or water use is not assessed here.

Chapters 2 and 3 presents project goal and scope in more detail and the approach to LCA and modelling of systems. The potentials of the overall approach to provide answers as well as the intrinsic limitations of the study are emphasized. Chapter 4 presents the inventory analysis and data. Chapter 5 presents and discusses carbon footprint results, while Chapter 6 holds and overall interpretation of results. Appendices hold a comprehensive set of supportive core data and literature.

2 Goal definition

The overall goal of the project is to quantify the greenhouse gas (GHG) consequences of alternative bioenergy pathways in the Danish energy system in the time frame 2013 to 2050 using a life cycle perspective. The life cycle methodology, LCA is therefore at the core of this study. Focusing on GHG emissions alone, the study is a so-called Carbon Footprint assessment.

2.1 Decision support

The study shall support the Danish Energy Agency (DEA) and Danish energy policy decision makers in the development of the Danish energy system, and the results and findings of the study are input for decision making in both design and regulation of the energy and transport sector. The focus of the study is especially on bioenergy, and it shall support design of regulation influencing the choice between alternative biomass categories and conversion pathways to be part of such energy system designs.

The scope of decision support is, thus, decisions that can influence:

› The type and quantity of biomass and conversion pathways to meet specific energy and transport system requirements

› The origin of the biomass and the way it is it produced – to the extent this can be influenced by targeting the demand towards specific suppliers on specific conditions

The scope of decision support does not comprise decisions on regulatory incentives for land governance and GHG emission governance internationally or in other countries supplying biomass to the international markets.

Figure 3-1 strives to illustrate this scope of decision support.

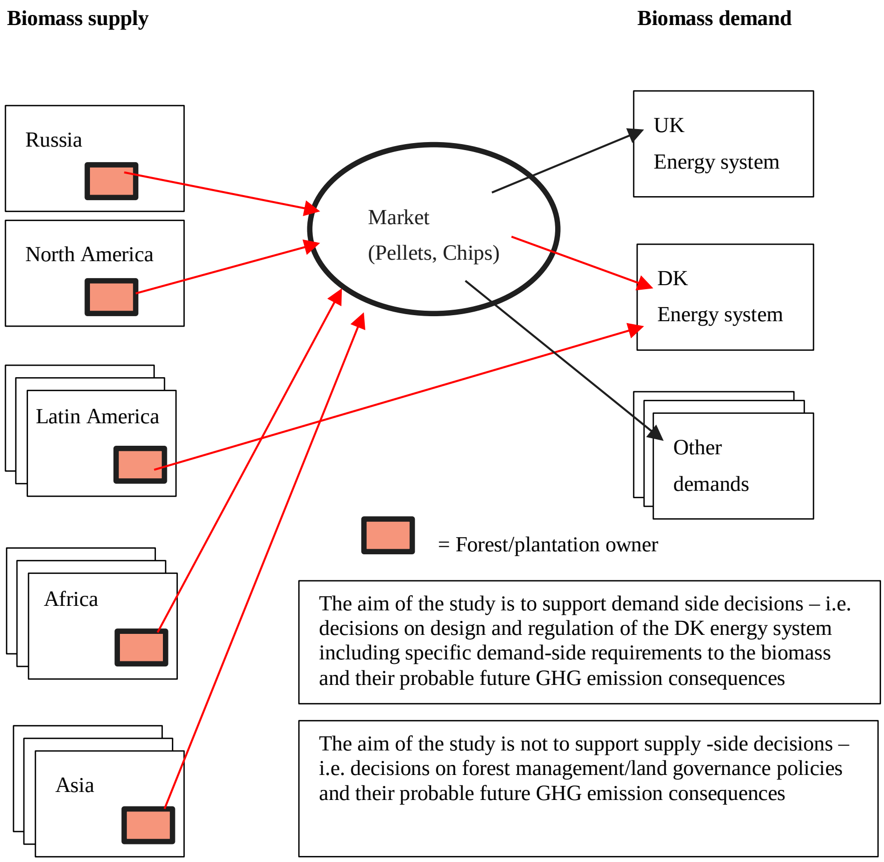


Figure 2-1 The scope of decisions supported by the study comprises decisions on energy and transport system design and demand-side regulation of biomass used in this system

2.2 Methodological approach

The study applies an LCA approach to assessing the Carbon Footprint. In brief, LCA is a standardized comparative environmental assessment methodology (ISO, 2006a;b) which consists of assessing and comparing the environmental impacts of alternative products, services or systems from a whole-system or "cradle-to-grave" perspective. Additional details on the general principles of the LCA methodology can be found in Sonnemann & Vigon (2011), Rebitzer et al. (2004) as well as Finnveden et al. (2009).

The present study applies the so-called "consequential" LCA methodology as opposed to another approach referred to as "attributional LCA", because the consequential approach is judged best suited for decision support.

In practice, there are two essential differences between the "consequential" and "attributional" approach to modelling the studied systems. The first is the way the two approaches deal with processes having multiple product outputs. Attributional LCAs aim to ascribe all impacts from the studied system to a single 'main product' output from the system by some way of partitioning the various flows (emissions, resource extractions, etc.) involved in the system between the studied main product and its co-products. Consequential LCAs instead expand the system and aim to include the alternative products on the market displaced by the co-products. The other major difference is a logical implication of applying system expansion, and regards the type of data included in the LCA model. While attributional LCA uses "average data" (e.g. an average of all electricity sources used in a given national electricity mix), consequential LCA includes "marginal data" only, i.e. data representing the processes and/or suppliers that are responding to changes in demand by corresponding changes in supply.

Additional information on the implications of these LCA methodologies, including illustrative examples, is available in Hamelin (2013) as well as in Weidema & Schmidt (2010), among others.

The goal of the consequential LCA (here Carbon Footprint) is to study the consequences of the decisions, it aims to support. The consequence of decisions on the design of the Danish energy system, e.g. with respect to wood imports, is an incremental change of demand and supply from and to the biomass market. The demand may, further, be targeted towards specific suppliers on specific conditions, e.g. through certification schemes, and may, thus, also aim to ensure specific carbon emission conditions from the contracted supplier.

But beside this demand-side influence on a contracted supplier; policies, schemes and decisions on land governance/forest management of biomass market suppliers in general are not targeted by the study, because the targeted decision makers are not those in charge of land governance decision at forest owner and supply country level. With respect to supply-side alternatives, therefore, the study aims to identify a range of biomass supply options and land use change (LUC) options under varying political land governance conditions, which are likely to represent a probable range of carbon footprint implications of biomass supply in the future.

Inherently, having the goal of reflecting the consequences of decisions, the Carbon Footprint assessments shall strive to look into the future and seek to represent the consequences the various biomass uses and conversion pathways will have in the future. The further implication of this is the need to understand and define the future – or more concretely, the part of the future that is likely to be significantly influenced by the decisions studied in this report. Predicting the future is, however, uncertain, and seeking a predictive approach to scenarios for the future is believed to be insufficient and likely also misleading. Therefore, an explorative approach is followed looking at various potential future developments and situations, not only within the Danish energy system, but within systems outside Denmark likely to be significantly influenced by the studied decisions.

The implication of this approach is that LCA results become 'conditional' or 'circumstantial' meaning that a given result shall aim to represent the Carbon Footprint of a given decision under given circumstances or given framework conditions and assumptions. Importantly, such framework conditions and assumptions shall be transparent, and the interpretation of results shall respect and reflect the conditions under which they are seen as valid. Therefore, rather than striving to give a result with a given uncertainty, the approach is to provide several results with each their dependency on framework conditions and assumptions.

2.3 Type of decisions and related research questions

The conceptual idea behind the consequential approach is that any result is seen as an answer to a question. When, for example, comparing the calculated Carbon Footprint of alternative biomass conversion pathways, the aim is that the difference between them shall reflect the resulting difference in GHG emissions, when choosing one alternative over the other. The question answered by the result of such a comparative assertion is, thus: “what is the difference in GHG emissions as a result of choosing one alternative over the other?”. This implies that the types of decisions and research questions supported by the study, and their potential consequences, should be understood in some detail.

A key aspect is to understand the outreach of decisions in scale, time and space, i.e. how big is the influence of the decision, how far into the future does it reach and what is the geographical outreach, cf. e.g. Wenzel (1998) and Weidema et al.(2009) describing key aspects of decision support in the consequential LCA approach.

2.3.1 The temporal outreach of decisions

Part of the goal of the study is to support the design of the Danish energy system up to and a little beyond 2050. The study, therefore, shall look this far ahead. The decisions to be supported are, however, decisions to be taken in the nearer future, but their consequences reach further out. The study, thus, distinguishes between two types of decisions based on their temporal outreach:

5 Decisions with a shorter term outreach and without significant technology lock-in aspects, e.g.:

- decisions on plant operation or fuel choice only (no investments done)
- decision on lifetime prolongation of existing equipment reaching only like 10-15 years into the future (i.e. life time prolonged by max 15 years)

6 Decisions with a longer term outreach, e.g. decisions on new investments in energy conversion plants (like a new pellet fired or straw fired large CHP plant) which will by all chance have to last for a lifetime of the equipment like 30 – 40 years

2.3.2 The spatial outreach of decisions

The spatial outreach of decisions follows the geographical boundaries of the markets influenced by the decisions. Inherently, decisions on district heating grids and electricity production are to a wide extent bound to the physical location and transmission bottlenecks of such grids, whereas decisions on biomass and biofuel purchase follow the responses to changes in demand from such markets, which in some case are international/global (as for wood pellets), regional (as for straw) and local (as for manure). But also in some cases, when comparing and deciding on alternative uses of domestic biomass residues, like straw or manure, there can be implications on imports/exports, e.g. of alternative biomass types, influencing international markets, when the system consequences of induced and displaced products are followed. This will be further illustrated in the section on scope definition.

2.3.3 Research questions

The Carbon Footprint assessments reported here shall, thus, reflect the consequences of:

- a given scale of demand of a given biomass type
- produced under given background conditions
- when used in a given conversion pathway,
- placed in a given system design and supplying a given energy service within this system,
- in a given period of time from 2013 to 2050 and beyond

This task can be translated into concrete questions to be answered and aspects to be clarified. This can be summarized as follows:

<u>The individual biomass conversion pathway</u>

- What is the carbon footprint of the conversion pathway?
- How does it depend on the origin of the biomass and on contextual relations, including the scale of demand, the degree of land governance and GHG emission governance?
- How does it depend on the energy system in which it is applied, and how does it vary over time with the expected variation of the energy system?

<u>Comparing and prioritizing pathways</u>

- How do the Carbon Footprints of pathways providing the same functional outputs of heat, electricity and transport fuels compare?
- How should a given biomass resource be prioritized and used in the energy system with the aim of reducing the Carbon Footprint – i.e. how do pathways compare across conversion to different functional outputs

- How does this prioritization depend on the origin of the biomass and the energy system in which it is applied, and how do the priorities vary over time with the expected variation of the energy system

Designing and assessing the energy system as a whole

- Does the choice of biomass conversion pathways have any whole-system implications when designing a complex and interlinked system with combination of many conversion pathways – and if so which?

- How does the total system biomass demand and Carbon Footprint depend on the strategy of the whole-system design and the prioritization of biomass conversion pathways within it?

The study is set up to address these questions, and will allow an interpretation of them.

3 Scope definition

3.1 Temporal scope

The temporal scope of the study follows the temporal outreach of the supported decisions, as described in the goal definition. It means that the study looks around 40 years ahead, i.e. from 2013 until 2050 and a few years beyond.

The timeline is, moreover, broken down into four time periods in accordance with the key milestones of Danish energy policy, i.e. 2013-2020, 2020- 2035, 2035-2050 and 2050+. These key milestones comprise that wind power makes up 50% of electricity consumption in 2020. In 2030, coal is completely phased out and so are oil boilers for heat. In 2035, all heat and power is renewable and in 2050 all energy and fuel supply for both the energy and transport sectors is fully renewable. The milestones are shown in Figure 4-1.

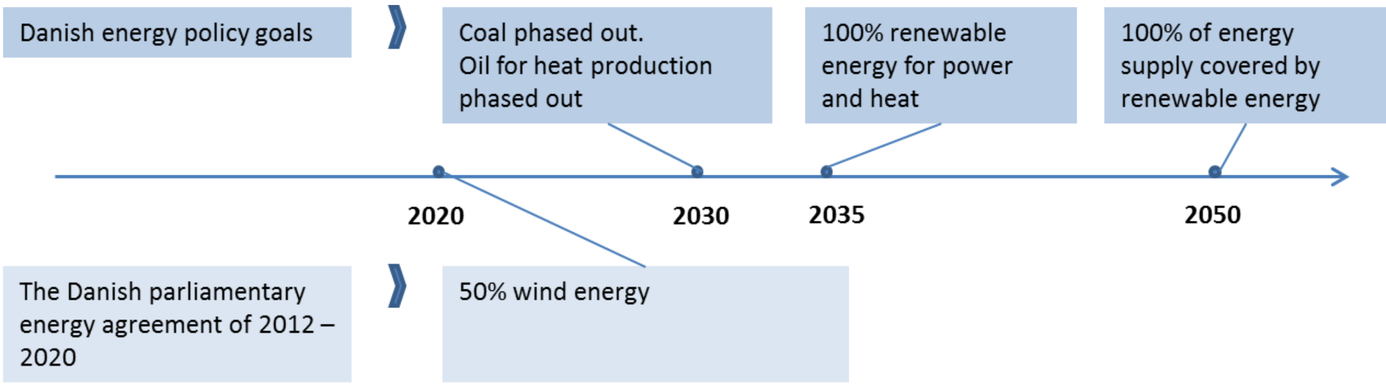


Figure 3-1 The milestones of the Danish energy policy as defined by the Parliament energy agreement of March 2012 and the Government's energy policy

As time goes, technologies will change and so will the system in which they are applied. To reflect this, the following data is modified over time according to the chosen modelling scenarios in 2020, 2035 and 2050:

- Efficiencies of the conversion technologies
- Type of marginal biomass type and origin
- Marginal energy types for electricity, heat etc.

- Other inputs for the conversion technologies
- Energy consumption for the conversion technologies

For the whole system scenarios the temporal scope includes only 2050.

3.2 Geographical scope

The geographical scope is inherently defined by the location of the induced and avoided processes as also described under the goal definition. In practice, the following geographical scope applies:

- The heat grids are very local and entirely Danish

- The electricity grid is Nordic and covers Denmark, Sweden, Norway, Finland and Northern Germany. Beyond this extension, bottlenecks today prevent further significant transmission. But such bottlenecks are frequently broken by new transmission lines, and the electricity grid is continuously expanding over time

- Manure is a very local biomass resource transported only 10-20 km. In the future, manure concentration technologies may be introduced allowing for a wiser transport distance

- Straw is a regional resource, mainly traded within country borders, but some is traded across borders, as an example straw is purchased from Germany and taken to a power plant in the city of Odense around 150 km from the German border. In the future, straw pellet production may allow for a longer straw transport distance

- Woody biomass is predominantly traded as pellets, and the market is international

The geographical cope of the study build on the above considerations and assesses e.g. biomass provision deriving from all over the world. It does not, however, include any specific local conditions in or outside Denmark, but use general models and literature data for biomass provision in boreal, temperate and tropical climate regions as well as general literature data on conversion technologies..

3.3 Carbon Footprint approach

Carbon footprint values herein are reported as CO_2-e/MJ. In the calculation of the carbon footprint of a biomass conversion pathway, including any land use change in forestry and/or agriculture, we sum up all CO_2 emissions and uptakes into a total net emission/uptake and divide them by the total harvested biomass in 20 and 100 years respectively in order to express emissions per MJ biomass harvested. All carbon footprints have, thus, been calculated using both a 20 years' timeframe (GWP20) and a 100 years' timeframe (GWP100), and includes only the warming effect of the emitted Greenhouse Gasses from changes in carbon stocks. For the 20 year average, the conventional GWP20 is used to translate non-CO_2 greenhouse gases emissions into CO_2-equivalents, and for the 100 year average, the GWP100. However, except for pathways including biogas and manure, other GHG than CO_2 is not relevant or of minor importance. For more on this calculation see section 5.2.1.

There is an ongoing debate concerning how to account for the timing of GHG emissions. Some argue that timing and the dynamics of emissions mean a lot, due to among other issues the so-called ‘tipping point’ problem, i.e. that high emissions from e.g. C-stock reductions now followed by uptake later on may have higher climate impact than the long term average, because the short term atmospheric GHG increase may lead to cascading effects. Others find that the long term net atmospheric increase is the main cause of climate change and that shorter term variations mean little or nothing. In this 'budget' view it is possible to quantify how much more GHG (CO_2-e) our civilization can emit in order to stay below a two degree Celsius increase.in temperature. The Emission Gap report by UNEP represents this view (UNEP, 2012). This report combines these views by recognizing that both the end point and the emission reduction path that leads to an end point emission level are important. For more on this discussion and implication for bioenergy system analysis see Bentsen & Stupak (2013), section 8 or the latest IPCC Assessment Report (IPCC AR5, 2013).

The dual timeframe allow for discussion of results in relation to both the reduction path and the reference end point in 2100. GWP100 is applied in National GHG inventories submitted by parties to the convention on climate change and the Kyoto Protocol (KP), and thus in member state's reporting and accounting towards EU obligations, yet in IPCC Assessment Reports, GWP20 is recognized in as an alternative (alongside GWP500).

In particular for biomass derived from forests, GWP20 and GWP100 may provide different perspectives due to the importance of long regrowth/rotation cycles on the carbon balance. The dual timeframe for footprints is furthermore introduced to alleviate the current, and by any means fragmented and unconsolidated discussion on 'carbon debt' in the bioenergy constituency. Carbon debt, in short meaning the lag time between the carbon emissions and sequestration in some fuel wood production systems (Dehue, 2013), is however found to be site, species and management specific, for example see Galik et al (2012), Jonker et al (2012), and Lamers and Junginger (2013), and it is not within the scope of this study to analyse forest holding specific GHG balances. This does not in any way preclude that carbon debt could be relevant for particular biomass production systems. For more on geographic scope, see next section.

3.3.1 Counterfactuals

In analysis of carbon footprints several types of counterfactual scenarios could be considered for the fate of the carbon, both at land use and product level. In this study the alternative to harvest for bioenergy from primary forests is continued unmanaged growth, whereas for all other forest biomass production systems the counterfactual is land use change or continued management. Specific counterfactuals are outlined in appendix A-E.

On product level, alternative non-energy use of the various biomass types mentioned above could be considered. In this study, non-energy use of woody biomass is not considered as a counterfactual directly, thus eventual carbon storage in wood products in the build environment, furniture or likewise is not included in calculations. This does not preclude that some alternative uses of wood may, e.g. through substitution of cement in buildings, altogether deliver more GHG savings than as bioenergy, as demonstrated by some (Sathre & O'Connor, 2010).

3.3.2 Non-GHG climate forcings

Changes to hydrological cycles, albedo, heat exchange, species composition in stands, particle emissions or other biophysical processes caused by changes in land use or management practices driven by bioenergy demand but potentially influencing local meteorological conditions, and if of significant scale also the global energy balance, is, however, not included. For examples of discussions of these aspects see e.g. Cherubini et al. (2012), Bellouin & Boucher (2010) on albedo, Choobari et al. (2014) on dust, Ban-Weiss et al (2011) on heat exchange, Kundzewicz (2008) on links between the hydrological cycle and climate forcing and Bonan (2008A and Bonan 2008B), Hansen et al. (2005), Kabat et al. (2004) or Steffen et al. (2004) for general introduction and overview. The latest IPCC Assessment Report also gives a brief overview of other forcings (IPCC AR5, 2013)

3.3.3 Local to global scale

GHG impacts are site and management specific, as found by a recent literature reviews conducted by Lamers et al (2013) confirming the findings of earlier reviews by Lattimore et al (2009). The land use types used in this study for the identification of biomass marginal are idealized proto-land types, which does not allow for assessing specific geographies or atypical site specific carbon balances. To ensure that these land use types are representative of a wide range of specific conditions, Monte Carlo simulations of 500 specific conditions for each land use types under each climate regime have been undertaken to arrive at a reasonable average number for the carbon stocks. See more in relevant appendix.

3.3.4 Transport emissions

Finally, it should be noted, that initial undertaken, show that emissions transportation of biomass where insignificant compared to other emission categories, and have thus been excluded from the assessment of pathways. For more on calculated values see appendix F, section 4, p.239.

3.4 Technological scope of conversion pathway assessments

3.4.1 Biomass types

The study was confined to include the most significant biomass categories for a Danish energy system, i.e.:

- Manure
- Straw residues from agriculture
- Woody biomass

Woody biomass, in turn, may be domestic or imported. The study does not distinguish between these, because the market for wood pellets and chips is assumed to be international, the marginal thus being one and the same.

The wood pellets or chips may derive from different sources of wood, and the study comprises different origins such as: thinning residues, plantation wood and wood harvested from existing forests. Plantation is assumed to be able to take place on different types of land, including marginal land, grassland, forest land and agricultural cropland.

3.4.2 Conversion technologies and pathways

The study has assessed to Carbon Footprint of 16 biomass conversion technologies all together. The technologies were selected in order to represent a spectrum from ‘conventional’ technologies being already widely used (e.g. wood and straw boilers, and direct combustion CHP plants for continuous electricity production) to advanced technologies such as thermal gasification pathways, and the use of hydrogen to upgrade syngas and biogas to methane and liquid fuels.

The following technologies are addressed in the project:

- Direct combustion (for CHP, industrial heat and district heat)
- Torrefaction as part of one pathway with direct combustion and gasification
- Thermal gasification and syngas production (for CHP and PP)
- Anaerobic digestion of animal slurry (mono-digestion), and co-digestion of slurry with: straw, energy crops
- Biomass to liquid synthetic fuels using chemical synthesis of syngas from wood and energy crops (for transportation)
- Electrolysis assisted production of biomethane and synthetic fuels based on electricity
- Fermentation second generation for bioethanol as transport fuel

The different combinations of feedstock and conversion technologies, and different used of co-products and main products, are referred to as ‘pathways’. Pathways were selected when seen to represent the key conversion technologies today as well as the most promising emerging technologies for a future renewable energy system. The pathways were partly selected due to their widespread use in existing energy supply, partly due to their perspective and potential role in future energy systems. Moreover, the study includes key pathways within heat, power and transport fuel production and the key woody biomass conversion pathways as well as key domestic residues conversion pathways in order to facilitate comparisons between these and allow for decisions on prioritizing these biomass categories. One specific aspect behind the choice of pathways was a wish to allow for supporting decisions on how to best prioritize biomass resources in the energy system.

The 16 pathways included are:

Heat supply:

1 Wood boiler

2 Straw boiler

Continuous electricity supply:

3 Wood CHP continuous power production

4 Straw CHP continuous power production

5 Manure biogas CHP continuous power production

6 Manure-straw co-digestion biogas CHP continuous power production

Flexible electricity supply:

7 Wood gasification with syngas reforming to SNG for CHP flexible power production

8 Manure biogas with hydrogenation into SNG for CHP flexible power production

9 Manure-straw co-digestion biogas with hydrogenation into SNG for CHP flexible power production

Transport fuel supply:

10 Wood gasification with syngas hydrogenation into methanol

11 Wood gasification with syngas hydrogenation into DME

12 Manure biogas with hydrogenation into SNG for fuel

13 Manure-straw co-digestion biogas with hydrogenation into SNG for fuel

14 2nd generation straw ethanol for short range transport services and with lignin and molasses co-products used to displace other woody biomass, e.g. in wood gasification pathways

15 2nd generation straw ethanol for long range transport and lignin and molasses co-products used to displace other woody biomass, e.g. in wood gasification pathways

16 2nd generation straw ethanol for long range transport and lignin used to displace other woody biomass, e.g. in wood gasification pathways, while molasses is used for biogas upgraded by hydrogenation and used for flexible power production

3.5 Technological scope of whole-system assessments

Part of the goal of the study is to reveal any system implications of the individual biomass conversion pathways. System implications may arise for several reasons, most importantly:

- As a consequence of constrained biomass resources, and
- As a consequence of synergistic and antagonistic effects of pathway combinations

Constrained biomass resources: when prioritizing a constrained resource like e.g. straw residues for one conversion pathway inherently other demands must rely on other resources. Further, some functional requirements of the whole energy and transport system may be supplied without the use of biomass, like e.g. heat or short distance road transport, implying that prioritizing biomass pathways for this leads to higher biomass demand. The overall system demand, therefore, varies with different conversion pathways.

Synergistic and antagonistic effects: When prioritizing biomass in conversion to fuels and upgrading renewable gases like biogas or syngas by hydrogen, heat losses will inherently occur. But such losses can be used for heating services, giving rise to synergetic links between conversion pathways compared to e.g. prioritizing biomass directly for heat and then converting other biomass to fuels. Many such links and combinations between biomass conversion pathways exist, and finding a good way to 'lay the puzzle' can result in lowering the overall biomass demand.

As part of the present study, therefore, a number of scenarios for a fully renewable Danish energy system in 2050 are developed. The modelling for the energy system design of these is done with the EnergyPlan modelling tool[1]. The EnergyPlan tool is an hour-by-hour energy system modelling tool which encompasses heat, electricity and fuel for the transport sector.

Four categories of alternative energy systems are modelled, all achieving a 100% renewable energy supply. The models assume different degrees of advances in energy conversion pathways, thus entailing varying degree of biomass use from

[1] Version 10.1 available for download at: http://energy.plan.aau.dk/energyplanadgang/index.php

low biomass consumption of around 200 PJ/year (= 40 GJ/person/year) to more than 600 PJ/year (=120 GJ/person/year). The purpose of this is to reveal the consequences of different strategies for the design of a fully renewable energy system ranging from one extreme to the other and to demonstrate the scale of the supply and demand of bioenergy in the renewable energy system. The four categories of system models comprise:

1 Standard bioenergy scenarios: a conventional bioenergy scenario, within which there is no electrification of heat and transport, i.e. no heat pumps and no electric vehicles. This implies the use of biomass in direct combustion technologies for heating, for CHP and PP, and for transport fuels, and no electrolysis, hydrogen or carbon capture.

2 Electrification scenarios: electrification is almost fully implemented in heat (heat pumps and electric boilers) and short range transport (electric vehicles). Biomass is used only little in boilers, but still widely used in direct combustion for CHP and PP, and for heavy transport fuels. No use of electrolysis, hydrogenation or carbon capture.

3 Electrolysis scenarios: the electrification scenario is advanced further by inclusion of substantial electrolysis and hydrogenation of syngas and biogas. But still no carbon capture.

4 Bio-carbon capture and recycling scenarios: the electrolysis scenario is further advanced by including carbon capture on stationary emission sources, i.e. CO_2 emissions from CHP, PP flexible power and heat facilities. CHP and PP are modelled as fuel cells and carbon is assumed captured from quite pure CO_2 flows from these at the quantity available at stationary facilities only. The CO_2 is hydrogenated into methane, methanol, DME or jetfuel.

These calculations will reveal to what extend new technologies and alternative energy infrastructure setups are needed to reduce the biomass consumption.

They will also show how different types of biomass can be used in combination with different conversion technologies to deliver the similar functional output, the effect of prioritizing a specific conversion technology and how the alternative conversion technologies interact with the surrounding energy system.

Finally it is through the modelling of the alternative scenarios that it is shown how the alternative conversion technologies are able to integrate renewable intermittent electricity production. By efficiently integrating wind, wave and solar energy with electrification, electrolysis and carbon capture, the reliance on biomass based energy is reduced.

All four categories of system designs supply the same functional unit in terms of conventional electricity, heat and transport services. Some transport services such as aviation, ship freight and long distance heavy duty road transport requires energy dense fuels to be delivered, while others such as personal vehicles or public transportation for short distance can be displaced by electrified propulsion with relative ease by integrating technologies such as BEV, PHEV and DEV. In three of the system design categories, electrified transport is prioritised wherever possible, resulting in a high penetration of electrification in the transport sector and a significant reduction in fuel demand. The fourth system design category only includes a moderate integration of electrified transportation, which implies that the transport sector is predominantly powered by biofuels. This does not imply that the physical and chemical properties of the biofuels are supposed to be exactly identical in all of the system designs. In other words the different types of biofuels are assumed to be readily able to displace each other, albeit with different tank-to-wheel properties, which in turn will result in different levels of demand for biofuel in terms of energy. In some system designs it is relevant to consider the effect of integrating alternative means of transportation.

The choice of technology is inherently connected to the type of biomass feed available, and requires the integration of different energy infrastructure setups to operate. A number of variants within each of the four described scenarios groups are, therefore, modelled to reveal dependencies of the choice of biomass-pathway combinations. This is further elaborated below.

The standard bioenergy scenario: This system design category comprises biomass heavy scenarios. In this design, the energy infrastructure largely resembles that of today. Wind penetration is at least 50 %, but fuel production is largely detached from heat and power production. The energy system is heavily dependent on large scale biomass and biofuels. The characteristic of these system designs are that biomass/biofuel is preferred in order to avoid the need for electrolysis. Heat and power is being produced in conventional combustion power plants.

The electrification scenarios: The second system design category introduces electric boilers and heat pumps for heat supply in the industry, the district heating grids and space heating in individual housings. This allows for a higher wind penetration, which in turn will reduce fuel consumption in boilers and power plants. Compared to the first system designs, the short range transport sector (personal cars) is heavily electrified through the introduction of BEV, HEV, PHEV and DEV. However, biofuels are still being produced independently of the rest of the energy system.

The electrolysis scenarios: This third system design category comprises a gas scenario. These systems introduce SOFC for heat and power production. In these system designs, most of the biomass is being converted to SNG either through anaerobic digestion or thermal gasification, while direct combustion of solid biomass is reduced to a minimum. This allows for a continued use of the extensive natural gas network in Denmark. Wind penetrations are higher than in the first and second system designs, due to the introduction of electrolysis allowing for a higher degree of wind power surplus compared to conventional electricity demand. This does in turn allow for some “boosting” of the available biomass carbon by hydrogenating syngas and biogas. However, even with a high scale of electrolysis, the dependency on biomass is still significant.

The carbon capture and recycling scenarios: This fourth system design category comprises biomass light scenarios – relative to the others. In these system designs, the biomass consumption is reduced to a minimum by introducing the maximal scale of electrolysis and hydrogenation through carbon capture from stationary facilities. As such, biomass is displaced wherever possible. By increasing the wind penetration to above 90 %, all biofuels will be produced using some kind of electrochemical technology. To regulate such a high penetration, the capacities of regulating technologies such as heat pumps and electrolysers are increased significantly. Yet without the introduction of carbon capture technologies it is not possible to cover the demand of carbon based fuels in the transport sector. Therefore, all biofuels are being produced through the addition of hydrogen.

Within each of the system design categories, a number of scenarios are developed to show the implication of different variations of prioritizing biomass. It was judged that the most uncertain aspect of prioritizing biomass lies in the use of straw residues. Whereas it seems likely that manure will end up in some form of wet fermentation pathway, and woody biomass in some dry gasification pathway, it's a bigger question which pathway straw is likely to follow. For this reason, variations were made especially for straw conversion, within each of the four system design categories.

In this way, the study has ended up developing all together 15 whole-system designs. These system designs are further described in Chapter 4 and illustrated as Process Flow Diagrams in Appendix J.

The developed system designs are:

Standard bioenergy:

1 Straw for biogas in manure co-digestion

2 Straw for kerosene

3 Straw for CHP

Electrification:

4 Straw for biogas

5 Straw for kerosene

6 Straw for CHP

7 Straw for CHP and full by-pass on CHP.

This full by-pass on CHP means that the CHP is developed to switch quickly and 100 % to heat and back to CHP, in response to the fluctuation power production. This is a technology having a high focus among Danish power industry.

Electrolysis:

8 Straw for biogas

9 Straw for biogas high yield (meaning pretreatment of straw by extrusion leading to increased bio-degradability)

10 Straw for bioethanol

Bio-carbon capture and recycling:

11 Straw for biogas

12 Straw for biogas high yield

13 Straw for bioethanol

14 Wood boilers in industry (independently of the type of supply for wood pellets and chips)

15 Methane as energy carrier

Please refer to Chapter N.N and Appendix J for further details of the system designs.

3.6 The functional units and the four levels of modelling

To address the goal of the project and provide support for decisions on the strategy for developing the Danish energy system, the modeling is performed and results are presented at four levels:

1 A unit process database including data on input and output flows of the biomass types and conversion technologies. This is provided in appendix H

2 LCA of individual biomass conversion pathways expressed per unit of functional output (e.g. 1 kWh electricity)

3 LCA of individual biomass conversion pathways expressed per unit (MJ) of biomass input

4 LCA of whole energy systems expressed per unit of total functional output from the Danish energy and transport system

These modelling levels will be described in this section.

3.6.1 Modelling level 1

At the modeling level 1, a database is established providing the basic data on the biomass conversion technologies.

This conversion technology database at level 1 comprises data on biomass input and energy inputs to the conversion process, as well as emission data. Also data on energy conversion efficiencies and functional outputs. In case the conversion process implies several functional outputs, these are all maintained as such, and no allocation of data between outputs is done. More unit operations may be covered by the data, and a simple outline of the involved unit operations will be included as illustrated in figure 3-2

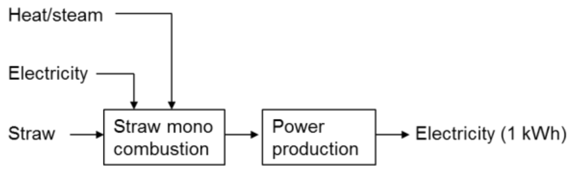


Figure 3-2 *Example of a process flow diagram illustrating the involved operations represented by the data*

The illustrated process Flow diagram in Figure 3-2 and the subsequent Figure 3-3 to 4-5 are only meant to illustrate the principle of modelling. The real model for the case of Straw CHP is shown in Chapter 4.

3.6.2 Modeling level 2

Modeling level 2 comprises the Carbon Footprint assessments of the biomass conversion pathways expressed per functional output for each of the studied functional output types, i.e.:

- 1 kWh of continuous power production
- 1 kWh of flexible power production
- 1 MJ of heat - industrial process heat/steam or district heating
- 1 MJ of transport fuel

The results are normalized per one selected functional output by eliminating any other outputs by expanding the system with the avoided alternative for other outputs. See the illustration in Figure 3-3:

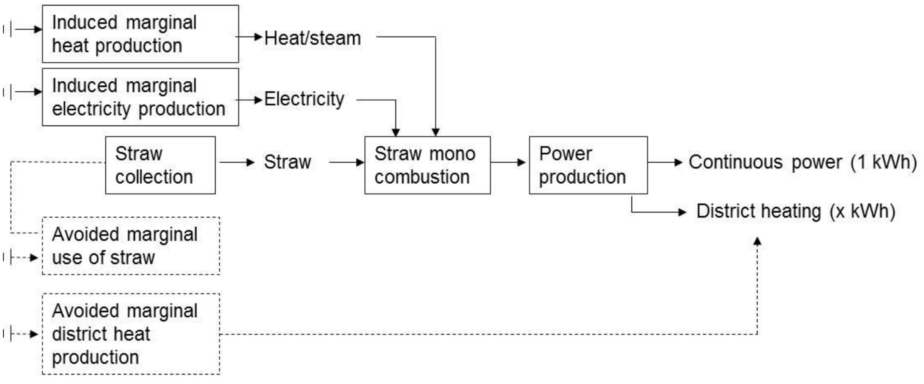


Figure 3-3 *Principle of the process flow diagram behind the biomass conversion pathway LCAs at level 2*

The model also includes the avoided marginal use of the land and/or the residual biomass when relevant. Furthermore, it includes induced and avoided marginal energy supplies.

The functional unit used to normalize results depends on the conversion pathway and the type of functional output in question, cf. the list above.

The Carbon Footprint results at this level allow comparing one pathway providing a given functional output (like e.g. continuous/non-flexible power) with another pathway providing the same type of functional output, but comparisons between pathways providing different types of functional outputs cannot be done at this level.

The Carbon Footprint assessments at this level aim at answering questions like e.g.: *How can flexible power be produced with the lowest potential impact (with respect to the Carbon Footprint) – under the energy system assumptions and other future framework conditions in question?*

3.6.3 Modeling level 3

Modeling level 3 comprises the Carbon Footprint assessments of the biomass conversion pathways expressed per biomass input, i.e. per 1 MJ of biomass input, to the specific biomass conversion pathway in question. An example of a system modeled at level 3 can be seen in Figure 3-4:

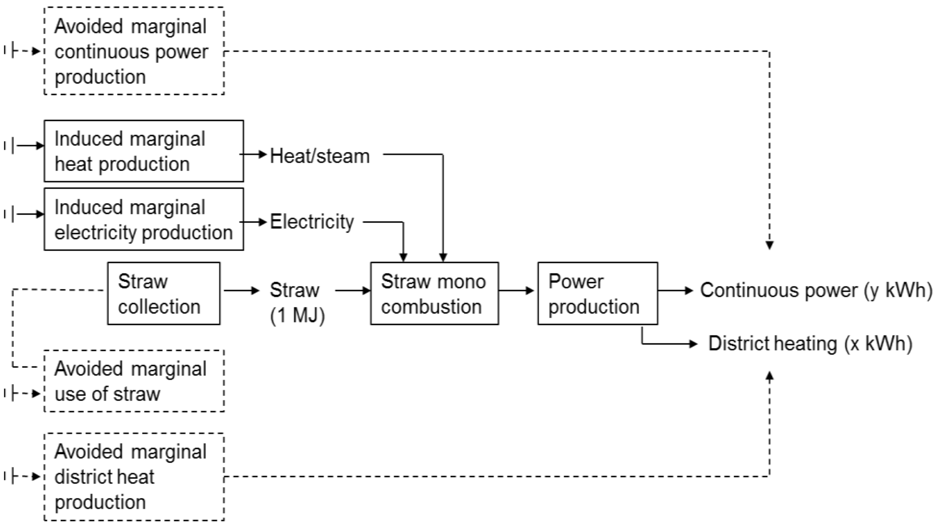


Figure 3-4: Principle of the process flow diagram behind the biomass conversion pathway LCAs at level 3

The difference between the model at level 2 and 3 is that <u>all</u> functional outputs are modeled to replace the alternative (marginal) supply of the same functional outputs in the studied system, including the primary functional output. In this way, conversion pathways providing different types of functional outputs can be compared, allowing to answers questions like: *How is a given biomass type best* *used (with respect to the Carbon Footprint) – under the energy system assumptions and other future framework conditions in question?*

3.6.4 Modeling level 4

Modeling level 4 comprises the Carbon Footprint assessments of the entire Danish energy system expressed per one and the same total functional output of the whole energy and transport system. The functional output delivered by each system is based on data from the CEESA study (Lund et al., 2011). This study comprise a thorough investigation of the Danish energy and transport systems and included a variety of analyses of energy savings and structural changes (for example some personal transport shifting to rail) prior to finally defining the demanded end use services of energy and transport.

The defined annual energy consumption and transport demand identified in the CEESA study and used in the present study divided by type is found in Table 3-1.

Table 3-1 Annual demand for energy and transport used as functional unit in the whole-system designs of this study

Traditional electricity demand	Space heating demand	Process heating demand	Personal transport demand	Freight transport
88.8 PJ/year	171.7 PJ/year	76 PJ/year	163,000 Mpkm[2]/year	164 Mtkm[3]/year

The total share of the transport demand covered by aviation is believed to consume 24.5 PJ jetfuel annually by 2050. The level 4 modelling has paid special attention to pathways for jetfuel production, because of the unique high quality standards defining jetfuel as a petrochemical product. The study has identified and included pathways able to produce synthetic jetfuel from biogenic resources - both with and without the addition of hydrogen. The process flows of these pathways and how they were included in the modeling of each system can be seen in appendix J.

Additionally, and considered as part of the functional output, each system design is to return 169 kT of 'soil-stable' carbon to the agricultural sector. In this context 'soil-stable' carbon is defined as the biologically slowly degradable part of the straw carbon, which stays in the soil over time. To this end, each system design must either return this after a conversion pathway, e.g. as digestate from biogas fermentation, or plough down a portion of the straw, which in turn prevents this from being used for energy purposes.

An example of the system modeled at level 4 is shown in sections 4.2 and 5.1. Modeling level 4 is provided and applied in this project to allow comparing full system designs in which the complex system network itself defines the induced and

[2] Person km
[3] Tonne km

avoided marginals of heat and power. The reason for including this modeling level is that:

- the decisions and comparisons to be supported by the Carbon Footprint assessments in this project involve long term system designs which are not yet implemented. Thus the degree of freedom to choose and also compare different approaches to and designs of a renewable energy system in e.g. 2050 is large.

- the fully renewable energy system is characterized by a very large degree of system integration, i.e. creating links and synergies between producers (e.g. wind turbines) and consumers (e.g. battery cars and heat pumps) of electricity as well as conversions between electricity and transport fuels through interactions between electrolysis, hydrogen and biomass conversion pathways.

- biomass is a constrained resource and potentially the main contributor to environmental impacts in the fully renewable energy system. These overall environmental properties of the whole system, therefore, lies in the elegance and synergy created in the whole system design, and not in the environmental performance of the individual conversion pathways seen in isolation.

These aspects inherently renders it quite difficult to assess a given biomass conversion pathway in isolation, as it to a wide extent is its system integration qualities that renders it attractive, and also at the end leads to its resulting Carbon Footprint implications in a systems perspective.

3.7 General aspects of the biomass models

In the consequential modelling, the marginal supply is defined as the supply being the response to the changes in demand deriving from the decision studied. This marginal supply is inherently, therefore, a function of both scale, place and time of the studied change in demand/supply, i.e. it matters where an extra demand or supply is located, it matters when the extra demand/supply is placed on the market, and it matters how big it is. Further, it also matters what type of market the demand is placed on, i.e. if the biomass is purchased through an international biomass Exchange or maybe placed with a specific forest owner, maybe even on specific conditions of sustainable or certified forestry.

The approach to identifying the biomass marginal is probably the most critical of all methodological issues in this study, because the Carbon Footprint results will be very sensitive to the assumptions on the biomass marginal.

The biomass modelling in general always comprises two aspects, i.e.:

- Direct life cycle implications: The environmental consequences resulting from the various activities (or life cycle stages) associated to the production of these biomasses (e.g. soil preparation, fertilization, harvest, etc.). These are the implications before any system expansion, and in case land use is implied, it is also referred to as DLUC.

› System implications: The environmental consequences occurring as a result of using these biomasses (or the land needed to grow it) for bioenergy instead of using it for their previous uses. These system implications are giving rise to different "life cycle consequences". These are the implications due to system expansion, and in case land use is implied, it is also referred to as ILUC.

System expansion occurs either when a constrained resource (e.g. straw, manure) is taken from another fate or use, or if a production of a product is displaced, as e.g. when agricultural land is used for energy crops at the expense of food/feed crops. The use of such constrained resources or displacement of other products triggers market responses leading to various consequences, among which is the replacement of the used resource or displaced product. The production and handling of this substitute is included in the modelling and referred to as system expansion or "system implications".

The direct life cycle implications of using manure and straw will be modelled according to the models in Hamelin (2013) and as described in Appendix G. For the use of woody biomass, detailed models are given in Appendices A – E. An overview of the system implications considered for the selected biomass types are presented in Table 3-2. For a given biomass, there is, in some cases, more than one system implication that has been considered (as shown in Table 3-2).

Table 3-2 System implications considered for the biomass sources involved in the assessment

Biomass source	**System implication**
Agricultural residues	
Straw (wheat straw)	Avoiding incorporation (ploughing) of the straw to soil (details of the applied model are given in Appendix G)
Animal slurry	Avoiding reference slurry management (details of the applied model are given in Appendix G)
Woody biomass (residues and bioenergy plantation) †	
Woody residues (thinnings, other residues)	Avoiding on-site decay (details of the applied model are given in Appendix D)
Forest remaining forest (punctual harvest from existing un-managed forest) (natural regrowth after harvest)	DLUC, including changes in sequestration capacity** (details of the applied model are given in Appendix B)
Plantation on forest land	DLUC, including changes in sequestration capacity** (details of the applied model are given in Appendix A)
Plantation on marginal land‡	If no other uses of the marginal land: DLUC** If this land could have otherwise be used to grow food/feed/energy crop (through inputs and investments): DLUC and ILUC*,** (details of the applied model are given in Appendix C)
Plantation on grassland (high C or low C)δ	DLUC and ILUC**,β (details of the applied model are given in Appendix C)
Plantation on cropland	DLUC and ILUC**

† Three locations (biomes) were looked at for the origin of the plantation and residues: boreal, tropical and temperate.

δ High C and low C grassland have been considered

**See Appendix A-E for more details on how DLUC consequences were considered, and Appendix F for ILUC consequences.

‡ This corresponds to degraded or "un-used" land. It should however be noted that this scenario was not selected as a marginal biomass source, as detailed in Chapter 4.8.

* Land that is marginal today - but good enough for establishing a plantation - may well in the future be good enough for food/feed production as well, if future prices for food/feed and agricultural inputs makes it attractive enough.

β The extent of ILUC will here depend on various parameters such as if the grassland was un-managed or grazed, and if grazed, to the extent the productivity in cattle production could be increased (see Appendix G for more details).

3.8 Identifying manure and straw marginals

The consequences of using manure and straw – being constrained resources taken from alternatives uses/fates – are briefly introduced in Table 4-2, and described in detail in Appendix G.

3.9 Identifying candidates for woody biomass marginals

The marginal biomass supplies for the various time perspectives and framework conditions have been identified by a two tier approach:

1. Using an reasoning related to the economy and governance and to the scale of demand and supply - mainly related to the identification of candidates the marginal supply at a smaller global scale and shorter term

2. Using a partial equilibrium econometric model called GLOBIUM (Havlik et al., 2011) to reveal probable candidates for responding biomass supplies on a large scale global biomass demand and on the longer term

The short term decisions in the Danish energy system context are likely to relate to lower global biomass-for-energy demand scenarios, simply because the decisions to be supported are likely to occur soon and last for a shorter time period, and therefore at a time where global bioenergy demand is not very much higher than today.

Longer term decisions are more likely to relate to larger scale global biomass-for-energy demands.

3.9.1 The influence of economy and governance

A higher demand for biomass due to bioenergy policies worldwide will contribute to increasing biomass market prices in general although price development drivers for specific product categories (e.g. wood panels, paper, and construction wood) may be unlinked. In a more simplistic market view, however, increased demand may have a two-sided impact on forestry and agriculture.

On the one hand, it increases the incentive to change management regimes to produce more biomass of the type with the most attractive price and market, and forestry may for this reason develop towards higher yields and also higher C-stock: when energy-biomass gets a higher value. Better prices for biomass for energy may mean that the bioenergy market altogether becomes more important in terms of contribution to the profit margin for the forest owner. This means the incentive to co-optimize timber and bioenergy production increase which in turn can imply higher overall biomass yields and stocks in the forest. This was already observed in Swedish forestry (Berndes et al. 2012) and German forestry (Schweinle et al., 2013). However, at the same time in certain geographies and on certain national markets with low integration or other barriers, non-commercial forest owners may not fully orient themselves towards global market prices. Private economy considerations, inheritance or self-dependency from auto produced wood may guide management decisions for than markets prices (USDA, 2008). The fact that the average forest holding size and ownership structures varies significantly across EU (European Commission, Directorate General for Agriculture and Rural Development, 2012), USA (USDA, 2008) and globally, may therefore explain why it has been reported that roundwood currently finds large scale direct use in energy production in certain EU countries (EC, DG ENTR, 2013, p. 299), probably mostly so in household boilers. For wood pellets specifically, Sikkema et al. (2013) finds that it is likely that within a decade (by 2020) or so more than half of all wood pellets produced in the world will be traded internationally, indicating that currently local or regional markets dominates.

The same holds true for agriculture, where increased prices on the bioenergy markets give incentive for multi-cropping and changed breeding developments towards higher biomass yields as opposed to only high kernel yields. On the other hand, higher bioenergy market prices also increase the incentive for new land cultivation and hereby deforestation and C-stock reduction.

Which of these developments has the stronger influence on overall global C-stock change is believed to depend on the development in land governance. If a strong international and global policy to avoid further deforestation is enforced, it will have a high influence on the cost of land and create high incentives for intensification of crop yields, forestry yields and animal production. This would most probably imply increasing C-stock in both forestry and agriculture hand-in-hand with increased biomass production. But if land governance is weak or insufficiently global, i.e. not enforced sufficiently by the key nations having land areas potentially in danger of further deforestation or C-stock reduction, there is a risk that C-stock reduction happens in such regions of the World.

In some cases, it is experienced that business economy for the farmer can lead to planting energy crops on farmland, depending on the specific conditions including subsidy schemes and other economic drivers. An example is the US ethanol industry, which is heavily subsidized, and also recent developments in biogas application have led to agricultural shift towards energy crops. In Germany, 7000 biogas plants exist depending to a large extent on energy crops like maize and grass. The area used to produce these energy crops is around 800.000 ha (equal to one third of Danish agricultural land), and the production of biogas from these crops equals around 1% of German energy consumption. Also in Denmark, subsidy schemes and regulation promotes the addition of energy crops to manure in order to render manure biogas more attractive. In the case of energy crops for solid biofuels, it has been acknowledged in Sweden that conditions can prevail leading to crops like willow being attractive in a business perspective (Azar and Berndes, 1999).

Conditions are, thus, seen that energy crops, including woody crops, can be an interesting business case for farmers. This does, however, not necessarily mean that plantation on cropland candidates as one of the most probable sources of woody biomass supply, because it depends on policy including subsidy schemes and CO_2 price. But the point is that it is seen before, and can happen again, that the economic framework conditions for farmers end up creating an attractive framework for energy crops also for woody biomass.

3.9.2 The significance of the scale of demand

An important background assumption is the scale of global bioenergy demand. If the overall demand for bioenergy remains small, more is available for a Danish demand, and also the most Carbon Footprint friendly ways of providing biomass will remain available. On the other hand, if global bioenergy demand increases to a very large scale of demand for climate reasons or other, i.e. other nations follow the same development as pursued by Denmark, one might ask, if competition for biomass implies that marginal demands are pushed towards biomass supplies of other origin than were available at the smaller scale.

At present, the global scale of demand is still relatively small, and some countries in Europe are the predominant customers. On the shorter term, therefore, all biomass categories are potentially available. Pre-commercial thinning and harvesting residues from timber production is a category often mentioned as an option for a biomass type with low carbon footprint. The scale of such residues available is, however, limited. Chum et al. (2011) state total roundwood production to be at the scale of 15-20 EJ/year, and Bang et al. (2013) find the total forest product output to be around 25 EJ/year of which nearly 15 EJ/year is sold for energy while timber and other products constitute the rest. Total timber production being, thus, around or below 10 EJ/year, there is a limit to the scale of residues available, some of this potential being already used for paper production and energy. Our estimate is that thinnings and harvesting residues above a scale of bioenergy demand of 5 EJ/year is not a realistic biomass marginal – but until then it can potentially be a marginal or part of the marginal. Further, the biomass potential lying in the C-stock increase from co-optimization of a multi-output forestry, i.e. timber and energy products, giving rise to increasing C-stock and biomass harvest together, is also limited by the scale of the market for timber products. It is difficult to see this rise much beyond 10-15 EJ/year of timber (roundwood), and the related co-product of energy biomass from such forest optimization is believed to be limited to the same order of magnitude. At a smaller scale, therefore, such biomass categories may represent potential marginal, while at a larger scale, other more abundant categories of biomass like plantation are more realistic marginals.

The point of addressing the smaller scale is to identify potential marginal biomass supplies for the shorter term decision in the Danish energy policy. For decision with a the longer term influence, the study incorporates background conditions representing a World with a larger bioenergy demand in order to reflect a world adapting a climate agenda and aiming at meeting the demands of the 2 degree C scenario. According to Chum et al. (2011) a review of 164 long-term energy scenarios showed bioenergy deployment levels in year 2050 ranging from 118 to 190 EJ per year for less than 440 ppm CO_2eq concentration targets (25th and 75th percentiles). Looking at the characteristics of current hour-by-hour models used when designing the Danish renewable energy system, it seems that many such studies tend to underestimate the need for biomass to balance fluctuating power production, cf. also the section on the whole-system scenarios (level 4) in chapter 7. In any case, however, the scale of biomass demand in renewable energy systems on the longer term is high. Chum et al. (2011) estimates the total available biomass potential by 2050 to be in the range of 100 – 300 EJ/year, and the demand is, thus, seen to be depending on using more or less the full potential. At the larger scale of demand, therefore, only the large scale categories of biomass can come into play as marginals.

3.9.3 Identifying candidates for biomass marginal supply in a larger scale global demand scenario

As part of the effort to identify potential marginal biomass supply, a partial equilibrium econometric model called GLOBIOM (Havlik et al., 2011) developed by the International Institute for Applied Systems Analysis (IIASA) was used. The model is used to simulate which categories of biomass would come into play (on the market) under varying conditions. The GLOBIOM model can briefly be characterized as follows:

The model comprises agricultural and forestry sectors incl. bioenergy and the World divided in 30 economic regions. A representative consumer is modelled through a set of so-called iso-elastic demand functions. Land cover types include cropland, grassland, short rotation tree plantation, managed forest, unmanaged forest, other natural vegetation. The model is calibrated based on the biophysical model EPIC, and calibrated to year 2000 FAOSTAT activity levels and solved in 10-year time steps.

Food demand increases linearly with population, and GDP per capita changes determine demand variation (depending on income elasticities). Scenario on future diets were built based on (FAO, 2006): Consumption does not exceed 3600 kcal/cap/d, except for USA (these numbers include waste). Net afforestation with traditional forest is not taken into account.

The existing GLOBIOM model has been run under three different baseline pathway conditions, the so-called SSPs (Shared Socio-economic Pathways) representing a specific development in background framework conditions. See

Appendix L for further explanation of the GLOBIOM model and the SSP2 scenario.

The SSP2 was applied for this study, as the BAU development in this SSP is judged to be the most realistic basis. In this baseline development pathway, GLOBIOM models how much biomass can be expected to be sold on the market at different biomass price levels from low to high. In this study price levels of 1.5, 5 and 8 US$/GJ of biomass is used. Moreover, the model at these price levels was run under the condition from very low CO_2 prices (0 US$/ton) to relatively high prices (50 US $/ton) to represent both low and high incentives to avoid biogenic CO_2 emissions. Figure 4-5 shows the outcome of the model run under these conditions, presenting the consequence in terms of the changes in land use modelled to happen.

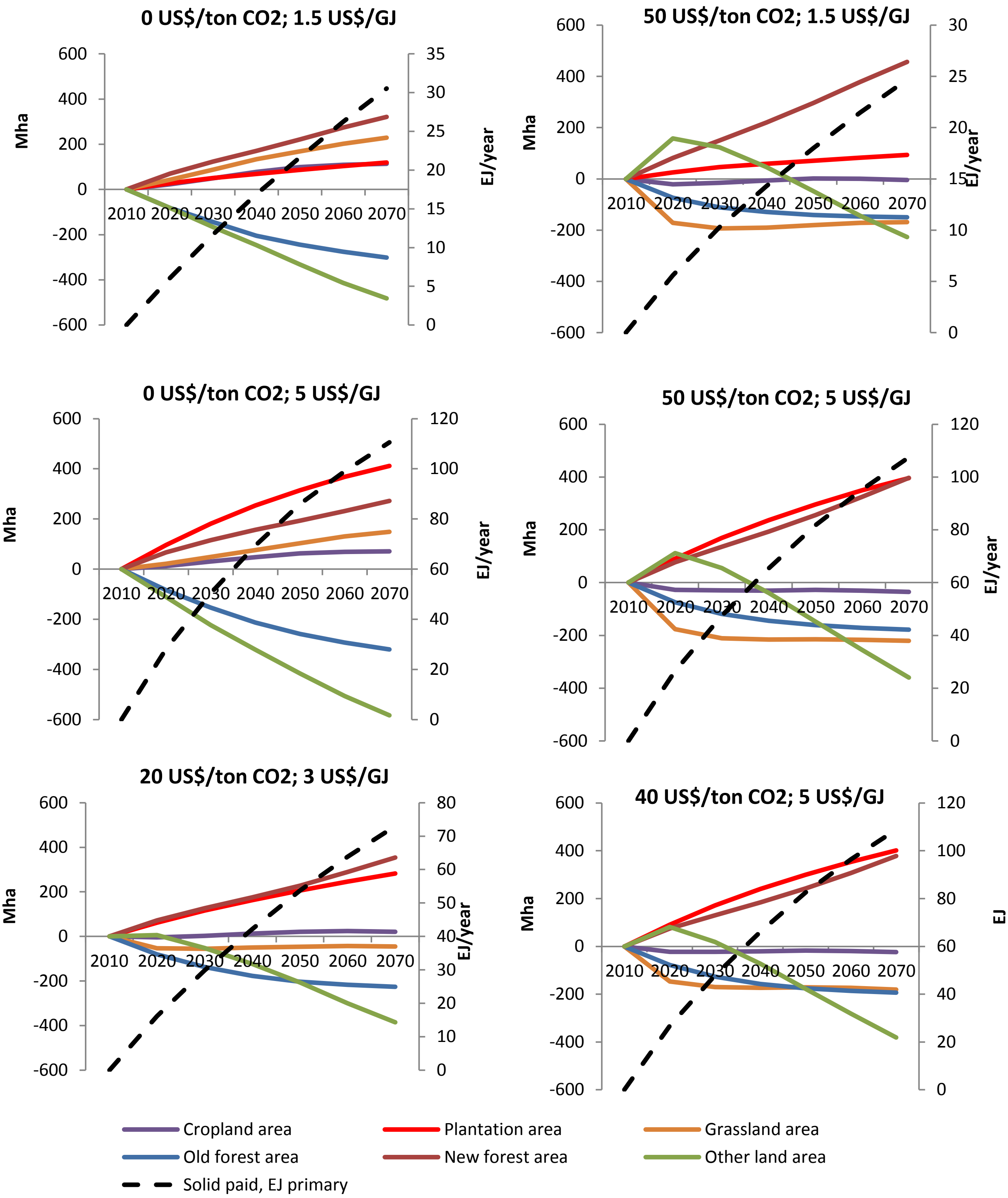


Figure 3-4 *Models of total LUC at global scale at various CO_2 and biomass prices using GLOBIOM. 'Solid paid' represents the energy equivalent of the solid biomass modelled to be harvested and sold under the given conditions*

A closer look at the responses to changing biomass prices and CO_2 prices, as identified by the model, reveal the following:

Plantation land: Plantation is seen to always increase compared to 2010 level. It responds very much to the biomass price, at high biomass prices, plantation is the predominant land increase. This is inherently logic as plantation is happening in order to harvest and sell biomass. At low biomass price, plantation does not increase much, and the relatively low biomass harvest in these scenarios may come also from harvest from old forests and to a lesser extent new forest. Plantation area does not respond much to CO_2 price, but its location does. At a high CO_2 price, plantation predominantly happens at land with low carbon stock (like grassland), while at a low CO_2 price, the plantation is seen to happen at old forest land and other land (including savannah).

New forest land: New forest land is seen to increase from 2010 onwards in all scenarios. This almost lies inherent in the definition, as new forest land in GLOBIOM is defined as forest less than 10 years old. The increase in new forest land is not responding to biomass price at all, which is logic as the incentive for establishing new forest land is not the sale of biomass for energy. Increasing CO_2 price, however, give rise to increasing new forest land, presumably because establishing new forest land can be a way to cost-effectively reduce net GHG emissions for a country. In conclusion, new forest land cannot be a significant part of the marginal, as it does not respond to demand of biomass (i.e. increasing biomass prices).

‘Other land’/Savannah: Savannah and other similar land types with relatively high carbon stock are believed to be the dominating response under ‘other land’. This land type responds only very little to biomass price, but quite dramatically to CO_2 price. This seems logic, because e.g. savannah is not mainly a biomass provider, but rather the land type to potentially be hosting a new plantation. At low CO_2 price, ‘other land’ is lost quite rapidly from 2010 and onwards. At higher CO_2 price, ‘other land’ initially increases, but after 2020 ‘other land’ is at a large scale and pace lost for plantation. In fact, in all scenarios, after 2020 or 2030, the loss of ‘other land’ is the fastest responding land use decrease of all, showing thus that savannah is a main part of the biomass marginal after this time under all conditions.

Old forest land: Old forest land is seen to decrease quite significantly under all biomass and CO_2 price conditions. The pace of decrease is sensitive to the CO_2 price, and at zero CO_2 price the decrease is almost twice the decrease at 50 US$/ton CO_2 in 2050. A significant part of the decrease is probably windfall, diseases and fires, which implies a demand insensitive baseline for the decrease. This is sustained by the fact that the decrease, at constant CO_2 price, is seen to be rather insensitive to biomass price, even though there is a small response in terms of larger decrease at increased biomass price.

Grassland: Grassland is seen to keep increasing at low CO_2 prices, while it responds by rapid decrease at increasing CO_2 price. It seems that both new forest plantation and ‘other land’ can increase at the expense of grassland at low biomass price, while at high biomass price, plantation is the dominating displacer of grassland. Moreover, the model shows that the use of grassland for plantation is the first response from 2010 onwards, but under all conditions, the decrease of grassland stops around a scale of supply between 10 and 40 EJ/year, corresponding to 2020 or somewhere between 2020 and 2030. Presumably because it is the most attractive land type as host for expansion of plantation, new forest and also cropland, but also constrained by scale, so the potential for expanding further on grassland is relatively quickly used up in a large scale global biomass demand scenario. Our conclusion is that plantation on grassland is mainly a part of the marginal in the first periods in time.

Cropland: Cropland is the land type varying the least. It is sensitive to CO_2 price, and at low CO_2 price cropland keeps increasing while at high CO_2 price it is more constant. It is also, even though to a lesser degree, sensitive to biomass price, and higher biomass prices implies less cropland at constant CO_2 price. As the graphs in Figure 4-5 show the net development, it is difficult to deduct how much plantation on cropland that may take place, because this may be followed by a further ILUC within which cropland is subsequently displacing forest, grassland or other land. But the fact that cropland does show some sensitivity to biomass price indicates that such mechanisms may take place within the models of GLOBIOM.

Figure 4-6 illustrates the breakdown of these land use developments on the 11 world regions comprised in GLOBIOM. The purpose of this is to show where in the World the land use change is modelled to happen. This is done for the combination of high CO_2 price and high biomass price only, but it is not judged to differ significantly for other combinations. As seen, the predominant increase in plantation is happening in Latin America (South America) and Sub Saharan Africa, and the predominant decrease in other land, old forest and grassland is also found here. This is no big surprise, as these regions are where the largest areas are found.

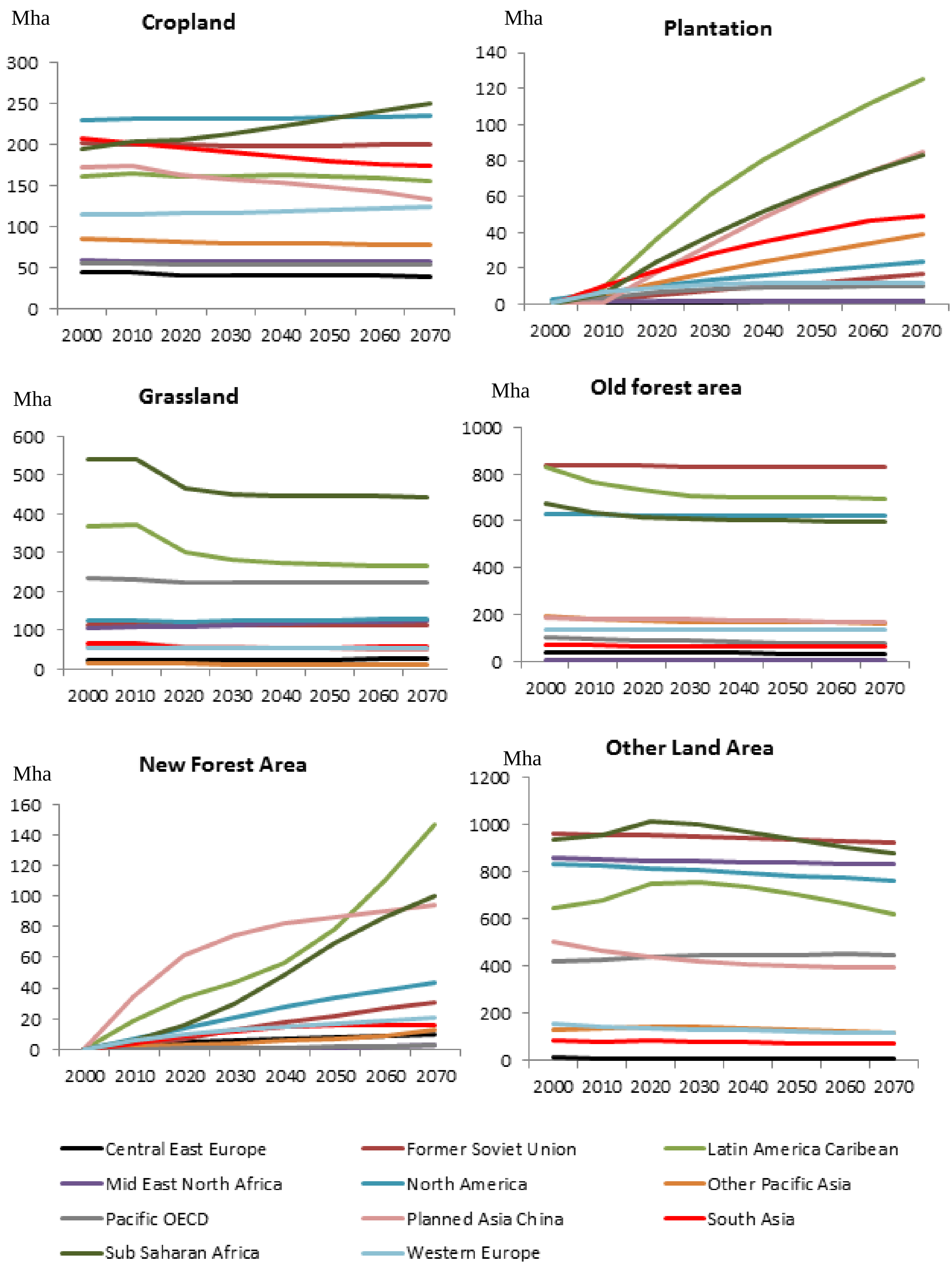


Figure 3-5 Development in Land Use in 11 regions of the world, as modelled in the partial equilibrium model GLOBIOM at CO_2 price of 50 US$/ton and biomass price of 5 US$/GJ

As the objective of the consequential LCA in this project has been to identify the response to an incremental change in biomass demand deriving from a Danish import, is was tried to use the modelled data to illustrate an incremental price level change, thus presumably revealing the difference in land use going from one price level to the next. Figure 4-7 shows the outcome of this at high CO_2 price and high biomass price.

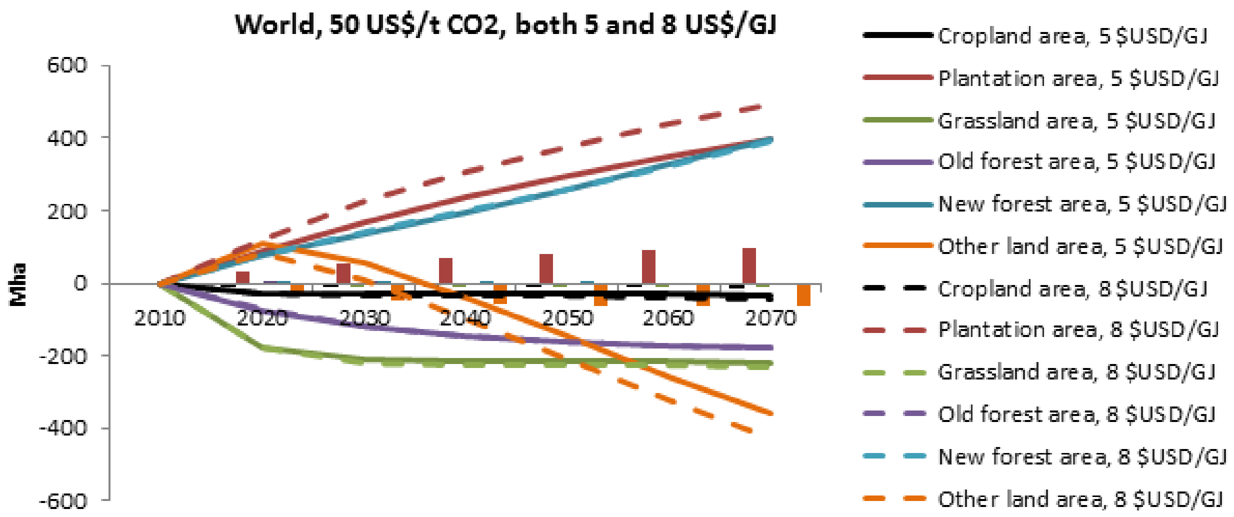


Figure 3-6 *The difference in land use change (LUC) at biomass price of 5 and 8 US$/GJ – simulating the incremental change in LUC at incremental biomass demand increase*

The change in price level obviously gives rise to a change in land use, and the model hereby reveals which change in land use this causes. As the figure shows, the predominant response to this incremental change is an increase in plantation and a decrease in ‘other land’ indicating that the increased biomass supply happens by establishing plantation on the savannah or similar land types, predominantly in Sub Saharan Africa and Latin America as indicated by Figure 4-6.

There may, however, be non-land use related responses to the increased biomass price level, as for example intensification and harvest of forest biomass without changes in forest area, i.e. harvest from ‘forest remaining forest’. A data extraction was done to identify the significance of this, as illustrated in Figure 4-8.

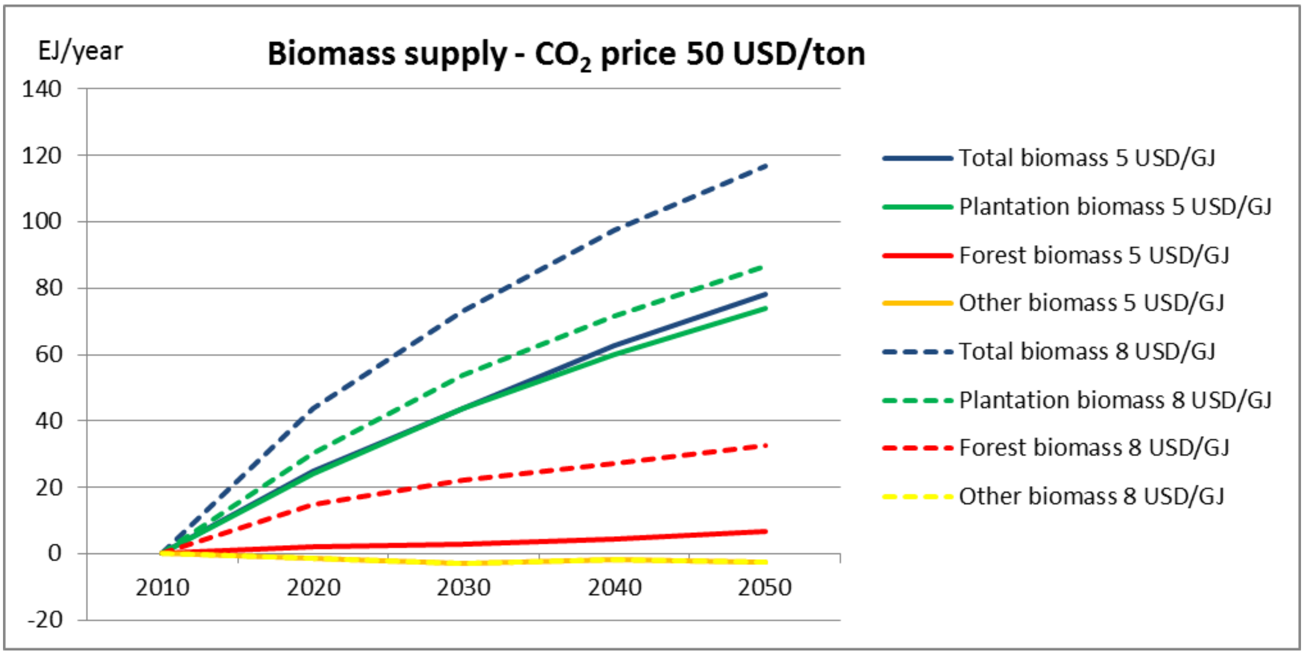


Figure 3-7 *The difference in biomass supply at biomass price of 5 and 8 US$/GJ – simulating the incremental change in supply at incremental price increase*

As illustrated by Figure 3-7, the major increase in biomass supply from 2010 onwards derives from plantation at a biomass price of 5 USD/GJ, and only a small part come from forest biomass. Forest biomass here means harvest from forest remaining forest, as plantation on forest land would imply the biomass to be plantation biomass. But at a biomass price of 8 USD/GJ, an increasing part begin to derive from forest biomass, and looking at the increment only, it shows that among two thirds of the increase in biomass supply when going from 5 to 8 USD/GJ in fact derive from forest biomass – according to the data of the SSP2 model run.

3.9.4 Summarizing the potential candidates for biomass marginal supply

Based on the models and finding presented, relevant biomass supply categories identify are identified, discussed and interpreted in order to establish candidates for the marginal supply in response to a Danish demand of biomass for energy.

First of all, domestic manure and straw biomass is believed to represent marginal supplies in the sense that the marginal is their alternative use – as already described. For manure the avoided alternative is the state-of-the-art Danish conventional manure management, and for straw the avoided alternative is ploughing down. These models are described in Appendix G.

Secondly, domestic wood is considered sold to and purchased from the same international markets as imported wood, thereby having the same marginal. For this biomass, the marginals are divided into marginal representing a smaller scale, shorter term biomass demand and a larger scale, longer term demand.

3.9.5 Small scale bioenergy demand – shorter term wood marginals

This marginal represents decisions with shorter term consequences like decisions on operations and fuel type – not involving investments with a long term return on investment. On the short term, a low CO_2 prices is foreseen to prevail on the markets in question, i.e. within the countries potentially supplying wood, like Canada, Russia, USA and Latin America. Looking from the best case to the worst case situation, potential candidates for biomass marginal on the shorter term to can be:

<u>2013 – 2020</u>

1. Best case: Biomass from pre-commercial things and harvest residues and from forest intensification
2. Medium case: Plantation on grassland with no or low ILUC
3. Medium case: Plantation on cropland
4. Worst case: Harvest from existing forest, i.e. forest remaining forest

Harvest from forest landscapes with increasing C-stock at increasing harvest is a realistic part of the marginal at a smaller scale of demand. When the harvest of biomass for energy exceeds the scale of timber production, and bioenergy becomes the sole customer, this marginal supply is no longer possible.

Pre-commercial thinning wood and harvest residues and co-product output from forest intensification are expected to be available as at least part of the marginal up to a scale of 5-10 EJ/year. Historically, thinning wood has been used in virgin paper making, but paper industry is increasingly moving to plantation of e.g. Eucalyptus. Pellet production is observed to move in, where paper industry is moving out. But the question remains why paper industry moves for plantation for economic reasons (lower cost of wood feedstock), when pellet production is not expected to do so. A probable explanation is that establishing new plantation constitutes a bottleneck (there is a limit to the pace at which it happens) and that the options for new plantation are taken by paper industry for the time being, because paper production implies the higher added value of the two competing customers for new plantation. At some point, however, the bottleneck will be surpassed, and the lower feedstock cost of plantation wood may result in plantation being the marginal. It is difficult to give an estimate of a time horizon within which thinning wood can be judged to be part of the marginal, but maybe up to around 2020 or 2030? The development of where pellet production takes place should be followed.

The GLOBIOM model runs show that plantation on grassland can be a very probable marginal on the shorter term. But also this potential is limited by scale and in time. The decrease of grassland area stops around a scale of supply between 10 and 40 EJ/year, corresponding to 2020 or somewhere between 2020 and 2030, and beyond this plantation on grassland is no longer seen as a large scale contributor to the marginal biomass supply.

Plantation on cropland. As the profit margin of farmers from shifting to energy crops an under some circumstances be higher than from food/feed crops, also on a short term, this may also be a part of a market based marginal. The business case for farmers should be carefully investigated and understood, and a proper structure of incentives established, if it is an aim to avoid plantation on cropland from being part of the marginal woody biomass supply.

Harvest from old forest or plantation on old forest land. As the partial equilibrium model shows, a part of the land use change, especially at low CO_2 prices (as foreseen to prevail on the markets in question on the shorter term), is still decrease in old forest area – unless strong land use governance is assumed.

When purchasing biomass, care can be taken to ensure a specific origin, e.g. thinning wood from a specific forest owner. This helps ensure the origin and direct carbon footprint. However, if thinning wood over time become limited, other customers may be pushed towards other marginals by Danish customers taking the thinning wood. It is may also be that chips or pellets from thinnings and harvest from existing forest are quite closely related, i.e. traded on the same markets or even sold by the same company/forest owner. It may be difficult, even with quite strict control, to prevent forestry biomass from 'forest remaining forest' to enter the market.

Good governance and conscious sourcing of the demand towards pre-commercial thinning and harvest residues is judged able to ensure that such biomass is a predominant part of the marginal up to a global biomass demand of 5-10 EJ/year. But strong and global land use governance is believed necessary to prevent other biomass origins like plantation on cropland or harvest from existing forest to constitute some part of the marginal.

3.9.6 Larger scale bioenergy – longer term wood marginals

Based on the GLOBIOM model, and also based on an understanding of where the larger scale available land types are, it seems that plantation on grassland, savannah and old forest land constitute an aggregated marginal on the long term. Plantation on other land like savannah may be the predominant part of the marginal. The following candidates for the biomass marginal were found probable on the medium to longer term:

2020-2035:

1. Best case: Plantation on low C savannah
2. Medium case: Plantation on tropical grassland with high ILUC
3. Medium case: Plantation on high C savannah
4. Worst case: Plantation on forest land

2035-2050:

5. Best case: Plantation on high C savannah
6. Worst case: Plantation on forest land or harvest from forest remaining forest

2050+:

1. Best case: Plantation on high C savannah
2. Worst case: Plantation on forest land or harvest from forest remaining forest

3.10 The ILUC model

As highlighted in the recent study of Warner et al. (2013), two main approaches to model the environmental consequences (most often the GHG consequences only) of ILUC have been used in studies published so far: (i) economic equilibrium modelling; and (ii) deterministic modelling. This study draws on the second approach.

It is beyond the scope of the present study to elaborate on the details, strengths and drawbacks of these respective approaches. For this, the reader is referred to Warner et al. (2013), as well as to Marelli et al. (2011). Briefly, however, it can be highlighted that the choice of the deterministic approach was essentially motivated by its transparency advantage and by its reliability over time[4]. Further, equilibrium models constructed to study near-term marginal changes were judged less suited for producing the longer term outlooks aimed at in the present study.

The ILUC model considered in this study comprises two main mechanisms[5]:

(i) Transformation of non-cultivated area (nature) to cropland, also referred to as *land expansion* (or new land cultivation).
(ii) Increased yield per land area, also referred to as *intensification*

Land Expansion

To quantify the Carbon Footprint due to land expansion, or new land cultivation, it is necessary to:

i. Identify how much land is converted, where it is converted and which types of land are converted (biome types);
ii. Estimate, for all converted biomes, the releases of C from the vegetation and soil to the atmosphere.

In order to quantify point (i) above, a deterministic approach to ILUC (as e.g. described in Schmidt, 2008) was used. The methodology used as well as calculations are described and presented in Appendix F.

[4] i.e. the approach can be cross-checked and the results replicated by a third party in e.g. 5 years' time, while there are great chances that this would more difficult with an equilibrium model, be it because of the too high complexity of use it would involve for this third-party, because the exact version of the model used to generate the results is no longer available a few years after the study has been released, etc.

[5] As a consequence of the deterministic approach used in this study to model ILUC, price elasticity effects leading to e.g. a decrease food/feed consumption as a result of an increased demand for land were considered as short-term effects on prices and as such negligible for a longer-term outlook such at the one looked at in this study. These were thus not dealt with in this study. Such rationale was also used in Schmidt et al. (2012).

In order to quantify the releases of C due to land conversion (point ii above), the soil and vegetation carbon data from the Woods Hole Research Centre, as published in the "supporting online material" of Searchinger et al. (2008) have been used[6]. From this database, the amount of C in the soil and vegetation of all affected biomes (point i) was extracted. This allowed to calculate the amount of CO_2 emitted (or sequestered) during land conversion, where the following has been considered, based on the standard practices in various studies dealing with ILUC[7]:

› 25% of the C in the soil is released as CO_2 for all types of land use conversion, except when forests are converted to grassland, where 0% is released;

› 100% of the C in vegetation is released as CO_2 for all forest types as well as for tropical grassland conversions[8], while 0% is released for the remaining biome types (e.g. shrub land, non-tropical grassland, chaparral).

It should be noted that the above applies for the calculation of ILUC only, i.e. the situation where non-cultivated land is transformed to cropland. Cases where land is transformed to lignocellulosic plantations (here considered as DLUC) are covered in Appendix A-E. Calculations details for ILUC are presented in Appendix F, for selected ILUC examples.

Intensification

Intensification refers to the increase of crop yields as a response to a change in demand for land. Recent studies on biofuels or increased crop consumption involving economical modelling indicated that the share of the intensification response in replacing the displaced biomass is likely to be of at least 15% (Kløverpris, 2008; Marelli et al., 2011) and may potentially be as high as 70% (Marelli et al., 2011). In this study, a range has been considered regarding the intensification share of the displacement response:

Case 1: Low intensification (and high expansion): in this case, 15% of the change in demand for land is supplied by intensification

Case 2: High intensification (and low expansion): in this case, 70% of the change in demand for land is supplied by intensification[9].

Intensification may be achieved through three main pathways:

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[6] Other databases (i.e. IPCC) could have been used. See Appendix F for a discussion on the implications of this choice.

[7] E.g. Müller-Wenk and Brandão (2010); Laborde (2011); Searchinger et al. (2008).

[8] This is to be seen as a simplifying assumption (personal communication with Miguel Brandão, ILCA, January 2013, and with David Laborde, IFPRI, February 2013). In fact, from the data of Earles et al. (2012), whom detailed, for 169 countries, the fate of the above-ground residues when forest are cleared, it can be seen that even after 100 years, it is not exactly 100% of the C that is returned to the atmosphere, although the gap is negligible in most cases.

[9] This, however, does not always apply. For example, such high intensification was considered unlikely for soybean, a N-fixing crop independent of N fertilizers.

Input-driven pathway: this refers to any yield increases obtained through changes in farm inputs (e.g. fertilizers, pesticides, irrigation, etc.). The increases in yield obtained this way may however be reversible.

Innovation-driven pathway: this refers to any yield increases obtained through technological development (e.g. harvesting technologies allowing to recover more biomass, plant breeding, etc.), and is seen as a more permanent effect (Marelli *et al.*, 2011). However, a lag of ca. 20 years is likely before research and development activities actually translate into yield increases (Edwards *et al.*, 2010).

Multi-cropping/cropping-intensity pathway[10]: this consists to grow more than one crop on the same hectare of land for a given year, which in some countries allows a harvest all year-round. This currently represents 18% of the world's cropland, and higher crop prices can be envisioned to increase the profitability of this practice (Marelli *et al.* 2011). This is related to the input-driven pathway, since it has the consequence to involve more input.

In terms of environmental consequences, the input-driven pathway is the one that matters the most, especially when yield increases are obtained through increase use of nitrogen fertilisers (e.g. Melillo et al., 2009). For the purposes of the present study, the environmental implications of innovation-driven intensification will thus be neglected[11].

One challenge for the environmental assessment is then to determine the extent to which intensification is achieved through increased fertilizers. One simple way to address this could be to consider a range (e.g. 50% to 75%). This is the approach adopted in this study.

The proposed way to estimate the environmental consequences of fertilizers-based intensification is to use the approach described in Schmidt (2007), which uses crop yield dose-response figures to determine how much extra N is applied to selected crops likely to be affected by this form of intensification.

All calculations details for intensification are presented in Appendix F, where the amount of crop produced by intensification is presented, along with the GHG releases (and other environmental flows such as NH_3 and NO_3) for each of the cases where intensification is involved.

[10] Increase use of fallow land could also be included in this intensification category.

[11] Multi-cropping (a form of input-driven intensification) is reflected and accounted for in the case of soybean, see Appendix F. It can also be argued to which extent the innovation-driven intensification should be included in the LCA. The answer, of course, is to the extent that it would not have happened anyway (i.e. to the extent it is demand-driven). Although innovation-driven intensification is excluded of this study for simplification, this question, i.e. the understanding of the extent to which innovation-driven intensification is linked to the demand, could represent a valuable contribution in the iLUC debate.

3.11 Identifying the energy system marginals

Identification of marginal electricity, heat and transport in 2013 and 2020 in DK are based on the Danish Energy Agency's basic energy system projection for these years (The Danish Energy Agency, 2013). Marginal electricity, heat and transport in DK in 2035 is, likewise, based on a basic energy system projection for 2035 ('Basisfremskrivning 2035', The Danish Energy Agency, (2013)). For 2050, the identified marginal represent the most likely candidates for renewable energy supply of the various types of energy services in the system, and these are identified in collaboration with the DEA.

The selection of marginal energy supplies are done in accordance with the Danish Government's energy policy. Essential goals of this policy are, as previously mentioned, that electricity and heat supplies are to be covered by renewable energy by 2035 and that all energy supplies including transport – are to be covered by renewable energy in 2050. The range of energy system scenarios developed for the assessments all respect these goals.

The contextual condition of the study is that the DEA wishes to use the Carbon Footprint assessments as part of the knowledge platform in the design of the future Danish energy system. Overall, the question asked is, thus, "what is the Carbon Footprint consequence of applying a given pathway in a given system design"?, i.e. using 'piece of the puzzle' to replace other 'pieces of the puzzle'. In this sense, the identification of energy system marginal is deterministic, because the results inherently become conditional to the defined system into which the pathway is applied. But this is part of the goal definition, and reflects the DEAs need to judge how a given pathway will perform given the development of the energy system towards a fully renewable system with the given milestones in time.

Table 3-3 shows the selected energy system marginals. The ones in black text are the ones applied in this study, while the blue ones are alternative wishes from the DEA that at this point was not applied.

Table 3-3 Energy system marginals used in the LCAs. Legends: NG = Natural gas; PP = Pure Power; E-boiler = Electric boiler; 1 = Average electricity of the period (further specified in Table 4-2); 2 = the assumed biomass marginal of the period used in direct combustion CHP; 3 = the assumed biomass marginal of the period used in wood gasification with syngas reforming to SNG stored and used for flexible power; 5 = the same with final jetfuel production

		2013-2020	2020-2035	2035-2050	+2050
Electricity input	Continuous	Average[1]	Average	Average	Wind
	Flexible	Average	Wind	Wind	Wind
Electricity output	Continuous	Average	75% wind and 25% biomass[2]	75% wind and 25% biomass[2]	Wind
	Flexible	PP (coal)	PP (coal)	Biomass[3]	Biomass[3]
Heat/steam	Industrial	Boiler (NG)	Boiler (NG) Heat pump (wind)	E-Boiler (wind) Boiler (biomass[2]) Heat pump (wind)	E-Boiler (wind) E-Boiler (biomass[2]) Heat pump (wind)
	Small district heating	Boiler (NG)	Boiler (NG)	E-Boiler (wind)	E-Boiler (wind)
	Large district heating	Boiler (NG)	Boiler (NG)	E-Boiler (wind)	E-Boiler (wind)
Propulsion means	Short range	Fossil diesel	Fossil diesel	Electricity	Electricity
	Long range	Fossil diesel	Fossil diesel	Fossil diesel	Bio- DME[4]
	Jetfuels	Fossil jetfuel	Fossil jetfuel	Fossil jetfuel	Bio-jetfuel[5]

The average electricity is composed of a mix of different electricity production technologies, as specified in Table 3-3 and Table 3-5.

Table 3-4 The Danish Energy Agency has contributed with the following distribution of fuel types for the Danish electricity mix

	Coal	Fueloil	Natural gas	Bionaturalgas	Straw	Woodfuel	Waste	Biogas	Solar	Wind	Industry (fuel free)
2013-2020	25%	1%	10%	0%	2%	10%	6%	1%	2%	42%	3%
2020-2035	9%	0%	5%	1%	1%	16%	6%	1%	2%	57%	1%
2035-2050	0%	0%	2%	2%	1%	12%	4%	0%	2%	77%	0%

For the purpose of this report, the above table from the Danish Energy Agency has been simplified to reflect a simplistic electricity mix containing the largest and most important energy sources.

The chosen composition of electricity mix during the selected time periods for this project is found in the table below.

Table 3-5 Mix of average Danish electricity for continuous power production in the four time periods

	Coal	Natural gas	Woodfuel	Solar	Wind
2013-2020	29%	11%	11%	2%	47%
2020-2035	10%	5%	18%	2%	64%
2035-2050	0%	2%	13%	2%	83%
+2050	0%	0%	0%	0%	100%

4 Inventory analysis

4.1 Individual conversion pathways

The selected energy conversion technologies and the source of data are described in the following.

4.1.1 Direct combustion

Direct combustion of solid biomass in either a simplistic boiler for district heating or a more complex setup with a boiler and steam turbine for combined heat and power production are well known and proven technologies [Energinet.dk, DEA, 2012]. It is suggested that this technology is likely to be able to play a part in a 100 % renewable energy system even in a situation with a moderate to high penetration of intermittent electricity production. In the situation where renewable electricity production exceeds the immediate electricity demand, it possible to construct a bypass on the turbine in the combined heat and power plant which enables it to continue the production of district heating without producing electricity (Jeppesen, 2013), thereby increasing the share of the intermediate electricity production used directly in households, industry and transportation. The typical overall net efficiency of such boilers is in the range of 94 – 96 % (Jeppesen, 2013). The net fuel-to-electricity efficiency of the largest central combined heat and power plants are expected to reach 50 % or more by 2050 [95]. Boilers for district heating and heat and power production are in the MW range [Energinet.dk, DEA, 2012].

Biogas can also be converted to heat and power through combustion. This is typically done in a gas engine, which can operate either in single cycle or combined cycle [95]. The combined cycle gas engine is characterised by having a higher fuel-to-energy efficiency, but at the expense of some flexibility.

Alternatively it is in principle possible to combust biogas in gas turbines. Like gas engines these can operate either as combined cycle or single cycle. Like the gas engines, combined cycle turbines are less flexible in terms of regulating electricity production, but more energy efficient than the single cycle gas turbine [95]. Today most combined cycle gas turbines are constructed to operate within a very limited effect-range and moving outside of that range will reduce energy efficiency significantly (Jeppesen, 2013). Combined cycle gas turbines can be constructed either as steam extraction for highly efficient electricity production or with backpressure for heat and power production [Energinet.dk, DEA, 2012].

The effect of gas engines range from a few kW to the MW range. The efficiency of gas engines differs with the size. Generally the efficiency of the engine is increasing with increasing size [Energinet.dk, DEA, 2012]. Because gas engines are available for even small scale applications it is the most common choice for decentral heat and power production, when using gaseous fuels.

Common to all direct combustion technologies are that they are proven and robust technologies which make them reliable, but also imply that no major technological breakthroughs can be expected within the concept of direct combustion.

4.1.2 Thermal gasification and syngas production for heat and power production

Thermal gasification of biomass is a relatively immature technology with only few plants in operation today.

Solid biomass can be gasified with the purpose of producing a syngas with relatively high energy content. Prior to the gasification the solid biomass is heated under oxygen free conditions (pyrolysis), which splits the biomass into a gaseous fraction and a solid fraction called charcoal. The gaseous fraction contains primarily hydrogen, carbon monoxide, methane and tar, while the solid fraction still contains most of the carbon. In the gasification process the charcoal and the pyrolysis gas is heated to very high temperatures, typically in the range of 700°C to 2000°C, under the injection of oxygen and water in very controlled quantities (Jørgensen, U. et al. 2008). The product of this process is called syngas. The dry syngas is a mixture of primarily carbon monoxide, hydrogen and carbon dioxide, while often also containing small concentrations of VOC's and trace amount of inert gases such as nitrogen and argon (Meijden, C . et al. 2010). The exact composition of the syngas depends greatly on the specific technology. Some gasifiers perform the pyrolysis and gasification in the same chamber (Zhu, B. et al. 2009), while others perform them in separate chambers (Skøtt, 2011).

This process is motivated, if the solid woody biomass is to be used for heat and power production in any fuel cell application (Energinet.dk, DEA, 2012).

In Denmark, the Pyroneer gasifier technology is currently being tested on a pilot scale level. The syngas, which is produced from straw, is used to produce heat and power in co-combustion with fossil coal (Skøtt, 2011). According to Energinet.dk, DEA, 2012 the fuel-to-gas efficiency of the Pyroneer gasifier is 95 % at a scale of 100 MW_{th}.

It is expected that once in full scale it is possible to produce heat and power solely from syngas, which omits the need for coal (Jeppesen, 2013).

The Pyroneer gasifier is flexible with regards to fuel input and it is able to efficiently convert a variety of biomass types of different qualities to high quality syngas [95]. Primarily due to investment costs it is desirable that the gasifier is operated continuously, which imply that the heat and electricity produced from the syngas, is base load unless syngas storage is incorporated (Jeppesen, 2013).

Instead of direct combustion it is possible to oxidize the syngas in a solid oxide fuel cell. A solid oxide fuel cell with integrated gasification is able to achieve a fuel-to-electricity efficiency of 51 % and an overall efficiency of 96 % (Karl, J. et al. 2009).

4.1.3 Anaerobic digestion

Anaerobic digestion of manure and possibly a co-substrate is a relatively simple and well known technology (Energinet.dk, DEA, 2012). The product of the process is called biogas and is a mixture between 60 – 70 % methane and 30 – 40 % carbon dioxide (Energinet.dk, DEA, 2012). The raw biogas also contains impurities and gas cleaning is usually needed (Jørgensen, 2009).

The anaerobic degradation process, which is a bacterial process, can be divided into three overall steps. The first two are hydrolysis and acid formation. The primary products from these processes are acetic acid, CO_2 and hydrogen. Depending on the type of biomass the exact stoichiometry will vary. The third and final step is an anaerobic respiration called methanogenesis from which the product is methane. The acetic acid is likewise converted into methane but with CO_2 as a by-product. With lignin being the exception, almost any biomass can be used to produce biogas. This is because almost any organic substance can, in principle at least, can undergo anaerobic degradation.

In Denmark far the most common type of feed is manure and a co-substrate - typically organic waste products. In principle, manure can be the sole feed but it is most common that some other organic waste product is mixed into the manure. On its own, manure has a low yield per wet mass of input, because of low dry matter content. When mixed with other types of biomass feed, it is possible to increase dry matter content and thus the yield per wet weight (Energinet.dk, DEA, 2012).

The biogas can then be used to produce heat and base load power. Most Danish biogas plants have a gas-storage with a capacity equivalent to 12 hours of production (Energinet.dk, DEA, 2012). This enables the plant to match changes in energy demand within a day.

Other uses of the biogas such as regulating power or transportation is possible, but requires that the biogas undergoes a process called upgrading. This process converts the biogas into synthetic natural gas using either pressure swing adsorption or a water scrubber. Both technologies operate by removing CO_2 and other impurities from the biogas, leaving an almost pure stream of methane [95]. In both cases injection into the natural gas grid is advantageous since the gas grid can serve as both storage and distribution grid.

Alternatively the biogas can be upgraded by reacting hydrogen produced from the electrolysis of water, with the carbon dioxide in the biogas (Cheng et al. 2009). The advantage of this technology is the ability of converting excess intermittent electricity production to chemically bound and storable energy. The electricity-to-hydrogen efficiency in the electrolyser is assumed to be 70 % (on a LHV basis) (Clausen, L. et al. 2010).

4.1.4 Biomass to liquid synthetic fuels or biomethane using chemical synthesis of syngas

Instead of producing heat and power from the syngas it is possible to let it undergo chemical synthesis to convert it into a high grade liquid or gaseous fuel for transportation purposes.

It is for the purpose of this study considered four different fuels, namely synthetic diesel [97, 100] synthetic natural gas (Evald, A. et al. 2013; Meijden, C et al. 2010), methanol and DME (Evald, A. et al. 2013; Mortensgaard, A. et al. 2011; Edwards R, et al. 2011). Each of these fuels can be produced from the same syngas. By changing the catalytic material, temperature and pressure within the reactor it is possible to control which fuel is produced.

The advantage of synthetic diesel is limited changes in the fuel infrastructure, whereas minor changes are needed for methanol, significant changes for DME and major changes for SNG (Volvo 2008).

In contrast, the energy efficiency is greatest when producing SNG, followed by methanol and DME, while the efficiency of the synthetic diesel is the lowest (Evald, A. et al. 2013; Mortensgaard, A. et al. 2011; Edwards R, et al. 2011).

4.1.5 Electrolysis assisted production of biomethane, methanol and DME

Due to the stoichiometry of the syngas, there is a deficit of hydrogen in the syngas when converting solid biomass to liquid synthetic fuels or synthetic natural gas. This results in a lot of unconverted carbon, usually in the form of carbon dioxide, leaving the synthesis reactor. By adding hydrogen from the electrolysis of water to the syngas it is possible to increase the production of fuel and fuel efficiency of the biofuel plant (Mortensgaard, A. et al. 2011).

Another advantage of this technology is the ability of converting excess intermittent electricity production to chemically bound and storable energy. The electricity-to-hydrogen efficiency in the electrolyser is assumed to be 70 % (on a LHV basis) (Clausen, L. R. et al. 2010).

By incorporating integrated gasification using combined cycle of either a gas turbine or a solid oxide fuel cell it is possible to construct a highly energy efficient and load flexible power plant, which is also able to produce synthetic fuels when intermittent electricity production is in excess. A plant of this type is described in Buttler et al. (2013). The advantage of such a plant is that the gasifier can operate constantly. When intermittent electricity is in deficit it can be used to produce power and when intermittent electricity is in excess it can be used to produce synthetic fuels.

4.1.6 2nd generation ethanol fermentation

1st generation fermentation of biodegradable biomasses followed by distillation is a mature and proven technology which has been around for decades. 2nd generation on the other hand is a more complex and less mature technology and is hence less efficient in terms of primary output [97]. The primary output, which is bioethanol, used for transportation purposes. Other outputs such as C5 sugars, distillers dried grain with solubles and lignin are all co-products from bioethanol production [97]. These products can all be used at various energy plants, either as feed for biogas plants or thermal conversion plants. Some by-products can also serve as animal feed.

Where 1st generation bioethanol is produced from starch crops such as corn, sugar beets or wheat, 2nd generation bioethanol is produced from lignocellulosic biomasses such as miscanthus or straw [98]. The feed-to-fuel conversion efficiency is in the range of 25 – 55 % depending on the generation and how many co-products are produced [98] (Jeppesen, 2013).

These biomass conversion technologies are, then, modelled in a number of biomass and conversion technology pathways, see the models in the Process Flow Diagrams next section.

4.1.7 Process Flow Diagrams, PFDs

The figures in this section below outline process flow diagrams for the 16 pathways (two are identical) included in the study. The pathways included are:

Heat supply:
- Wood boiler
- Straw boiler

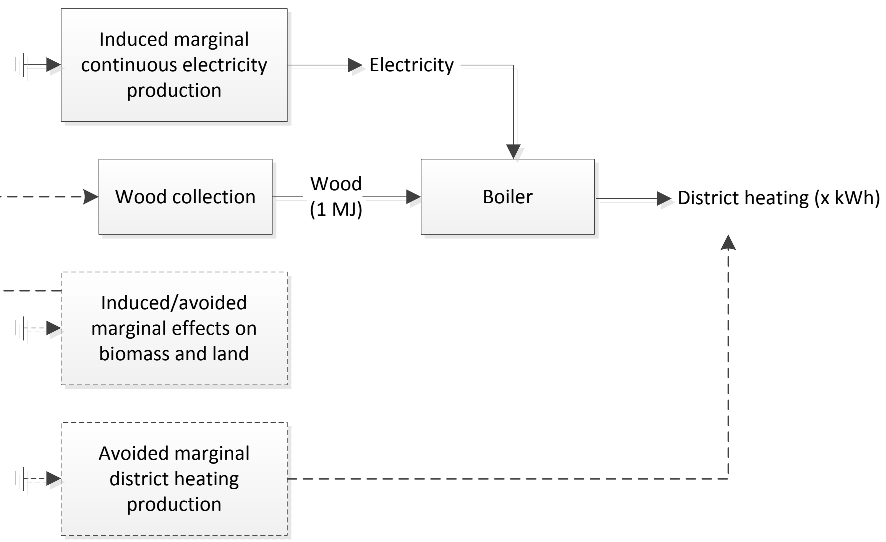
Continuous electricity supply:
- Wood CHP continuous power production
- Straw CHP continuous power production
- Manure biogas CHP continuous power production
- Manure-straw co-digestion biogas CHP continuous power production

Flexible electricity supply:

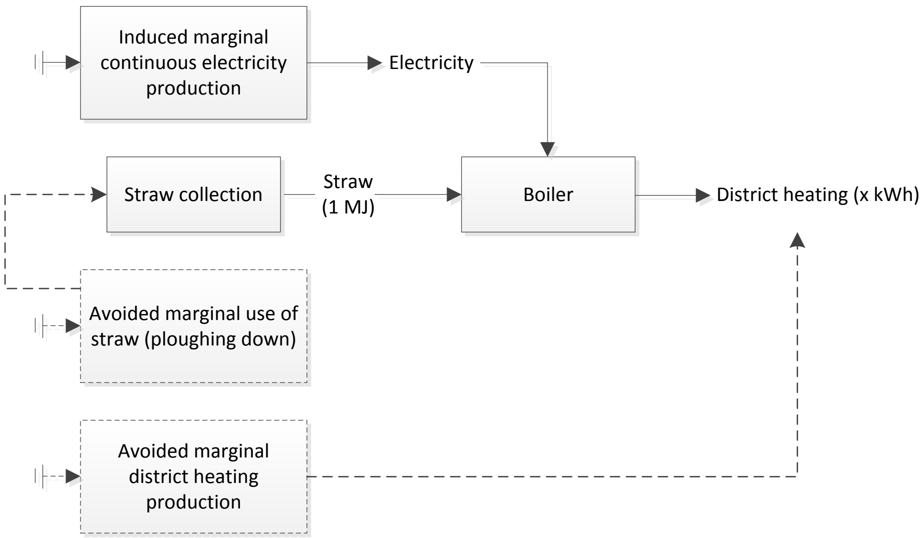
- Wood gasification with syngas reforming to SNG for CHP flexible power production
- Manure biogas with hydrogenation into SNG for CHP flexible power production
- Manure-straw co-digestion biogas with hydrogenation into SNG for CHP flexible power production

Transport fuel supply:

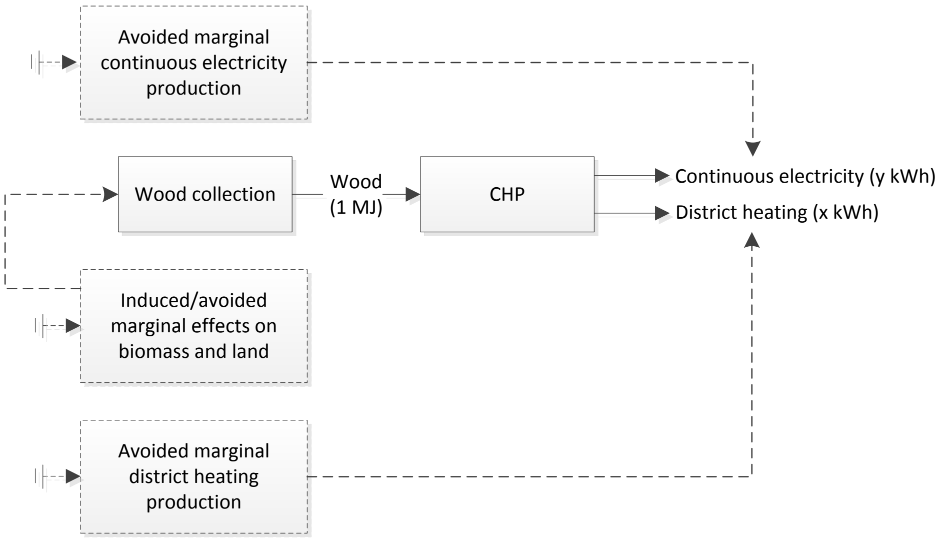
- Wood gasification with syngas hydrogenation into methanol
- Wood gasification with syngas hydrogenation into DME
- Manure biogas with hydrogenation into SNG for fuel
- Manure-straw co-digestion biogas with hydrogenation into SNG for fuel
- 2nd generation straw ethanol for short range transport services and with lignin and molasses co-products used to displace other woody biomass, e.g. in wood gasification pathways
- 2nd generation straw ethanol for long range transport and lignin and molasses co-products used to displace other woody biomass, e.g. in wood gasification pathways
- 2nd generation straw ethanol for long range transport and lignin used to displace other woody biomass, e.g. in wood gasification pathways, while molasses is used for biogas upgraded by hydrogenation and used for flexible power production



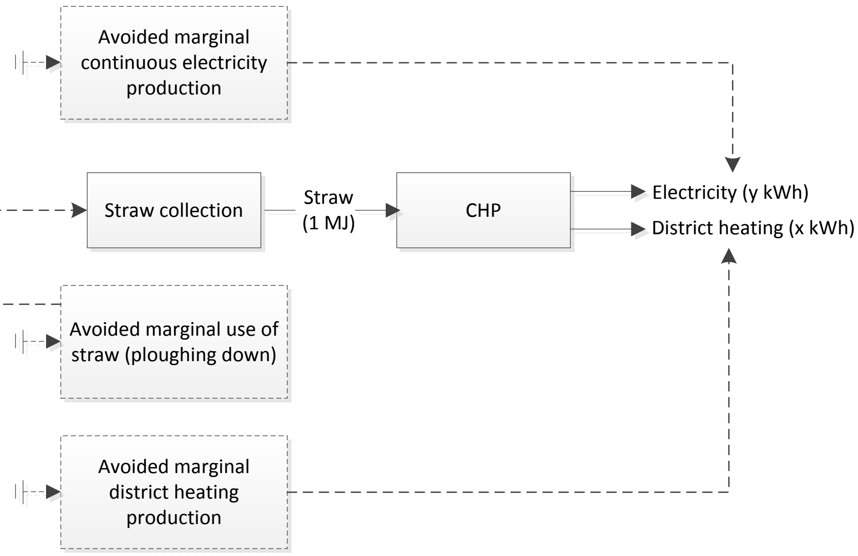
Wood boiler



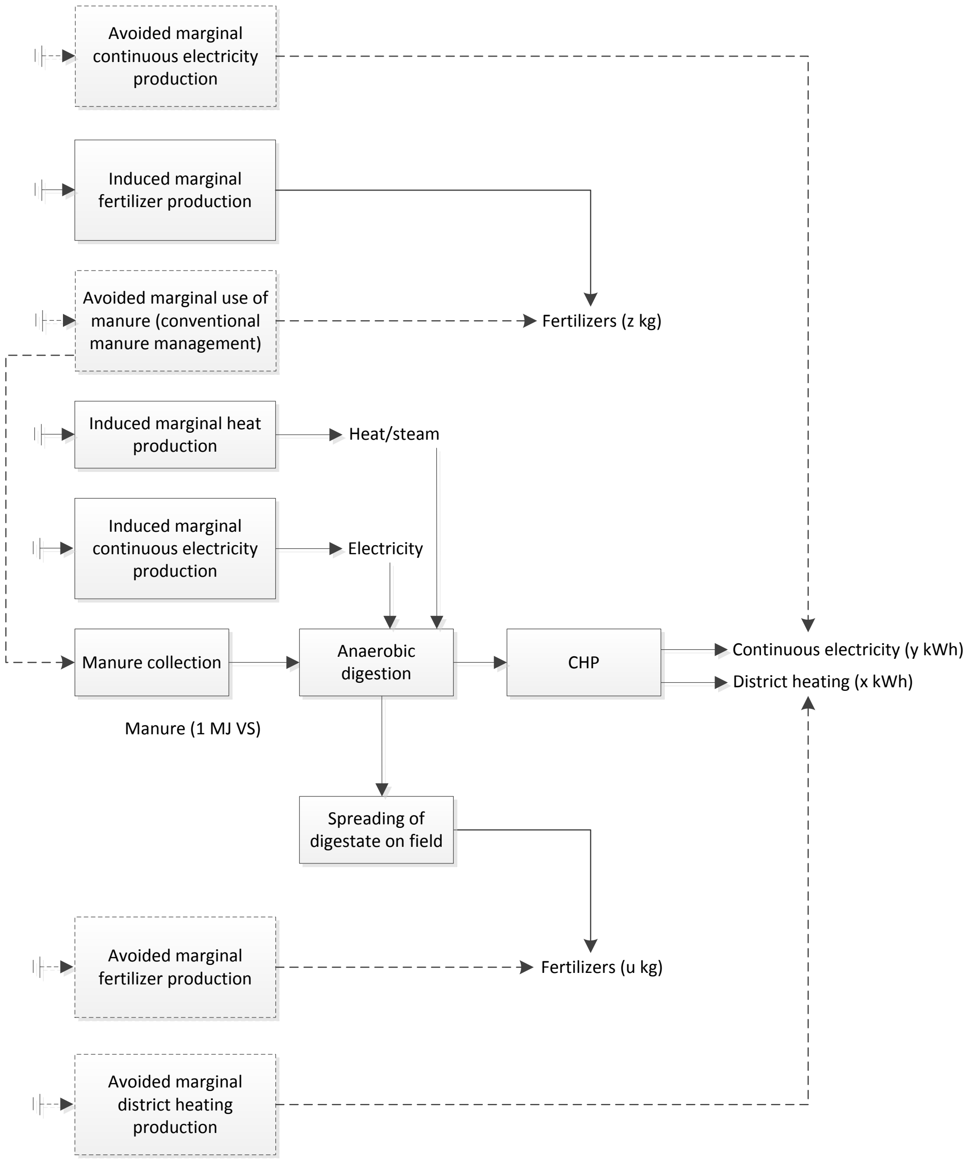
Straw boiler



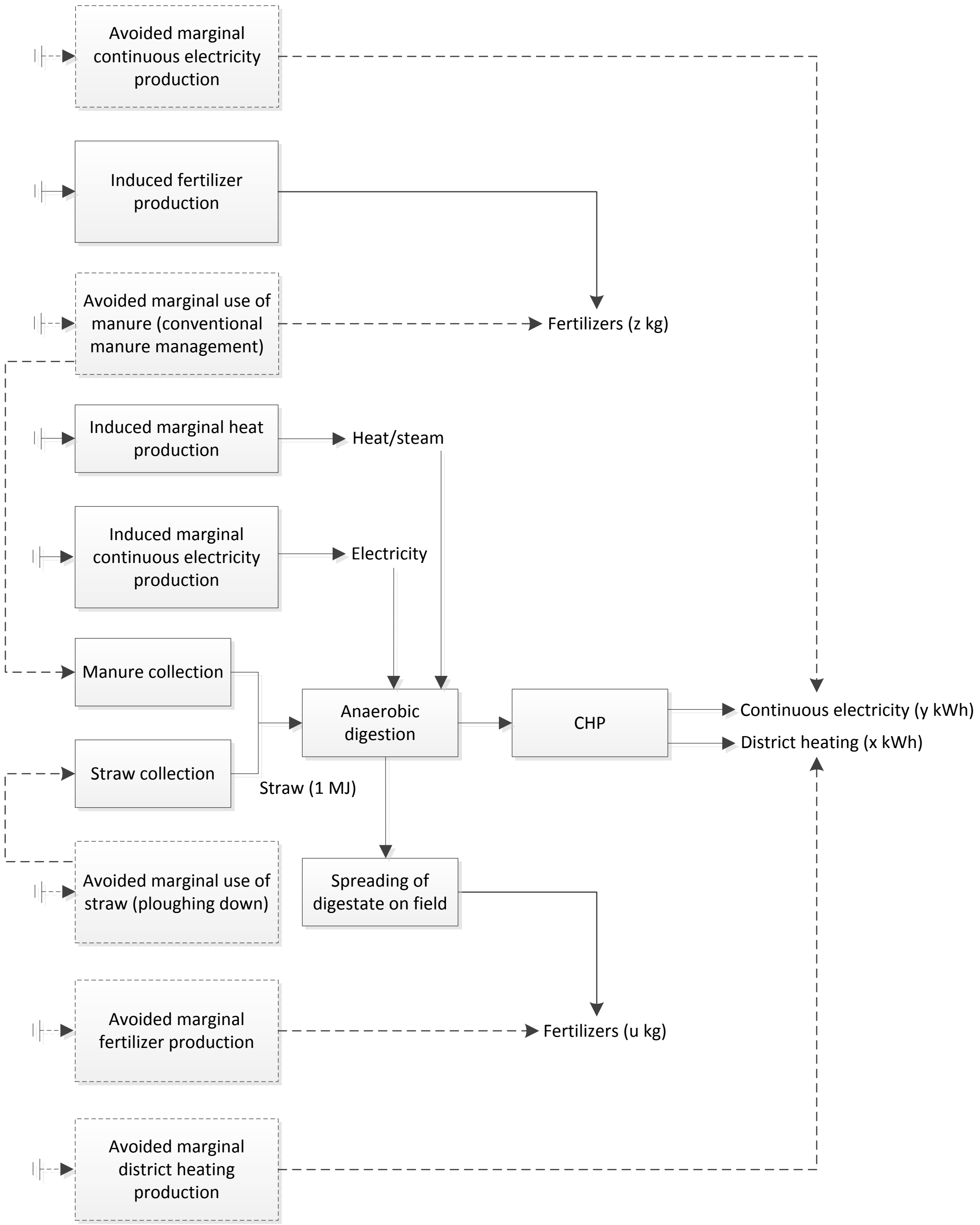
Wood CHP continuous



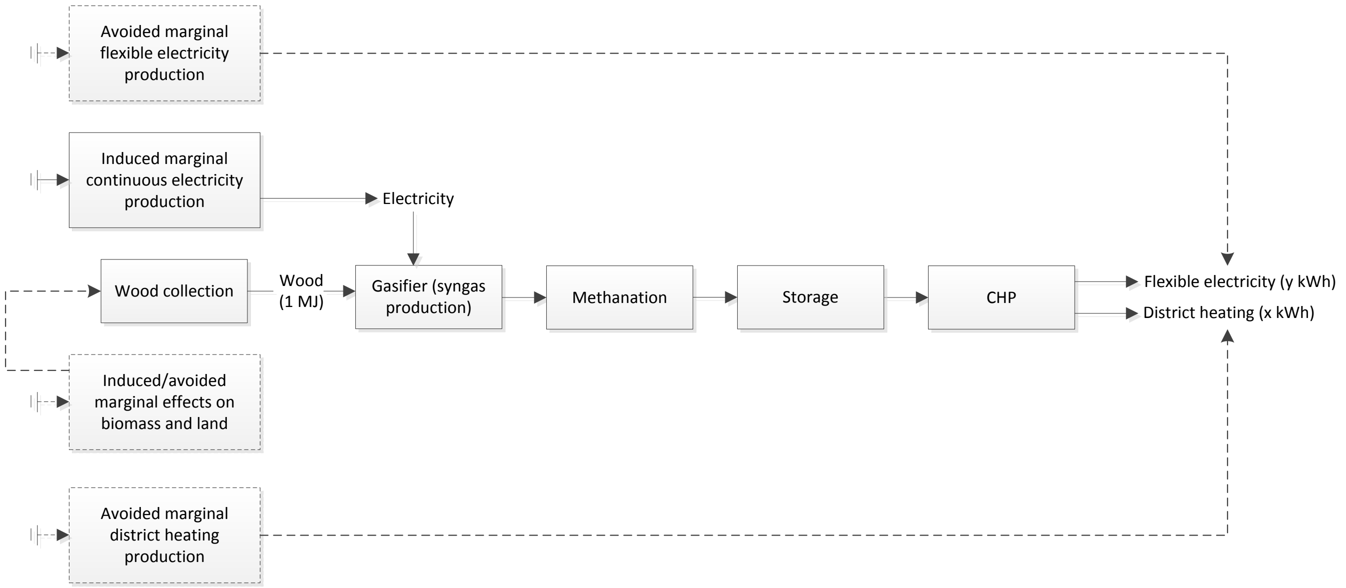
Straw CHP continuous



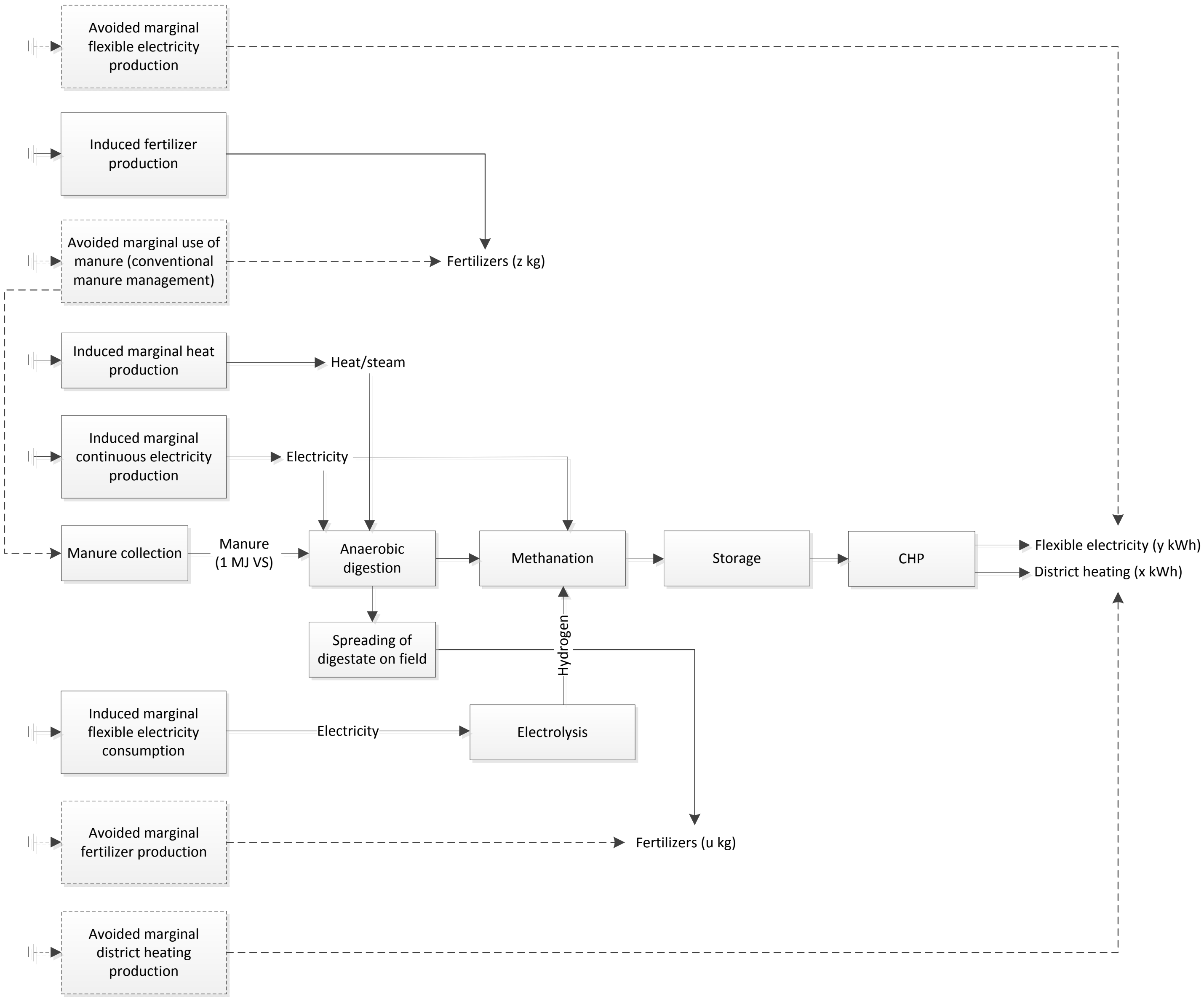
Manure biogas CHP continuous



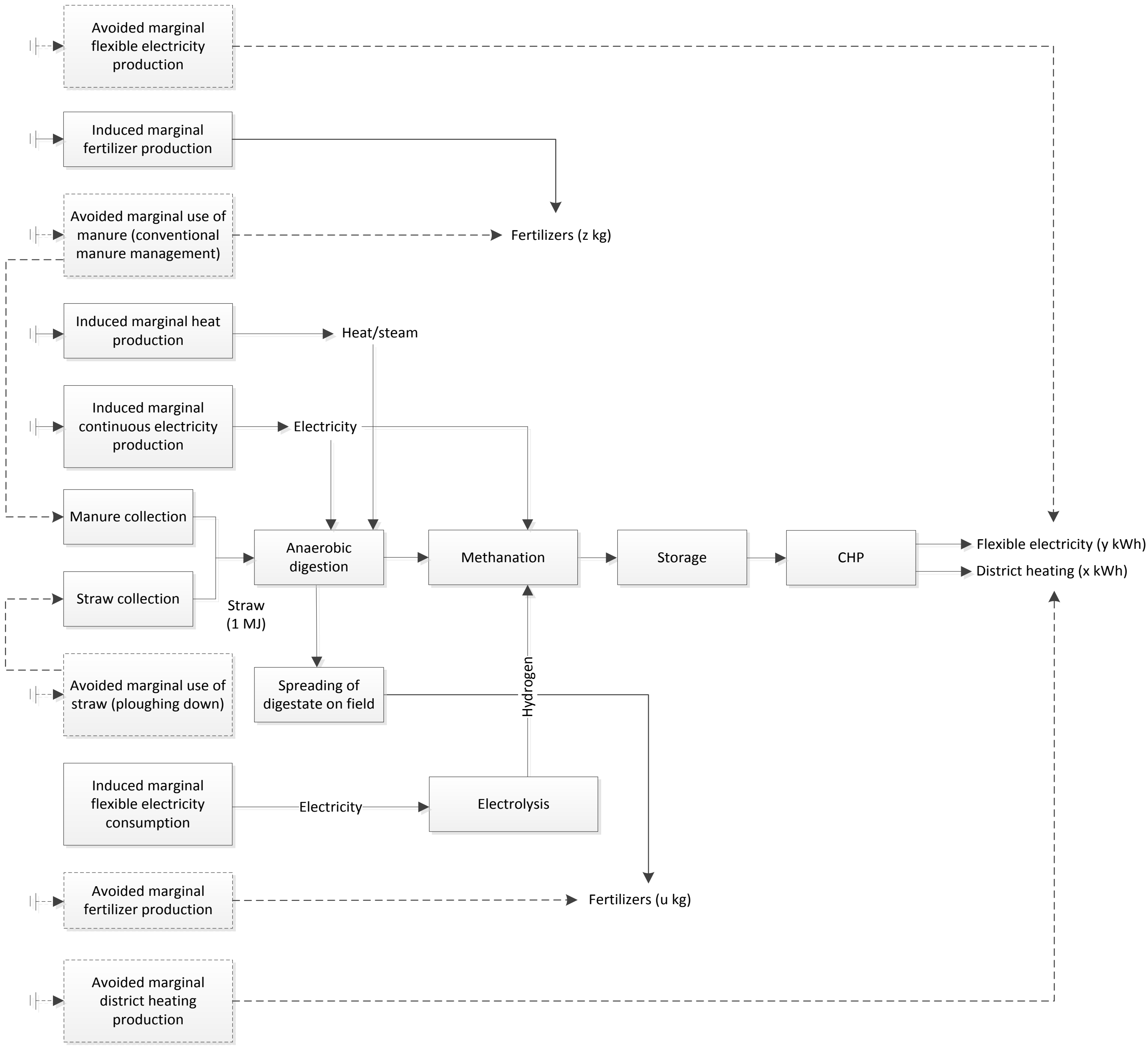
Manure-straw biogas CHP continuous



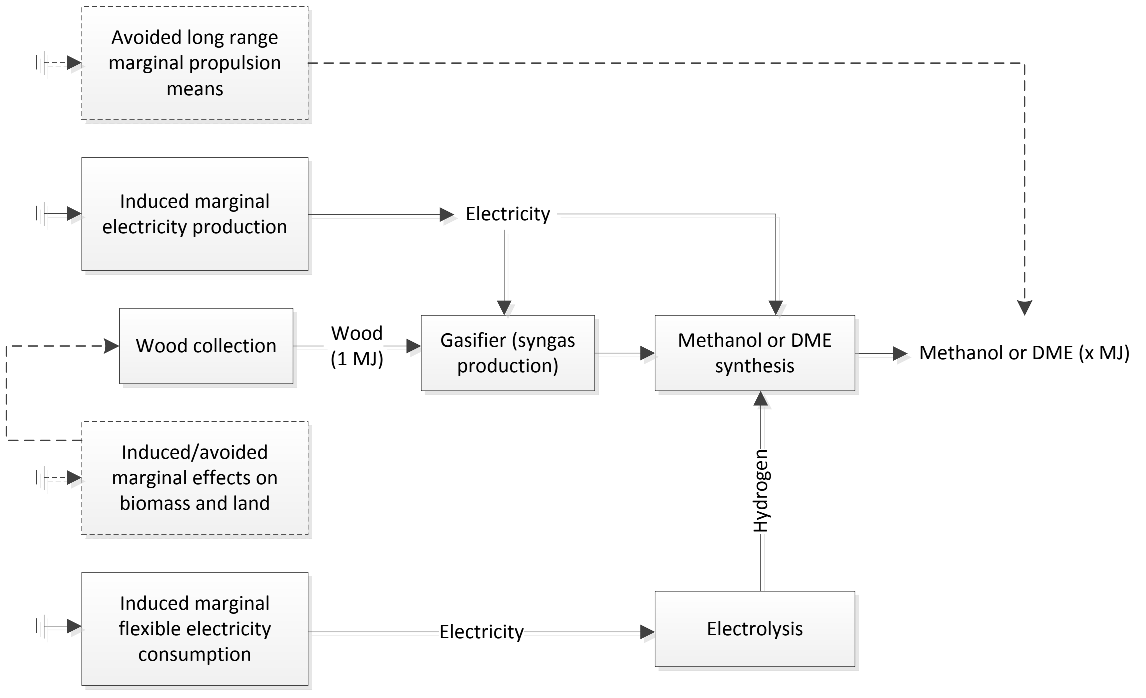
Wood SNG CHP flexible



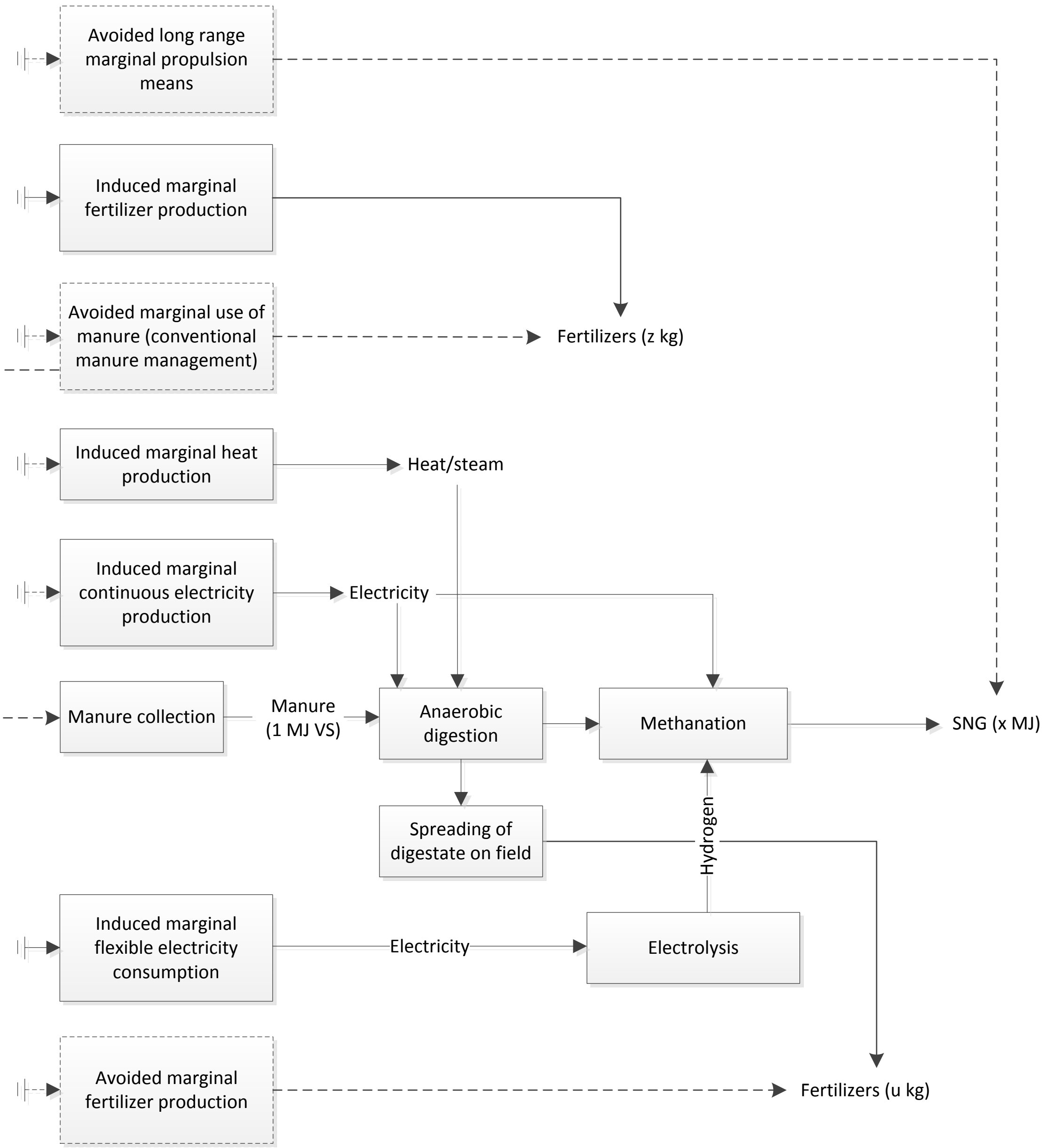
Manure biogas+H2 CHP flexible



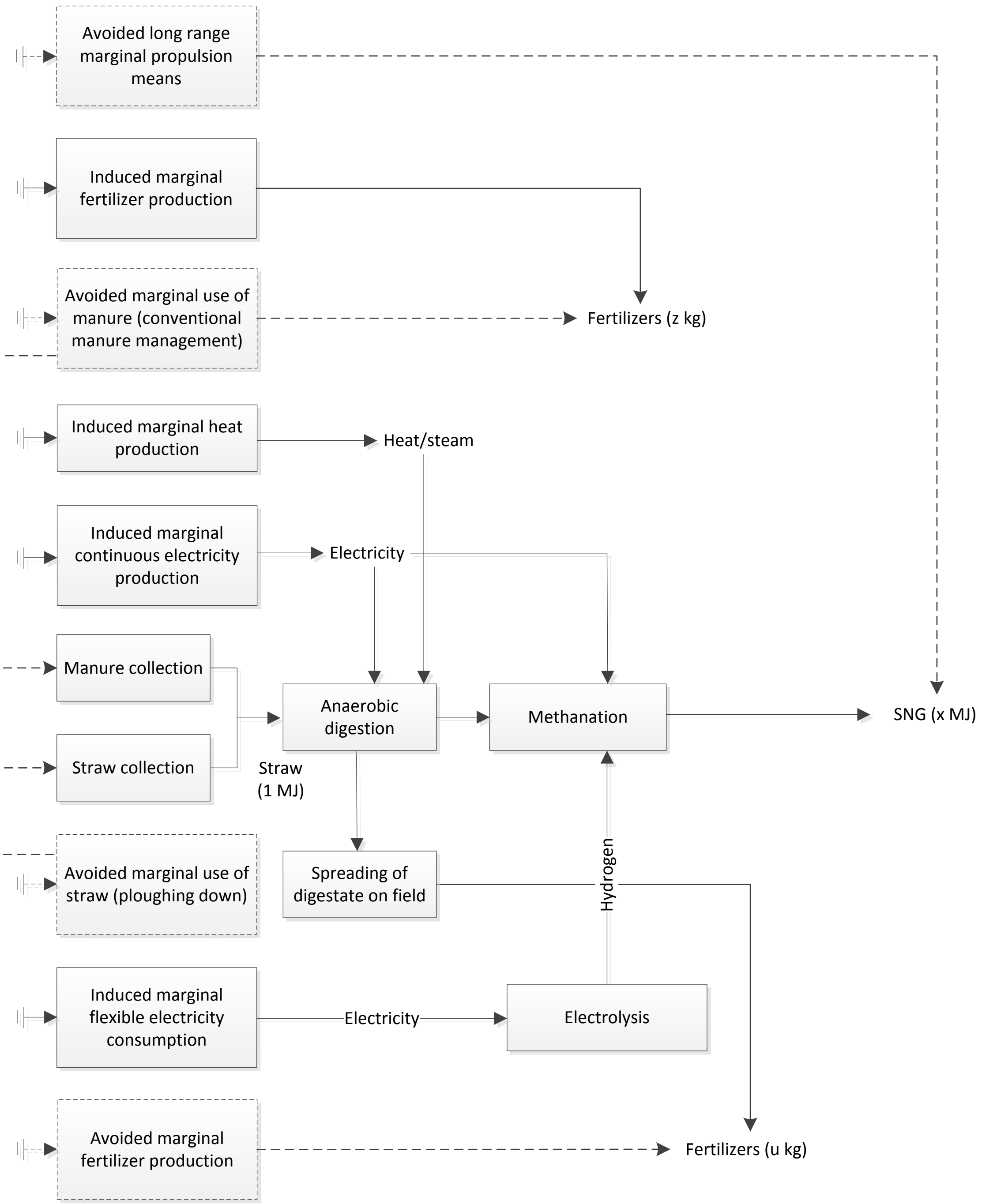
Manure-straw biog+H2 SNG CHP flexible



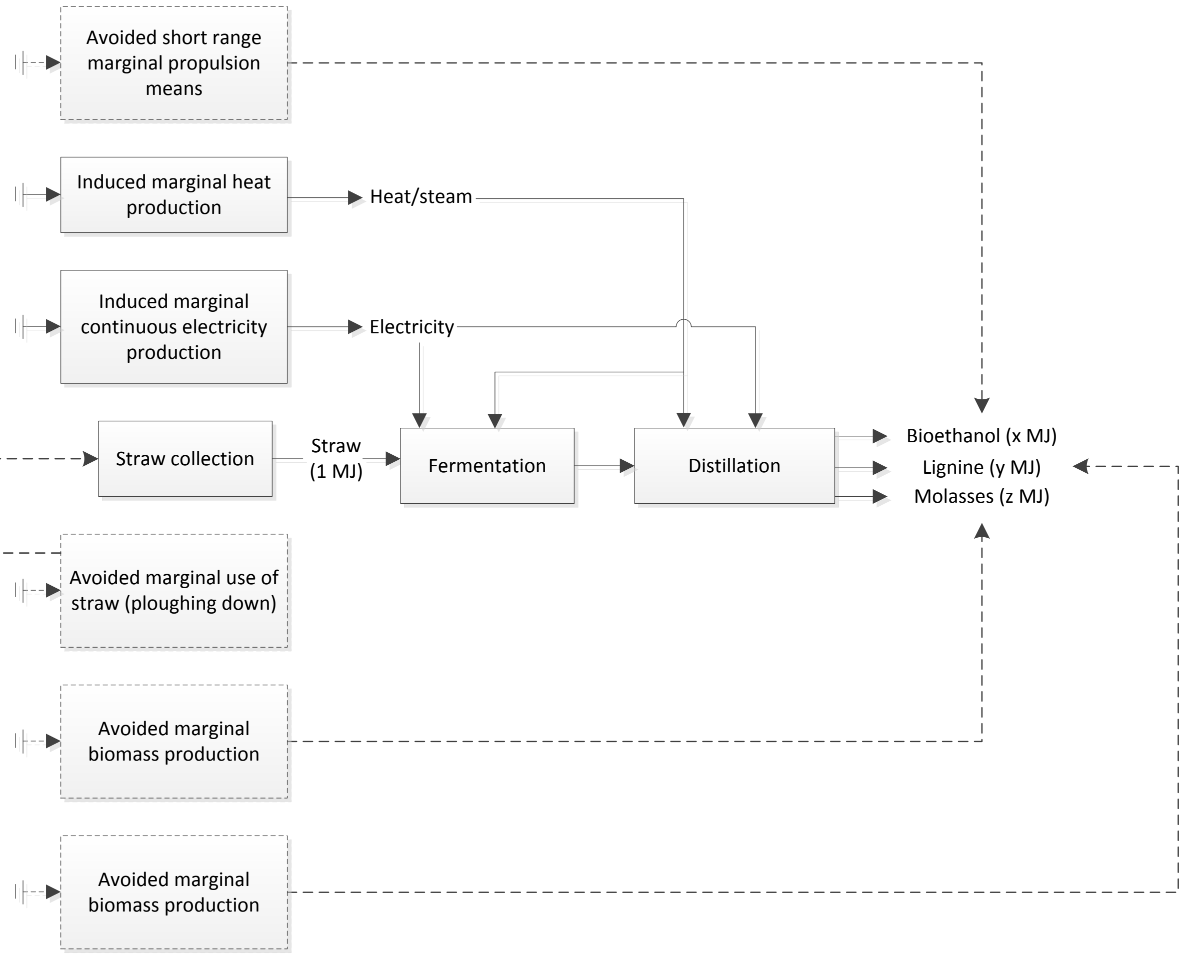
Wood+H2 methanol&DME



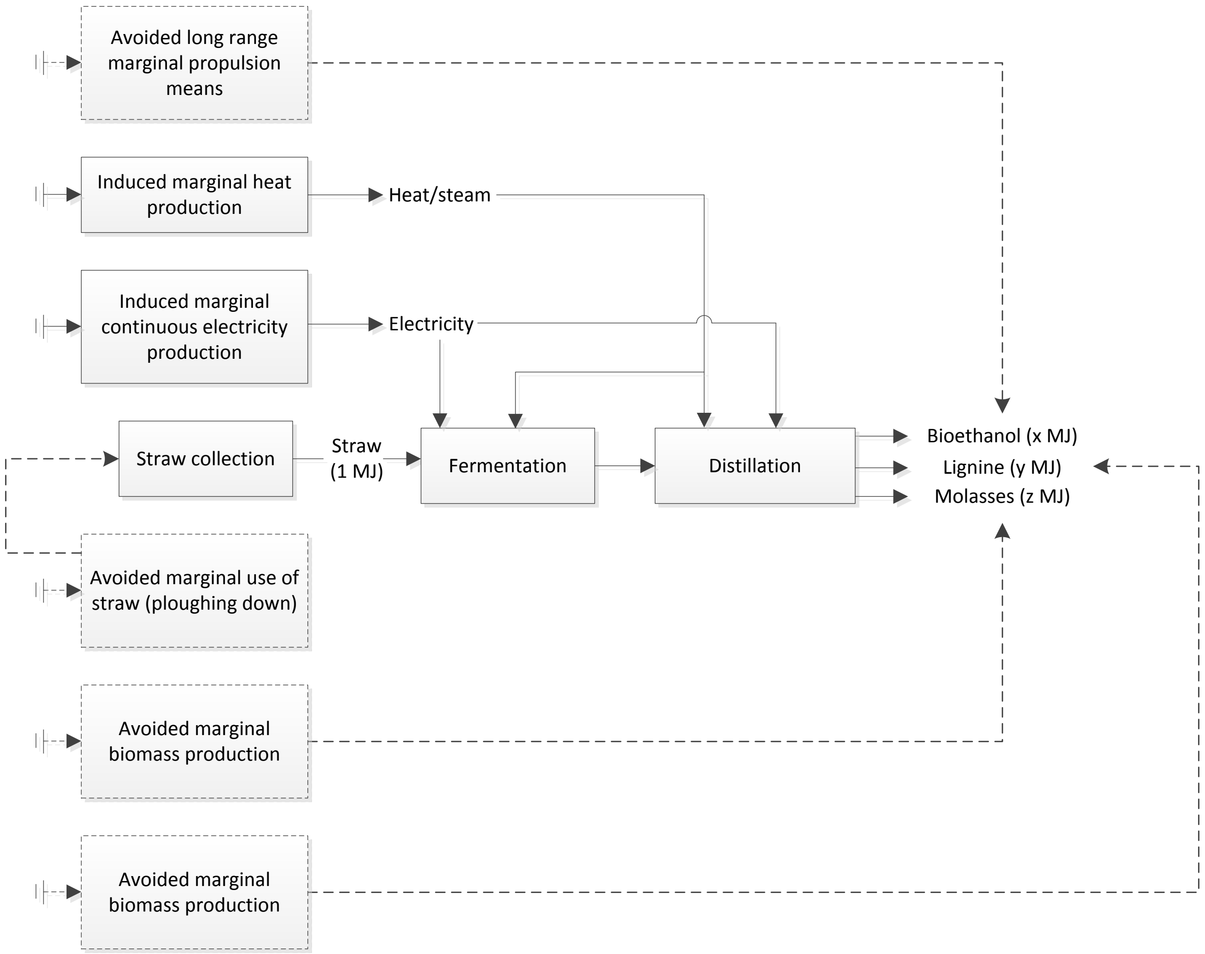
Manure biogas+H2 SNG fuel



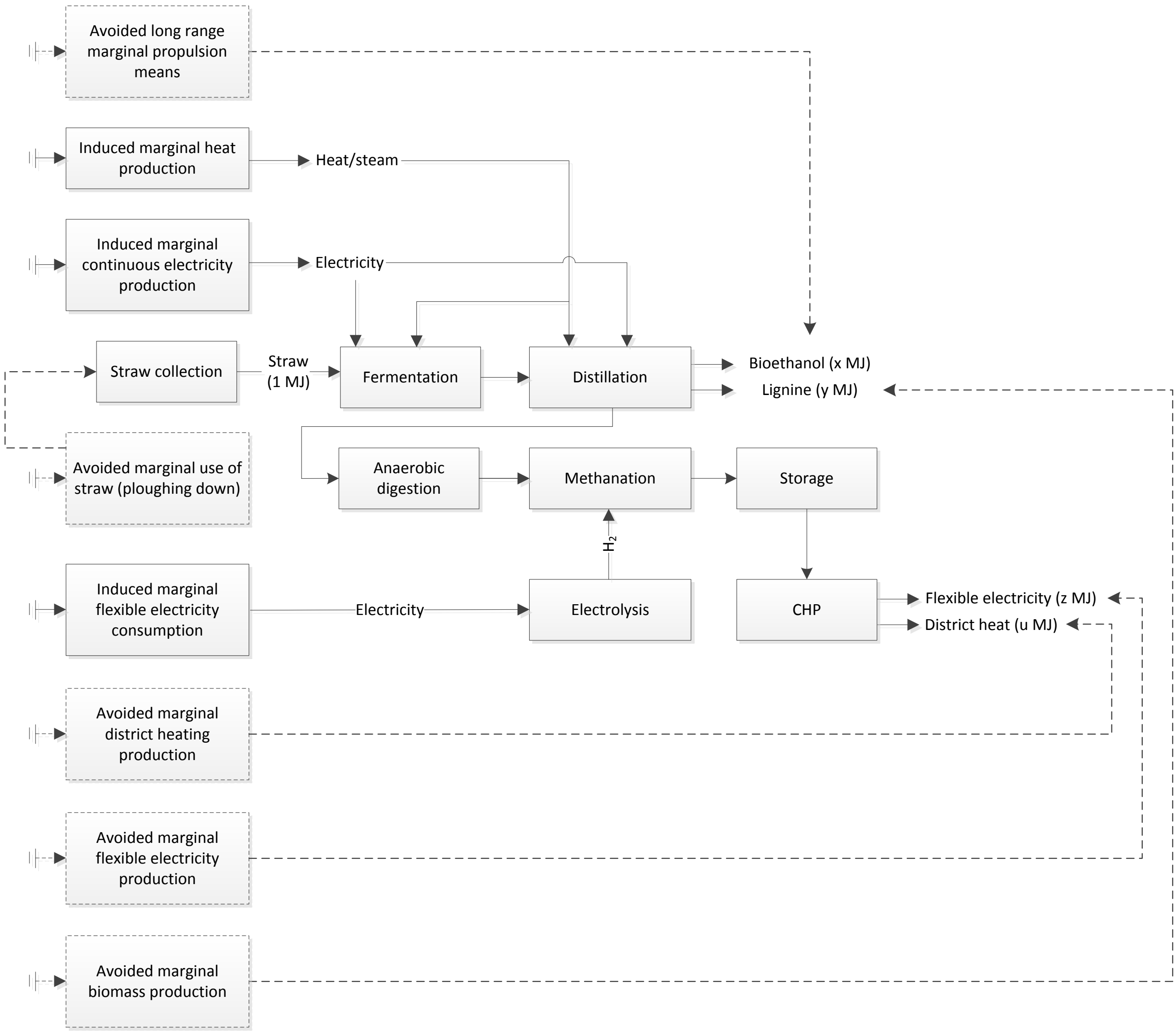
Manure-straw biogas+H2 SNG fuel



2G eth short range+syngas



2G eth long range+syngas



2G eth long range+syngas+biogas

4.1.8 Conversion technology inventory data

All inventory data of the modelled conversion pathways are reported in Appendix H.

4.2 Whole-system designs

A detailed energy system analysis is carried out using the modelling tool EnergyPLAN[12]. EnergyPLAN is an input/output model which performs a detailed analysis of a given year based on the given input data. This analysis is carried out in time steps of 1 hour each. A large variety of technologies can be included and to quantify these, key data, such as capacities as well as performances such as

[12] http://www.energyplan.eu/

distributions and efficiencies, is used. This is especially relevant when considering the fluctuating renewable energy sources, where the distribution of their electricity production is defined by external forces. This allows for the simulation of a variety of different energy system designs, through which it is possible to determine their ability to effectively utilize the fluctuating renewable energy sources. As part of this study it will be analysed how relevant elements can be utilized to increase flexibility and thereby ensuring the best integration of the fluctuating renewable energy into the energy system.

Assessment of the GHG emissions at level 4 is done based on the quantity and mix of primary energy supply as modelled in EnergyPLAN. Besides the pathways for biomass described in this study, a few additional technologies are included at this stage, including their life-cycle emissions of GHG. These extra renewable energy conversion technologies and their assumed emission factors are displayed in Table 4-1 below:

Table 4-1 Specific life-cycle GHG emissions from different renewable energy sources.

Type of renewable included	Specific life-cycle GWP20, 20 y. average	Specific life-cycle GWP100, 100 y. avg.	Unit	Reference
Wind power (both on- and offshore)	4	4	g CO_2-eq/MJ output electricity	Eco-invent database
Photo voltaic	68	68	g CO_2-eq/MJ output electricity	Andersen, 2013
Wave	4	4	g CO_2-eq/MJ output electricity	Assumed similar to wind power
Municipal solid waste	75	75	g CO_2-eq/MJ input waste	Nielsen, 2009
Maize silage	87	25	g CO_2-eq/MJ input maize silage	Appendix G
Vegetable oil	240	74	g CO_2-eq/MJ oil	As rapeseed oil, Appendix G

These additional emission factors for the whole-system assessments are included in order to give an exhaustive assessment basis for these systems. They are, however, characterized by being more uncertain that the ones of the 16 conversion pathways comprised by the individual pathway assessments of the study. But, as shall be further commented on in Chapter 5 on results and discussion, this does not invalidate the key findings of these whole-system assessments.

In addition to the four main scenarios, a set of sub-scenarios are developed to investigate the effect of introducing different technologies and pathways into each of the scenarios. Especially, the alternative technologies available for the conversion of straw have been of interest. In total are 15 alternative scenarios developed, each one modelled independently and the results are presented in Table 4-2 and Table 4-3 below. Additionally the modelling results of each scenario are presented in a PFD, an example of which is shown below in *Figure 4-1*. These 15 PFDs are available in appendix J.

The resulting inventory data, as deriving from the energy system designs modelled in EnergyPLAN, are shown in Table 4-2 and 4-3. Table 4-2 shows the main inputs of the various biomass categories, the renewable electricity production (wind, solar and wave) and the solar thermal production together with the intermediates of biogas and hydrogen produced and used in the system. These *inputs* are the overall sources of GHG emissions from the systems, and besides emissions from these inputs the only other significant emissions derive from the manure management and the biogas conversion processes themselves. All co-products from the various pathways are internally used, and the carbon footprint calculation is, thus, confined to calculating emissions from the input variables, the manure management and the biogas conversions. This is done and illustrated in Chapter 5-x on results and discussion of the level 4 models.

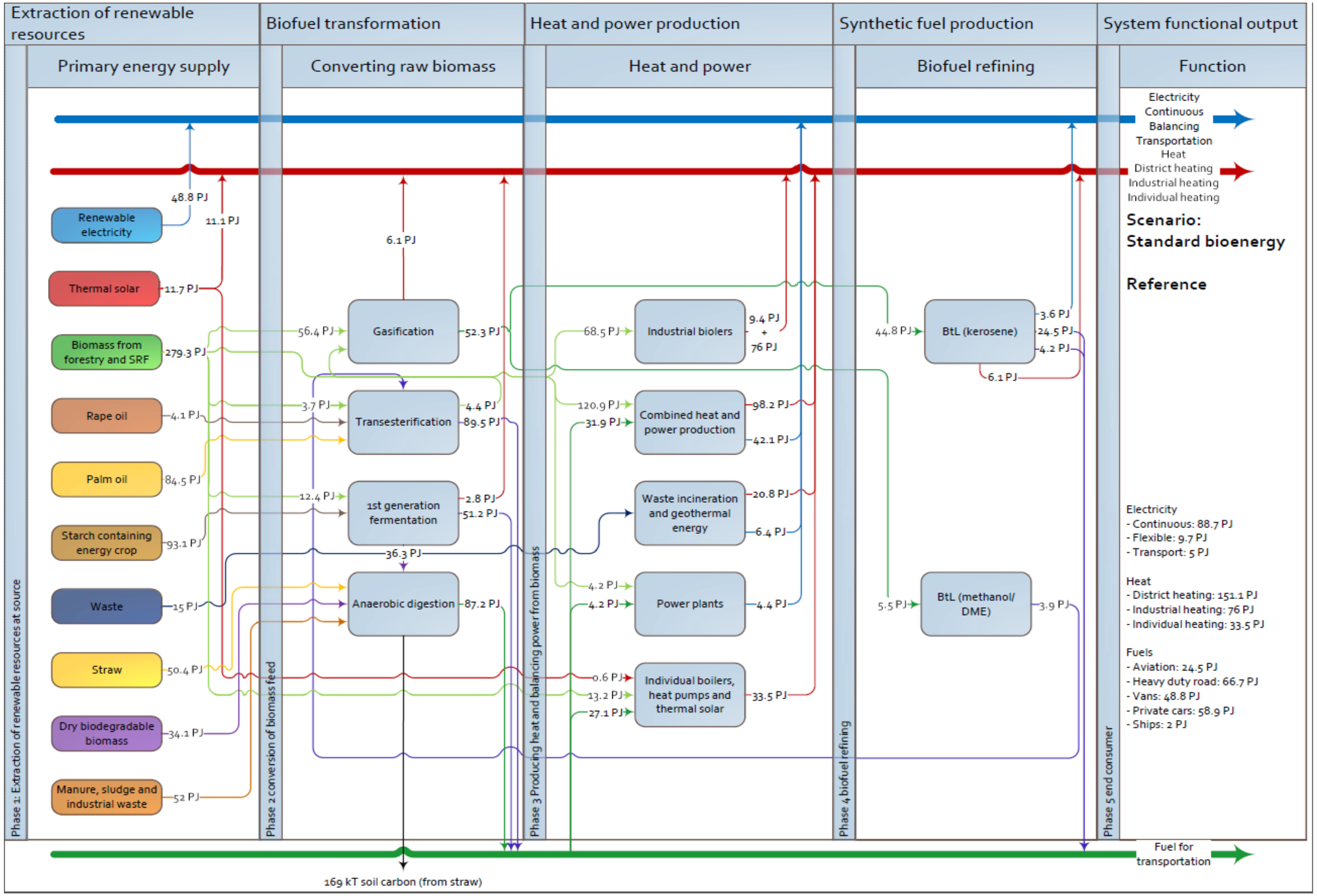


Figure 4-1 Example of a Process Flow Diagram of a whole system design. (see also Appendix J).

4.2.1 Whole-system inventory data

Table 4-2 Renewable energy supply divided by source in the 15 alternative 2050 scenarios. PES (primary energy supply), RES (renewable electricity supply) and the composition of bioenergy supply. Other = municipal solid waste, catch crops, grass from lowlands, garden & park waste, industrial waste, etc.

	PES	RES	Th. solar	Wood	Manure	Other residues	Straw	Energy crops	Total biom.	*Biogas output*	*H2*	Capt. CO2	RES : Bio	H2 : Bio	H2 : RES
Unit	[PJ/y]	[PJ/y]	[PJ/y]	[PJ/y]	[PJ/y]	[PJ/y]	[PJ/y]	[PJ/y]	[PJ/y]	[PJ/y]	[PJ/y]	[Mt/y]	-	-	-
Standard bioenergy															
Straw for biogas	673	49	12	279	40	46	50	197	613	87	0	0	0.08	0	0
Straw for kerosene	690	49	12	299	40	46	50	194	629	62	0	0	0.08	0	0
Straw for CHP	690	49	12	297	40	46	50	197	630	62	0	0	0.08	0	0
Electrification															
Straw for biogas	549	86	23	210	40	46	50	93	439	73	0	0	0.20	0	0
Straw for kerosene	569	86	23	234	40	46	50	90	460	47	0	0	0.19	0	0
Straw for CHP	570	86	23	231	40	46	50	93	460	48	0	0	0.19	0	0
Full by-pass on CHP	550	97	23	201	40	46	50	93	430	73	0	0	0.23	0	0
Electrolysis															
Straw for biogas	559	253	23	131	40	46	50	15	283	107	72	0	0.89	0.26	0.29
Straw for biogas high yield	557	250	23	122	51	46	50	15	284	122	70	0	0.88	0.25	0.28
Straw for ethanol	577	258	23	145	40	46	50	15	296	73	75	0	0.87	0.25	0.29
Bio-carbon capture & recycling															
Straw for biogas	557	308	23	89	40	46	50	0	225	61	95	5	1.37	0.42	0.31
Straw for biogas high yield	557	308	23	79	51	46	50	0	226	71	95	5	1.36	0.42	0.31
Straw for ethanol	569	308	23	101	40	46	50	0	238	61	95	5	1.30	0.40	0.31
Wood boilers in industry	549	256	23	133	40	46	50	0	270	61	95	5	0.95	0.35	0.37
Methane as energy carrier	552	308	23	84	40	46	50	0	221	92	98	2	1.39	0.45	0.32

Table 4-3 Primary fuel consumption divided by conversion process in the 15 alternative whole-system scenarios for 2050 SRF = Short Rotation Forestry, EC = Energy crop, DH = District Heating.

Type of fuel	Biomass from forestry & SRF *Including straw			Biodeg. biomass	H2	Starch cont. EC.	Straw	Vege-table oil
Conversion process	Boilers - Ind & DH	Combustion -CHP & PP	Th. gasifi-cation	Biogas plants	synthetic fuel plant	1st g. bio-ethanol	2nd g. bio-ethanol	Biodiesel plant
Unit	[PJ/y]	[PJ/y]	[PJ/y]	[PJ/y]	[PJ/y]	[PJ/y]	[PJ/y]	[PJ/y]
Standard bioenergy								
Straw for biogas	140	70	56	137	0	93	0	89
Straw for kerosene*	131	71	97	86	0	90	0	89
Straw for CHP*	132	71	94	86	0	93	0	89
Electrification								
Straw for biogas	48	104	55	137	0	13	0	65
Straw for kerosene*	47	101	96	86	0	10	0	65
Straw for CHP*	47	102	93	86	0	13	0	65
Full by-pass on CHP	50	93	55	137	0	13	0	57
Electrolysis								
Straw for biogas	10	0	118	137	72	0	0	0
Straw for biogas high yield	11	0	108	147	70	0	0	0
Straw for ethanol	9	0	132	86	75	0	14	0
Bio-carbon capture & recycling								
Straw for biogas	13	0	73	121	95	0	0	0
Straw for biogas high yield	13	0	63	132	95	0	0	0
Straw for ethanol	12	0	86	71	95	0	14	0
Wood boilers in industry	82	0	48	121	95	0	0	0
Methane as energy carrier	11	0	70	121	98	0	0	0

Considering the routes for straw, it is evident from Table 4-2 that whenever straw is redirected away from anaerobic digestion, the primary energy supply increases. This is irrespectively of whether the straw is used for combined heat and power or biofuel production. The responding marginal energy is wood, which in all cases increases with 12 – 24 PJ/year. This response is linked to the way the functional output of each system is defined, where the maintenance of soil carbon content has been included as part of the function of the system. This, therefore, requires a specific quantity of carbon from the straw to be returned to the Danish arable land in a way that ensures the same overall long term carbon content. Anaerobic digestion performs significantly better in this respect than any other straw conversion technology, because of the hard degradable carbon being returned to soil in the digestate, and consequently the availability of straw is drastically reduced when redirected from anaerobic digestion to other conversion pathways.

FromTable 4-2, it is evident that introducing electrification increases the ratio between RES and bioenergy from 0.08 to around 0.20, measured as PJ/year : PJ/year of RES:Biomass input. An additional increase in this ratio to around 0.88 is achieved by introducing electrochemical technology, i.e. electrolysis and fuel cells. In these scenarios, the ratio between hydrogen relative to bioenergy is around 0.25. First and foremost does electrochemical technology allow for an increased penetration of RES, but it also increases the flexibility and efficiency of CHP plants and pure power plants, thereby further reducing the demand for fuel. Finally, by introducing biogenic carbon capture, it is possible to recycle carbon from CHP plants, pure power plants and thereby hydrogenate this carbon, allowing it to serve as an energy carrier once again. By doing so, it is possible to achieve a RES to bioenergy ratio above 1.30 at a hydrogen to bioenergy ratio of around 0.40 , thereby bringing the consumption of bioenergy to a level around 200 PJ/year equivalent to 40 GJ/person/year.

Considering Table 4-3 it can be seen that not only is there a reduction in the consumption of biomass-based energy, there is also a change in the consumption pattern. Where the standard bioenergy scenarios are using a variety of biomass in numerous different conversion plants, the electrolysis and bio-carbon capture & recycling scenarios assume less varied biomass consumption delimited to a few biomass sources used almost exclusively for syngas or biogas production. This makes sense as gaseous fuels are considered more flexible in terms of power production and hence allow for a greater integration of fluctuating renewables in the electric grid.

4.3 Biomass inventory data

Background (or generic) life cycle inventory datasets were based on the Ecoinvent database v2.2[13] (Ecoinvent, 2010) (e.g. production of agricultural inputs such as

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[13] This study was facilitated with the LCA software SimaPro 7.3.3. SimaPro 8, which contains the Ecoinvent v.3.0 database, was not available/functional at the time of carrying out the project. (http://www.pre-sustainability.com/simapro8). Therefore, the study relied on the data from Ecoinvent v.2.2.

fertilizers[14,15], capital goods such as agricultural machinery to e.g. harvest the straw, etc.). Foreground (or system-specific) life cycle inventory data includes:

- Danish-specific data for manure management and biogas production (raw and digested, for fattening pig slurry): these are thoroughly detailed in Hamelin et al. (2014), and summarized in Appendix G;

- Danish-specific inventory for wheat straw: these are thoroughly detailed in Hamelin et al. (2012; 2014), and summarized in Appendix G;

However, no background processes for the cultivation and eventual fertilization of woody biomass systems have been considered. This should be seen as a limitation of the study, and as contributing to an underestimation of the total environmental impact of these systems (although likely insignificant, at least for the carbon footprint, as these involve land use changes).

4.3.1 Inventory models for greenhouse gas emissions from land use change and biomass supply

As background for identifying the GHG emission consequence of an incremental biomass supply for a Danish bioenergy policy, models have been established for land use change, LUC at ‘stand level’. Such models show the C-stock change, CO_2 emissions and biomass harvest from various types of forest and plantation. The models comprise:

- Thinnings from managed forests
- Harvest from managed forest
- Forest plantation
- Plantation on high carbon grassland/savannah
- Plantation on low carbon grassland – with and without indirect land use change, ILUC
- Plantation on marginal land
- Plantation on cropland – including indirect land use change, ILUC
- Domestic biomass residues: straw and manure

The methodological approach followed as well as the used literature references can be found in Appendix A to E.

All of these wooden biomass categories are modelled for both boreal, temperate and tropical climate zones, and the categories involving an ILUC is modelled

[14] Fertilizers are involved in manure-biogas systems (with or without co-digestion with straw), given the interactions between the raw manure or digestate with the mineral fertilizer production

[15] Calcium ammonium nitrate, diammonium phosphate and potassium chloride are considered to be the marginal mineral fertilizers, as described in Hamelin (2013), p. 15-20. The inventory for the fertilizers is from the Ecoinvent database (Nemecek and Kägi, 2007), but the inventory for nitric acid (involved in the production of calcium ammonium nitrate) has been corrected to 0.00248 kg N_2O per kg nitric acid, as explained in Appendix F.

including a low as well as a high ILUC estimate. The approach followed when modelling ILUC is described in Appendix F.

The domestic residues of straw and manure are modelled as described in Appendix G.

4.3.2 Key aspects and potential range of greenhouse gas emissions from future biomass for energy

Inherently, biogenic emissions are caused by the fact that the carbon stock (C-stock) on the World's land areas decrease, predominantly due to deforestation, including biomass from vegetation above ground as well as below ground and including carbon previously accumulated in the soil. As a major cause of biogenic emissions is the deforestation or decrease in C-stock, an option for reversing the development is, of course, inherently an afforestation or increase in C-stock again. It can be said that the presence of large land areas with low C-stock also represents a potential for CO_2 uptake from the atmosphere by ensuring a C-stock increase again. There is, thus, a potential for increasing the C-stock on areas with low carbon stock and at the same time harvesting more biomass, and large areas with low C-stock exist due to very extensive use of the land, e.g. for grazing of animals. Further, there is also a potential for enhancing the efficiency of the animal production, thus releasing grassland for biomass-for-energy production. But, as mentioned earlier, also drivers for deforestation still exist.

Figure 4-2 illustrates the change in C-stock when, one the one side, increasing C-stock by establishing a plantation on carbon poor grassland in tropical climate, and, on the other side, decreasing C-stock by establishing a plantation on carbon rich woody savannah.

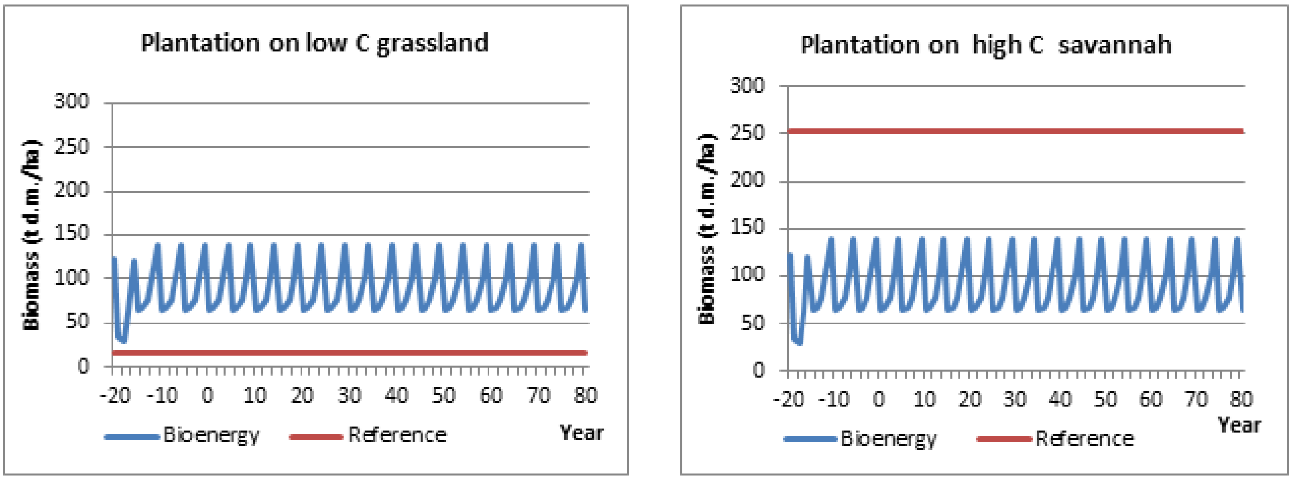


Figure 4-2 Changes in C-stock (biomass in ton dry matter (d.m.)/hectare) when establishing a plantation on low carbon stock grassland in the tropics versus on a high C woody savannah. Data, models and assumptions are presented in Appendices A to E

As evident from **Error! Reference source not found.**, there is a huge difference in he consequence for GHG emissions from biomass between producing biomass from plantation on carbon rich land like woody savannah and primary forest or from plantation established on carbon poor grassland. The illustration in **Error! eference source not found.** shows the change in C-stock in the case of tropical plantation and reference, and the rotation time of the plantation is relatively short, i.e. 5 years between each harvest. In temperate and boreal climate, rotation time of plantation is larger, e.g. up to 20 years, and the C-stock is, therefore, subject to slower variations. The time until the C-uptake from the regrowth of the forest has counteracted the initial emission can, then, be large.

The key aspect of modelling of biogenic GHG emissions from providing biomass for bioenergy is, thus, the net change in carbon stock.

Table 4-4 presents the outcome of the inventory models.

Table 4-4 *Modelled GHG emissions from individual biomass and LUC categories. CO_2 emission average normalised per harvested (and used for energy) biomass at 20 and 100 years amortisation. Data do* <u>*not*</u> *include transport emissions or processing emissions for chips/pellets. (continued next page)*

	Average emissions at 20 amortisation (g CO_2 per MJ removal)		Average emissions at 100 years amortisation (g CO_2 per MJ removal)	
Residues – thinnings				
Boreal	65		0.02	
Temperate	0.011		0.000	
Tropical	0.009		0.000	
Forest remaining forest (harvest from existing forest)				
Boreal	153		74	
Temperate	222		108	
Tropical	123		41	
Plantation on forest land				
	when utilizing initial removal	when **not** utilizing initial removal	when utilizing initial removal	when **not** utilizing initial removal
Boreal	110	529	53	104
Temperate	181	777	97	194
Tropical	87	383	45	67
Plantation on low C grassland – excluding iLUC from displaced animal feed				
Boreal	-62		-31	
Temperate	-82		-6.6	
Tropical	-15		-3.9	
Plantation on low C grassland – including iLUC from displaced animal feed (low and high estimate)				
	Low	High	Low	High
Boreal	-45	75	-27	-2
Temperate	-78	-9	-6	8
Tropical	-18	83	-5	16
	Average emissions at 20 amortisation (g CO_2 per MJ removal)		Average emissions at 100 years amortisation (g CO_2 per MJ removal)	
Plantation on low C grassland – including iLUC from grassland directly displaced into deforestation				
	when utilizing initial removal	when **not** utilizing initial removal	when utilizing initial removal	when **not** utilizing initial removal
Boreal	110	529	53	104
Temperate	181	777	97	194
Tropical	87	383	45	67
Plantation on high C grassland/savannah – lower and higher C-stock – not using initial removal				
	Lower C-stock	Higher C-stock	Lower C-stock	Higher C-stock
Tropical	14	43	3	9
Low C grassland converted to high C grassland – excluding ILUC from lost animal feed				
Boreal	-41		-5	
Temperate	-77		-6	
Tropical	-18		-3	
Plantation on marginal land				
Boreal	-32		-32	
Temperate	-85		-6.9	
Tropical	-15		-3.9	
Plantation on cropland – excluding iLUC from lost food/feed production				
Boreal	-32		-32	
Temperate	-85		-6.9	
Tropical	-15		-3.9	
Plantation on cropland – including iLUC from lost food/feed production (low and high estimate)				
	Low	High	Low	High
Boreal	-5	110	-24	-3
Temperate	-68	30	-2	17
Tropical	-9	52	-3	10

Table 4-4 cont Modelled GHG emissions from individual biomass and LUC categories. CO_2 emission average normalised per harvested (and used for energy) biomass at 20 and 100 years amortisation. Data do not include transport emissions or processing emissions for chips/pellets. (continued)

Straw (Denmark)		
	GWP20 (gCO_2-eq./MJ)	GWP100 (gCO_2-eq./MJ)
Temperate	24	11
Manure (Denmark, fattening pig, 6.9% TS, 5.5% VS)		
	GWP20 (gCO_2-eq./MJ VS)	GWP100 (gCO_2-eq./MJ VS)
Temperate	-164	-73

As shown in Table 4-4, the CO_2 emissions from the various types of biomass supply are expressed per MJ harvested and used for energy. The models of the forest and plantation biomasses (described in Appendix A - E) account for emissions from any change in carbon stock on the land in question, be it a decrease or an increase, as well as any subsequent cyclic emissions from the forest or plantation.

Emissions from burning/using the biomass for energy purposes are included in the values in the Table, i.e. the values are the net biogenic CO_2 emissions deriving from uptake and releases and thus reflect the changes in stock. Carbon stock changes, be it increase or decrease, appear initially, typically within the first few years, followed subsequently by cyclic emissions and cyclic changes in the carbon stock. The cyclic emissions balance, assuming a steady operation of the forest or plantation subsequent to the initial C-stock change, i.e. uptake and releases are equal – because a net average C-stock is maintained constant. See Figure 4-3 for illustration. Therefore, the initial C-stock change is the key contributor to the CO_2 emissions or uptake from the biomass. This initial emission/uptake is, then, normalised by the harvested – and used – biomass.

Assuming a long term steady-state cyclic operation of the forest/plantation, including a biomass harvest at every rotation interval, the initial emission/uptake will, of course, be 'diluted' more and more when normalised to the harvested biomass. On the very long term, the cyclic emissions dominate completely, and the net emission comes close to zero. In several cases, however, this will take several hundred years.

When doing plantation on forest land or savannah, it may happen that the initial biomass removal is used partly or fully for energy, and it may happen that it is not used. For plantation on forest land, we have modelled both situation, for plantation on savannah, we have assumed the initial biomass removal not used.

On the 20 year horizon, the specific GHG emissions from plantation on high C savannah is 43 g CO_2-eq./MJ and from plantation on forest land it is 87 or up to 383 g CO_2-eq./MJ depending on whether the initial C-stock removal is utilized or not (see Table 4-4). This implies specific GHG emissions on the 20 year horizon to lie in the range of 43 – 383 g CO_2-eq./MJ as the longer term marginal.

On the 100 year horizon, the specific GHG emissions from plantation on high C savannah is 9 g CO_2-eq./MJ and from plantation on forest land it is 45 or up to 67 g CO_2-eq./MJ depending on whether the initial C-stock removal is utilized or not (seeTable 4-4). This implies specific GHG emissions on the 100 year horizon to lie in the range of 9 – 67 g CO_2-eq./MJ as the longer term marginal.

From another study (Schmidt and Brandao, 2013), we have seen specific emissions og 6.5 to 45 g CO_2-eq./MJ for GWP 100 and 34 to 198 g CO_2-eq./MJ for GWP20. This range matches quite well the range we will get if taking a weighted average of plantation on savannah and forest land on the longer term.

4.3.3 The historic development of biogenic greenhouse gas emissions

In 2000, it was estimated (IPCC, 2000) that approximately 405 ± 60 Gt C during the period 1850-1998 had been emitted as CO_2 into the atmosphere from human activities. These emissions were caused by fossil fuel burning and cement production (67 percent), and land use and land-use change, LUC (33 percent), predominantly from deforestation.

According to IPCC (2007), annual GHG emissions in 2004 amounted to around 49 Gt CO_2-eq./year, of which around 31% were from agriculture and forestry – equal to around 15 Gt CO_2-eq./year from these two sectors together, cf. Figure 4-3. Likewise, UNEP (2012) estimated the agricultural & forestry emissions in 2010 to be around 11 Gt CO_2-eq./year.

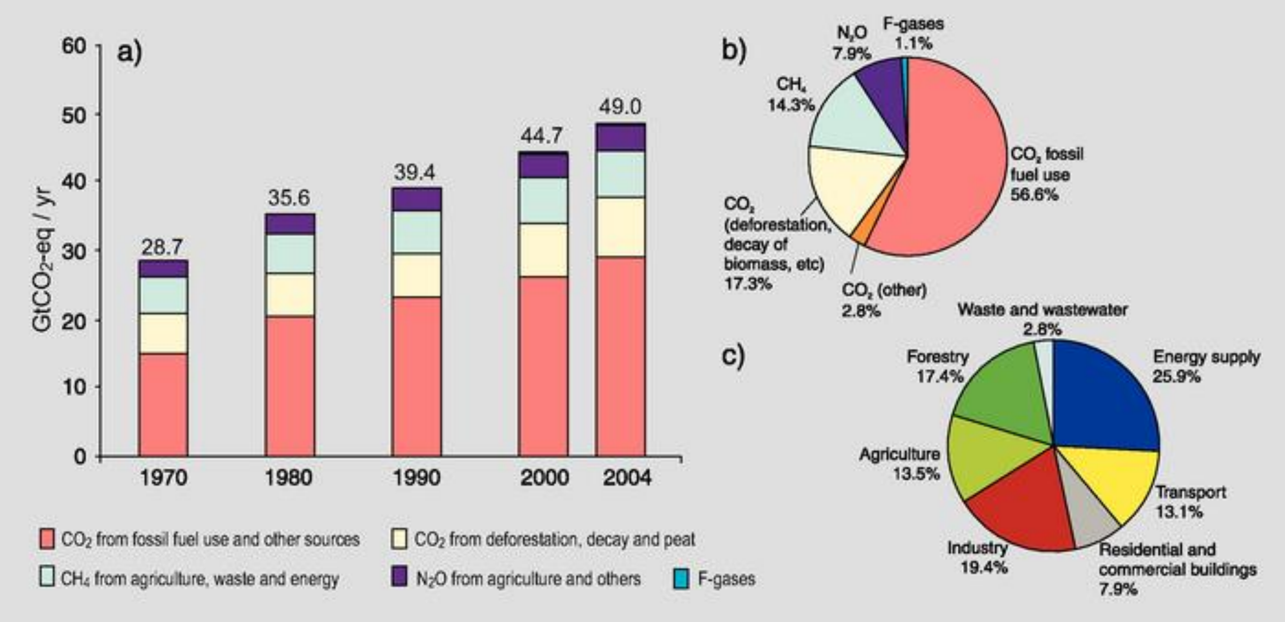


Figure 4-3 (from IPCC (2007). (a) Global annual emissions of anthropogenic GHGs from 1970 to 2004. (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO_2-eq. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2-eq. (Forestry includes deforestation.)

These agricultural and forestry emissions relate to the way we use the land. In order to understand the efficiency of our historic and present way of using land to provide food, feed and forestry products, the emissions are in the following related to the quantity of acquired products.

Based on data from FAOSTAT from 2011, Chum et al. (2011) finds the global harvest of major forestry and agricultural products to represent an energy equivalent around 80 EJ/year, i.e. a global industrial roundwood production of 15 to 20 EJ/yr, and a global harvest of major crops (cereals, oil crops, sugar crops, roots, tubers and pulses) of around 60 EJ/yr. Including agricultural residues and the informal sector use of forest residues (mainly for firewood), the total human appropriated part of the global net primary production, HANPP is larger, i.e. 219 EJ/year according to Krausmann et al. (2008). Bang et al. (2013) finds this figure to be 220 EJ/year based on FAOSTAT and other data.

Relating, thus, recent emissions from agriculture and forestry to the total appropriated biomass, HANPP by humans today, we arrive at a specific GHG emission of:

› *15 Gt CO_2-eq./220 EJ HANPP = 68 g CO_2-eq./MJ HANPP in 2004*

› *11 Gt CO_2-eq./220 EJ HANPP = 50 g CO_2-eq./MJ HANPP in 2010*

As illustrated in Figure 4-3, around 17% of this emission arose from forestry in 2004, including deforestation, while 13% arose from agriculture. Of this GHG emission, CO_2 emissions accounted for around 17% (i.e. almost entirely from forestry), while agricultural CH_4 emissions and N_2O emission accounted for the remaining 13 %. For comparison, combustion of natural gas give rise to around 55 g CO_2-eq./MJ combusted, and total supply chain GHG emissions from natural gas amount to around 78 g/MJ.

This business-as-usual emission profile from agriculture and forestry reflects the total pattern of drivers & barriers, and economic, sociological and technological realities of the World till now. As illustrated, deforestation has been a major source of biogenic emissions, and a key cause of deforestation is believed to be a low cost of land in many countries compared to other production factors in both agriculture and forestry – and accordingly, of course, an equally low degree of governance to avoid exploitation of the economic benefits from using new land by deforestation.

Figure 4-4 illustrates the development of net forest conversion, being the net result of deforestation and afforestation. As seen from the Figure, a net global reduction in forest area is still taking place.

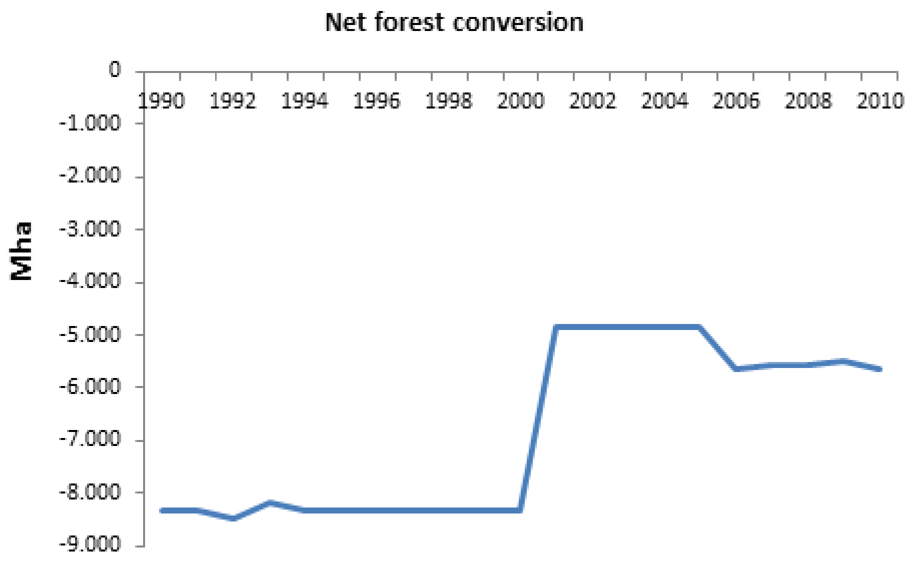


Figure 4-4 *Net forest conversion as the sum of deforestation and afforestation, retrieved from FAOSTAT (2013)*

5 Carbon footprint results and discussion

5.1 Carbon footprint of individual conversion pathways and their dependency on biomass origin and energy system timeline

As previously mentioned, 16 biomass conversion pathways were assessed representing the key conversion technologies today as well as some of the emerging technologies for a future renewable energy system. Each pathway was assessed in the four different time periods and on the background of each of the identified biomass marginals, including 8 types of woody biomass as well as domestic manure and straw. All are assessed in a 20 year time horizon as well as a 100 year time horizon, and all are assessed at the previously described level 2 and level 3. This adds up to a high number of combinations, 48 combinations per pathway to be exact, or 768 in total, each being , a life cycle carbon footprint assessment in itself.

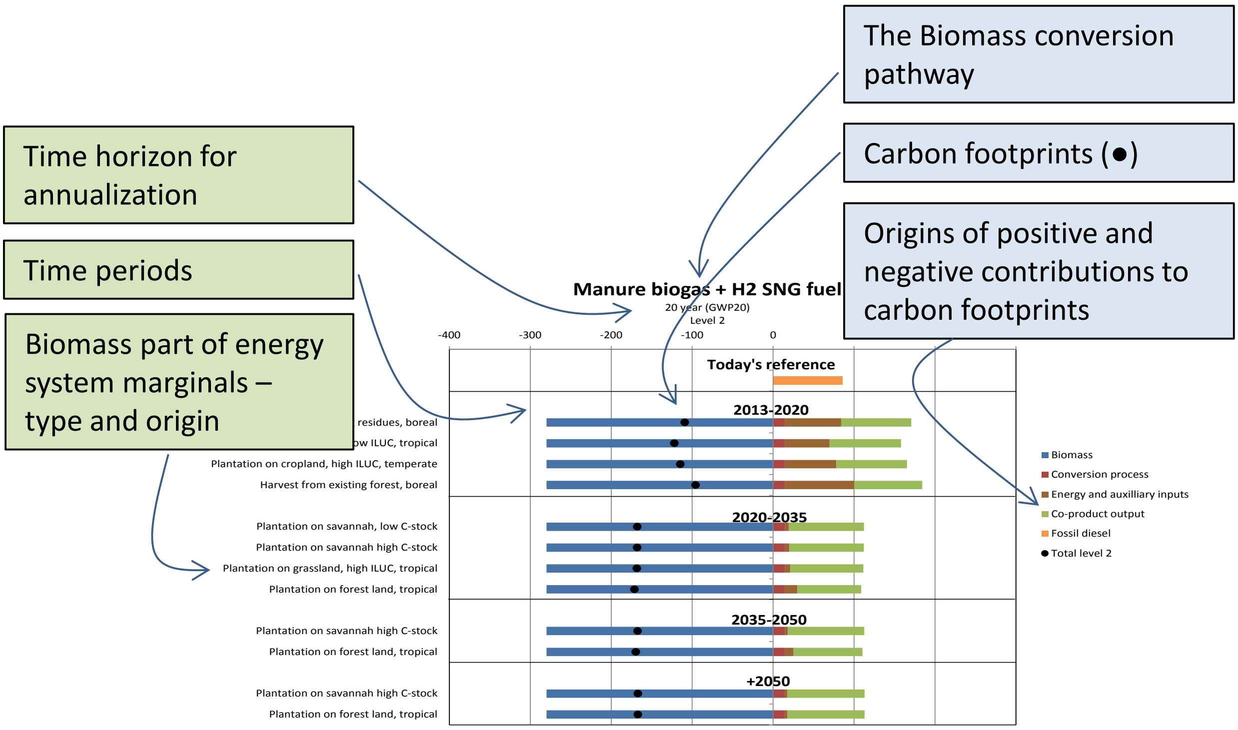
In this section the carbon footprint results are presented at both level 2 per unit of output and level 3 per MJ of biomass input. The key acknowledgements that can be extracted from these results are presented in relation to each pathway, and the key pathway model issues are briefly presented as well. In Appendix H, the key inventory data on each pathway are, moreover, presented as well as the overview of the data on the quite large variety of energy system marginal that we have used in the study of the pathways in the different time periods.

As already mentioned results are presented in two ways - at 'Level 2' and at 'Level 3'.

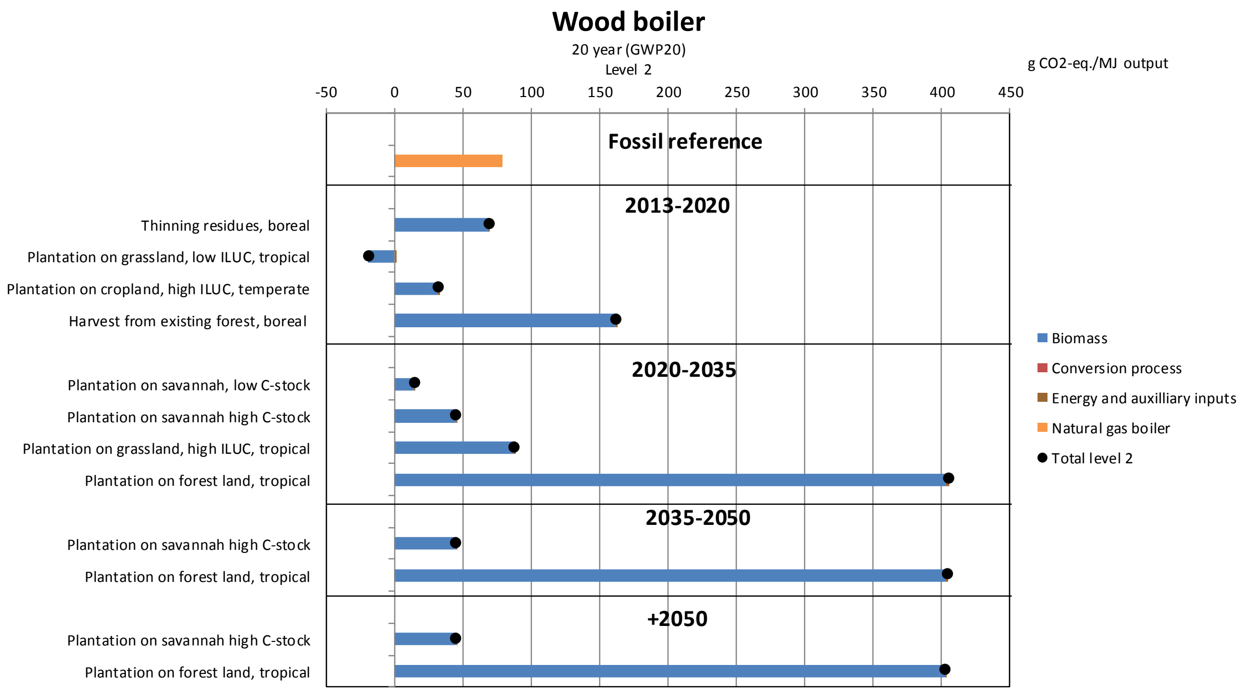
› 'Level 2' reveals greenhouse gas emissions relative to the amount of energy output (g CO_2 eq/kWh or g CO_2 eq/MJ)

› 'Level 3' reveals greenhouse gas emissions relative to the amount of biomass input (g CO_2 eq/MJ)

Accordingly there are four sets of graphics for each biomass conversion pathway covering each of the two levels and time horizons.



Presenting carbon footprints for biomass conversion pathways



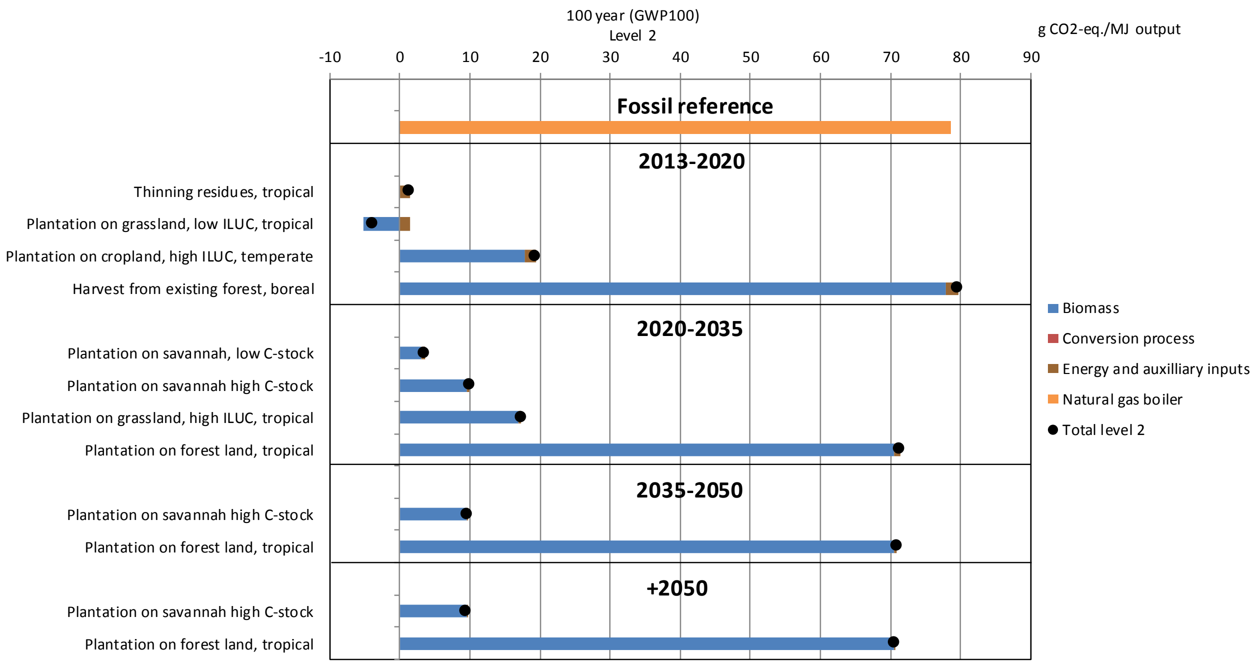


Figure 5-1 Wood boiler carbon footprint at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)

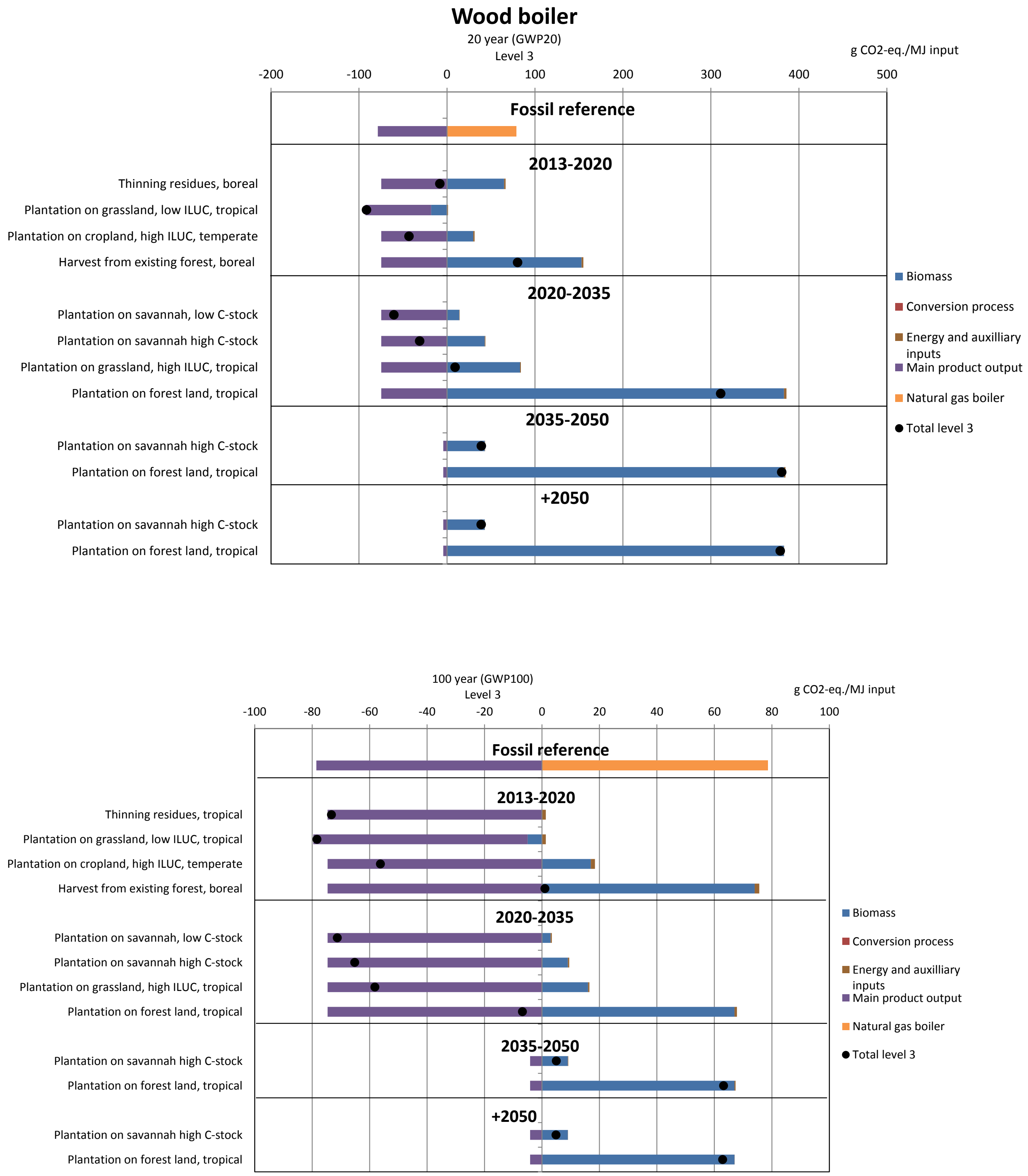
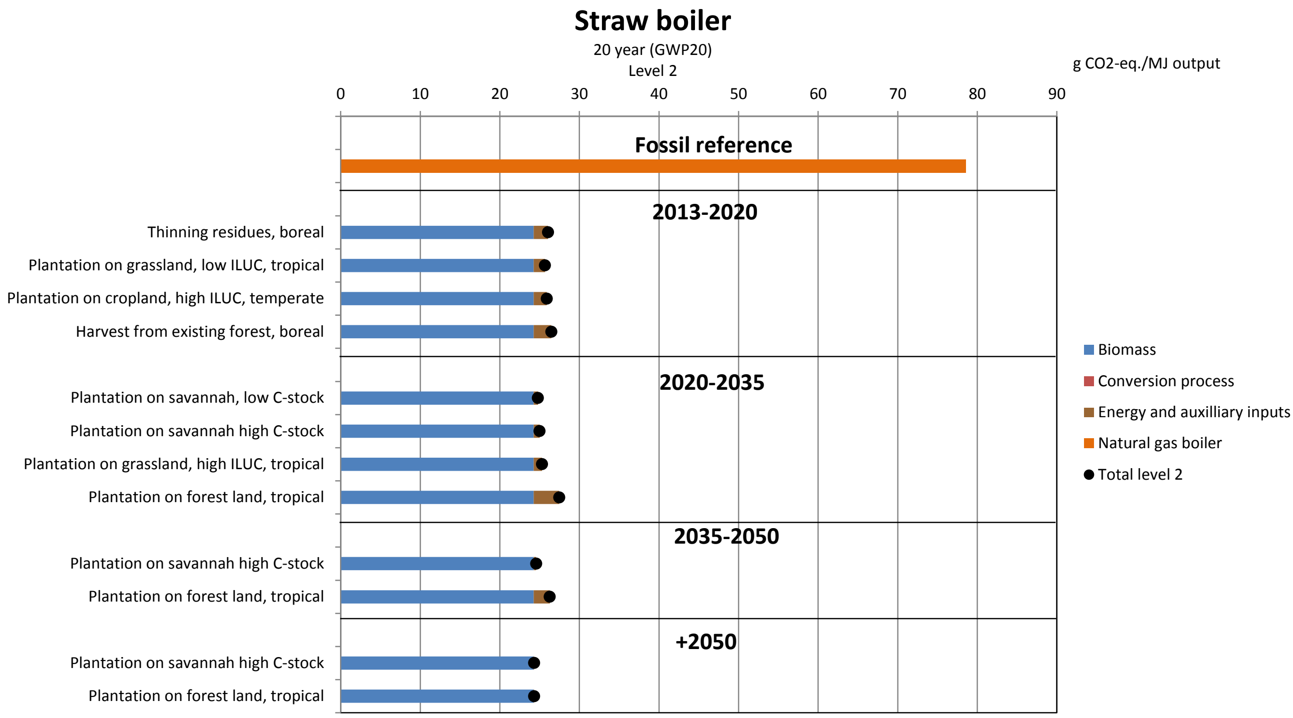


Figure 5-2 Wood boiler carbon footprint at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



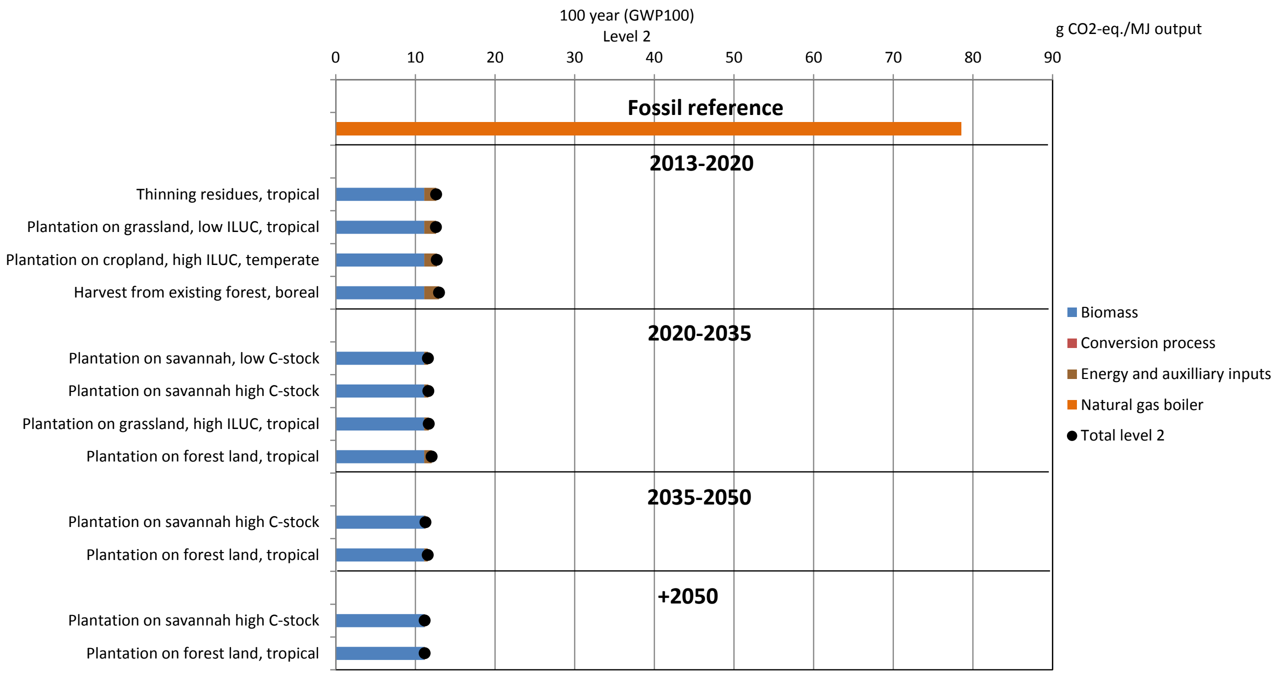


Figure 5-3 Straw boiler carbon footprint at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)

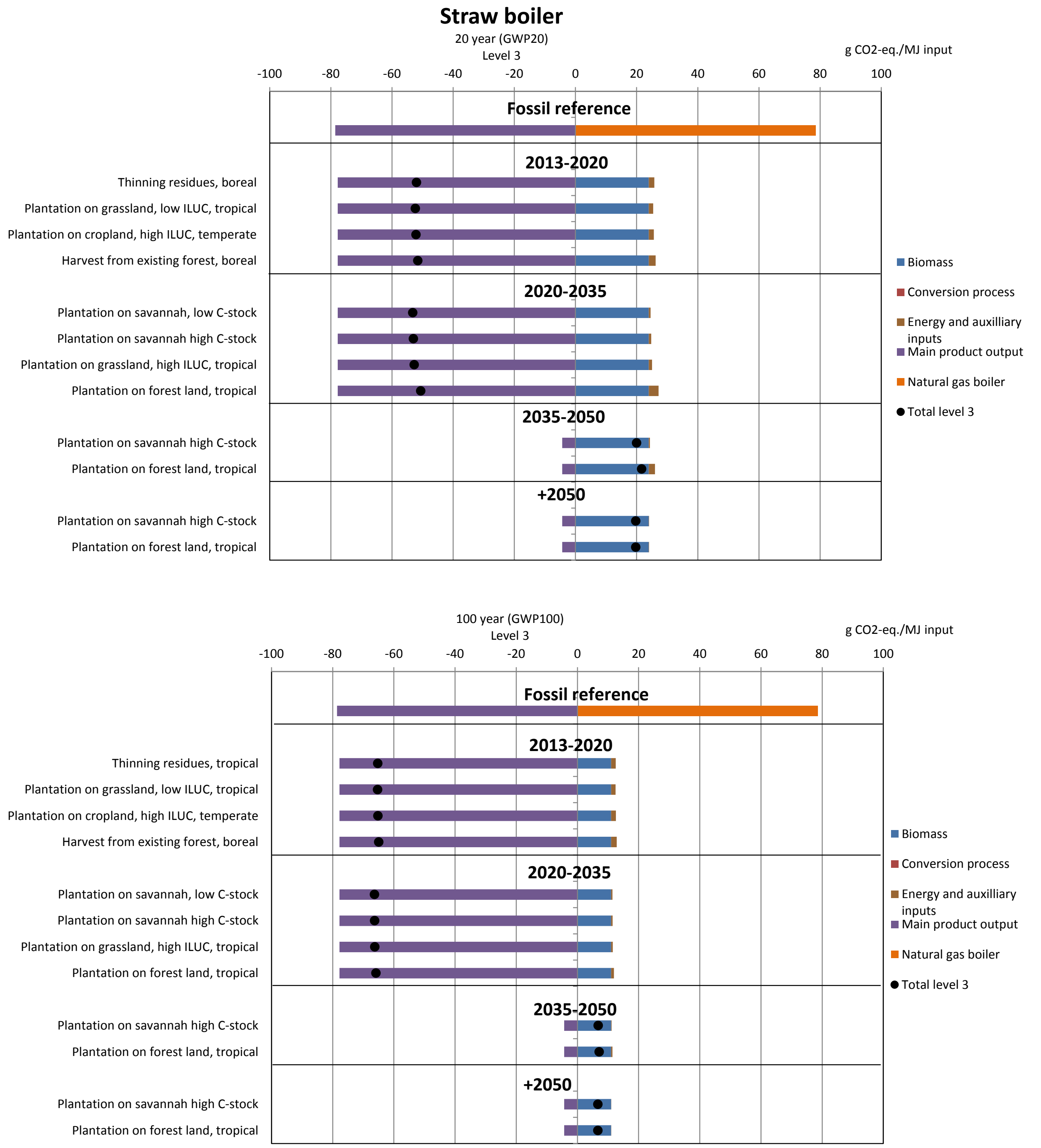


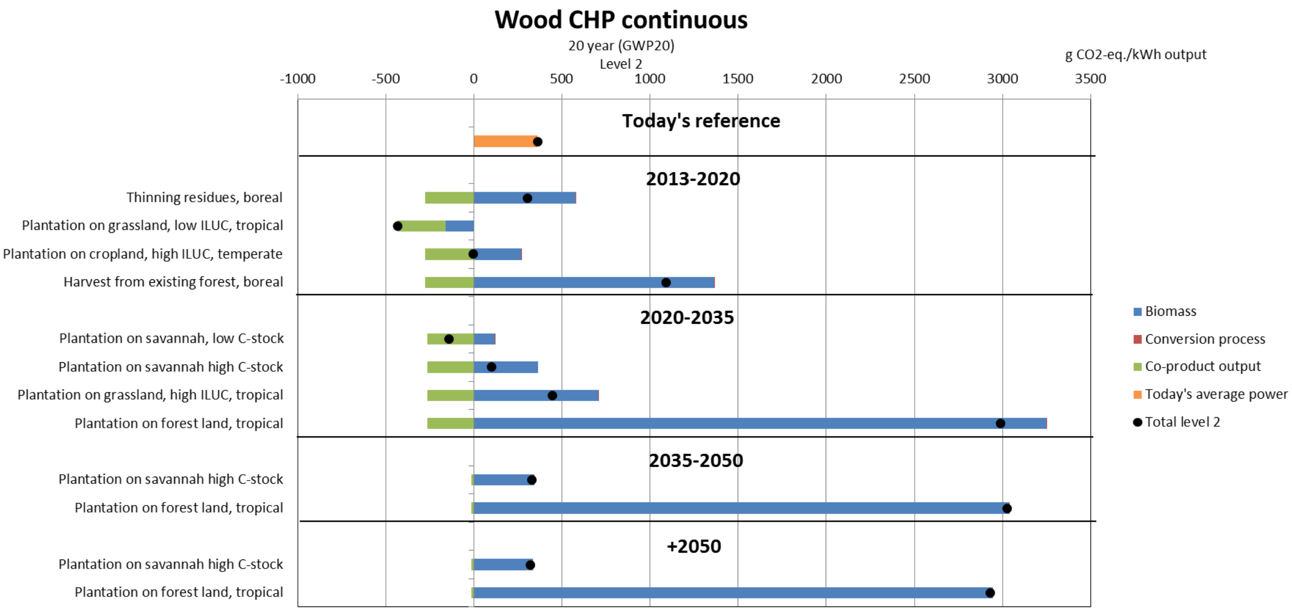
Figure 5-4 *Straw boiler carbon footprint at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)*

The wood boiler has a high thermal efficiency, no co-product output and a very small and insignificant electricity consumption. The emissions from the supply of biomass, therefore, mean everything. As Figure 5-1 shows, the range of possible GHG emissions from the life cycle system of a wood boiler is huge – from having potentially a very low and even negative emission if drawing on a tropical thinning wood marginal (or temperate, cf. Table 4-4) or wood from plantation on tropical grassland assuming a low ILUC to implying a very large GHG emission if implying plantation, especially on forest land and especially if seen in a 20 year time horizon.

As long as a supply of thinning wood or wood from plantation on low C grassland can be ensured, the emissions from the wood boiler is much lower than emissions from a natural gas boiler, being the fossil reference. As Figure 5-2 illustrates, however, the benefit of avoiding a fossil reference will disappear from 2035 and onwards – if assuming an energy system development in compliance with the energy policy of the Danish Government, and the attractiveness in term of reducing carbon emissions of prioritizing a biomass resource for heat after this period is small.

The straw boiler also has a high thermal efficiency, no co-product output and a very small and insignificant electricity consumption. The emissions from the supply of straw, therefore, are dominating. These emissions represent the soil carbon sequestration that the ploughing down of the straw would have led to, i.e. the net loss of soil carbon over the 20 year and 100 year time period respectively compared to ploughing down the straw. These are seen to be much smaller than fossil emissions from the natural gas boiler, but still significant. The GHG implication of the straw boiler does not vary a lot with the assumption on marginal biomass, the only variation seen to lie in the small electricity input, part of which is constituted of the marginal biomass, see Appendix H.

The straw boiler will lead to very large GHG saving compared to the fossil reference, especially seen in a 100 year time horizon and in the period from 2013 to 2035. After this period, heat supply is no longer based on fossil fuel, but assumed in this study to be based on electricity from a heat pump or electric boiler running on wind power. There is close to no benefit of displacing this, as illustrated in Figure 5-4, and the soil carbon releases from using straw instead of ploughing it down are badly invested by using it in a boiler, GHG wise.



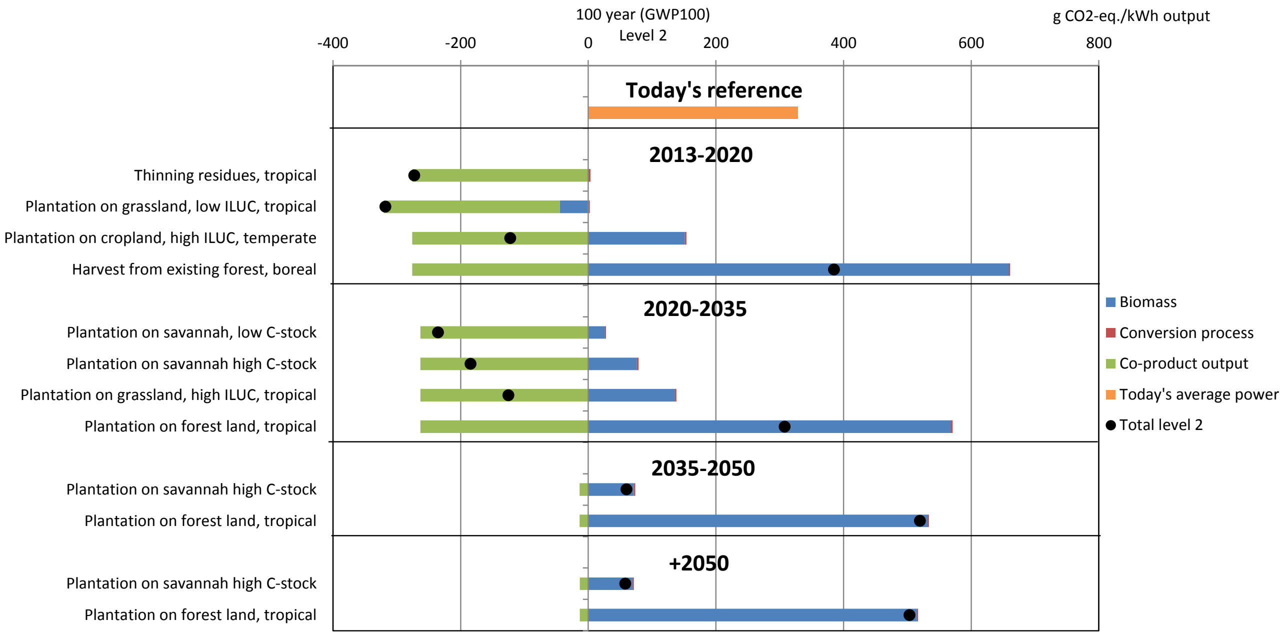
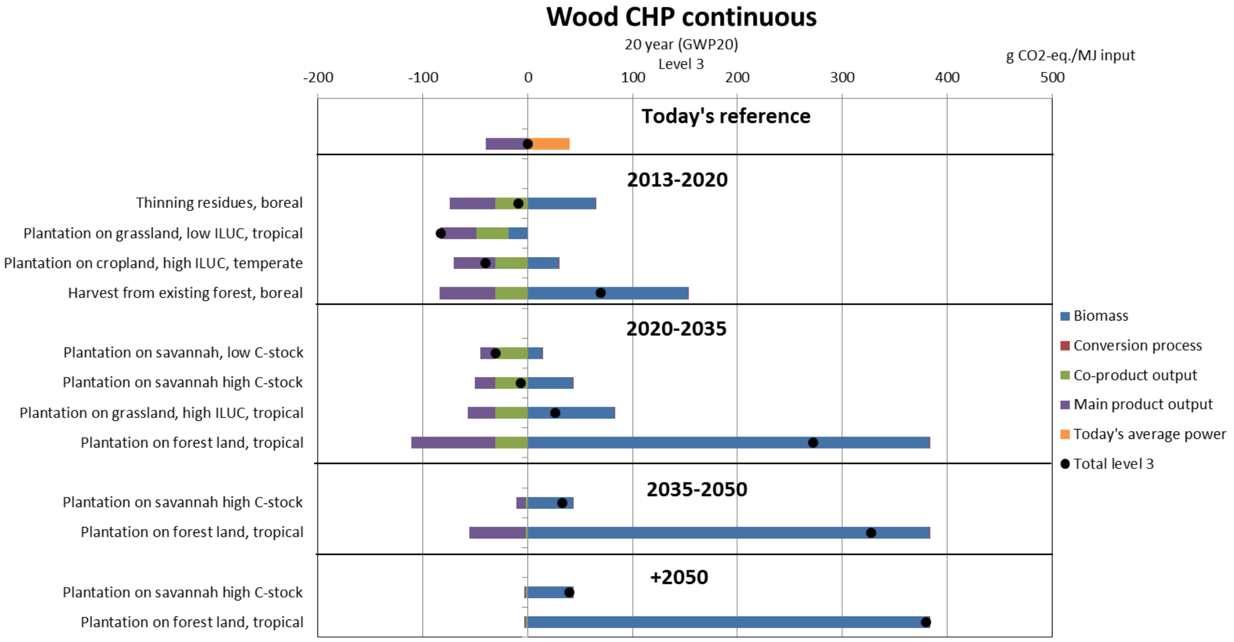


Figure 5-5 The carbon footprint of a wood CHP continuous power production at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



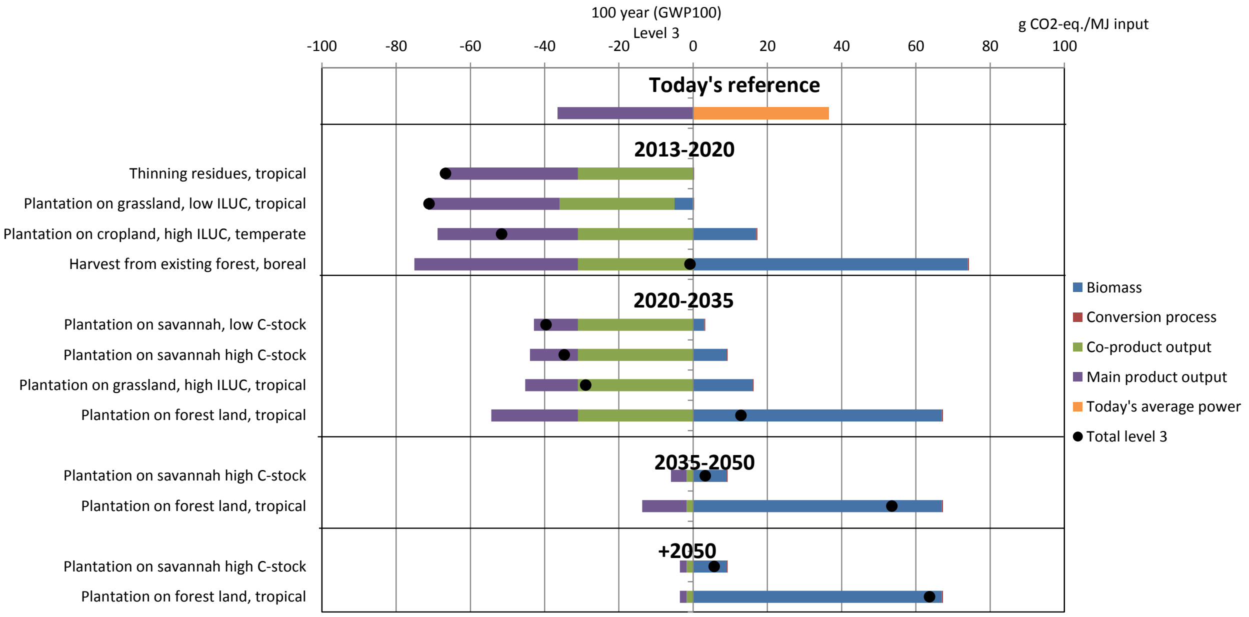
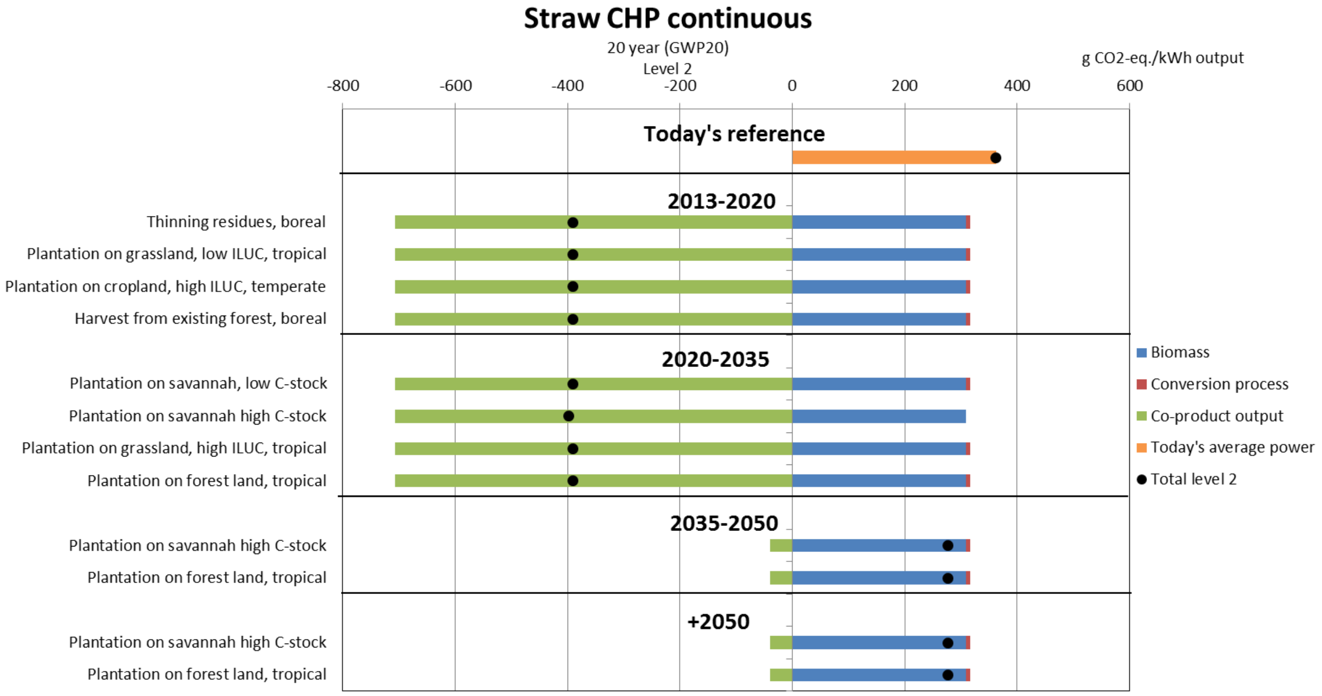


Figure 5-6 *The carbon footprint of a wood CHP continuous power production at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)*



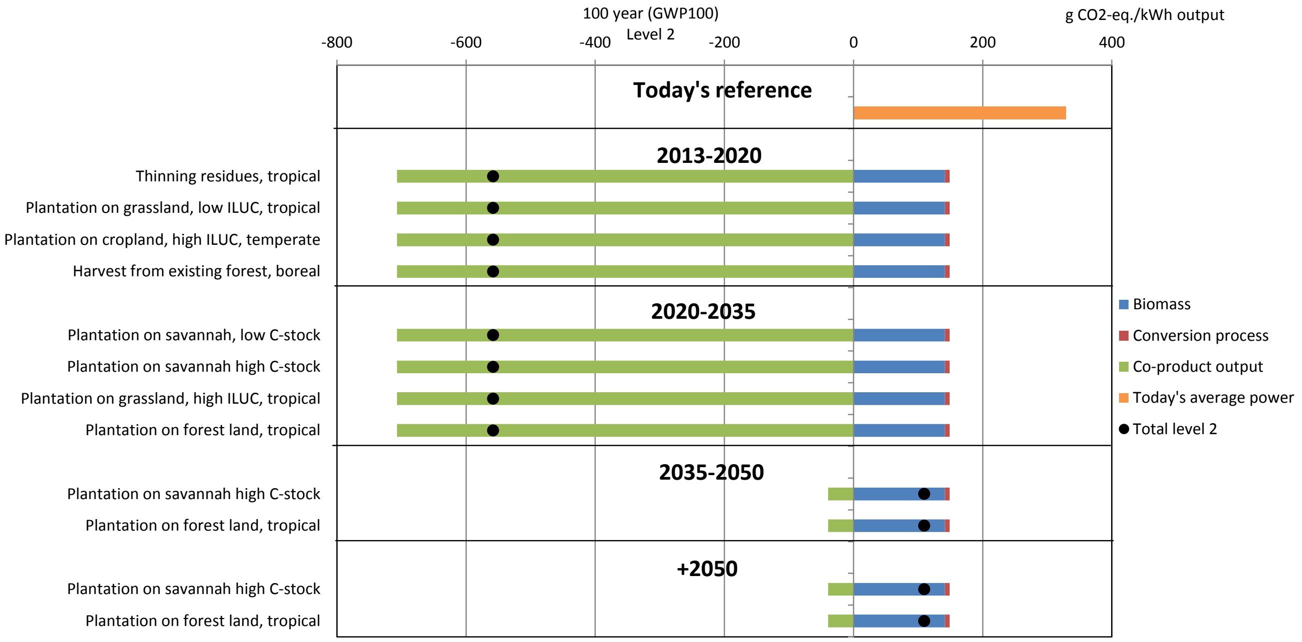
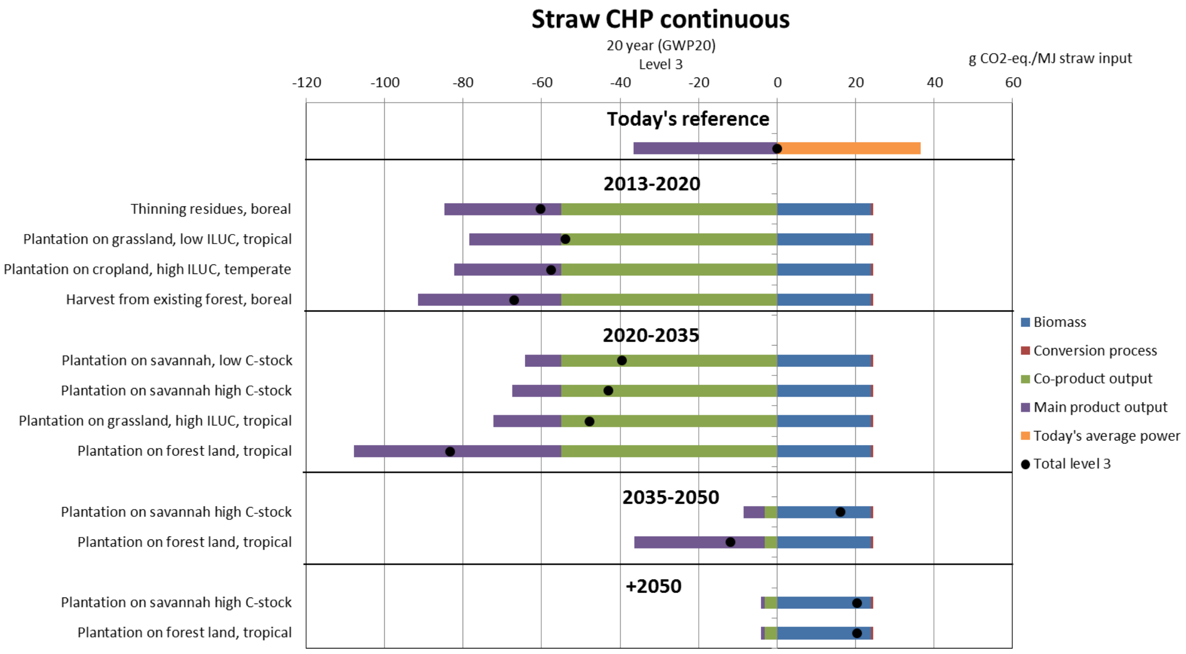


Figure 5-7 *The carbon footprint of a straw CHP continuous power production at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)*



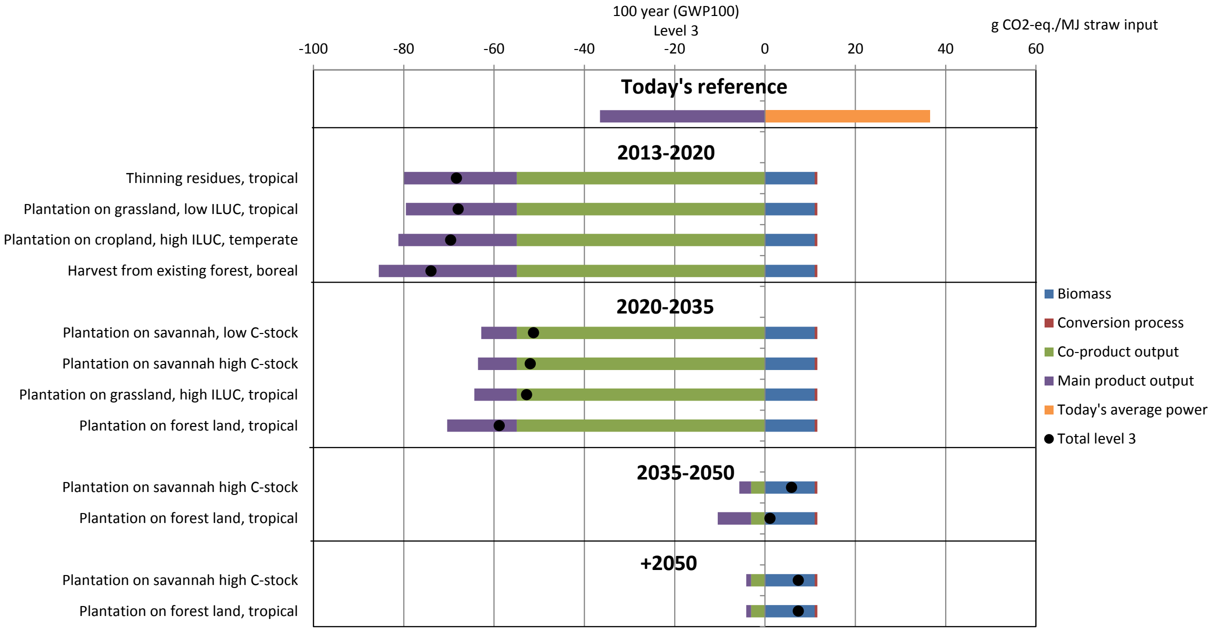
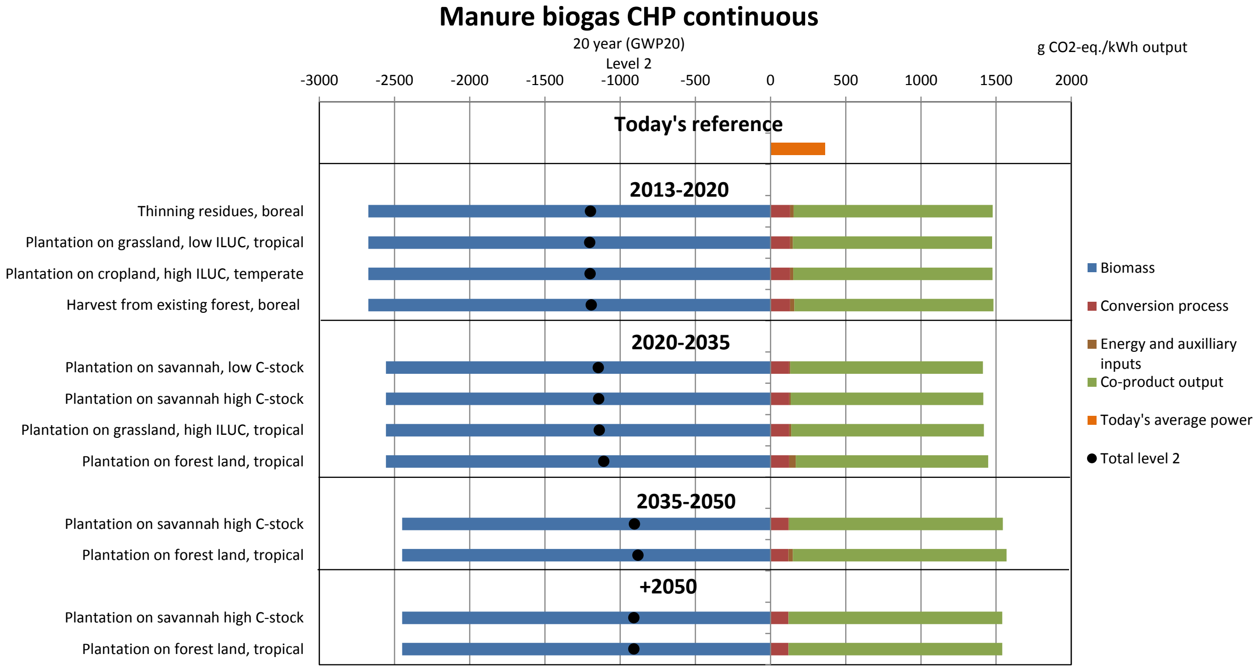


Figure 5-8 The carbon footprint of a straw CHP continuous power production at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



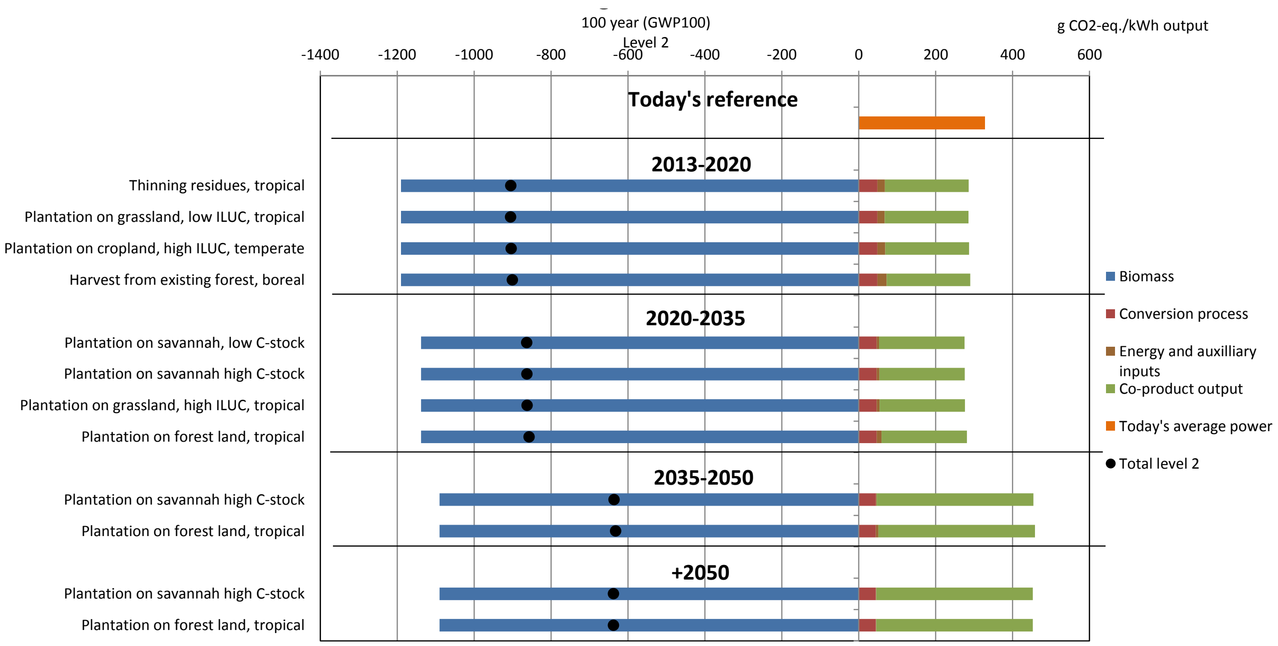
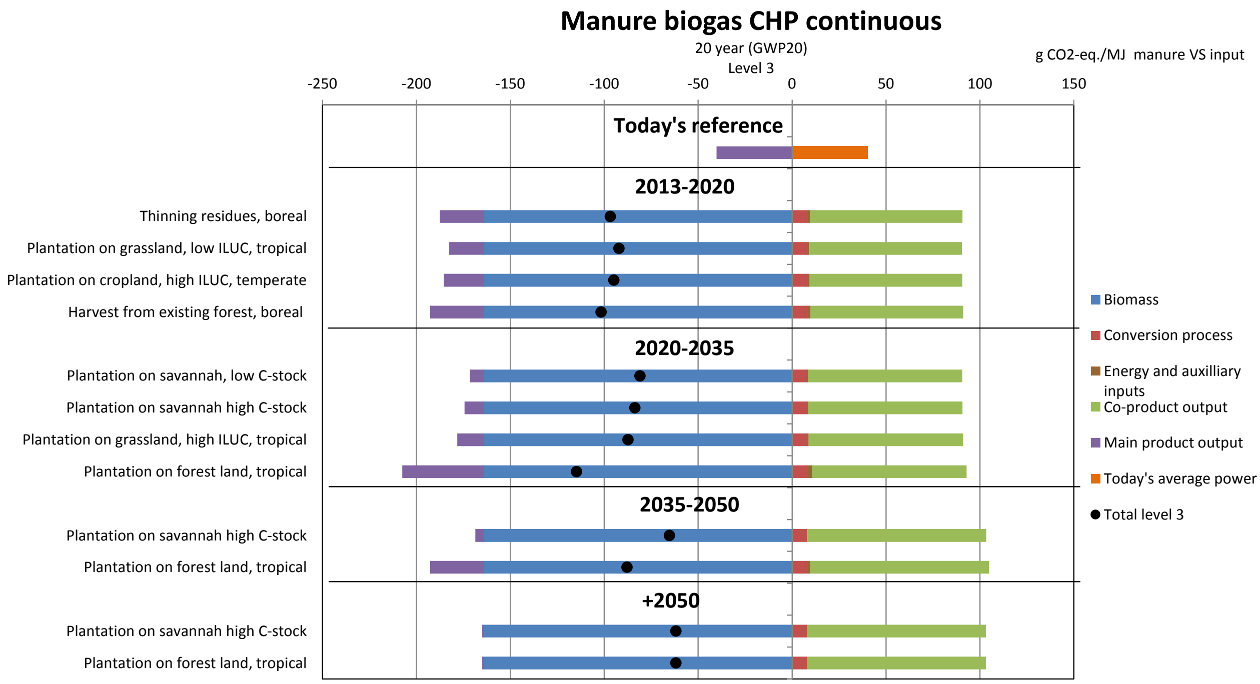


Figure 5-9 *The carbon footprint of a manure biogas CHP continuous power production at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)*



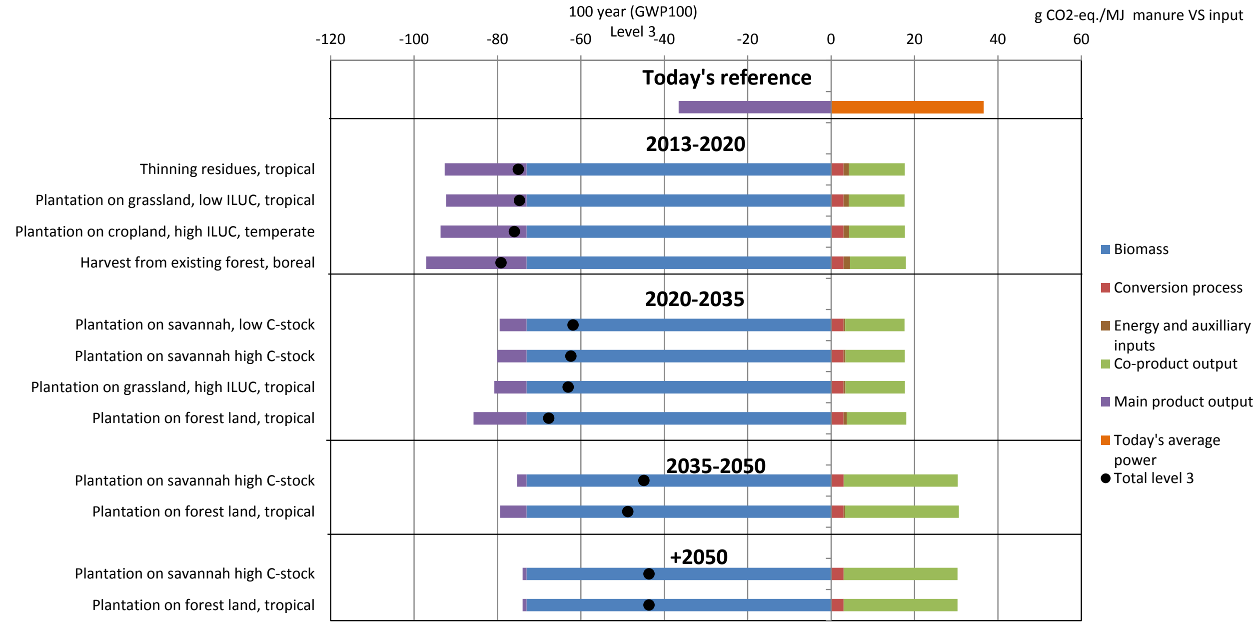
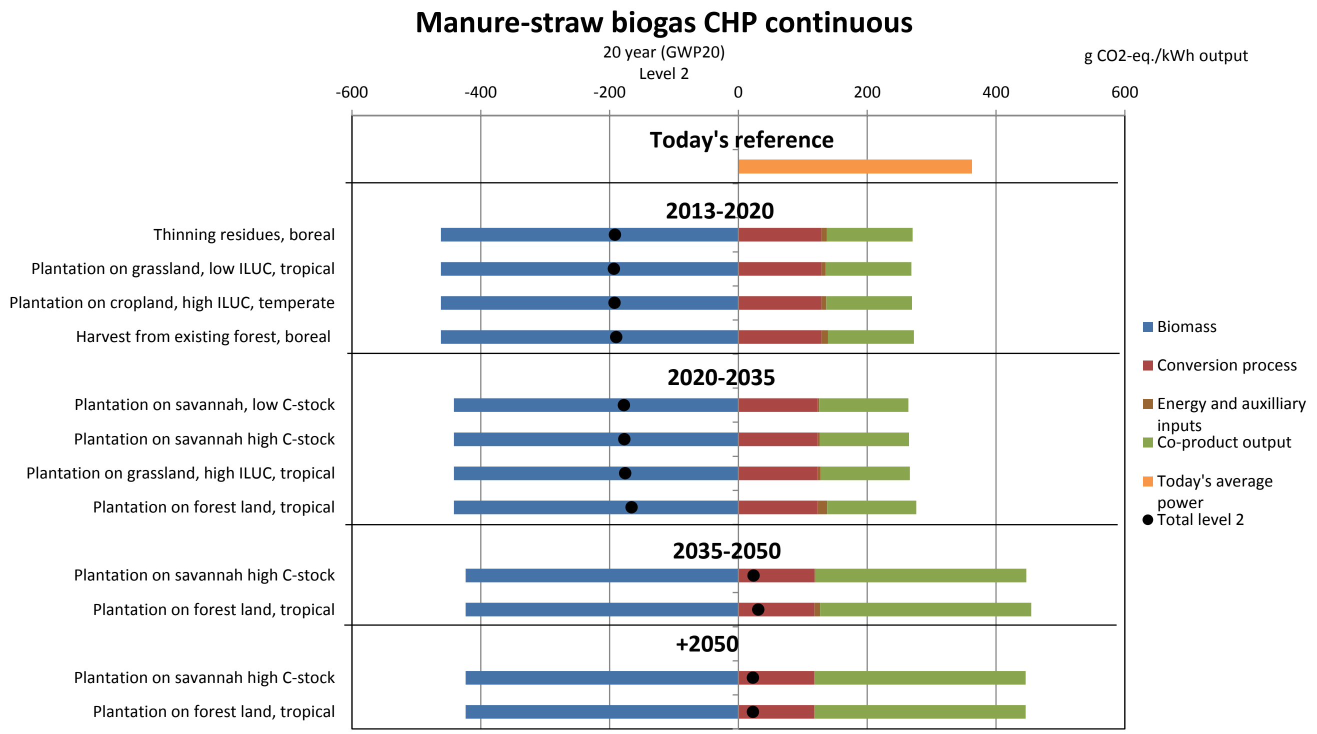


Figure 5-10 The carbon footprint of a manure biogas CHP continuous power production at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



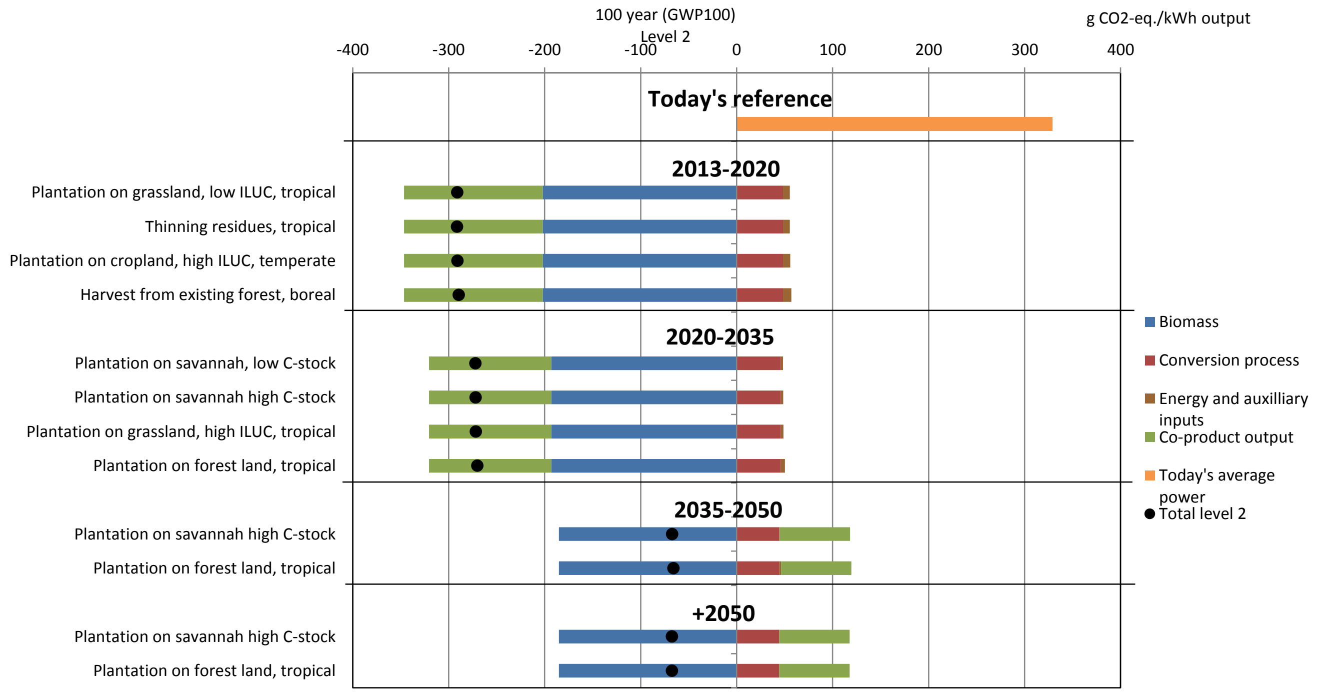
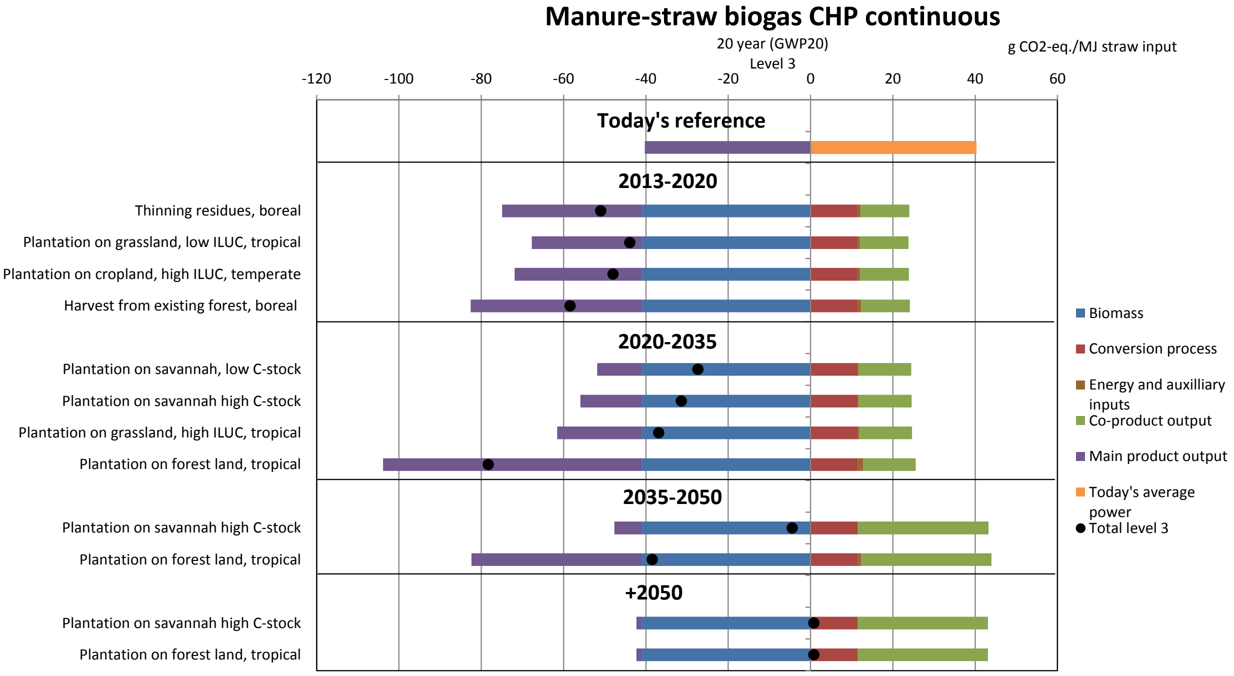


Figure 5-11 The carbon footprint of a manure-straw co-digestion biogas CHP continuous power production at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



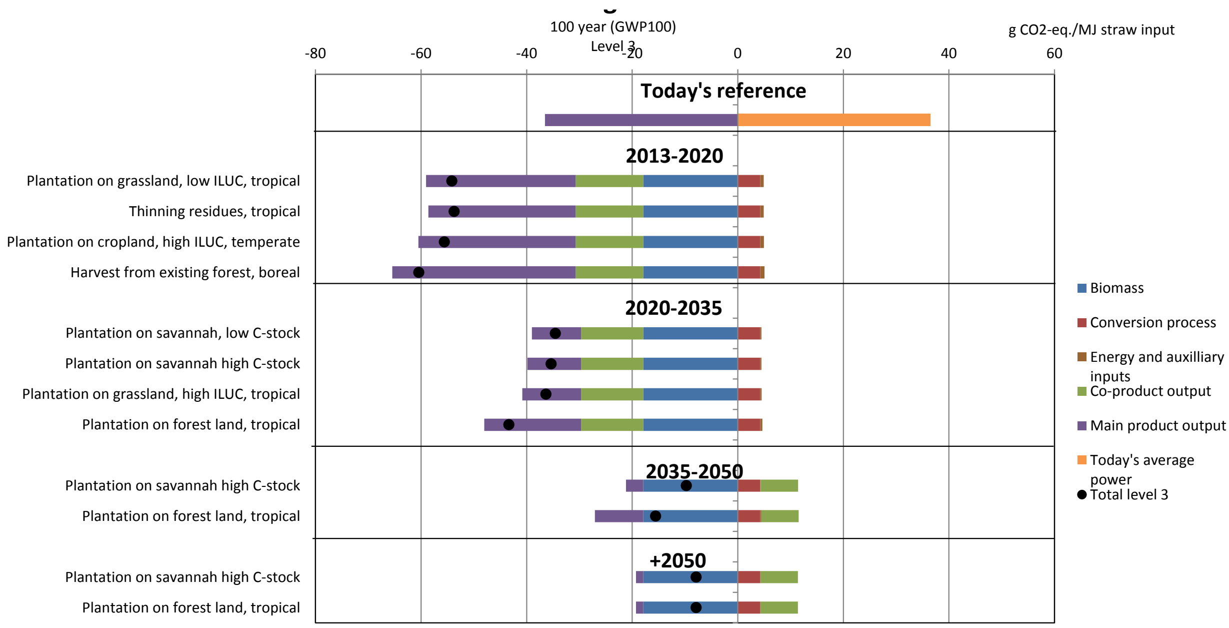


Figure 5-12 The carbon footprint of a manure-straw co-digestion biogas CHP continuous power production at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)

The wood CHP continuous power production (Figure 5-5) is a combustion technology (pulverized fuel) assumed to operate at around 40% electricity conversion efficiency and around the same heat efficiency in the first part of the time scale increasing up to 45 % electricity conversion efficiency in 2050 and beyond. In the 20 year time horizon, the emissions from the biomass supply can be very dominating if implying a problematic biomass marginal. But as long as a supply of non-boreal thinning wood or wood from plantation on low C grassland can be ensured, the emissions from this wood CHP conversion technology are much lower than emissions from today's mainly fossil based average Danish CHP production, being the reference for continuous power production. It seems wise, and manageable, to avoid boreal thinning wood and harvest from existing boreal forests implying deforestation.

As Figure 5-6 illustrates, moreover, the benefit of avoiding the marginal Danish continuous power production will largely disappear from 2035 and onwards – if assuming an energy system development in compliance with the energy policy of the Danish Government, and the attractiveness in term of reducing carbon emissions of prioritizing a biomass resource for continuous power production after 2035 is small compared to the risk of having a significant GHG emission related to the supply of the wooden biomass.

The straw CHP continuous power production (Figure 5-7) is a combustion technology (direct combustion in back-pressure mode) assumed to operate at around 28% electricity conversion efficiency and around 70% heat efficiency throughout the period. Expressed per kWh of power output, this high heat co-product output is seen to give rise to a high GHG reduction in the periods 2013 – 2035, where a natural gas boiler is assumed to be the avoided alternative. The lost soil carbon sequestration (= the biomass related emission in the Figure) is seen to be of the same magnitude as today's average continuous power production in the 20 year time horizon and about half of this in the 100 year time horizon. As no inputs or co-product outputs from the pathways draw on or displace woody biomass, the pathway is independent on the woody biomass marginal assumed.

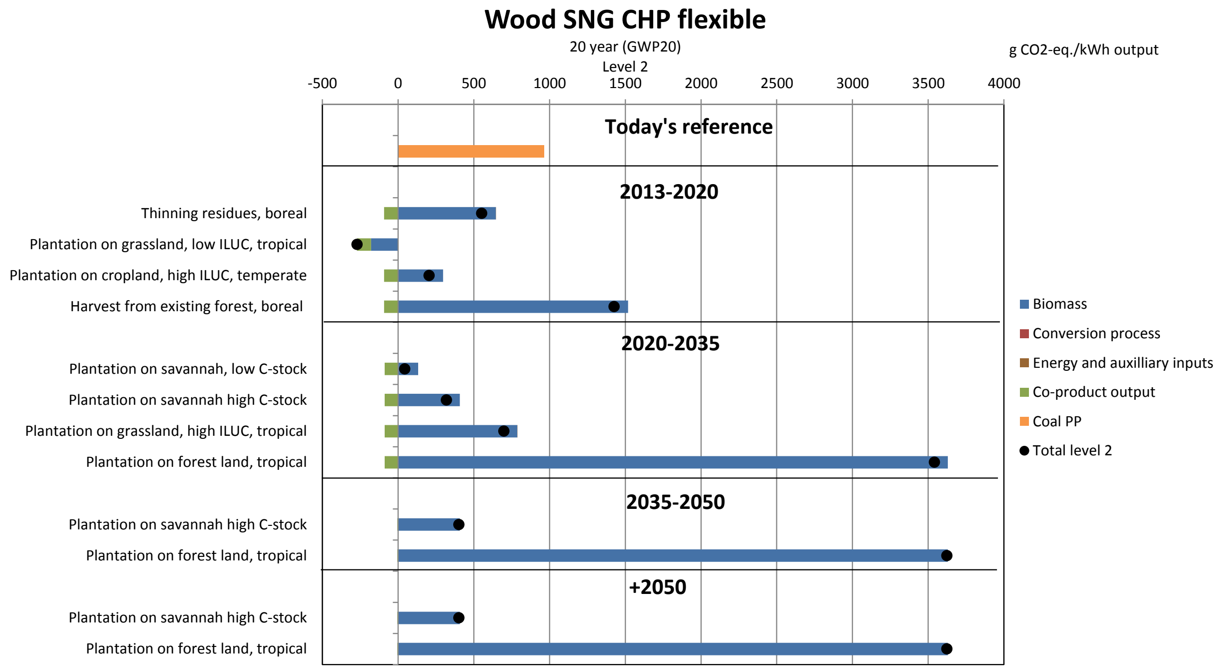
After 2035, the benefit from the co-product output of district heating is more or less gone, because an electric boiler running on flexible consumption against a heat storage – and therefore on wind power – is assumed from this periods onwards, and the attractiveness (in relation to GHG emission reduction) of using straw for continuous power production is lost. As seen from Figure 5-8, moreover, the GHG benefit of avoiding the alternative continuous power production on the grid (= the Main product output in the Figure 7-8) decreases over time as more wind power and biomass are assumed to penetrate into the Danish electricity system, replacing the fossil fuel part more and more. In 2035 – 2050, a wind power to biomass power share of the continuous electricity production of 75% to 25% is assumed, and in 2050 and beyond a full wind power production is assumed, see Appendix H for further details on the assumed marginal. As evident from Figure 7-8, the climate-wise idea of prioritizing straw for continuous power production is lost after 2035.

The pathway on manure biogas for continuous power production (Figure 5-9) is modeled assuming pig manure with a 6.9% dry matter content with 80% volatile solids (VS), and the biogas is assumed converted by direct combustion in a gas engine. Process emissions of methane of 1% of the produced biogas are assumed, covering fugitive emissions from the biogas plant as well as unburned methane passing through the engine. This is small compared to present state of emissions, but assumed realistic for future conditions. But even so, these methane emissions are seen to be very significant, amounting to almost one fourth of GHG emissions from today's average continuous power production. The uncertainty and sensitivity issues related to this are further discussed in section 7.2. The GHG emissions from the manure and digestate management are, however, totally dominating the picture. The huge avoided emissions from the biomass (= the manure) derive from the fact that conventional manure storage and field application is avoided when using manure for biogas, and the avoided methane emissions from storage and N2O emissions from field application due to this are very large relative to the produced kWh.

The emission data assumed for this part derives from the latest IPCC consensus report in this (IPCC, 2006), the share between methane and N2O being around 60/40. The same methane and N2O emissions from digestate management are included in the contribution from co-products in the Figure, but these are significantly smaller than from raw manure. The co-product output also included the heat output and the avoided alternative heat production from this. A specific biogas yield of 319 Nm3 of methane per ton of manure VS is assumed, and a 44% and 48% electricity and heat conversion efficiency from the gas in the engine is assumed in 2013, increasing to 48% on electricity in 2050, see Appendix H for further elaboration on the process specific data. As seen for the former pathways on continuous power production, moreover, the benefit of displacing the alternative continuous power production in the Danish energy system is reduced significantly after 2035 and fully lost after 2050.

The pathway on manure-straw co-digestion biogas for continuous power production (Figure 5-11) is modeled on the same manure and other assumptions as the former mono-digestion pathway on manure biogas, but with a mixture of manure and straw of 100 GJ of straw per 32,6 ton of manure, the calorific value of the VS in this manure being 39 GJ implying that two thirds of the inherent feedstock energy lies in the straw and one third in the manure part. A specific biogas yield of 278 Nm3 of methane per ton VS in the straw part is assumed and a yield of 319 Nm3 of methane per ton manure VS as for the mono-digestion. The same assumption for process emissions of 1% of produced biogas as for the mono-digestion. Also in the co-digestion pathway, the GHG emissions from the manure and digestate management are dominating, but to a lesser extent, because the manure part is only one third of the feedstock energy content.

The lost soil sequestration from the use of straw is included in the GHG emission from the biomass in Figure 5-12, but is much smaller than the benefit of avoiding conventional manure management. The benefit from avoiding the alternative continuous power production is much larger in the co-digestion pathway, relative to the other contribution, which again is due to the fact that the manure part only constitutes one third of the energy input in this case. As seen for all former pathways on continuous power production, the benefit of displacing the alternative continuous power production in the Danish energy system is reduced significantly after 2035 and fully lost after 2050.



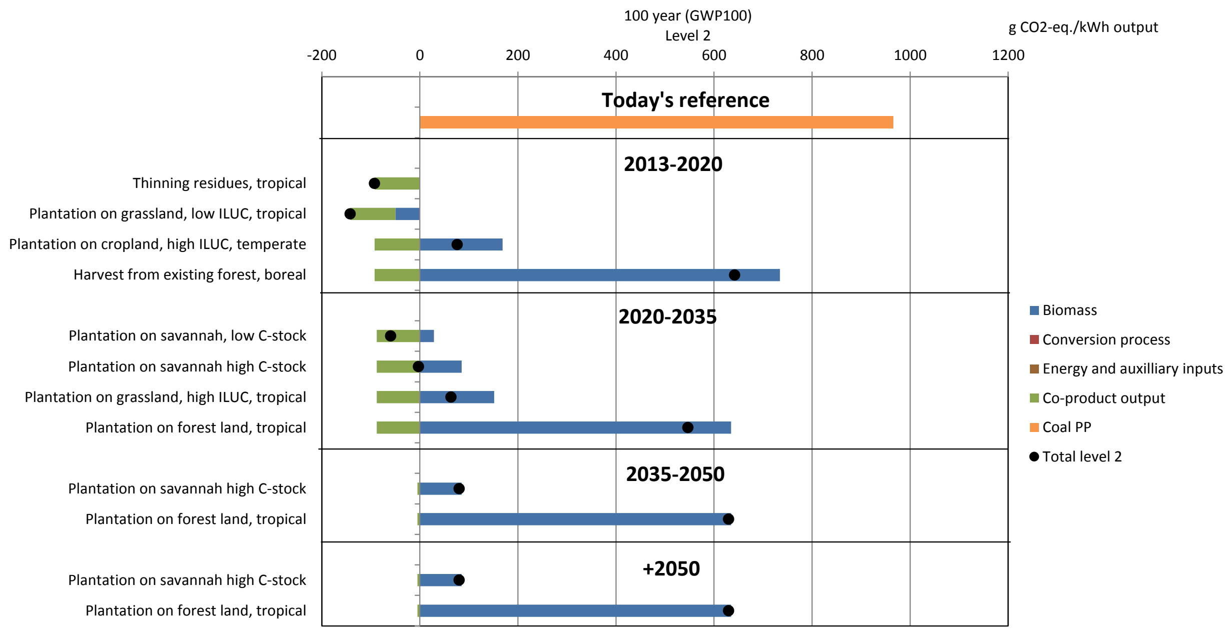
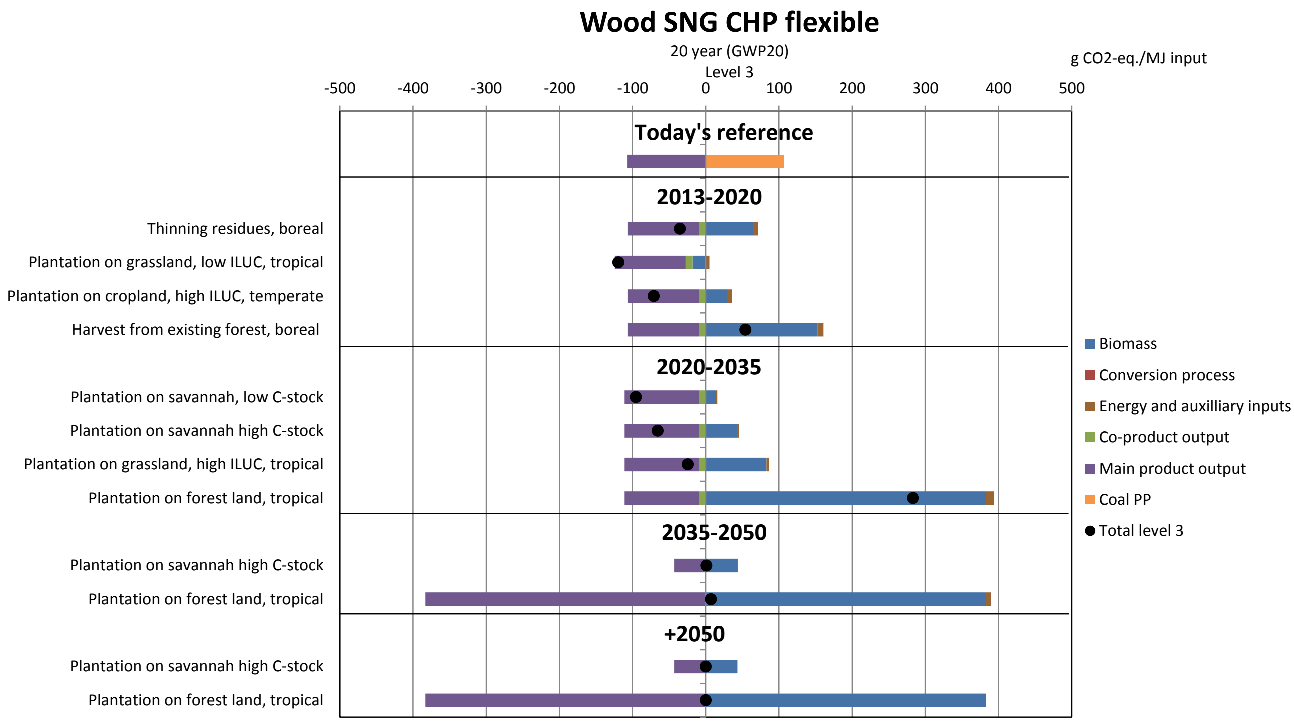


Figure 5-13 The carbon footprint of a wood gasification with syngas hydrogenation to SNG for CHP flexible power production at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



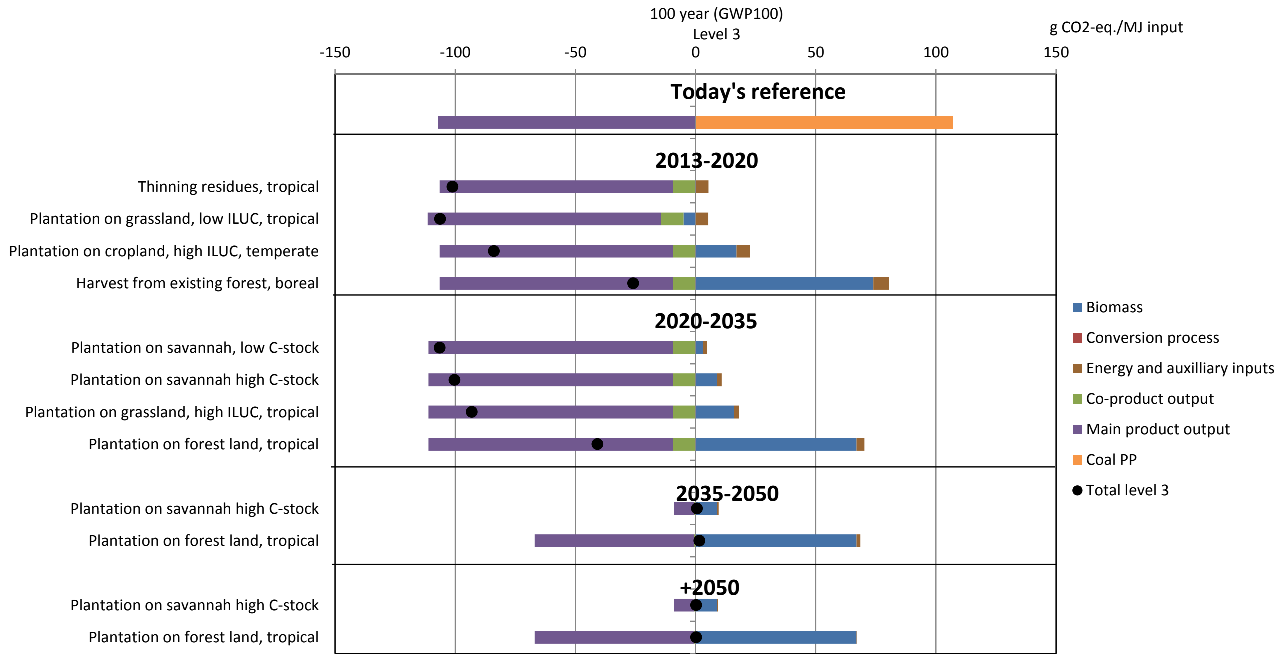
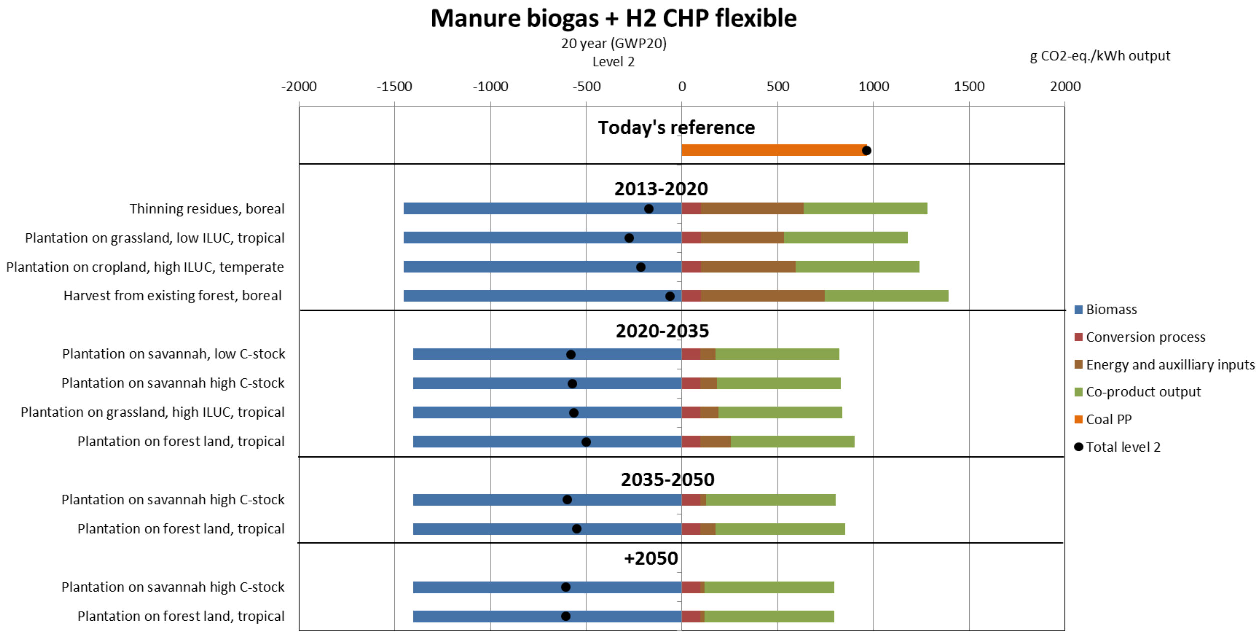


Figure 5-14 The carbon footprint of a wood gasification with syngas hydrogenation to SNG for CHP flexible power production at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



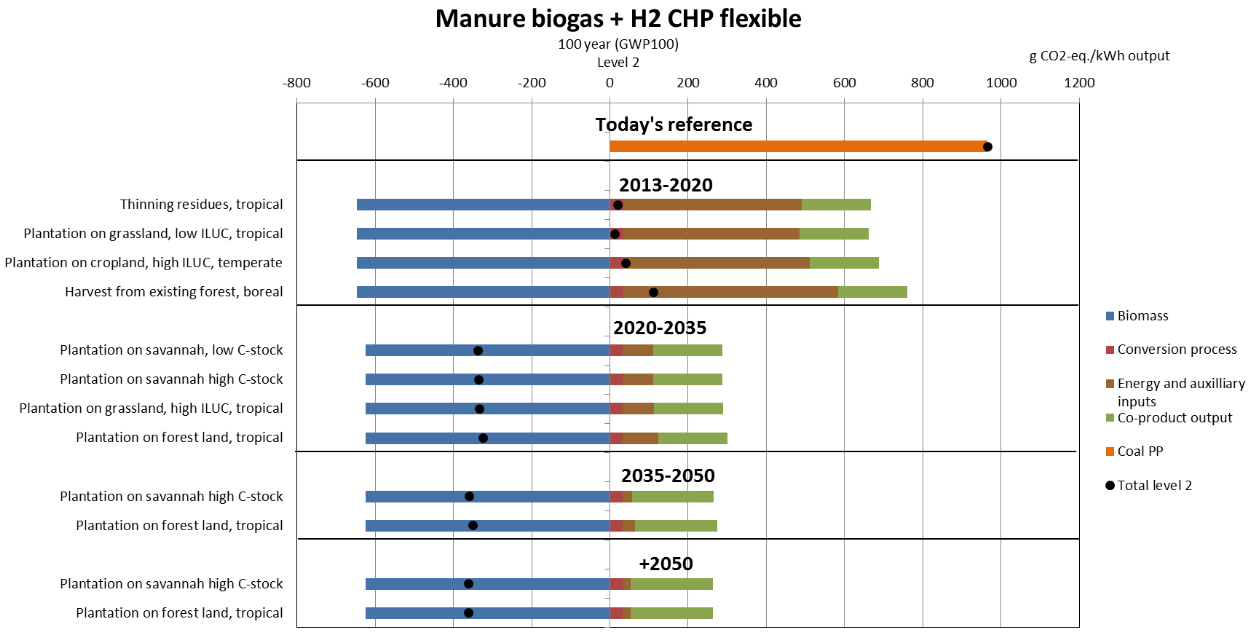
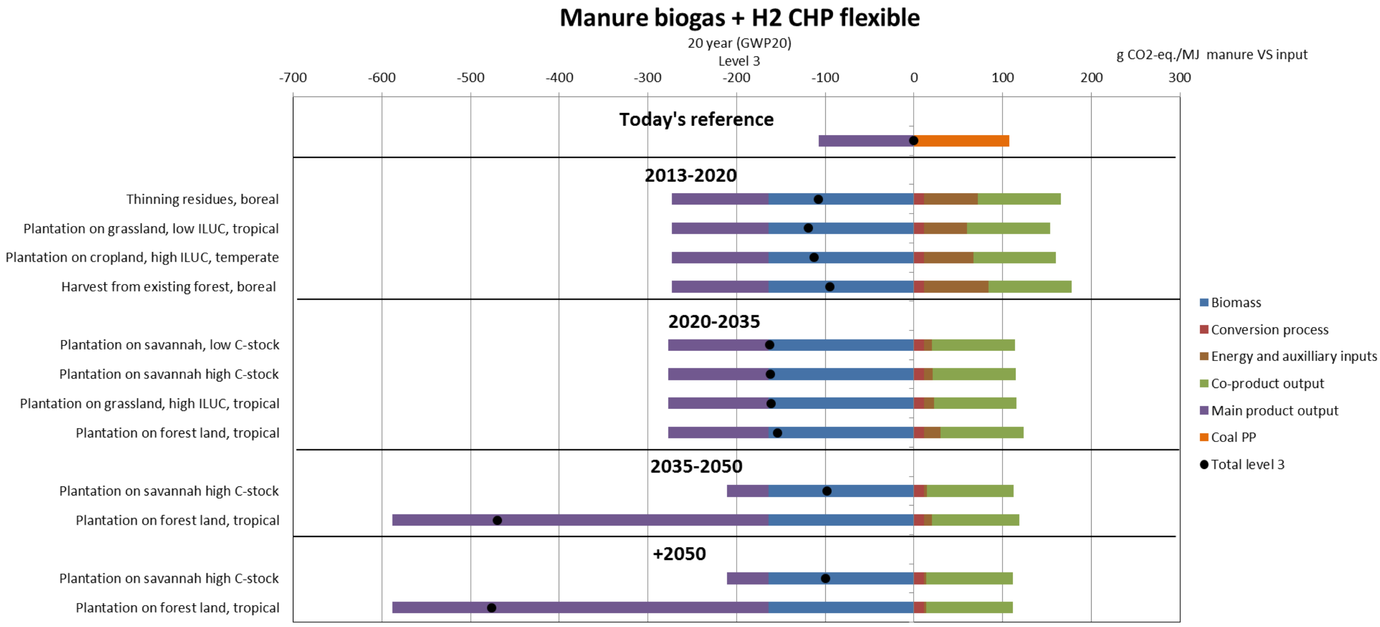


Figure 5-15 The carbon footprint of a manure biogas with hydrogenation to SNG used in CHP flexible power production at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



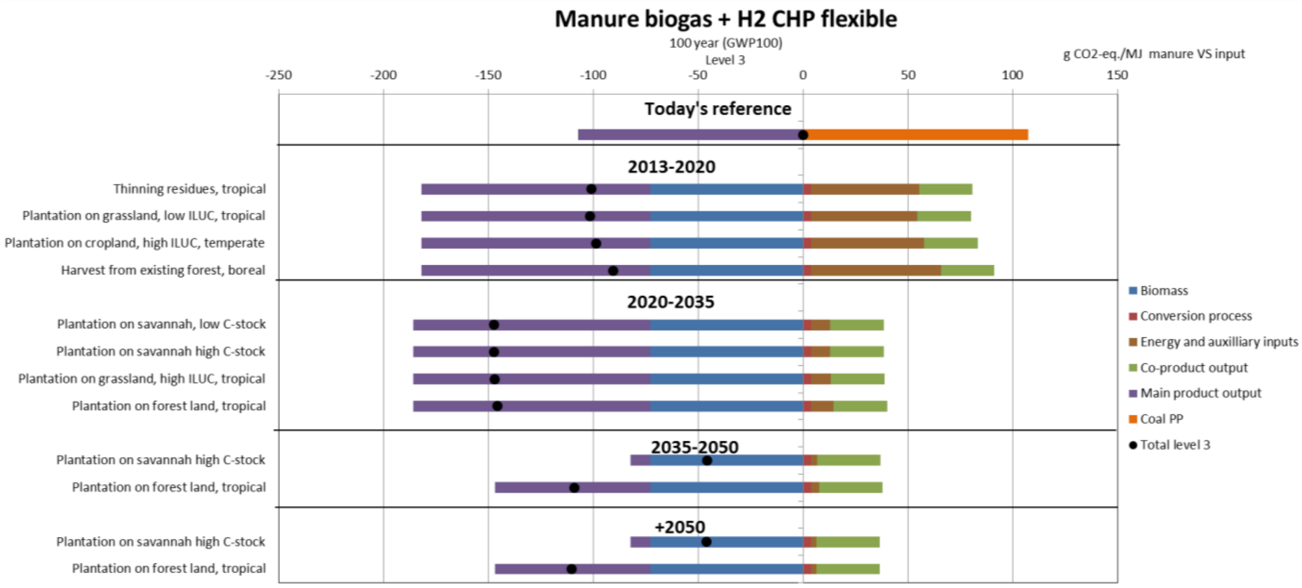
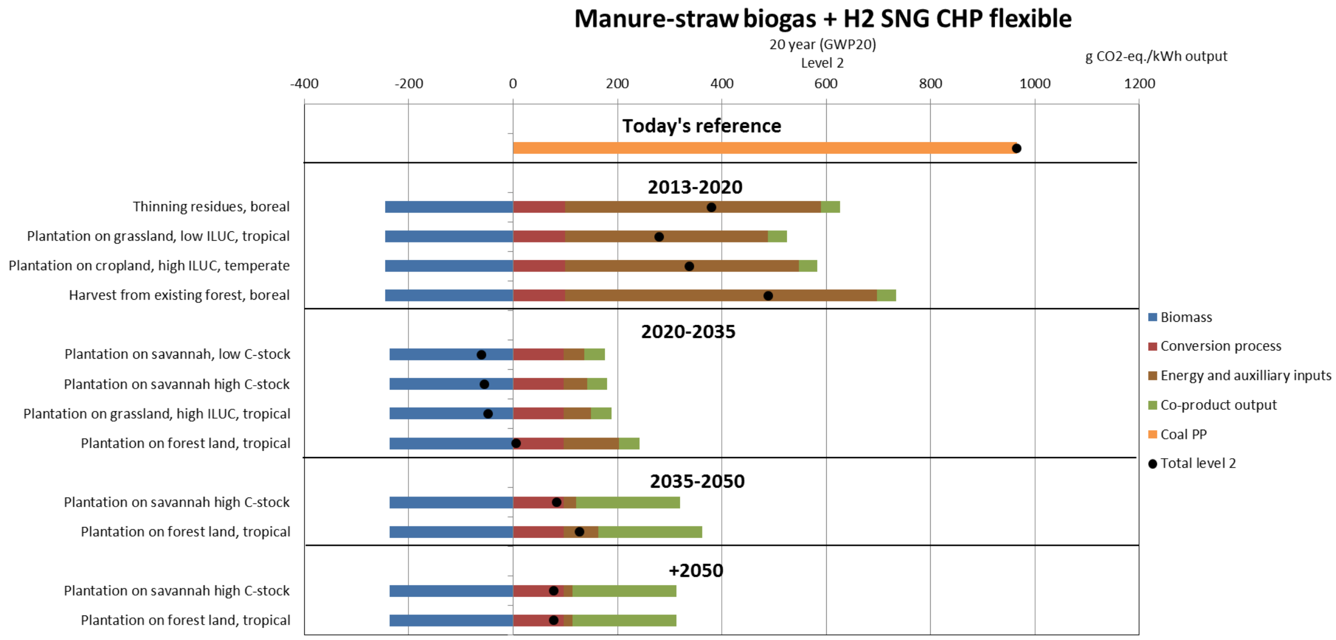


Figure 5-16 *The carbon footprint of a manure biogas with hydrogenation to SNG used in CHP flexible power production at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)*



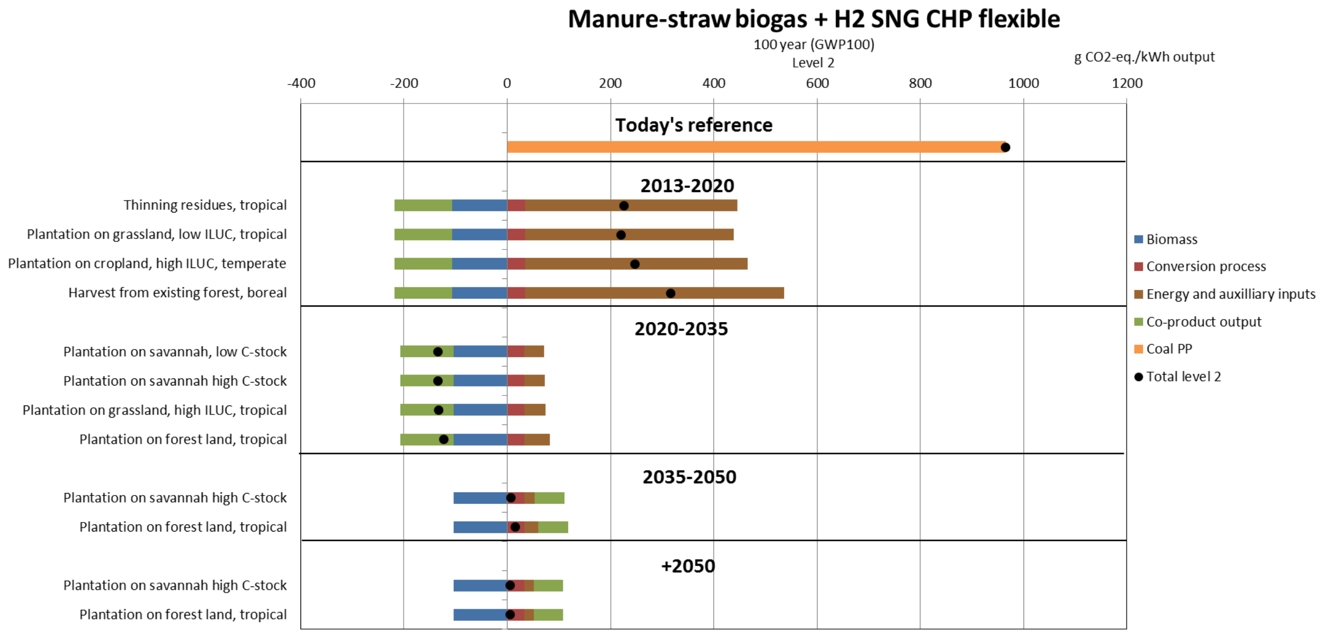
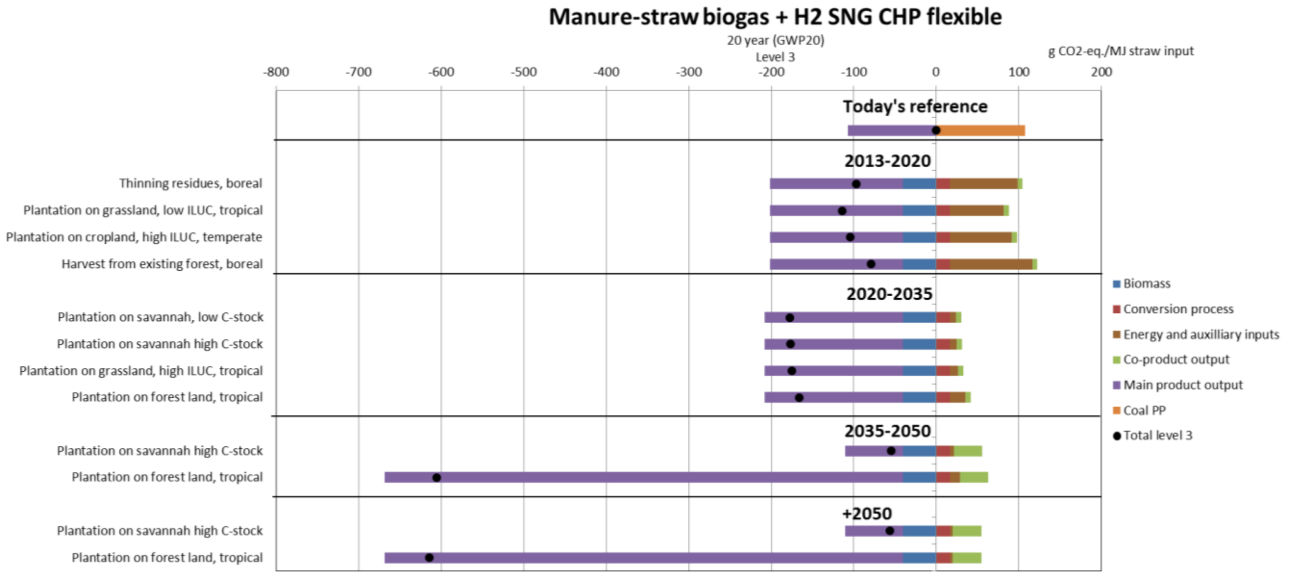


Figure 5-17 The carbon footprint of a manure-straw co-digestion biogas with hydrogenation to SNG used in CHP flexible power production at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



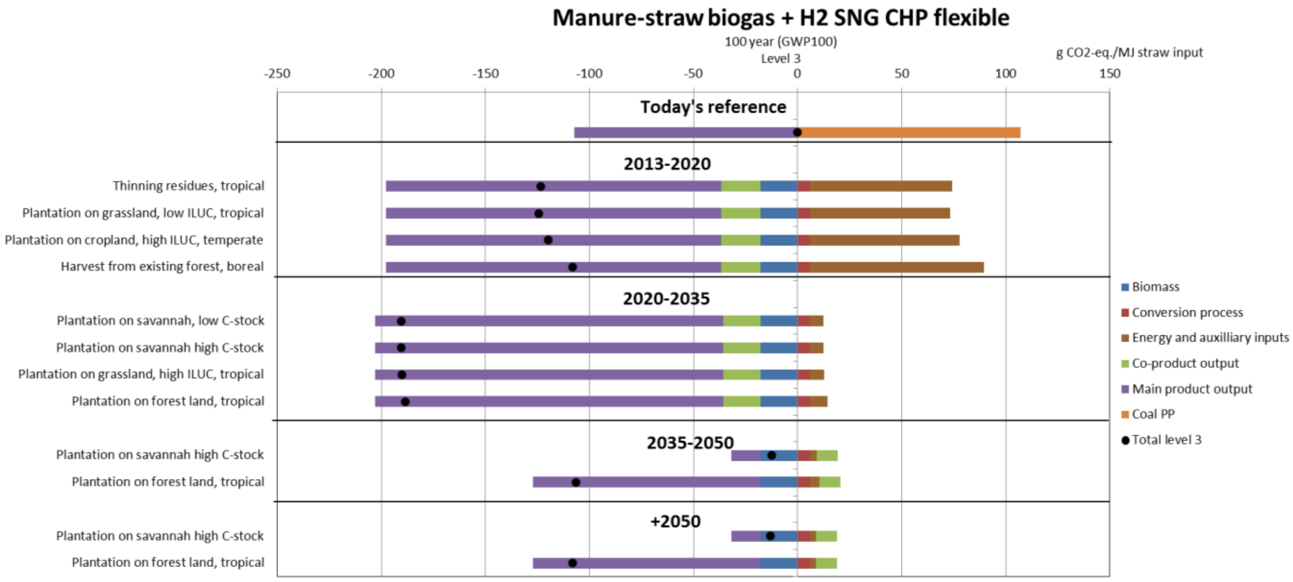


Figure 5-18 *The carbon footprint of a manure-straw co-digestion biogas with hydrogenation to SNG used in CHP flexible power production at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)*

The wood gasification (Figure 5-13) has been assumed to convert the wood to syngas with a 70% energy efficiency, where after the syngas is upgraded to SNG through hydrogenation, see appendix H for details. The SNG is assumed stored on the natural gas grid and used for flexible power production in a solid oxide fuel cell with an electricity efficiency of 53% increasing to 55% in 2050. Heat recovery for district heating is assumed to be 12% of biomass feedstock energy throughout the period.

Emissions from the biomass supply can be very dominating if implying a problematic biomass marginal, especially in the 20 year time horizon, and equal to or above emissions from coal PP. However, assuming plantation on savannah to be a probably marginal in the later time periods, where this pathway has its main potential, implies a large reduction in GHG emission compared to coal PP.

As Figure 5-14 illustrates, the benefit of avoiding the marginal Danish flexible power production is very large in the first two time periods, in which the energy system flexible power marginal is assumed to be coal PP (coal condensing mode power production). After 2035, the marginal flexible power production is set to be this very pathway, so in these time periods, the avoided alternative is the pathway itself, why the net GHG emission at level 3 is zero.

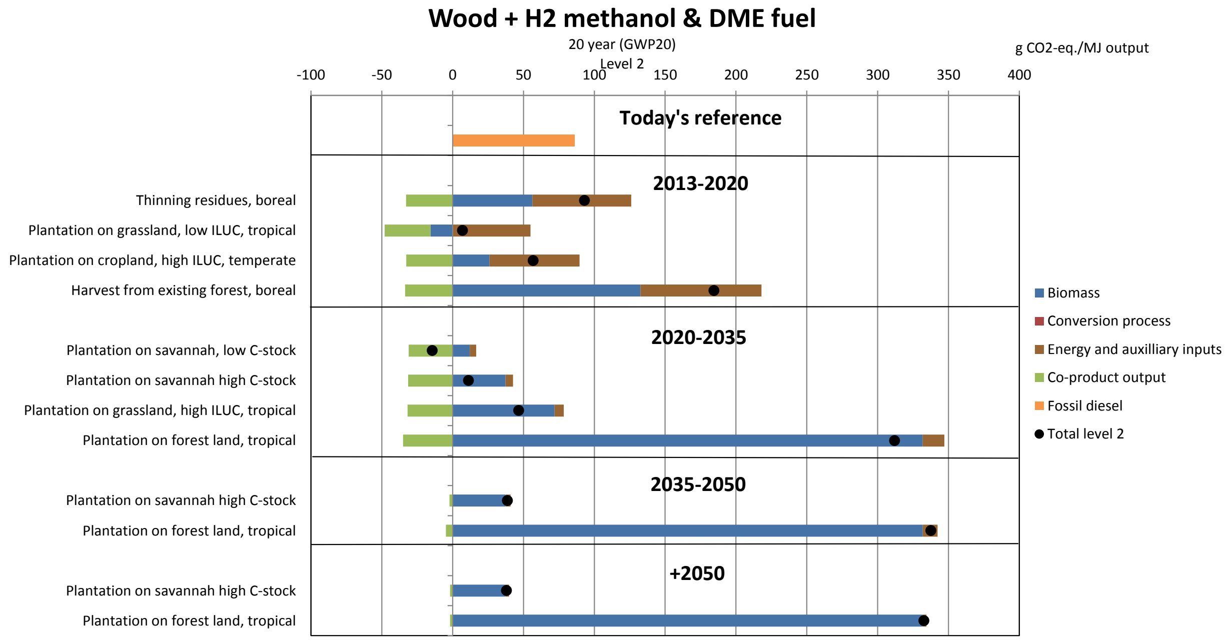
The pathway on manure biogas upgraded with hydrogen to SNG used in CHP flexible power production (Figure 5-15) is modeled on the same data basis as the manure biogas CHP for continuous power production on all the manure and biogas related aspects. The difference is that the biogas in this pathway is hydrogenated by hydrogen produced through electrolysis, and the electrolysis is assumed to run on flexible power consumption, which in the first time period is assumed to be average electricity and in the last time periods assumed to be wind power, cf. Table 3-3 on the identified energy system marginal. The SNG is assumed stored on the natural gas grid and used for flexible power production via a solid oxide fuel cell, SOFC. Avoided emissions from conventional manure management and emissions from digestate management are also dominating in this flexible power production case, as they were for continuous power production. The large emissions from energy input in 2013-2020 derives mainly from the flexible electricity consumption of the electrolyzer – but the technology as such is mostly interesting for later time periods, and for these, the flexible power consumption has a much smaller impact, as it derives, mainly from wind power, as the Figure shows.

The co-product output also includes the heat output and the avoided alternative heat production from this, see Appendix H for further elaboration on the process specific data. As Figure 5-16 illustrates, the benefit of avoiding the marginal Danish flexible power production is very large in the first two time periods, in which the energy system flexible power marginal is assumed to be coal PP (coal condensing mode power production). After 2035, the marginal flexible power production is the wood syngas based pathway shown in Figure 5-13 and Figure 5-14, and avoiding this alternative can be quite a large benefit in 2035 and beyond, if plantation on forest land becomes part of the biomass marginal.

The pathway on manure-straw co-digestion biogas upgraded with hydrogen to SNG used in CHP flexible power production (Figure 5-17) is modeled the same way as the manure biogas upgraded with hydrogen to SNG used in CHP flexible power. The only difference is that straw is added to the manure for a co-digestion, with a mixture of manure and straw of 100 GJ of straw per 32,6 ton of manure, the calorific value of the VS in this manure being 39 GJ implying that two thirds of the inherent feedstock energy lies in the straw and one third in the manure part. The electrolysis is assumed to run on flexible power consumption, which in the first time period is assumed to be average electricity and in the last time periods assumed to be wind power, cf. Table 3-3 on the identified energy system marginal.

The SNG is assumed stored on the natural gas grid and used for flexible power production via a solid oxide fuel cell, SOFC. Avoided emissions from conventional manure management and emissions from digestate management are also dominating in this flexible power production case, as they were for continuous power production. The large emissions from energy input in 2013-2020 derives mainly from the flexible electricity consumption of the electrolyzer – but the technology as such is mostly interesting for later time periods, and for these, the flexible power consumption has a much smaller impact, as it derives, mainly from wind power, as the Figure shows.

The co-product output also includes the heat output and the avoided alternative heat production, see Appendix H for further elaboration on the process specific data. As Figure 5-18 illustrates, the benefit of avoiding the marginal Danish flexible power production is very large in the first two time periods, in which the energy system flexible power marginal is assumed to be coal PP (coal condensing mode power production). After 2035, the marginal flexible power production is the wood syngas based pathway shown in Figure 5-13and Figure 5-14, and avoiding this alternative can be quite a large benefit in 2035 and beyond, if plantation on forest land becomes part of the biomass marginal.



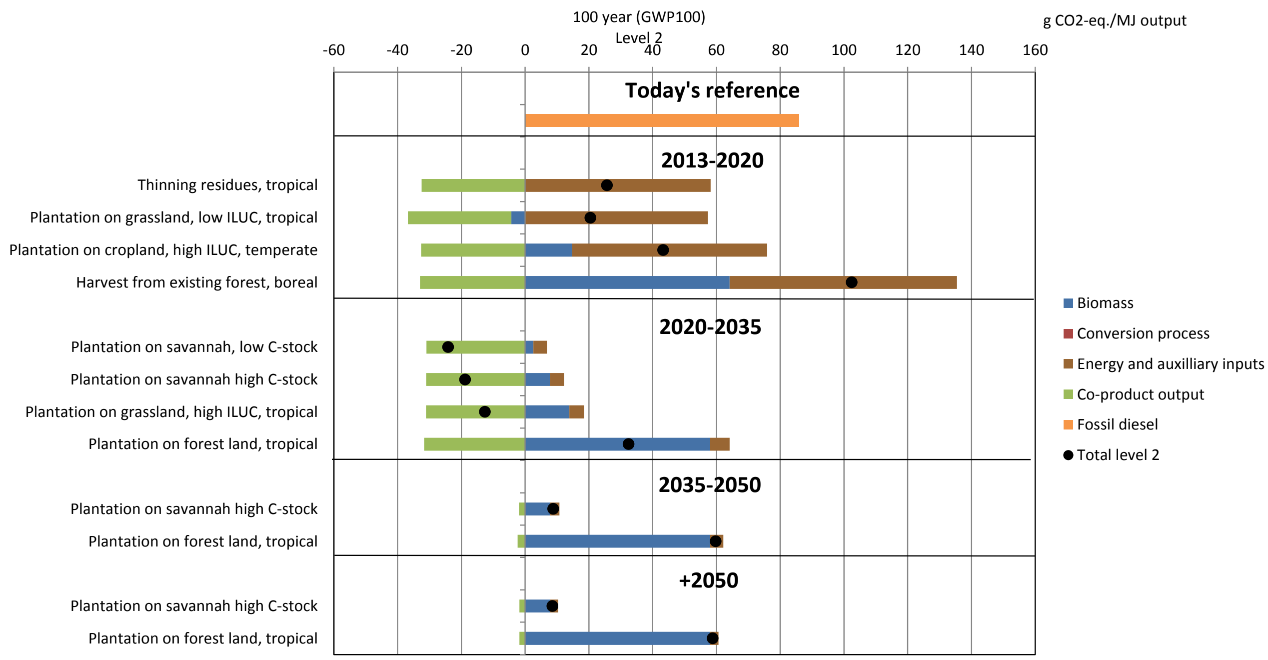
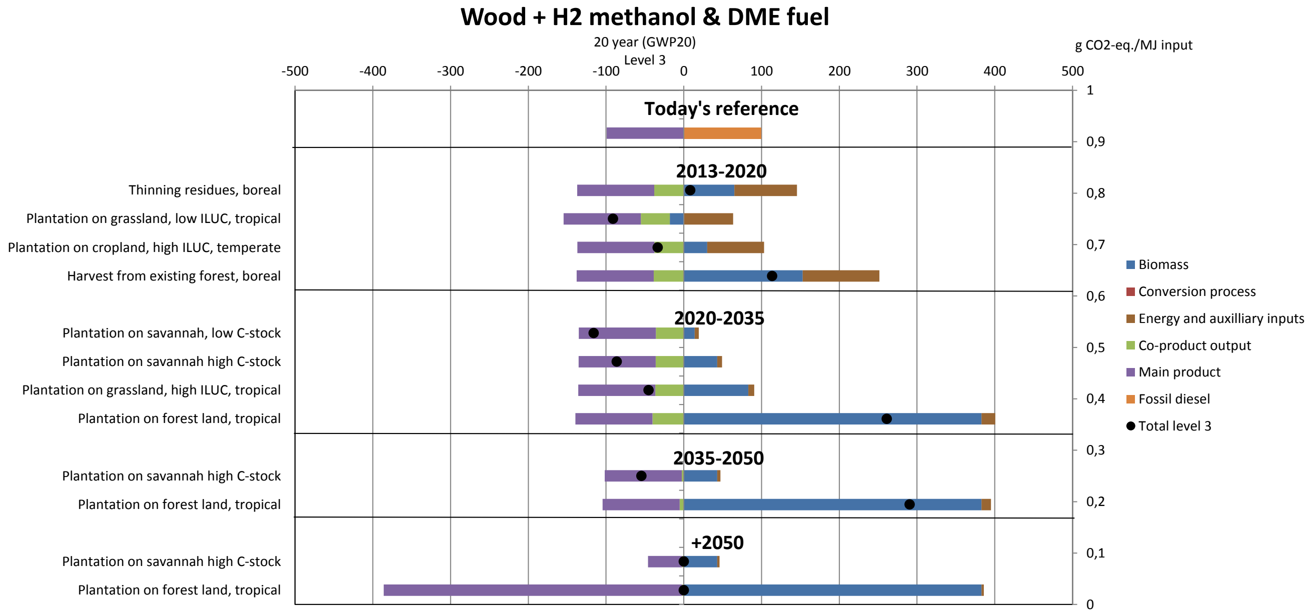


Figure 5-19 The carbon footprint of a wood gasification with syngas hydrogenation to methanol or DME for transport fuel at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



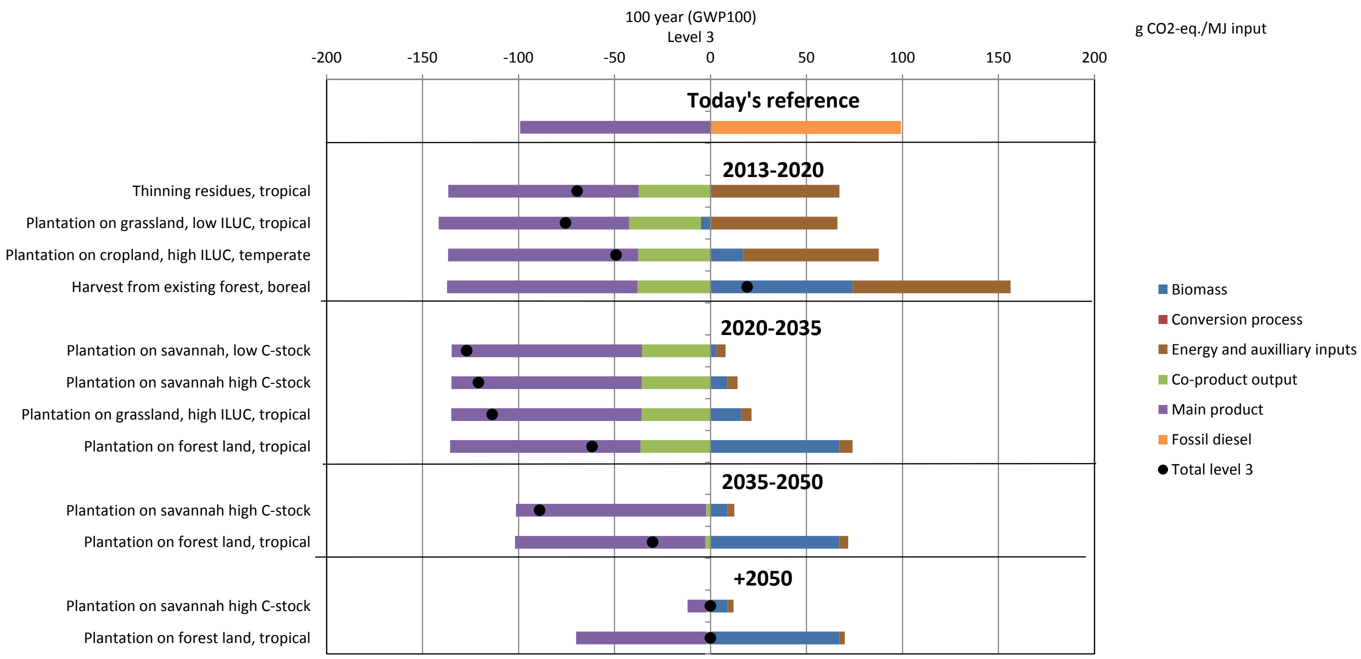
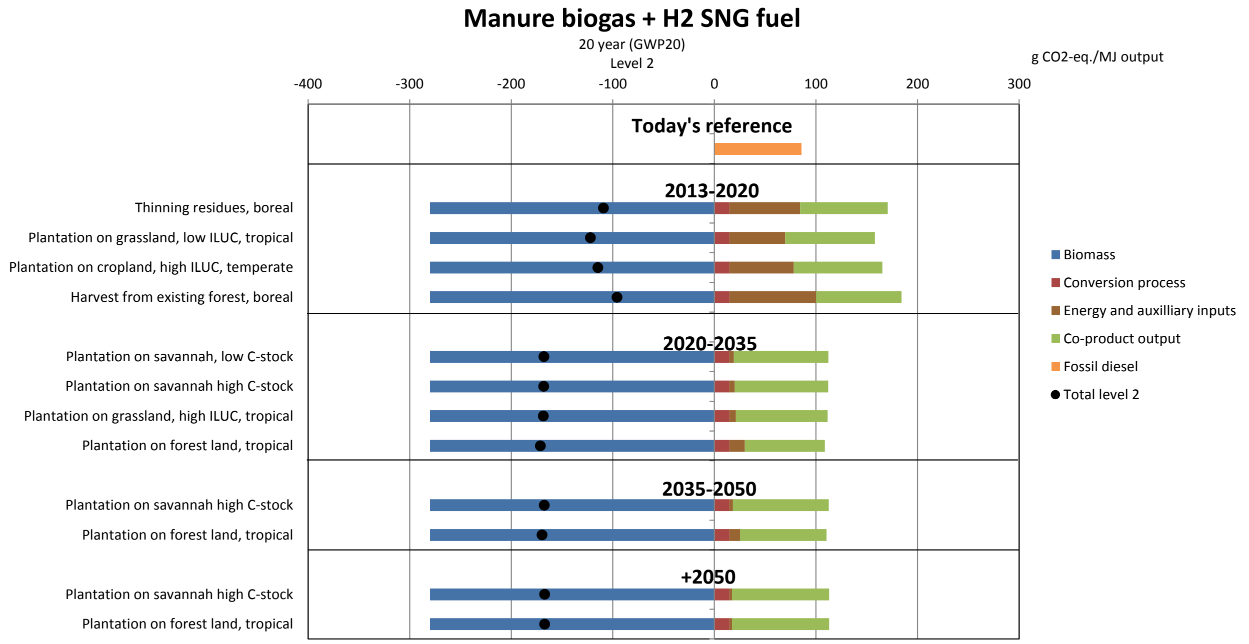


Figure 5-20 The carbon footprint of a wood gasification with syngas hydrogenation to methanol or DME for transport fuel at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



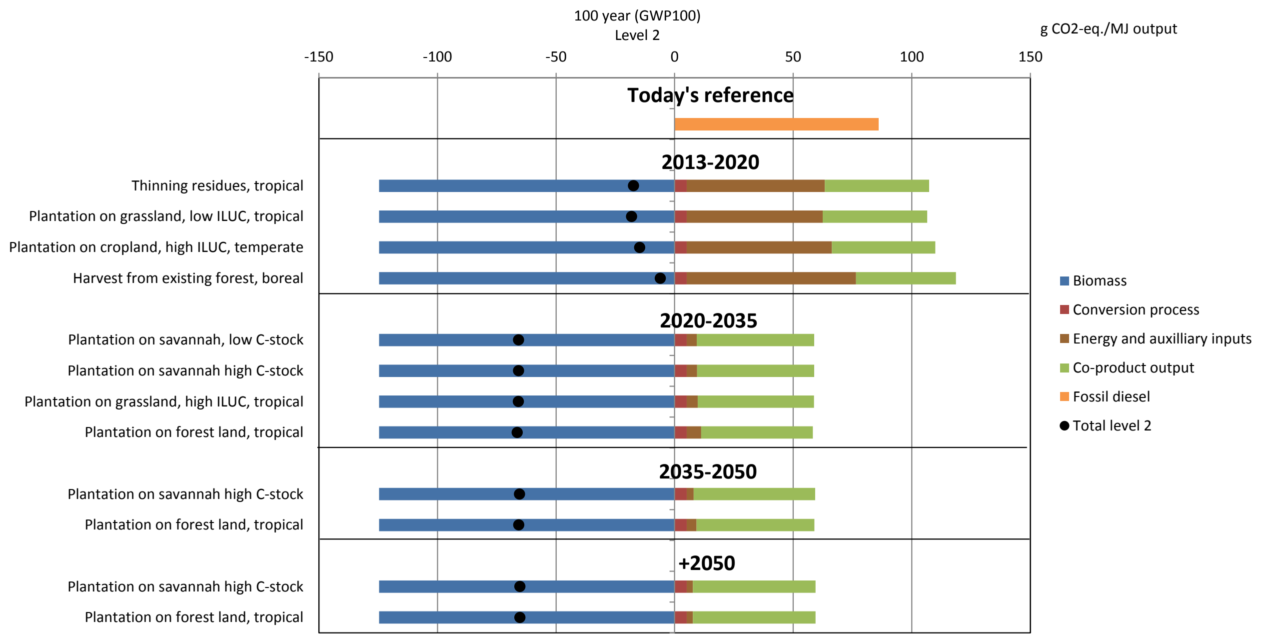
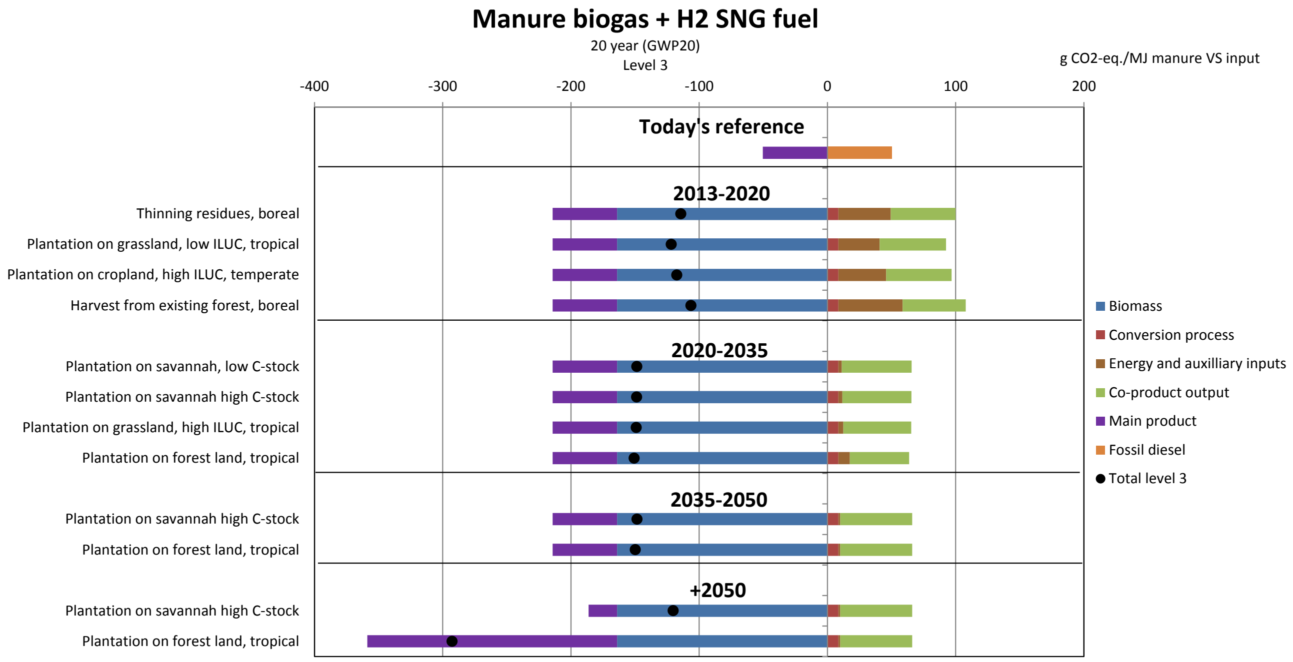


Figure 5-21 The carbon footprint of manure biogas upgraded by hydrogenation to SNG fuel at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



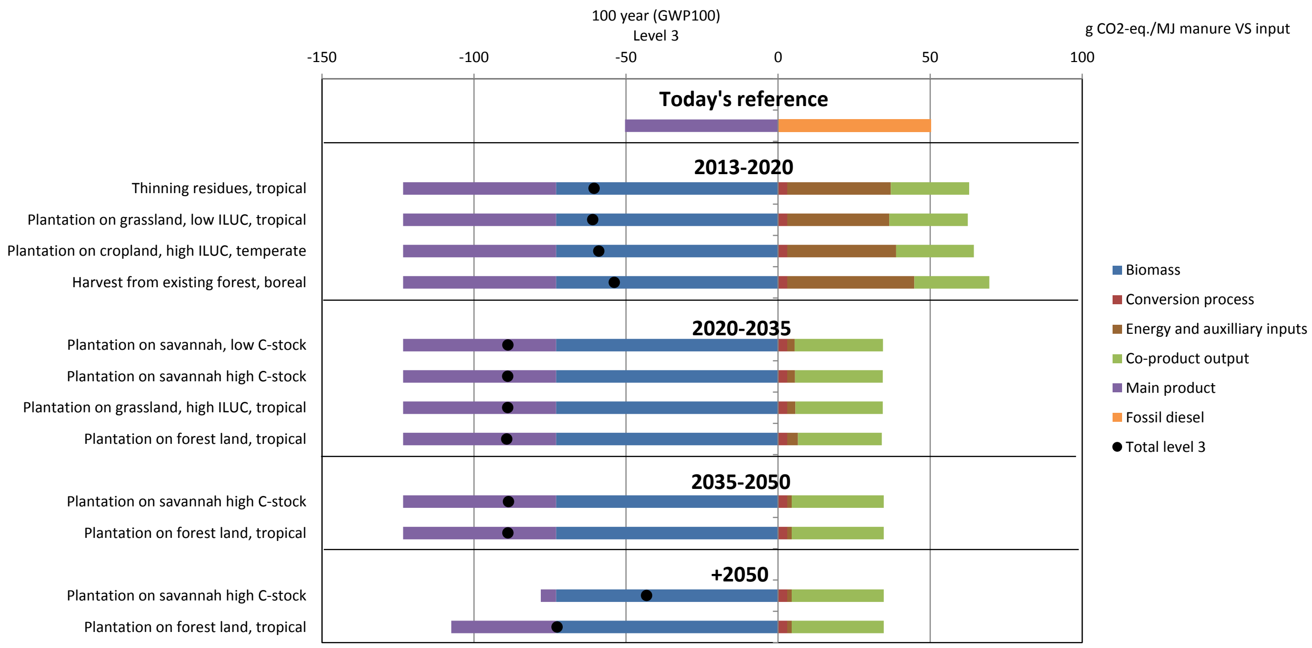
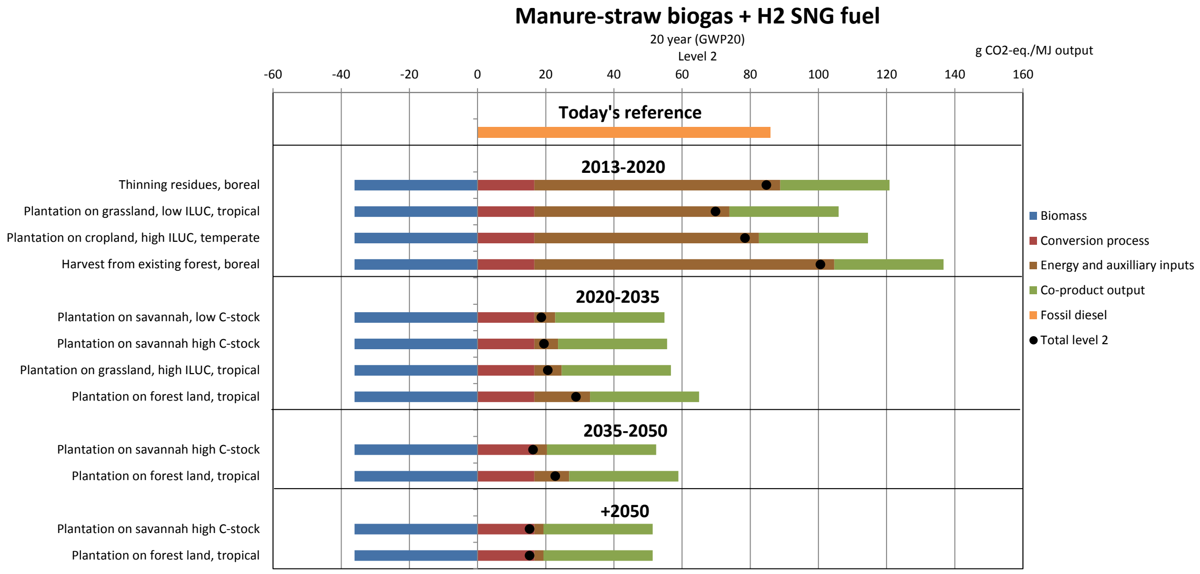


Figure 5-22 The carbon footprint of manure biogas upgraded by hydrogenation to SNG fuel at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



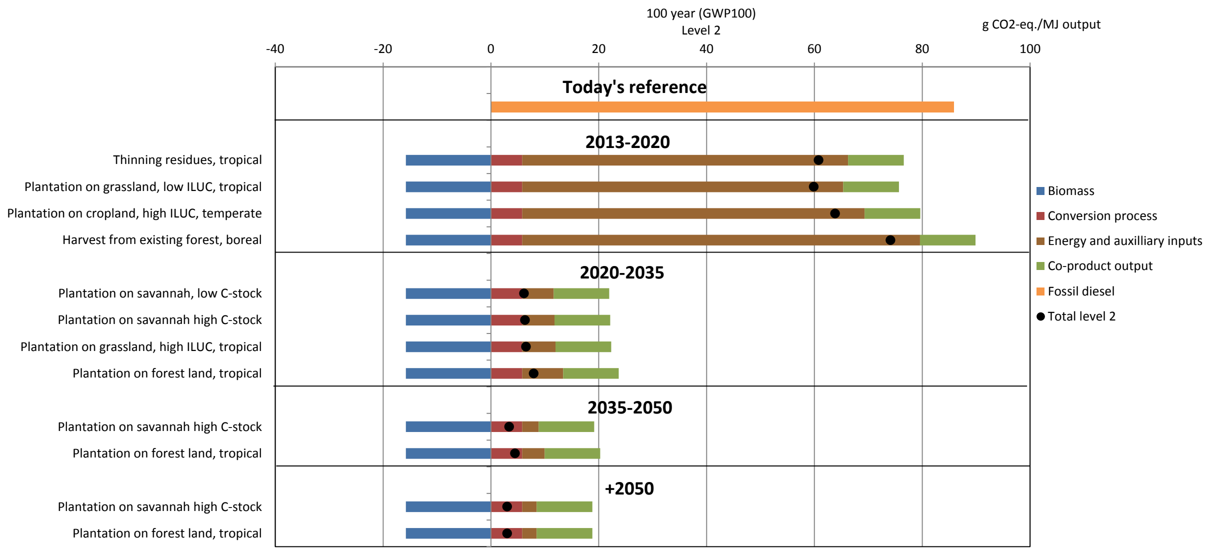
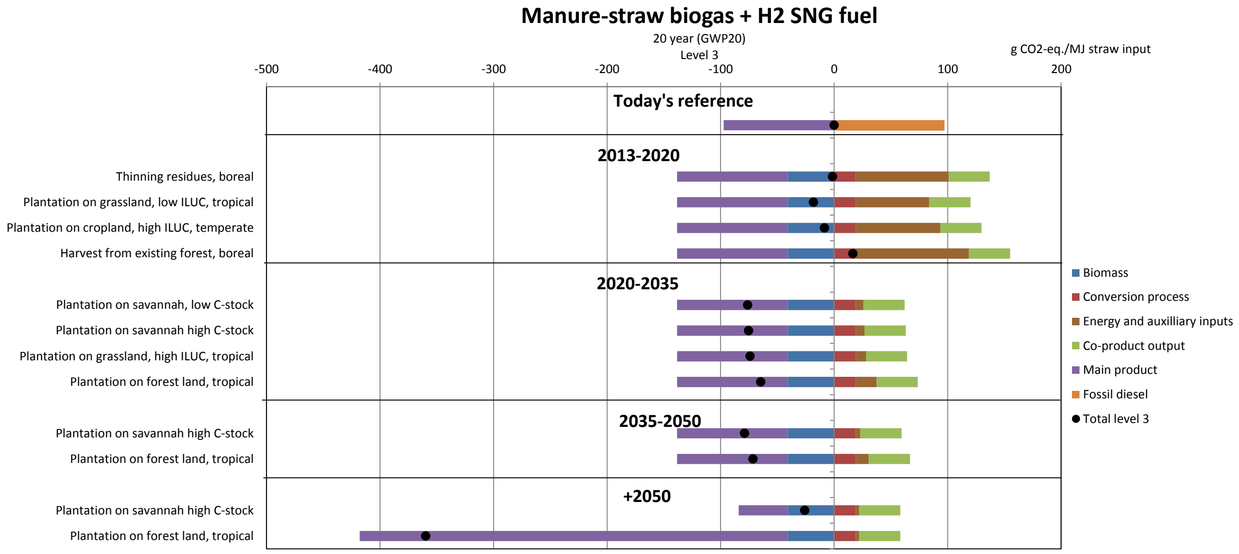


Figure 5-23 The carbon footprint of manure-straw co-digestion biogas upgraded by hydrogenation to SNG fuel at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph). The unit is g CO2-eq./MJ fuel output, not per kWh as stated in the Figure itself



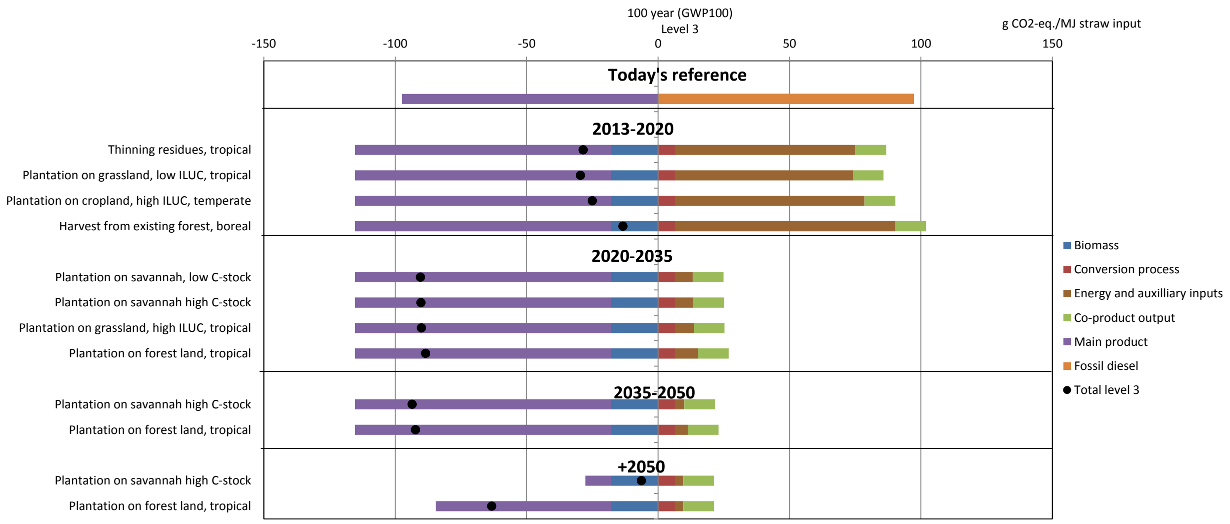


Figure 5-24 The carbon footprint of manure-straw co-digestion biogas upgraded by hydrogenation to SNG fuel at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)

This pathway (Figure 5-19) assumes a wood gasification to syngas and further reaction to methanol or DME by hydrogenation, see the assumed process data in Appendix H. As we have understood the references on this pathway, the production of methanol and DME from the syngas gives rise to the same basic conversion efficiency data per MJ of fuel output. Therefore, we have used this pathway foir both methanol and DEM. The electrolysis is assumed to run on flexible power consumption, which in the first time period is assumed to be average electricity and in the last time periods assumed to be wind power, cf. Table 3-3 on the identified energy system marginal. The large emissions from energy input in 2013-2020 derives mainly from the flexible electricity consumption of the electrolyzer – but the technology as such is mostly interesting for later time periods, and for these, the flexible power consumption has a much smaller impact, as it derives mainly from wind power, as the Figure shows.

Emissions from the biomass supply can be very dominating if implying a problematic biomass marginal, especially in the 20 year time horizon, and equal to or above emissions from the reference transport fuel, which is fossil diesel. However, assuming plantation on savannah to be a probably marginal in the later time periods, where this pathway has its main potential, implies a large reduction in GHG emission compared to fossil diesel. The fuel is assumed used for long range transport and to be the long range transport fuel marginal in 2050 and beyond. In the time three periods of 2013 – 2050, fossil diesel is assumed to be the marginal.

As Figure 5-20 illustrates, the benefit of avoiding the marginal long range transport fuel is very large in the first three time periods, in which the marginal is fossil diesel. After 2050, the marginal long range transport fuel is set to be this very pathway, so in these time periods, the avoided alternative is the pathway itself, why the net GHG emission at level 3 is zero.

The pathway (Figure 5-21) on manure biogas upgraded by hydrogenation to SNG fuel is modeled as described previously for the manure biogas upgraded for flexible CHP to and including storing the NG on the gas grid. The only difference here is that the SNG is then subsequently used for long range transport.

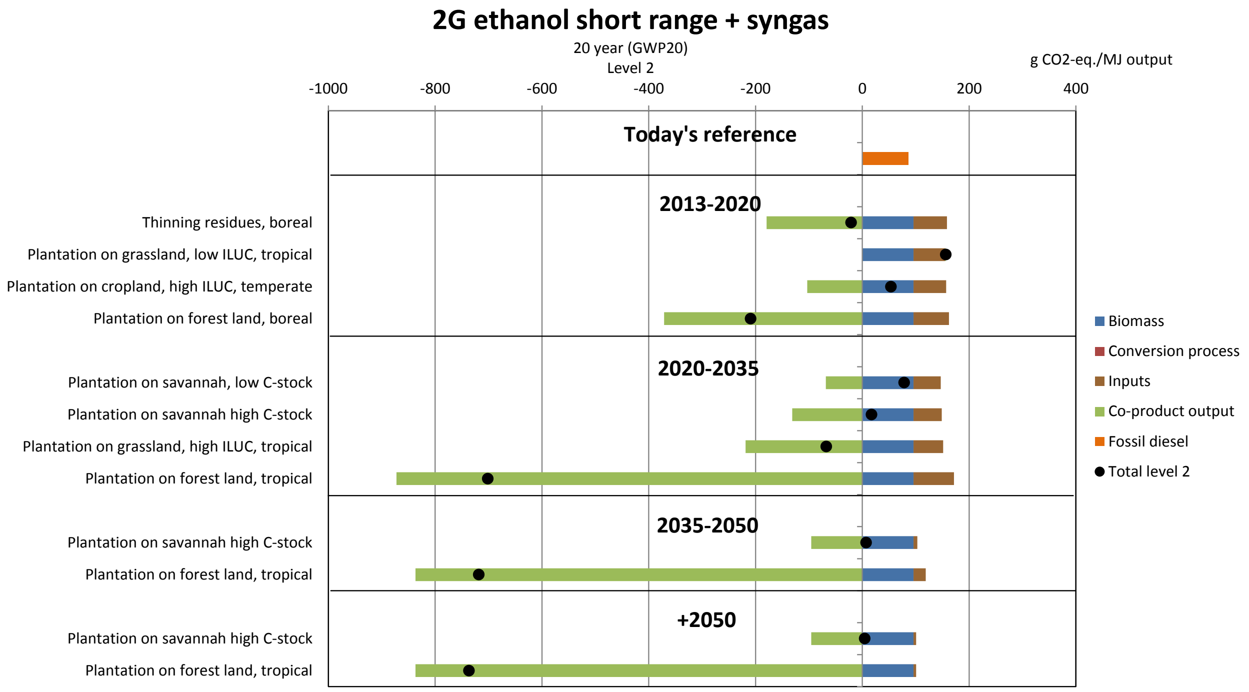
The GHG emissions from the manure and digestate management are, like before, totally dominating the picture. There is very little dependency on the biomass marginal, as it only enters into the continuous electricity consumption of the biogas plant itself. The large contributor to emissions from energy inputs in the first time period is the flexible electricity consumption of the electrolyzer, but in the later time periods, this becomes insignificant as the marginal for flexible consumption becomes wind power.

In the first three time periods (Figure 5-22) there is a large GHG reduction related to displacing the fossil diesel marginal, but also in the period after 2050, when the wood based methanol or DME is the marginal, there can be a large benefit of displacing this fuel by a biogas based SNG, if the biomass marginal turns out to involve plantation on forest land.

The pathway on manure-straw co-digestion biogas upgraded by hydrogenation to SNG fuel is modeled as described for the previous pathway and for the manure-straw biogas pathways for power production. The ratio between manure and straw is the same.

The GHG emissions from the manure and digestate management do not dominate the picture as much as for mono-digestion, because the straw constitutes the larger part of the feedstock energy input. There is very little dependency on the biomass marginal, as it only enters into the continuous electricity consumption of the biogas plant itself. The large contributor to emissions from energy inputs in the first time period is the flexible electricity consumption of the electrolyzer, but in the later time periods, this becomes insignificant as the marginal for flexible consumption becomes wind power.

In the first three time periods (Figure 5-24), there is a large GHG reduction related to displacing the fossil diesel marginal, but also in the period after 2050, when the wood based methanol or DME is the marginal, there can be a large benefit of displacing this fuel by a biogas based SNG, if the biomass marginal turns out to involve plantation on forest land.



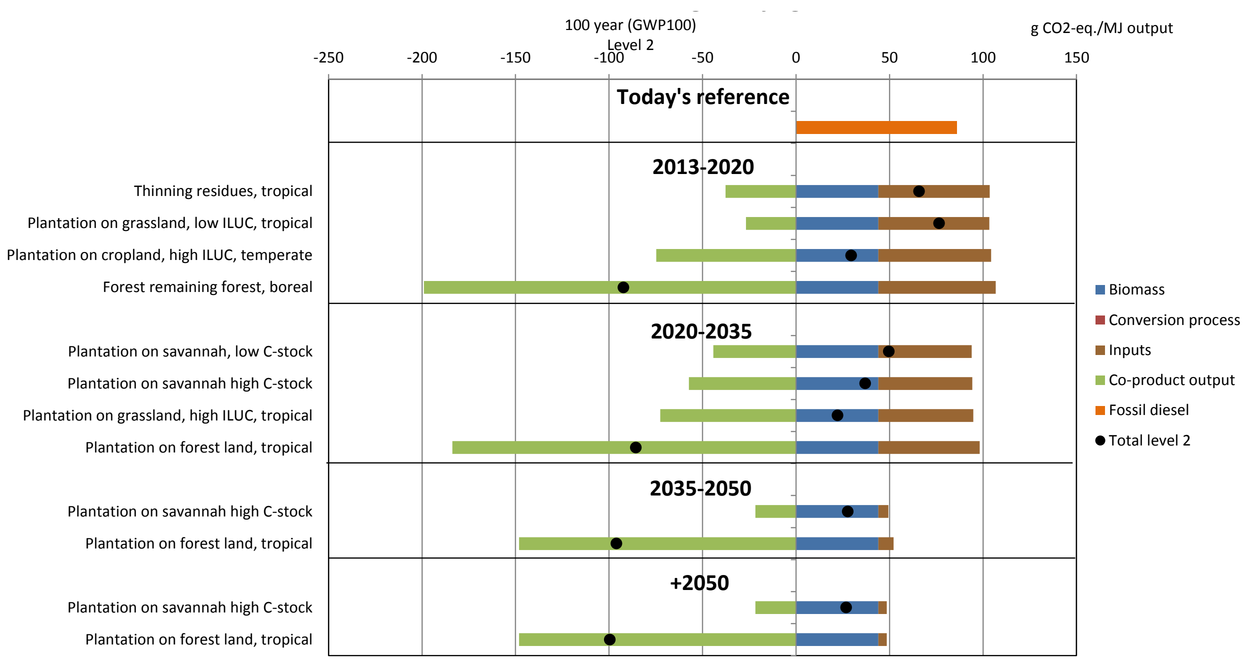
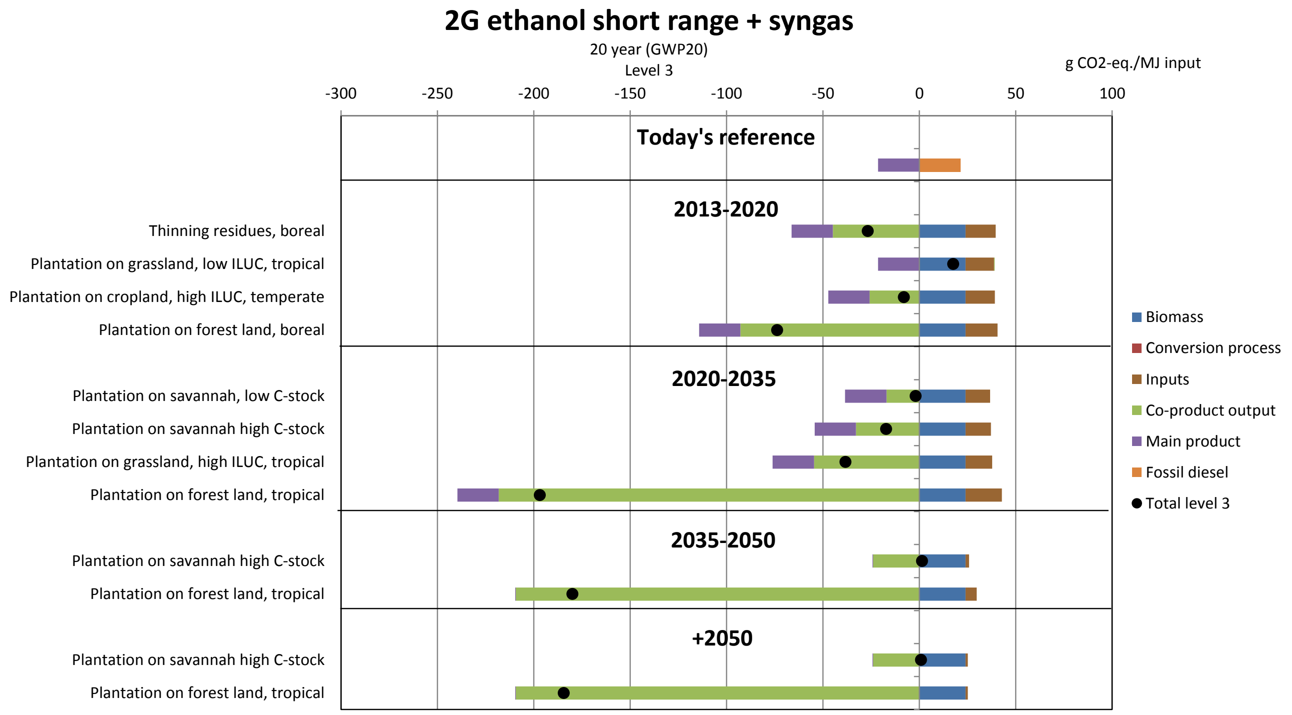


Figure 5-25 The carbon footprint of 2nd generation ethanol used in short range transport and co-products of lignin and molasses used as feedstock for thermal co-gasification with wood at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



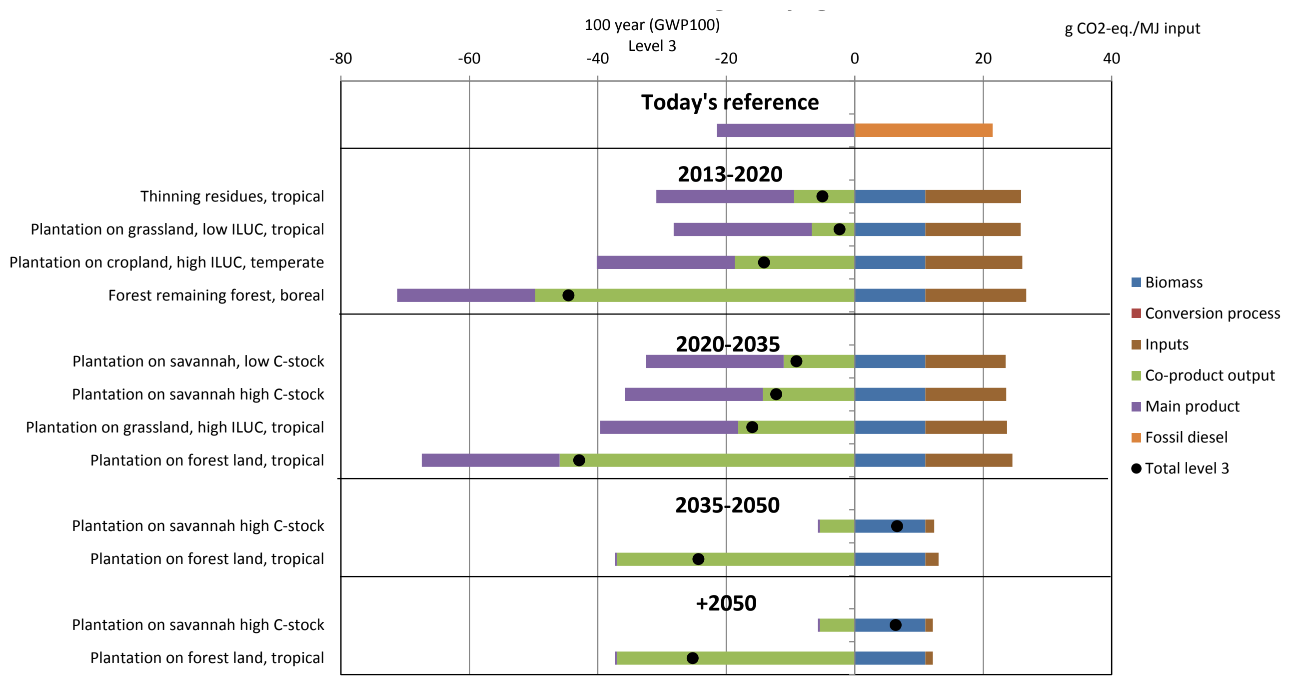
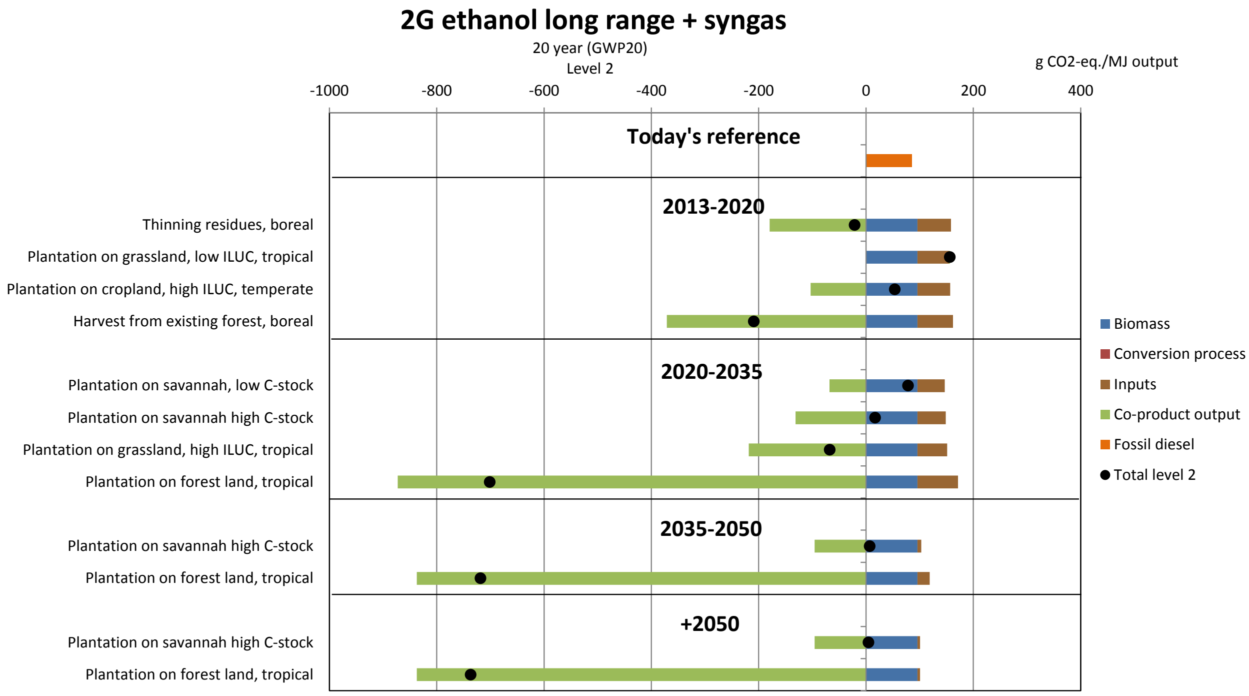


Figure 5-26 *The carbon footprint of 2nd generation ethanol used in short range transport and co-products of lignin and molasses used as feedstock for thermal co-gasification with wood at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)*



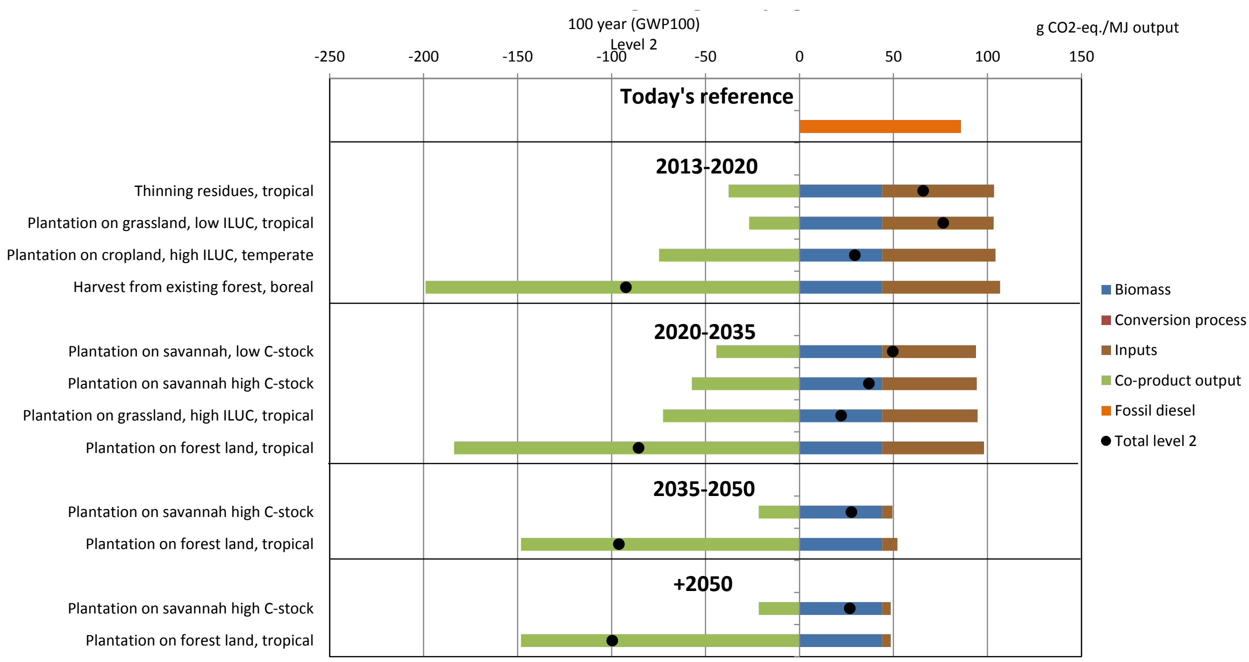
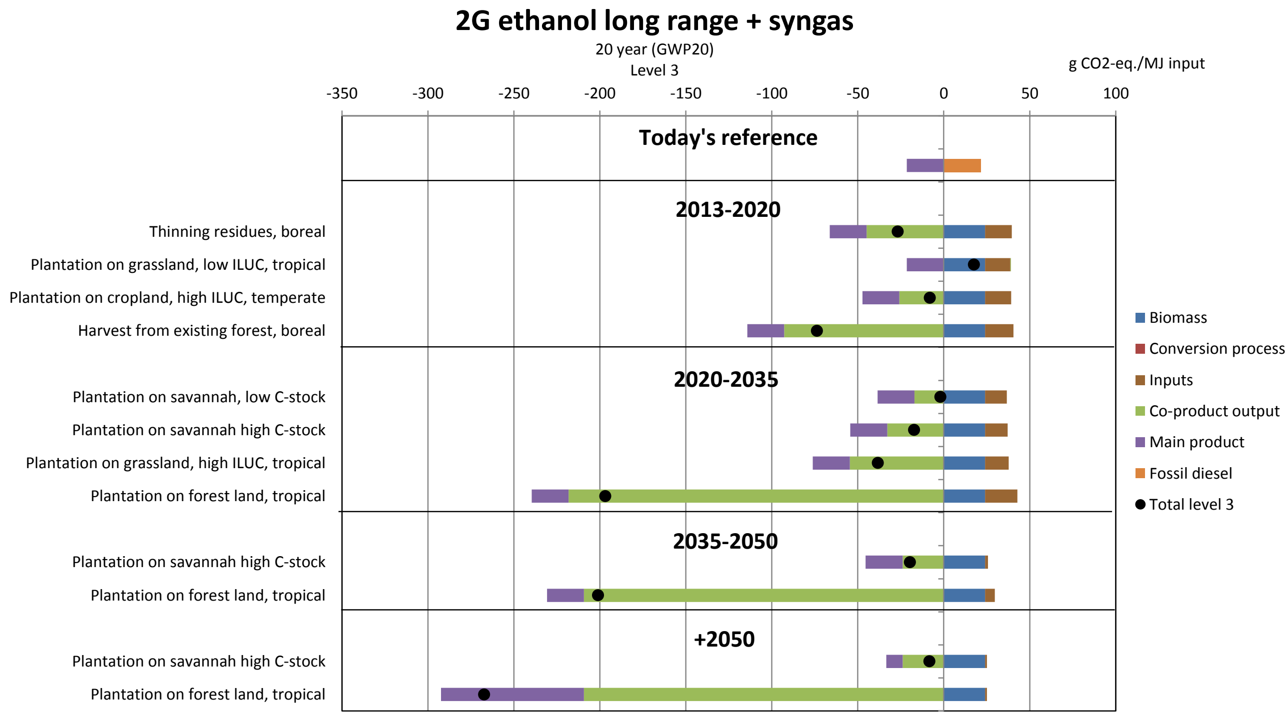


Figure 5-27 *The carbon footprint of 2nd generation ethanol used in long range transport and co-products of lignin and molasses used as feedstock for thermal co-gasification with wood at Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)*



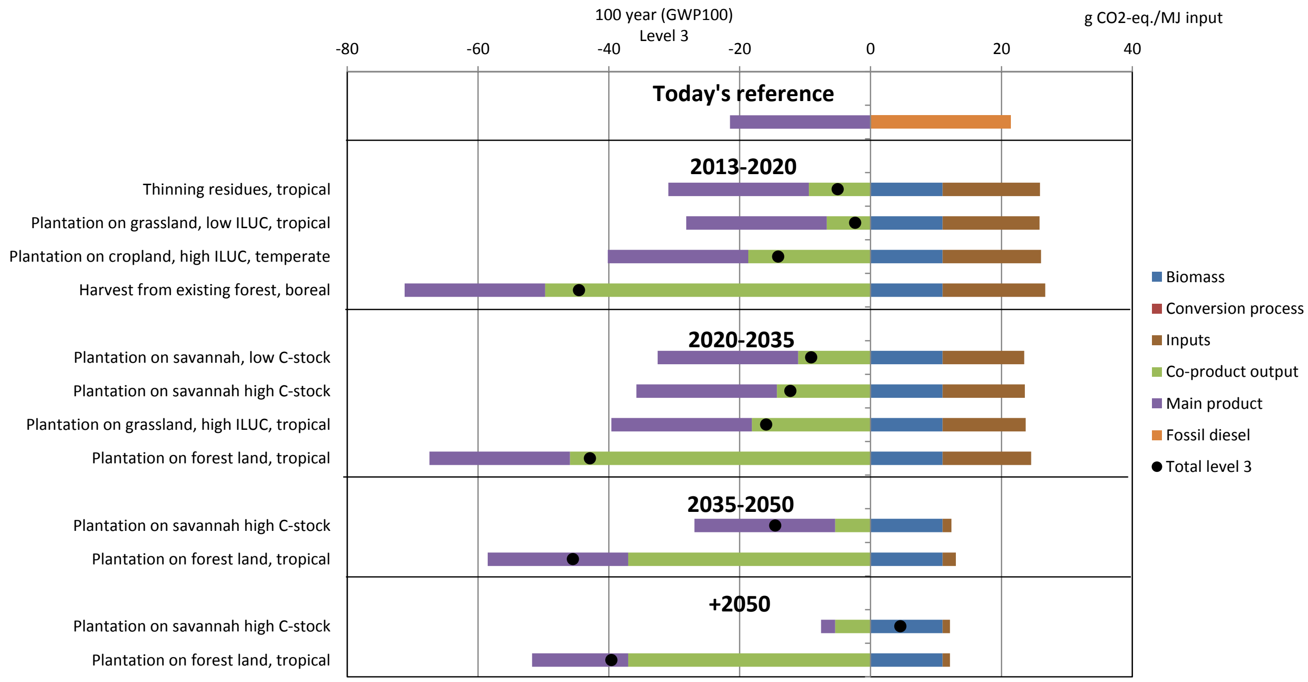
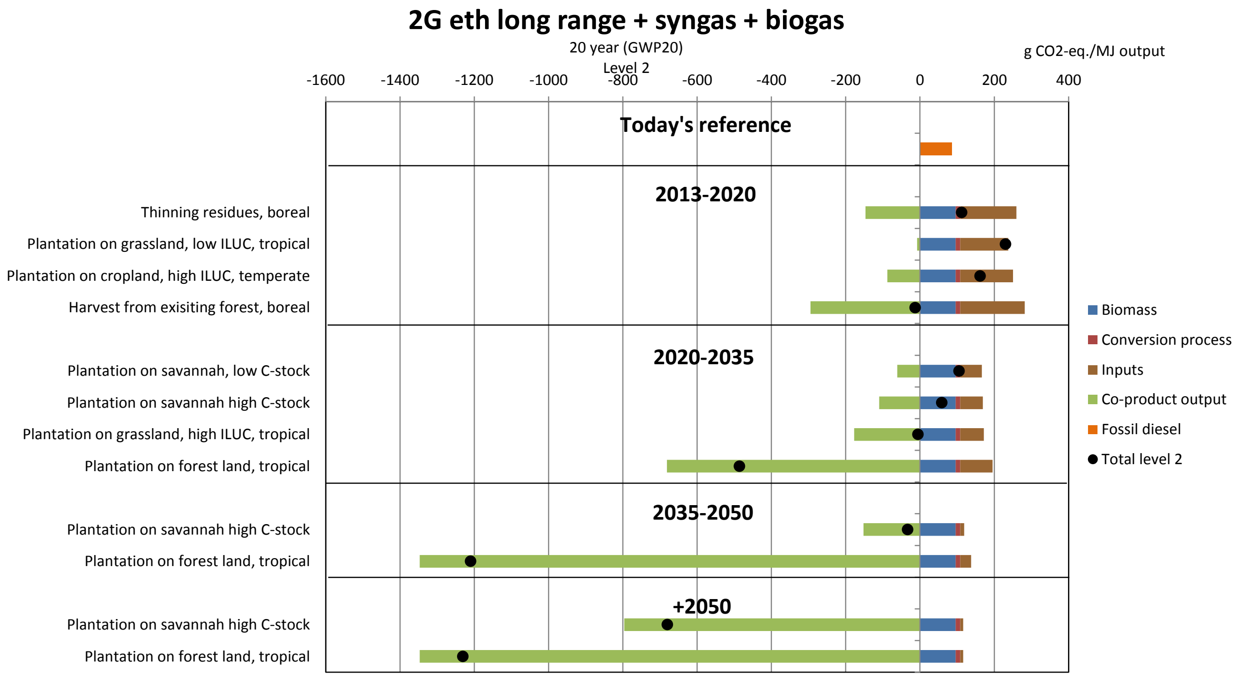


Figure 5-28 The carbon footprint of 2nd generation ethanol used in short range transport and co-products of lignin and molasses used as feedstock for thermal co-gasification with wood at Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)



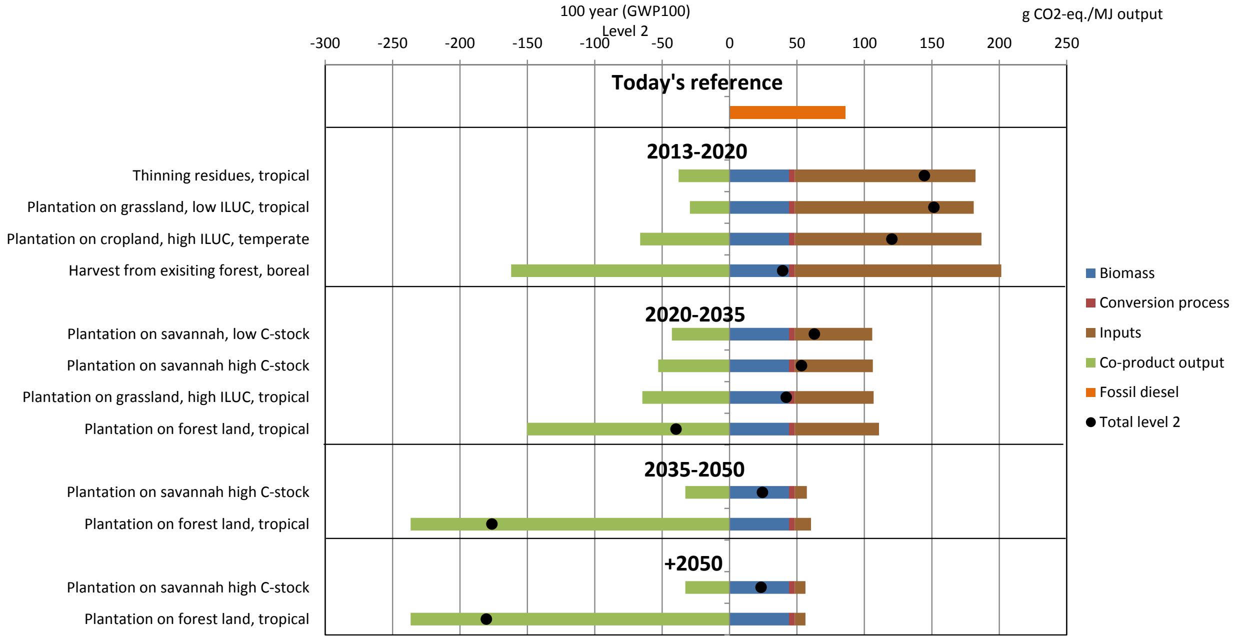
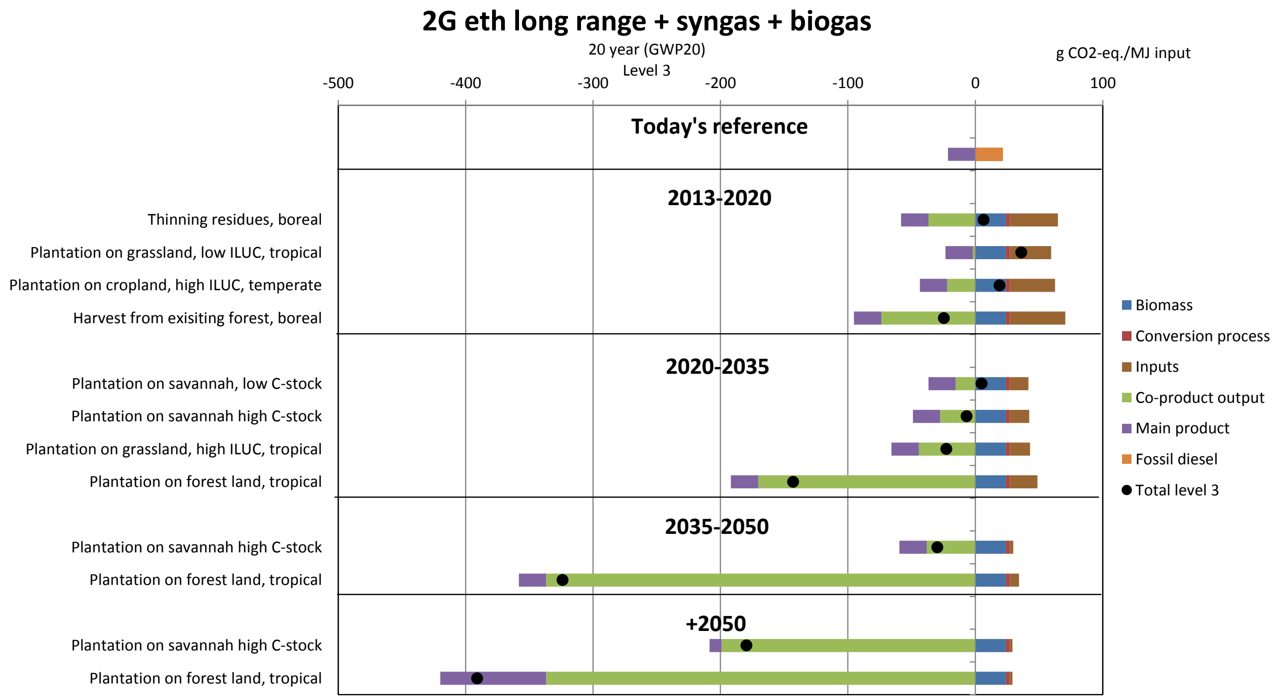


Figure 5-29 *The carbon footprint of 2nd generation ethanol used in long range transport. The co-products of lignin and molasses are used as feedstock for thermal co-gasification with wood and co-digestion with manure biogas respectively. Level 2 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)*



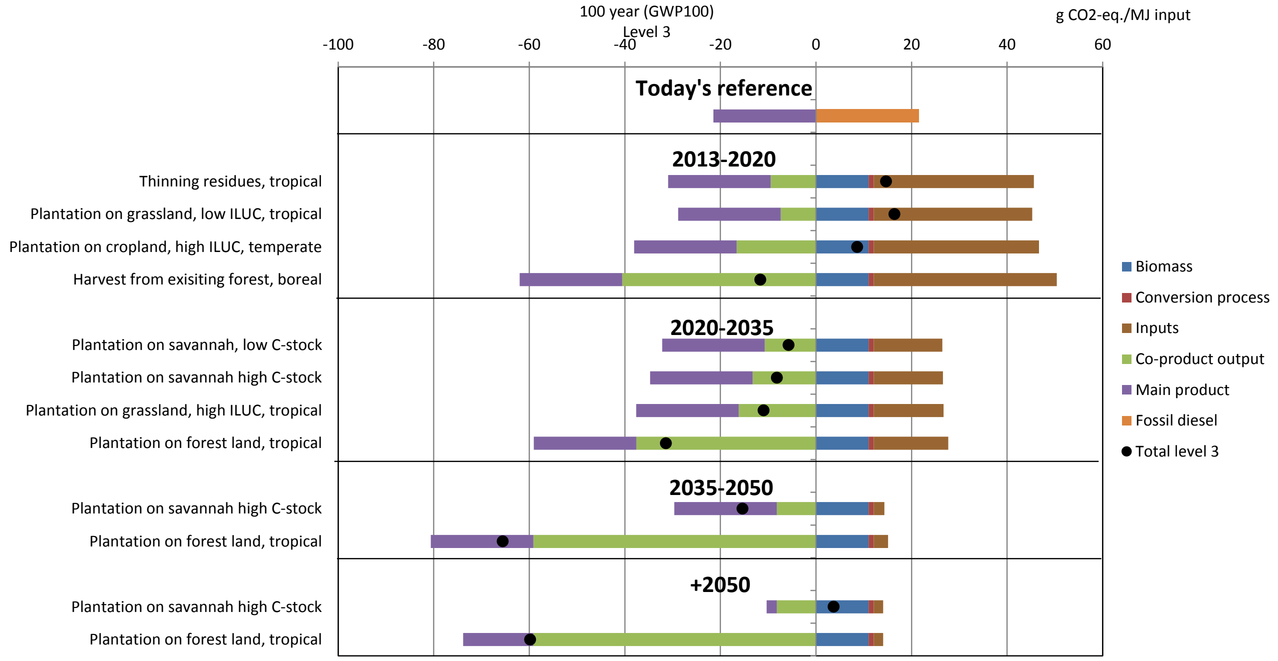


Figure 5-30 *The carbon footprint of 2nd generation ethanol used in long range transport. The co-products of lignin and molasses are used as feedstock for thermal co-gasification with wood and co-digestion with manure biogas respectively. Level 3 assessed on the background of different biomass marginal supplies from 2013 to 2050 and beyond at a 20 year time horizon (upper graph) and a 100 year time horizon (lower graph)*

The feedstock for the 2nd generation ethanol fermentation (Figure 5-25) is assumed to be straw. At 100 GJ straw input, an ethanol yield of 25 GJ is assumed together with an output of 42 GJ lignin and 25 GJ molasses. This is according to the used references. The first large scale facility was recently opened in Italy, and reports from here say (Ingeniøren 2013) a yield of 26% ethanol (MJ:MJ relative to straw input) including using the molasses in the ethanol fermentation itself. So the yield may seem overestimated in our references based on this information. The use of lignin and molasses in gasification is modeled as the same energy equivalents displaced wood, with lignin displacing 1 MJ: 1 MJ and molasses 1 MJ: 0.5 MJ, because it is very wet. The thermal energy for the conversion including the distillation is assumed to derive from the heat marginal of the period.

There is very little dependency on the biomass marginal (Figure 5-26), as it only enters into the continuous electricity consumption of the fermentation plant itself. The large contributor to emissions from energy inputs in the first time period is the thermal energy, and the large benefits lies in both the displaced wood by the co-products and the displaced fossil diesel in the two first time periods. In the last two time periods, however, there is no benefit from the displacement of the short range transport marginal itself, as this is assumed to be electric cars running on wind power. The attractiveness of prioritizing straw for ethanol for short range transport under these circumstances is, thus, small.

The pathway in Figure 5-27 is identical with the one illustrated in Figure 5-25 and Figure 5-26 with the only exception that the ethanol is now used for long range transport.

As seen from Figure 5-28, the benefit of displacing fossil diesel until 2050 is large, but potentially also the benefit of displacing the marginal after 2050 assumed to be the wood gasification and hydrogenation based methanol or DME illustrated in Figure 5-19 and Figure 5-20, especially if the wood marginal involves plantation on forest land.

The pathway Figure 5-29 is identical with the one illustrated in Figure 5-27 and Figure 5-28 with the exception that the molasses is now used in co-digestion with manure for biogas production. The molasses is very easily degradable, and a specific yield of 0.44 Nm3 of methane per kg VS is assumed, corresponding to around 87% conversion of the calorific value in the molasses to methane. The produced methane is assumed hydrogenated with hydrogen from electrolysis running at flexible consumption, and the produced SNG is stored on the gas grid and assumed used in flexible power production, thus, displacing the marginal flexible power of the period. The large input of energy and auxiliaries seen to contribute much to GHG emission in the first period derive from this flexible electricity as well as heat (mainly for distillation of the ethanol) and enzymes.

The small contribution from the enzymes is what is left in the period from 2035 and onwards, because the other inputs run on wind power in this period. In 2020 – 2035, also the heat (from natural gas boiler in this period) is contributing, whereas the flexible electricity here is assumed to derive from wind power, and in 2013 – 2020, all three inputs contribute.

As seen from Figure 5-30, and as compared to Figure 5-28, the benefit of using the molasses for biogas is large.

When comparing and interpreting the results, as they are presented in Chapter 7, several issues call for caution. Firstly, of course, the aspect of uncertainties related to data and assumptions. Secondly, the aspects discussed previously on the differences in functional outputs, rendering it impossible to compare across the categories of heat, continuous power, flexible power and transport fuel outputs. Thirdly, the aspect of constrained resources, i.e. that using a biomass resource like domestic straw for one pathway renders it impossible to use it in another – meaning that a given pathway cannot necessarily be seen in isolation. The levelled approach with level 2 and 3 is our way to strive to deal with the issues of incomparability and constrained resources. But one more aspect should be noticed, namely the fact that decisions in the energy system also influences agriculture in a way, we have to consider, i.e. with respect to soil carbon. We have dealt with this in the sense that we account for differences in carbon sequestration, when we model the overall system carbon balance behind the calculated carbon footprints. But the long term decrease in soil carbon may have more overall implications for soil quality and the longer term productivity of agricultural activities on the soil. In order to try to deal with this, we have approach the modelling on level 4 in the way, that we keep the long term soil carbon sequestration constant in the whole-system designs. This is done ensuring that the long lasting (over 100 years) carbon remaining in the soil from the domestic straw (and manure) residues is the same, which in turn means that the straw potential available for energy recovery becomes dependent on the conversion pathway it enters. If, for example, the straw is used in biogas co-digestion with manure, the majority (around 75%) of the non-easily degradable carbon remains in the digestate and the soil on the long term. If, on the other hand, the straw carbon enters a combustion pathway, either directly or via the lignin from 2G ethanol going to co-gasification, then the domestic straw potential is less, because more shall be ploughed down directly in order to maintain the long term soil carbon pool. In this chapter, we will guide the reader through the interpretation of the results with due respect to these cautions.

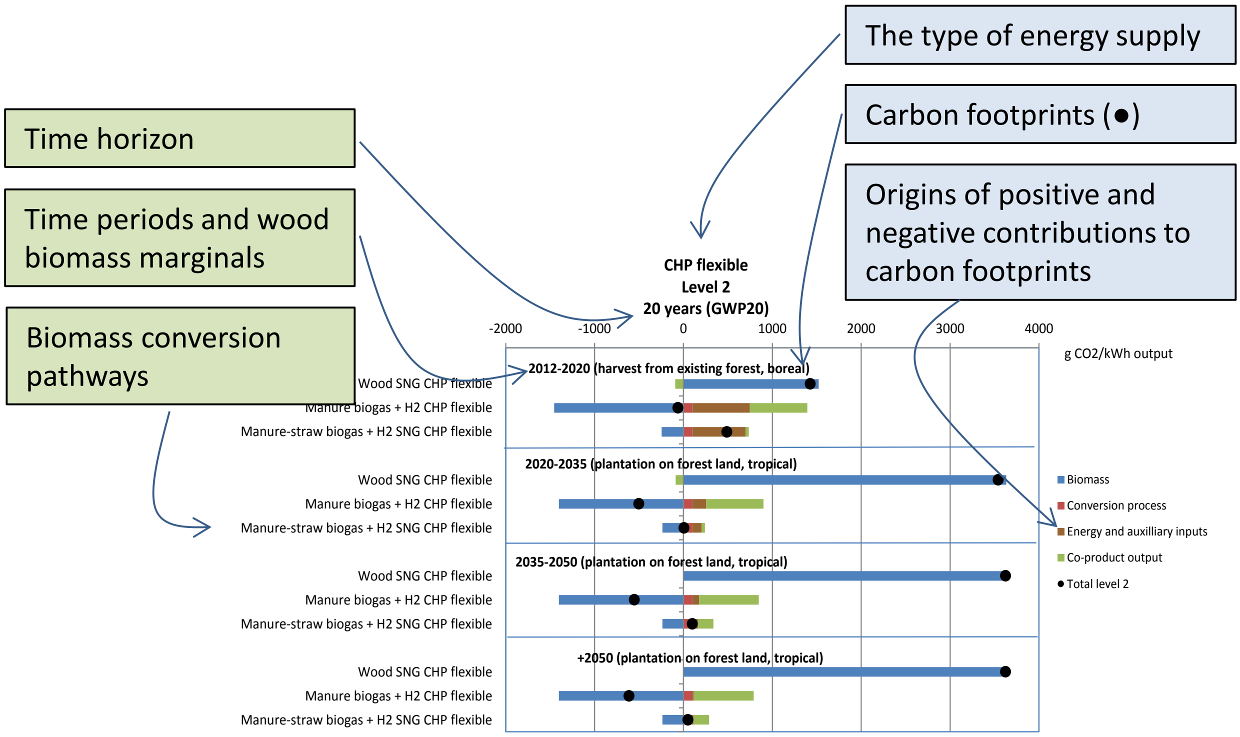
But first, we will discuss the uncertainties on data and assumptions on the pathways seen in isolation, se next section.

5.2 Comparison of heat production pathways

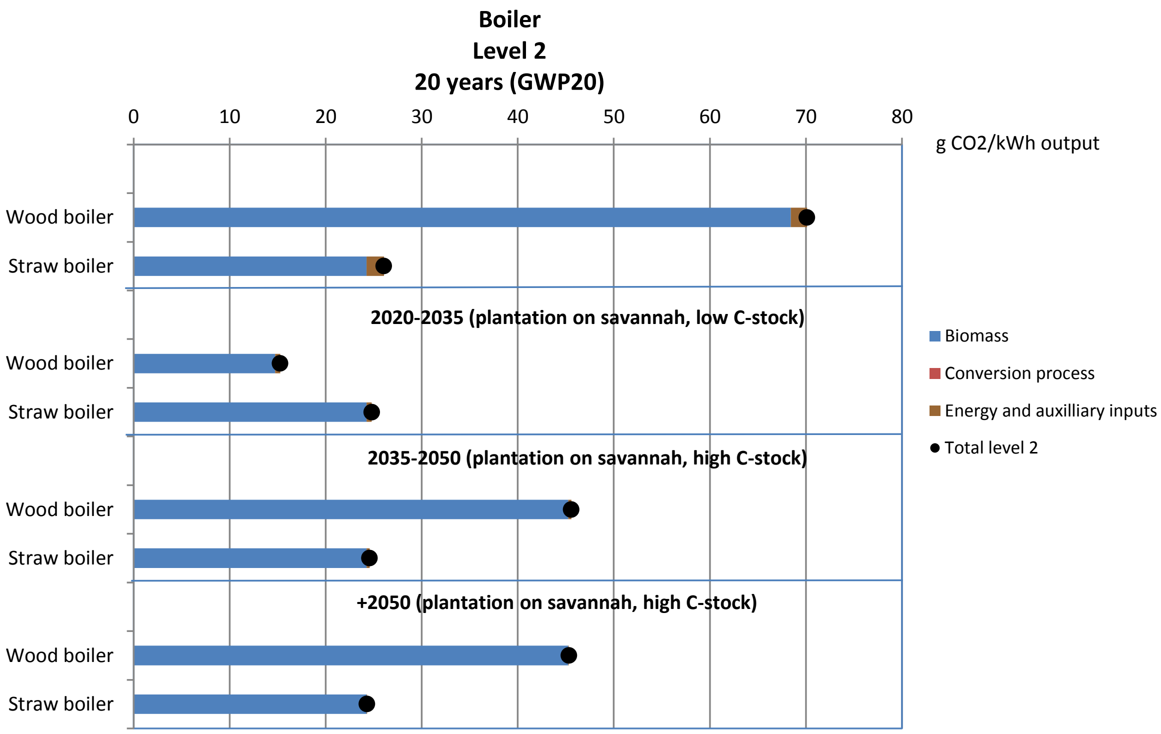
Guidance graphics

For biomass conversion pathways providing the same type of energy supply – either heat, power or transport fuel supply – carbon footprints are compared in the four time periods and assuming the relevant biomass marginals – the biomass type and its origin. Periods are 2013 – 2020, 2020 – 2035, 2035 – 2050, and 2050+. Greenhouse gas emissions are presented per energy output (level 2).

Results have been calculated for a 20 year and for a 100 year time horizon because the effect of greenhouse gas emissions depends on the time span in which these are seen. Accordingly there are two sets of graphics for each biomass conversion pathway.



Comparing carbon footprints across biomass conversion pathways providing the same type of energy supply



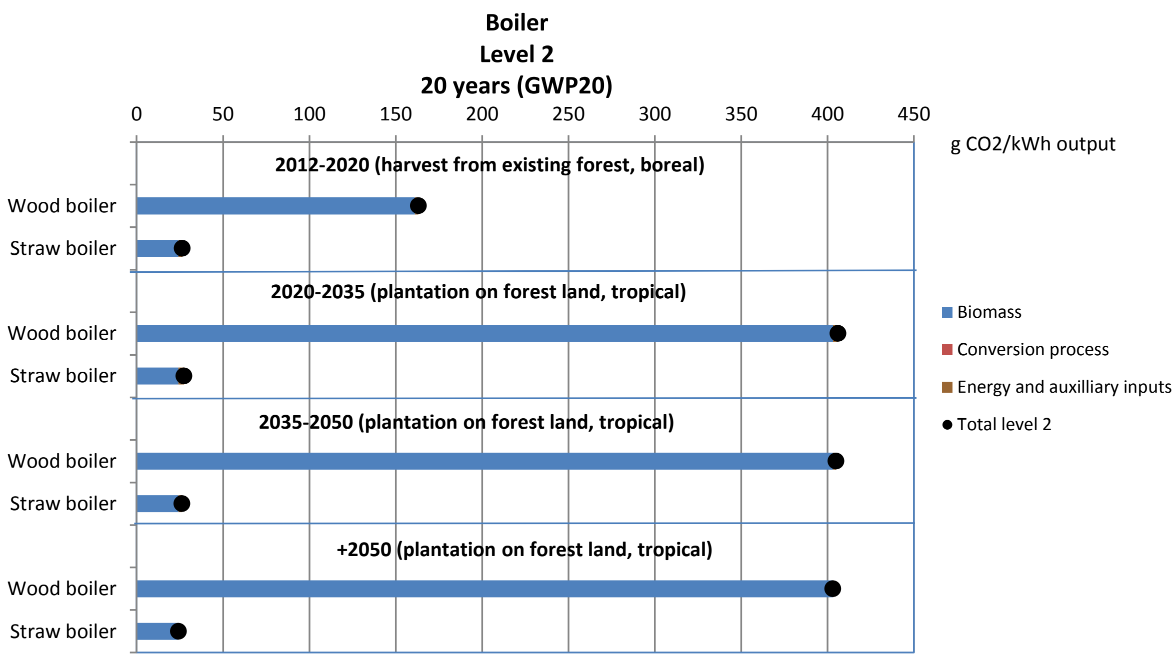


Figure 5-31 Comparing heat supply pathways at level 2 in the 20y horizon

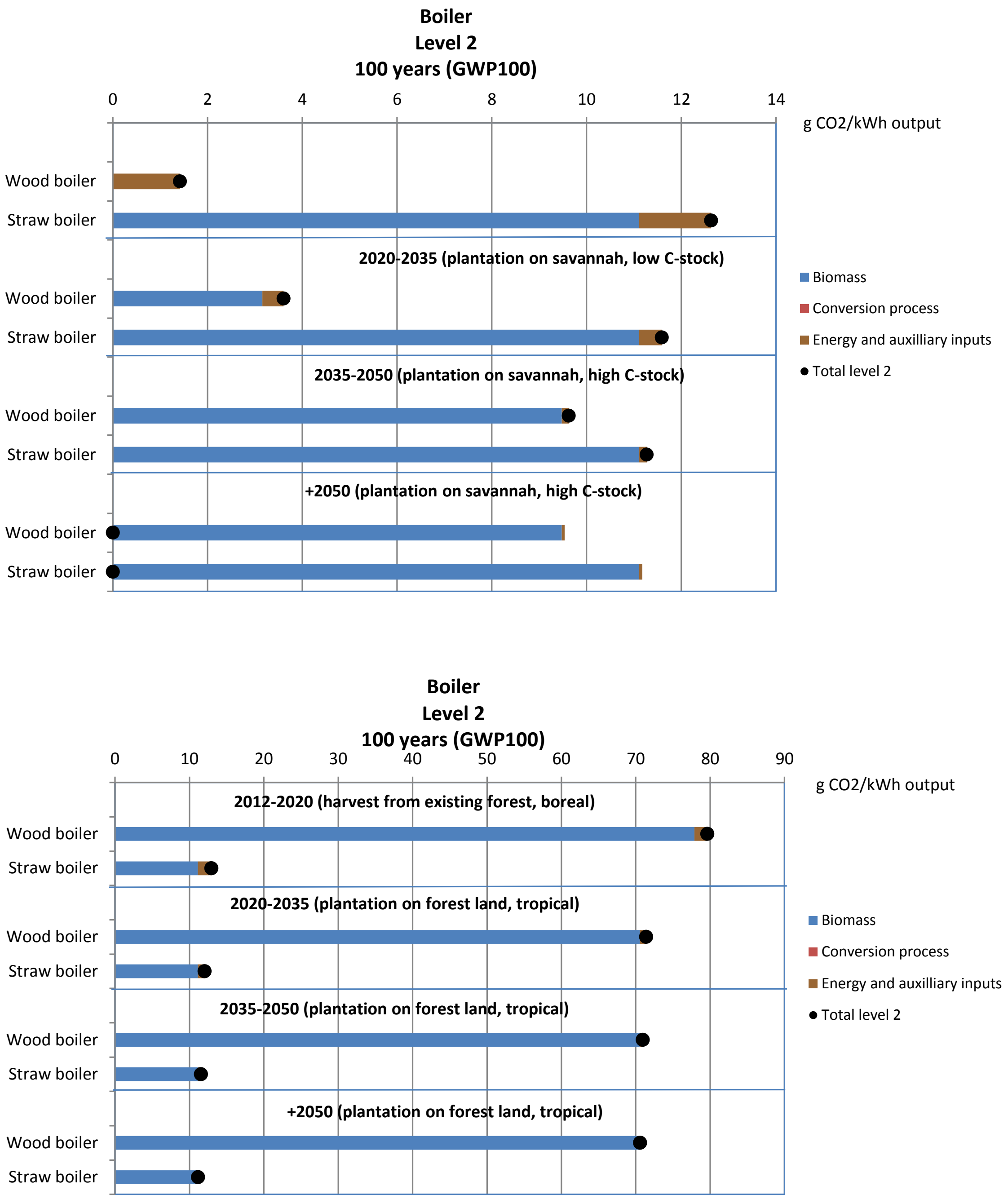
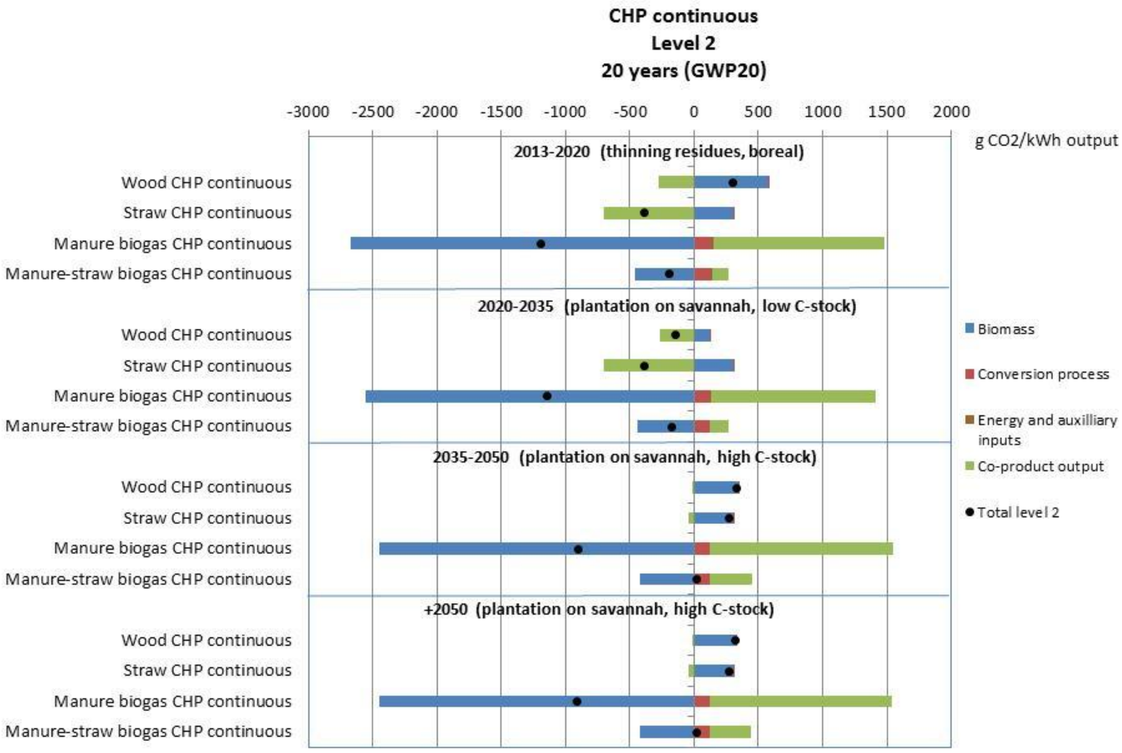


Figure 5-32 Comparing heat supply pathways at level 2 in the 100y horizon

From Figure 5-31 and Figure 5-32, it can be seen that the straw boiler under most assumptions has a lower carbon footprint than the wood boiler per MJ of heat output. But the wood boiler may have a lower footprint in case of using thinning wood from non-boreal forest. On the long term, if the biomass marginal is plantation on savannah or forest land, the straw bile seems to be the better choice for GHG reduction.

However, such a conclusion does not respect the need to prioritize the limited domestic straw, there may be a better way of using it. One has to look at level 3 (or even level 4) in order to conclude on the issue of prioritizing the straw.

5.3 Comparison of continuous electricity production pathways



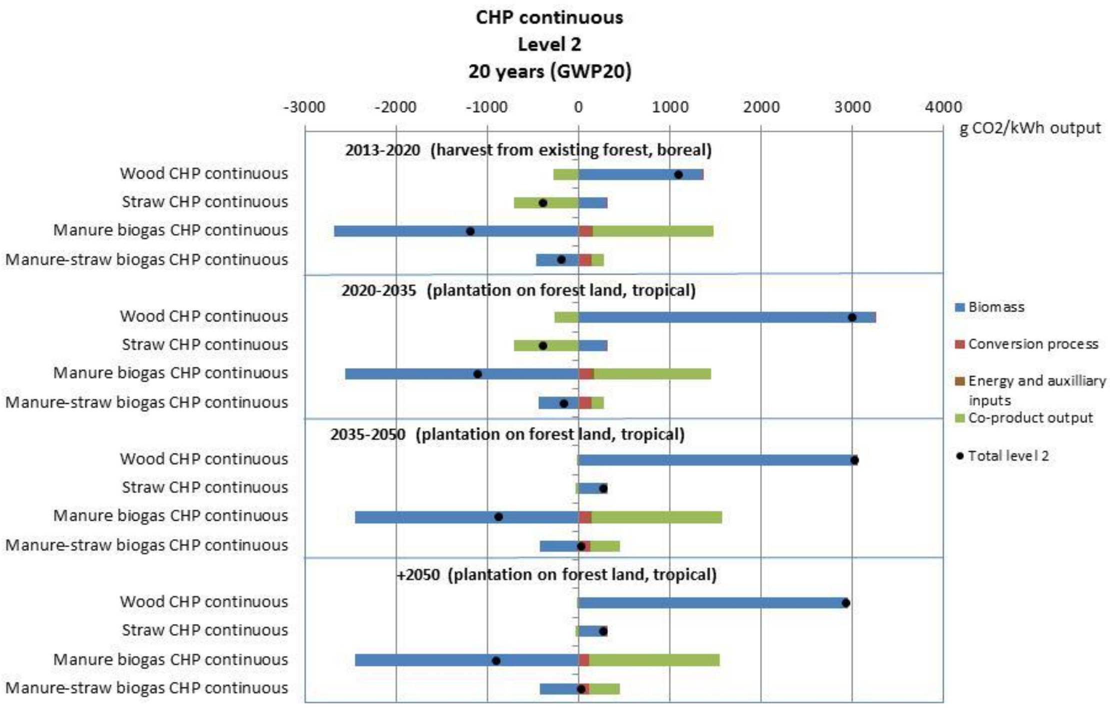
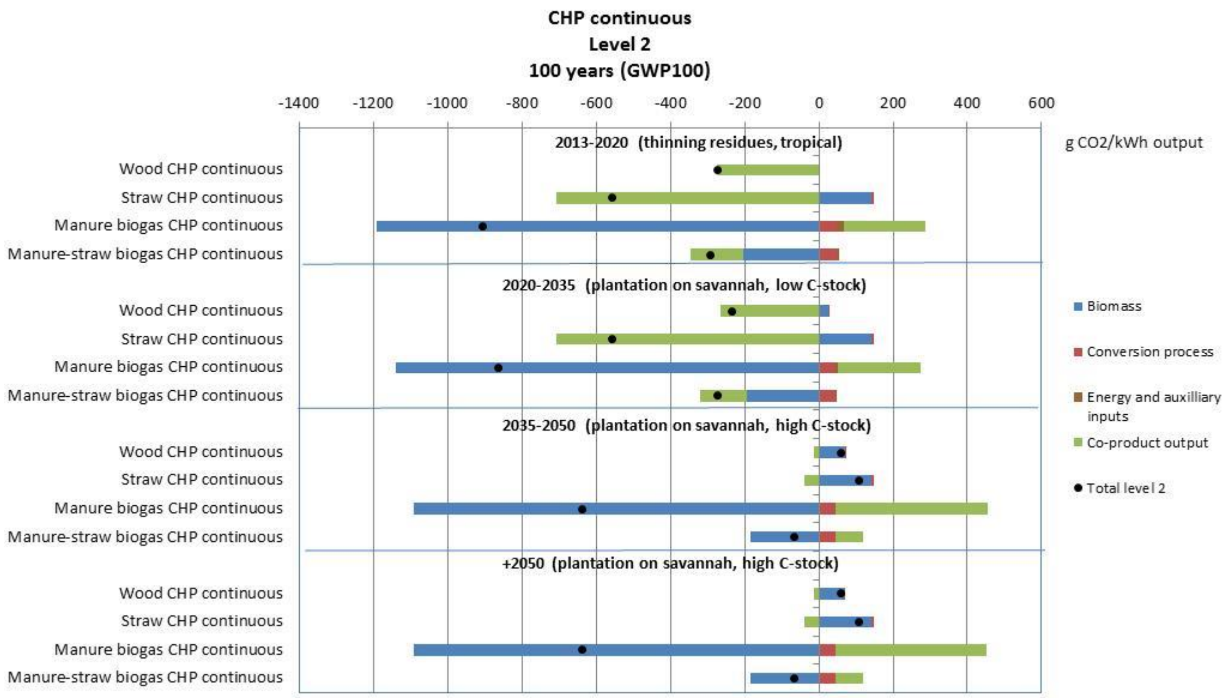


Figure 5-33 Comparing continuous power supply pathways at level 2 in the 20y horizon



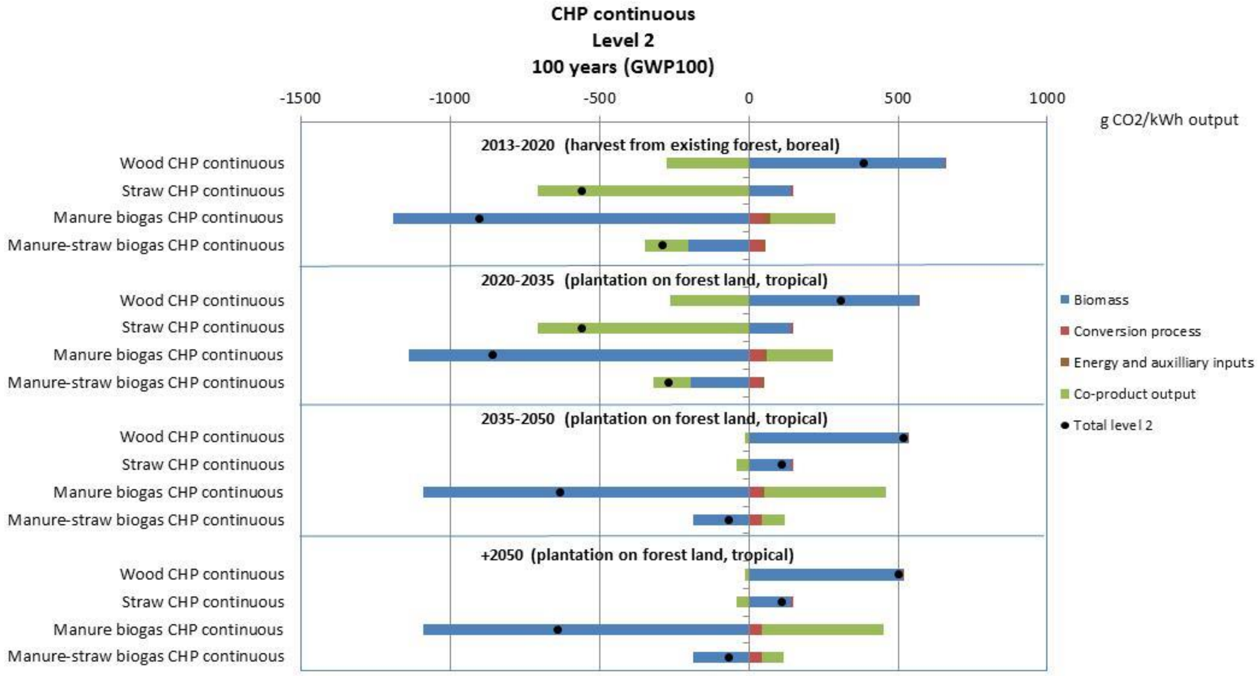


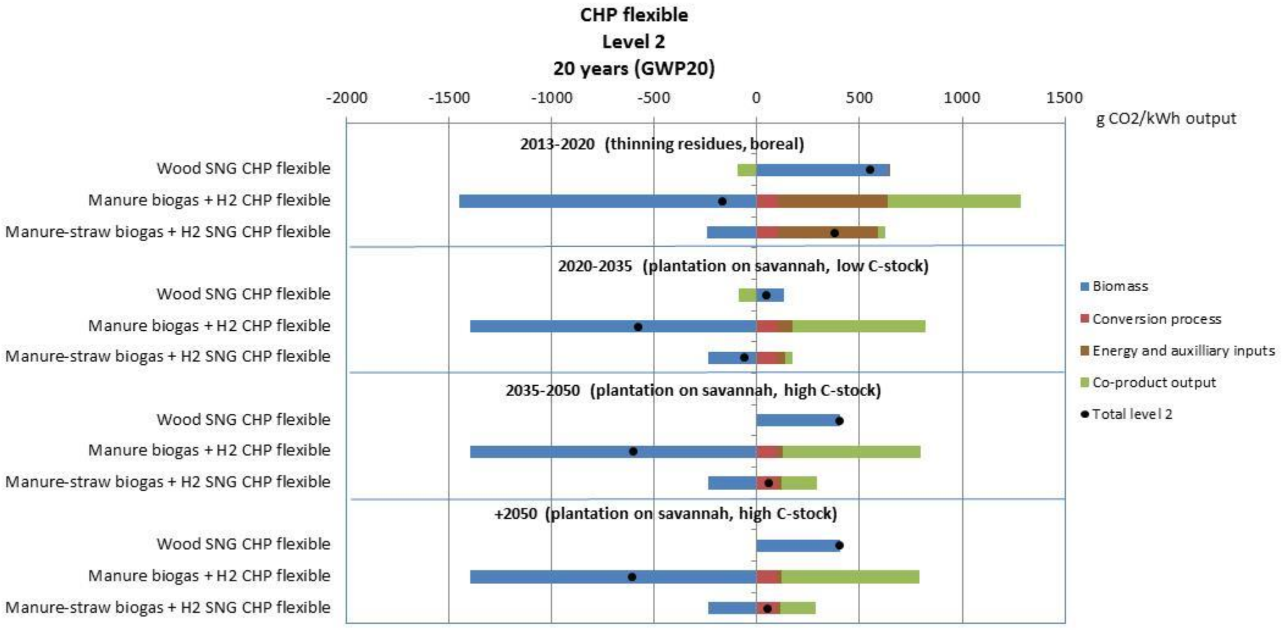
Figure 5-34 Comparing continuous power supply pathways at level 2 in the 100y horizon

From Figure 5-33 and Figure 5-34, it seems robust to conclude that biogas based production of continuous power performs better under all circumstances. It is rather independent on the assumptions of wood biomass marginal, and the benefit of changing the manure management towards biogas is always a domination aspect.

Also that the mono-digestion manure biogas pathway is preferable to manure-straw co-digestion GHG-wise. But, as we shall see, co-digestion with manure may be one of the best priorities of using straw. One shall note that at level 2, the carbon footprint is seen per kWh in isolation, not considering how much electricity overall, one can achieve from the feedstock. But this is dealt with at level 4.

However, as we shall see at level 3 and 4, using manure and straw for *continuous* power production is not the best priority in a system perspective.

5.4 Comparison of flexible electricity production pathways



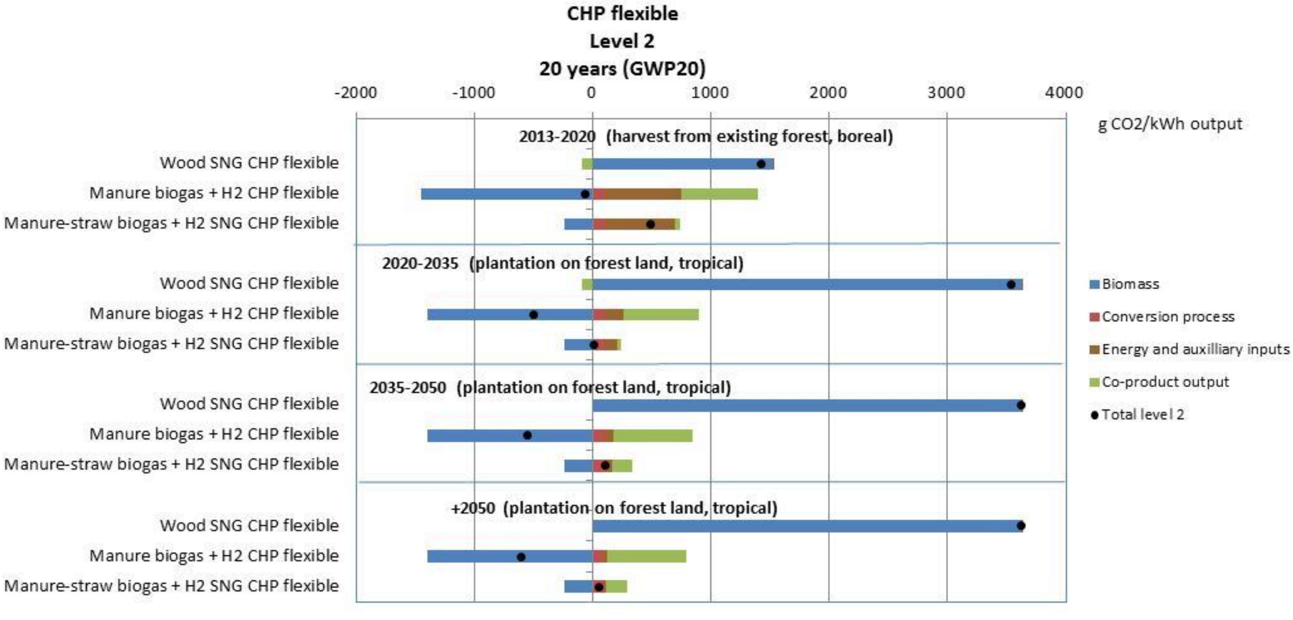
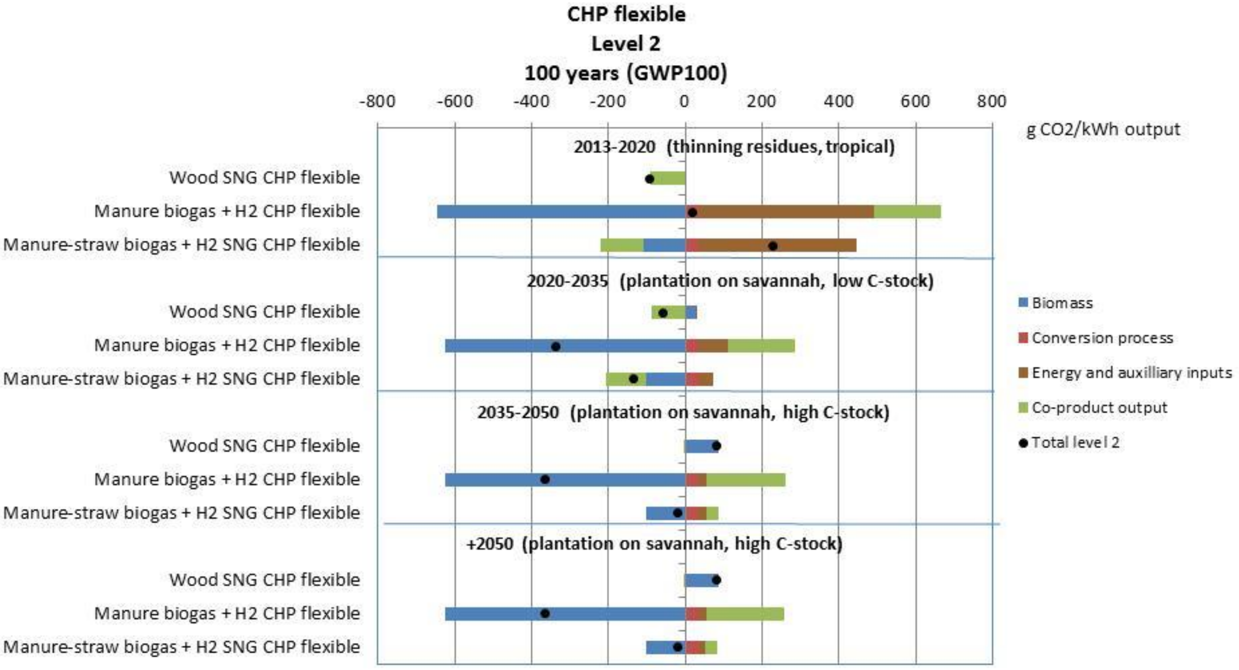


Figure 5-35 Comparing flexible power supply pathways at level 2 in the 20y horizon



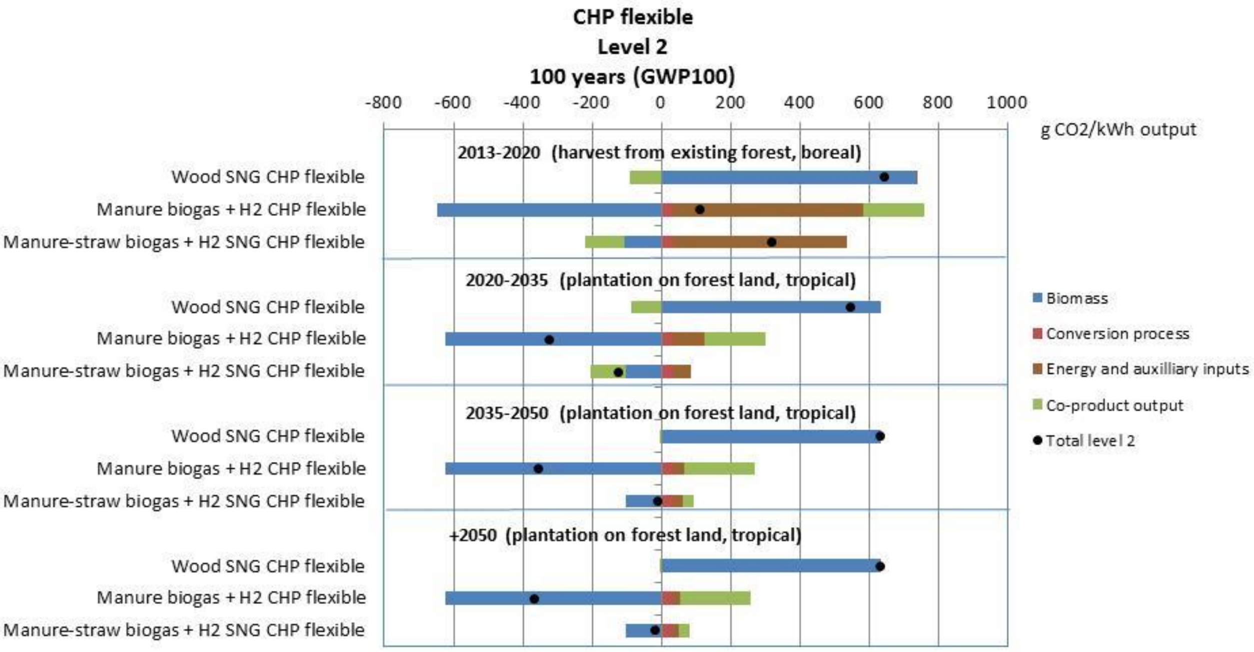


Figure 5-36 Comparing flexible power supply pathways at level 2 in the 100y horizon

From Figure 5-35 and Figure 5-36, it seems robust to conclude that biogas based production of continuous power performs better under all circumstances. It is rather independent on the assumptions of wood biomass marginal, and the benefit of changing the manure management towards biogas is always a domination aspect. Also that the mono-digestion manure biogas pathway is preferable to manure-straw co-digestion GHG-wise. In fact, also looking at level 3 and 4, we will conclude biogas pathways to be a good priority of flexible power production, see later. But, as we shall see, co-digestion with manure may be one of the best priorities of using straw. One shall note that at level 2, the carbon footprint is seen per. kWh in isolation, not considering how much electricity overall, one can achieve from the feedstock. But this is dealt with at level 4.

5.5 Comparison of transport fuel production pathways

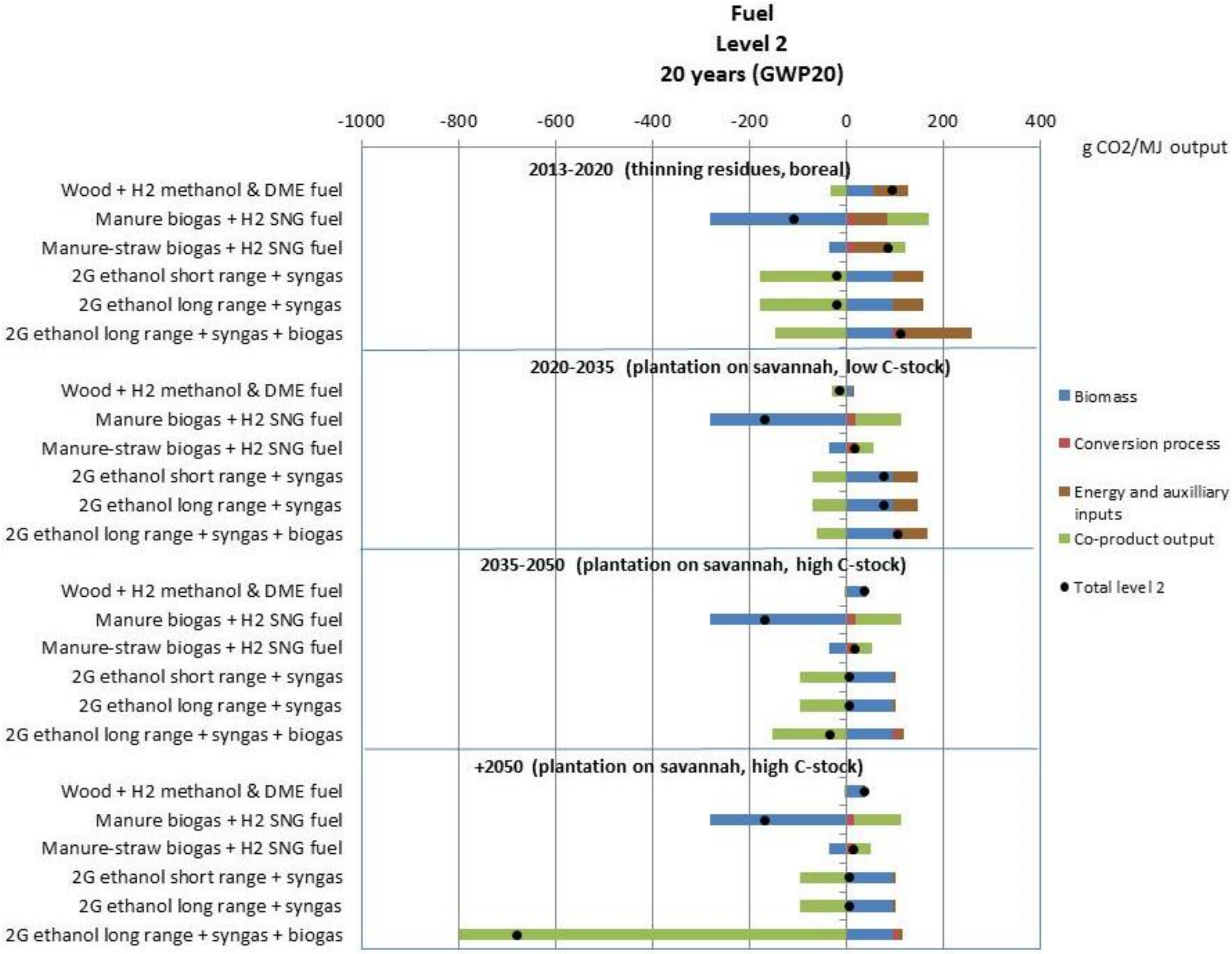


Figure 5-37 Comparing fuel supply pathways at level 2 in the 20y horizon

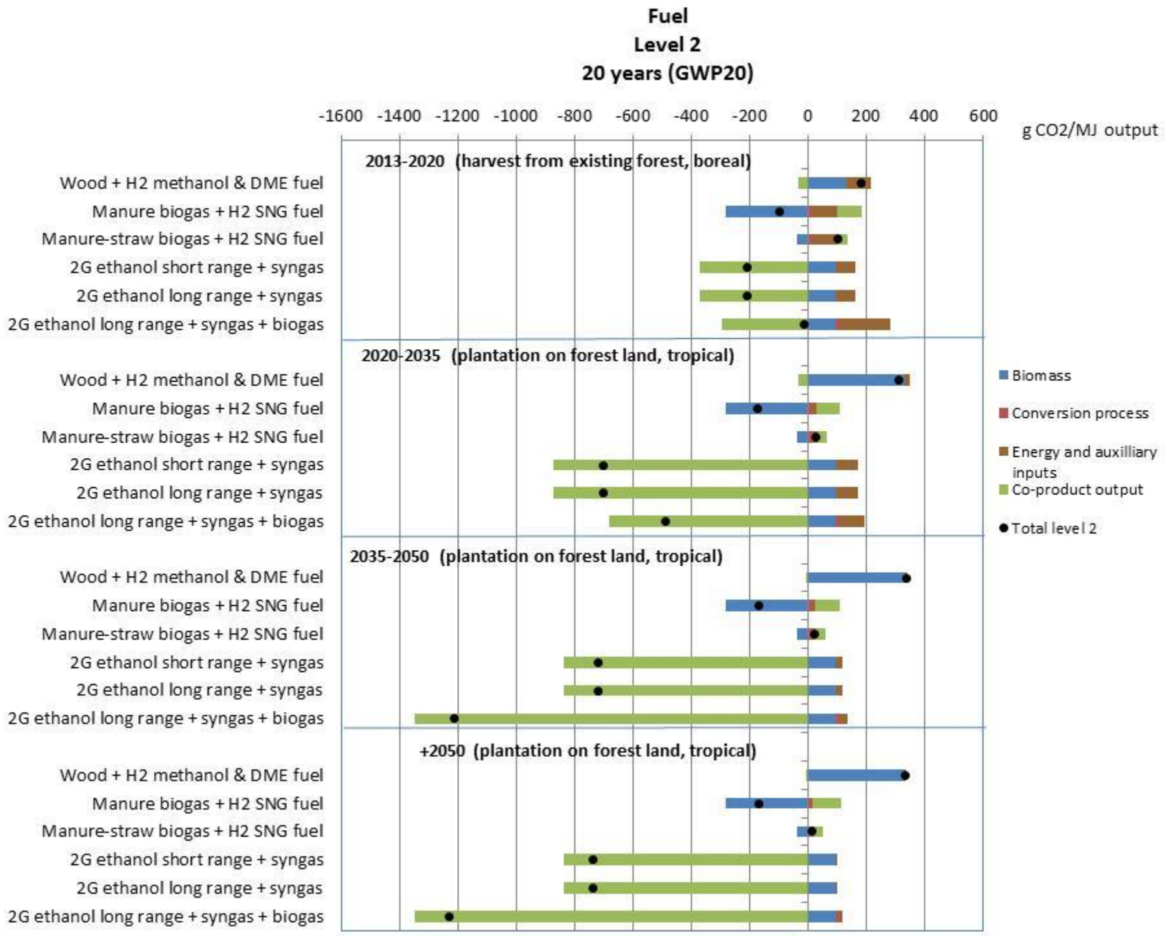


Figure 5-38 Comparing fuel supply pathways at level 2 in the 20y horizon

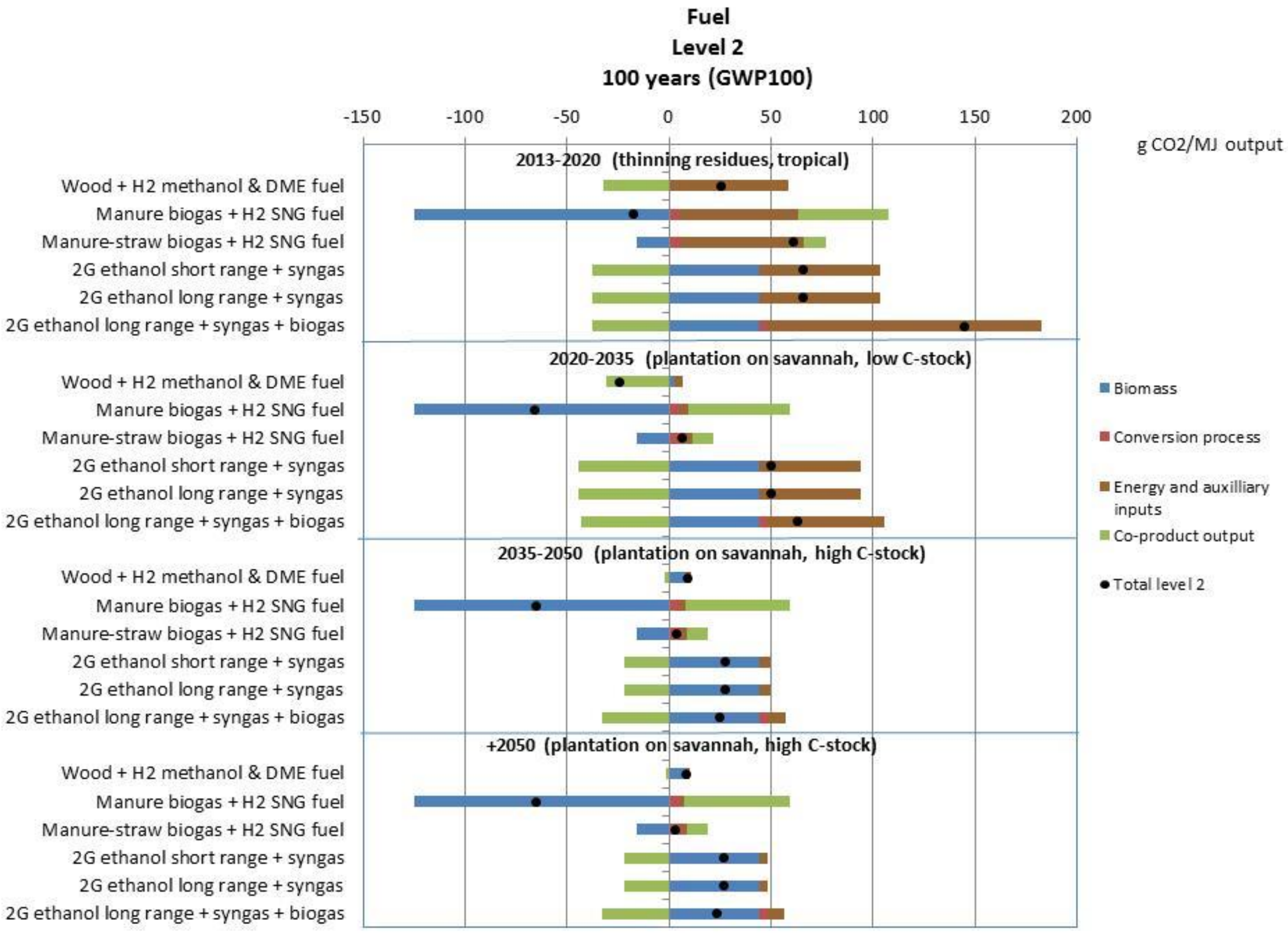


Figure 5-39 Comparing fuel supply pathways at level 2 in the 100y horizon

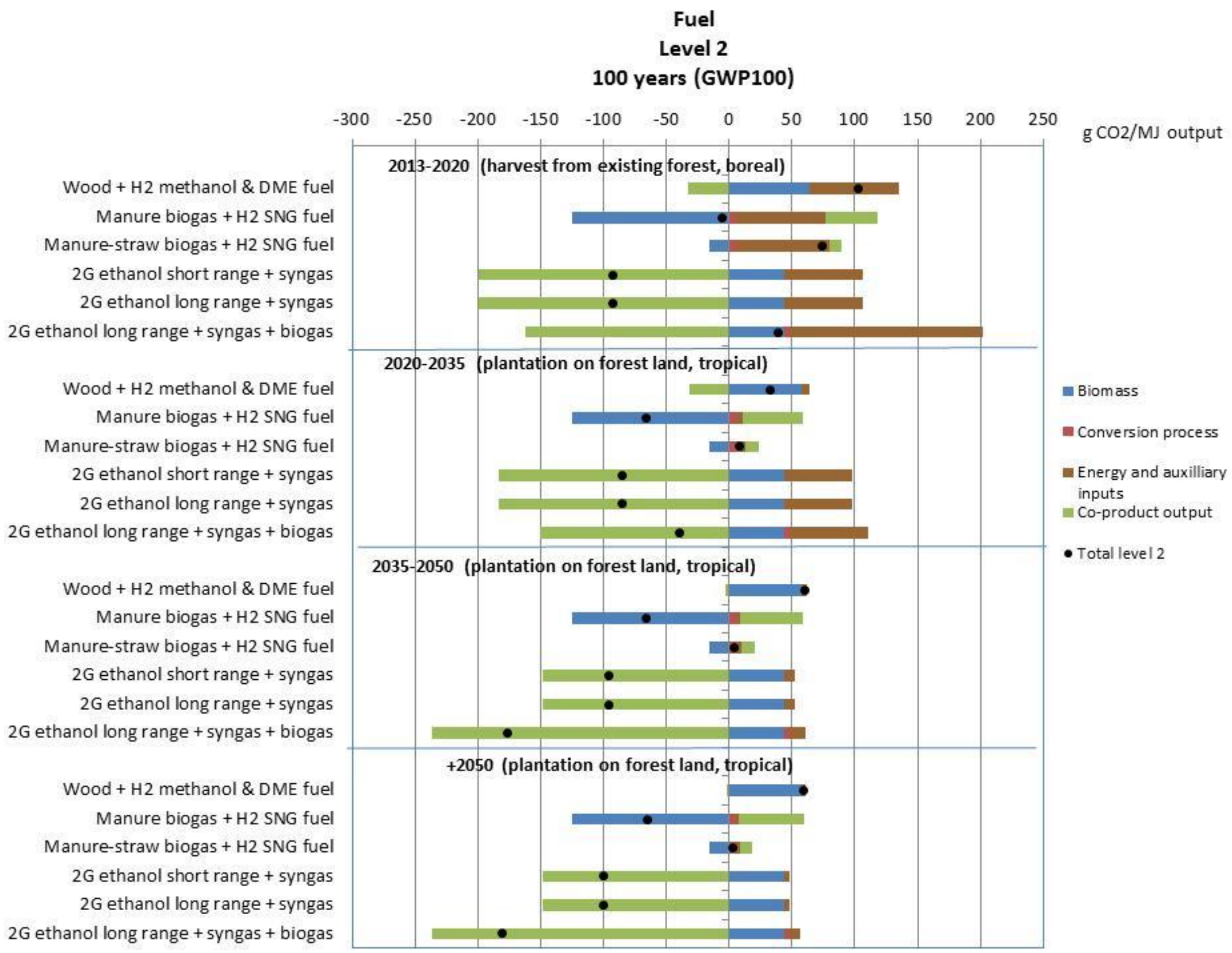


Figure 5-40 Comparing fuel supply pathways at level 2 in the 100y horizon

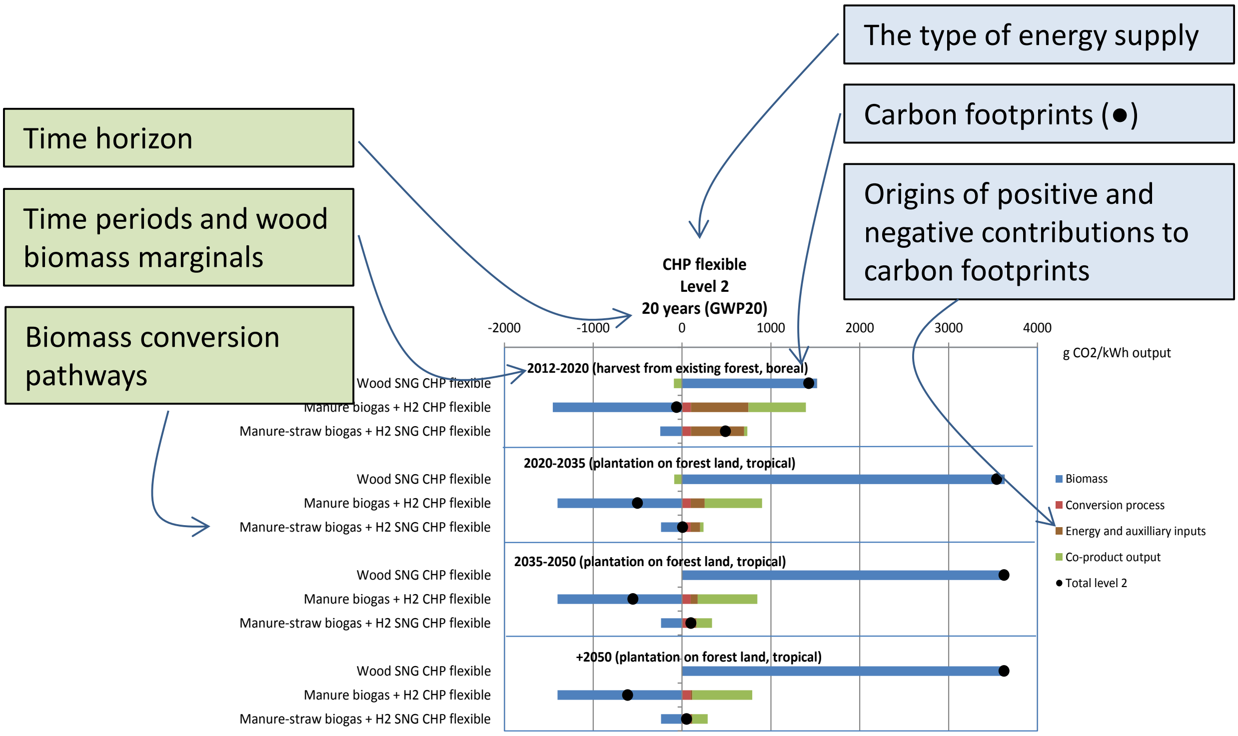
Looking at Figure 5-37 to Figure 5-40, the biogas and 2G ethanol pathways seem to have a lower carbon footprint than the wood based fuel. Depending on circumstances, biogas and 2G ethanol pathways can both be preferable. Level 3 and 4 will reveal further aspects of this.

5.6 Comparison of wood conversion pathways for different functional outputs

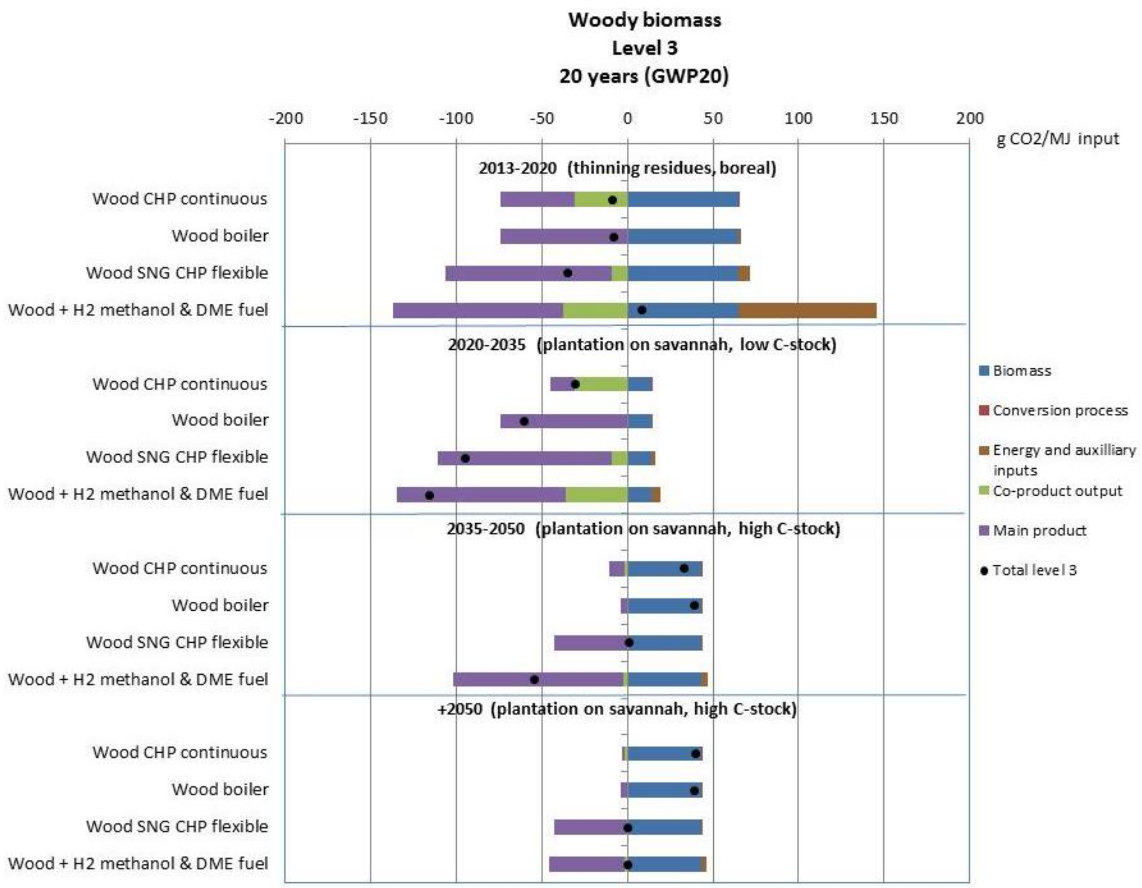
Guidance graphics

For biomass conversion pathways providing the same type of energy supply – either heat, power or transport fuel supply – carbon footprints are compared in four time periods and assuming the relevant biomass marginals – the biomass type and its origin. Periods are 2013 – 2020, 2020 – 2035, 2035 – 2050, and 2050+. Greenhouse gas emissions are presented per energy output (level 2).

Results have been calculated for a 20 year and for a 100 year time horizon because the effect of greenhouse gas emissions depends on the time span in which these are seen. Accordingly there are two sets of graphics for each biomass conversion pathway.



Comparing carbon footprints across biomass conversion pathways providing the same type of energy supply



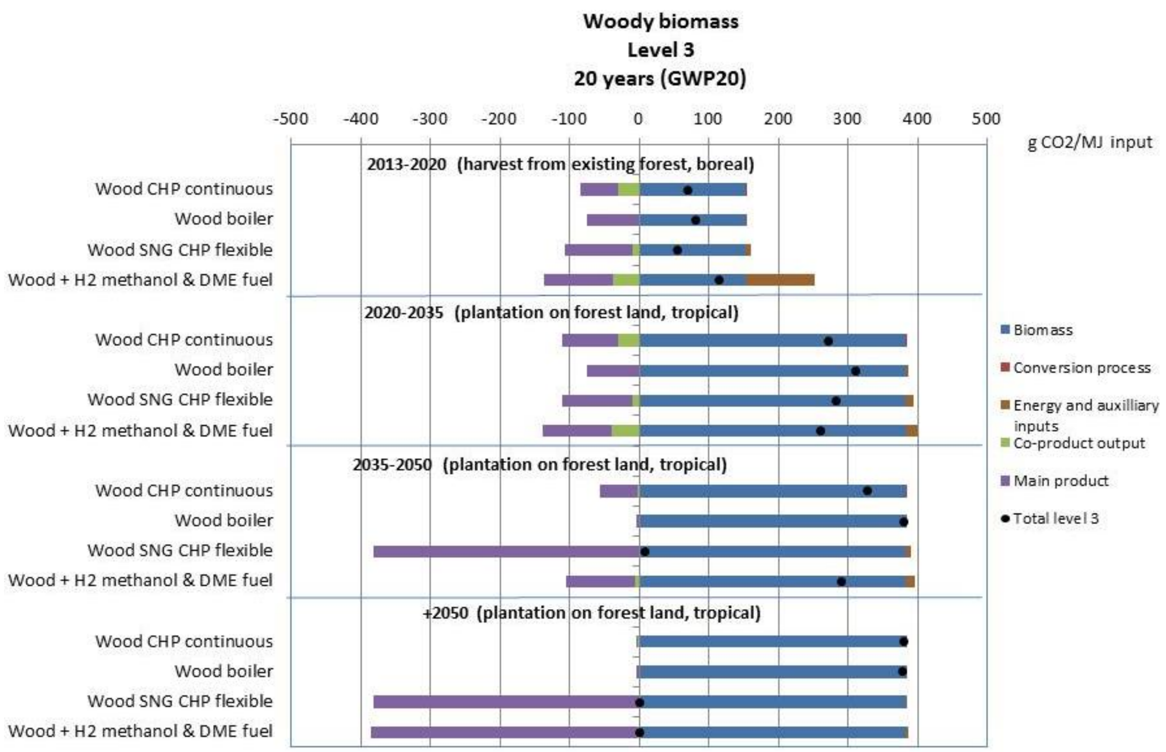
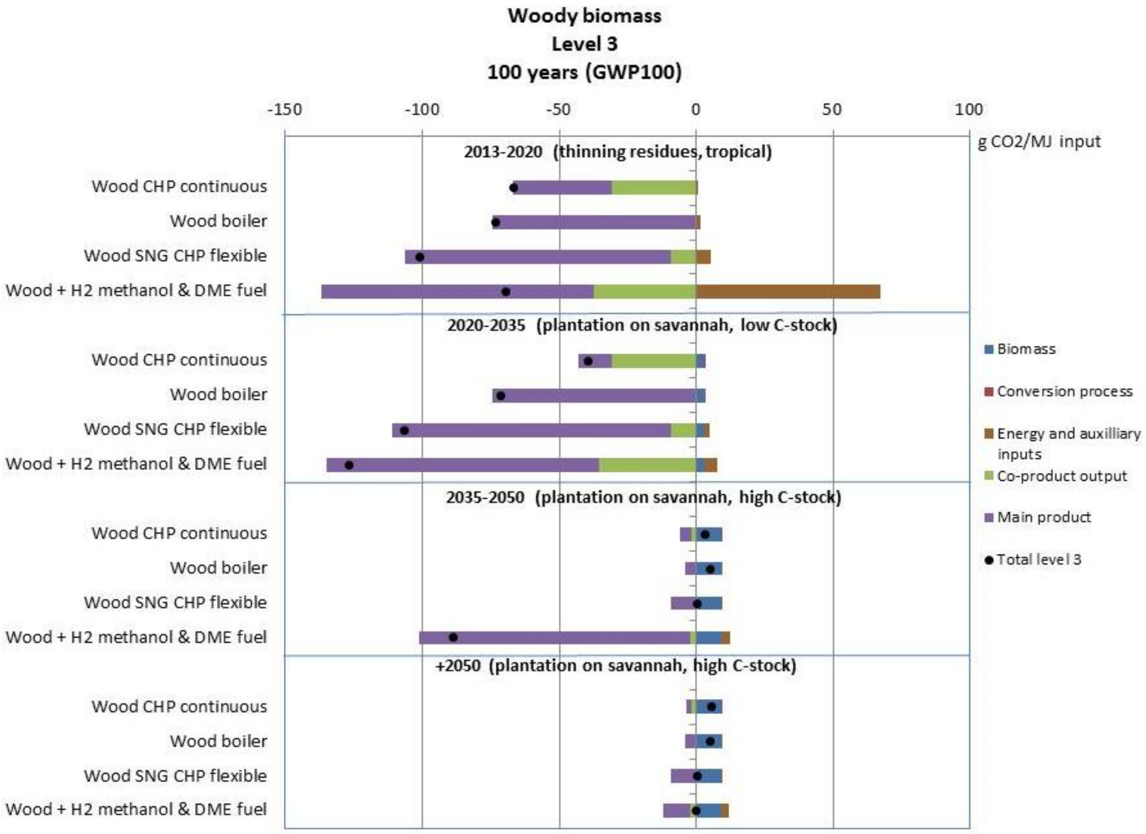


Figure 5-41 Comparing wood biomass pathways at level 3 in the 20y horizon



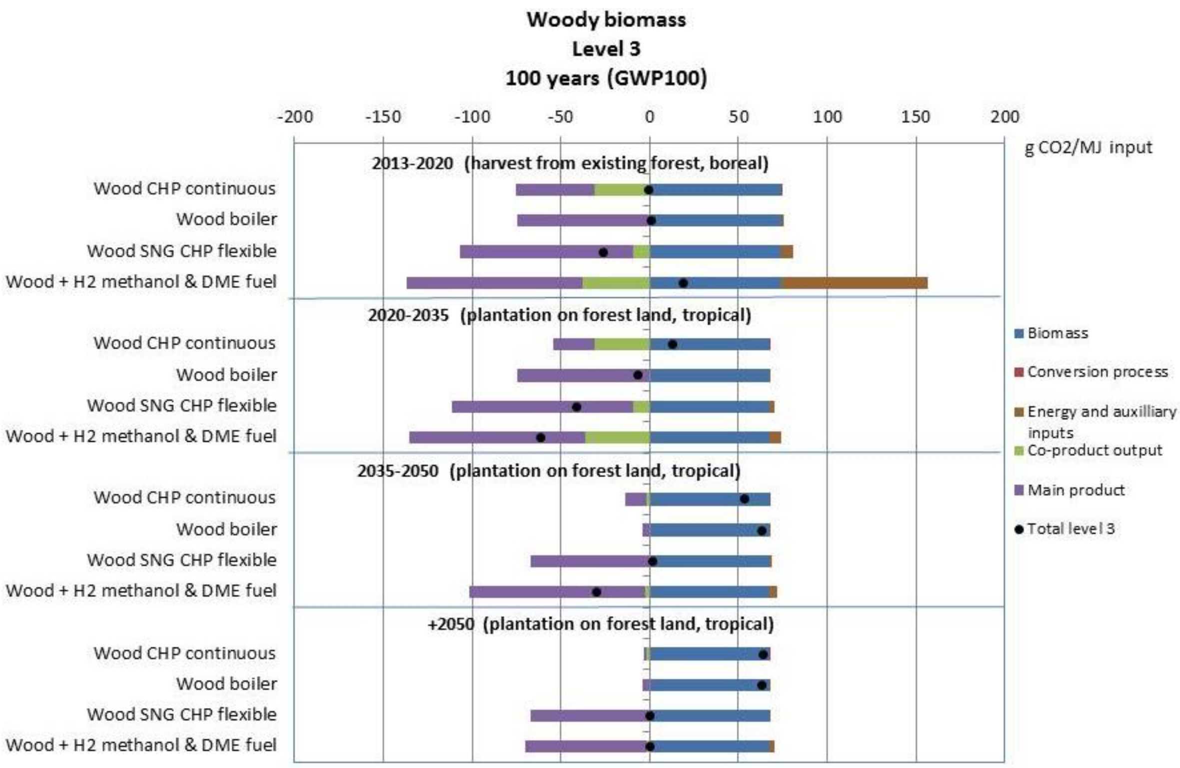


Figure 5-42 Comparing wood biomass pathways at level 3 in the 100y horizon

From Figure 5-41 and Figure 5-42, it becomes evident that prioritizing wood for conversion pathways with heat and continuous power outputs may be justified on the short term, but does not lead to GHG benefits in the long term renewable energy system.

5.7 Comparison of straw conversion pathways for different functional outputs

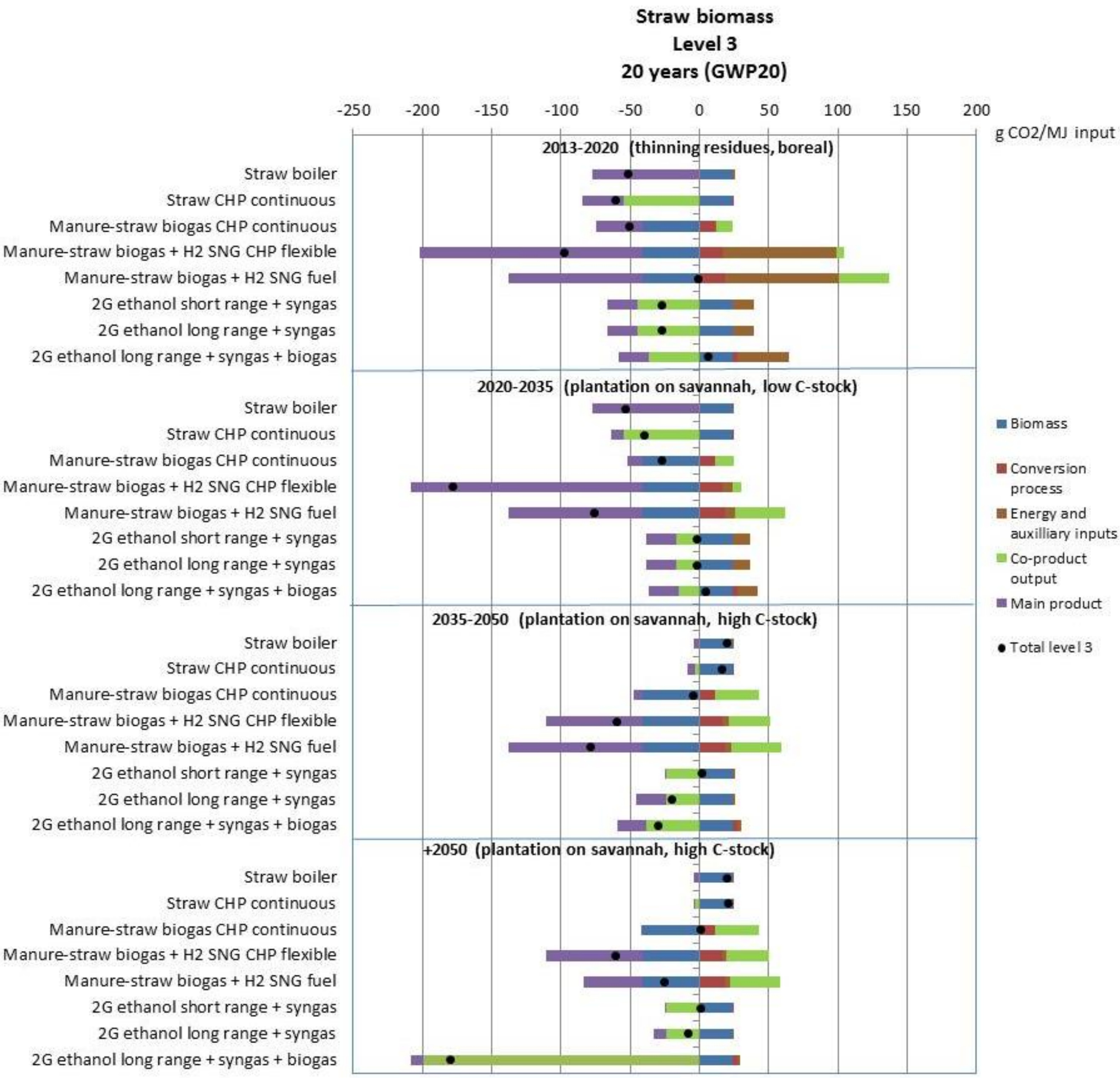


Figure 5-43 Comparing straw biomass pathways at level 3 in the 20y horizon

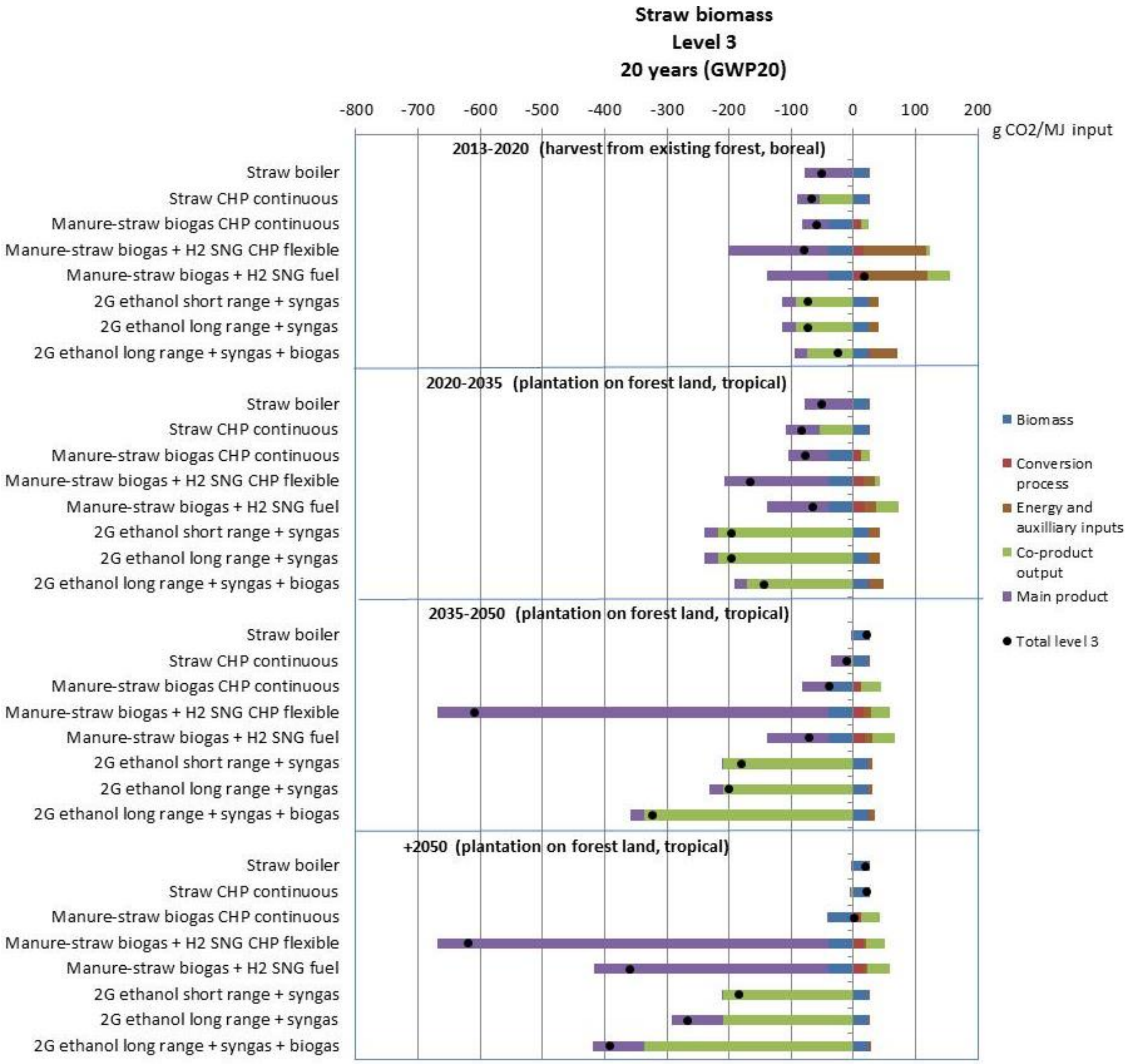


Figure 5-44 Comparing straw biomass pathways at level 3 in the 20y horizon

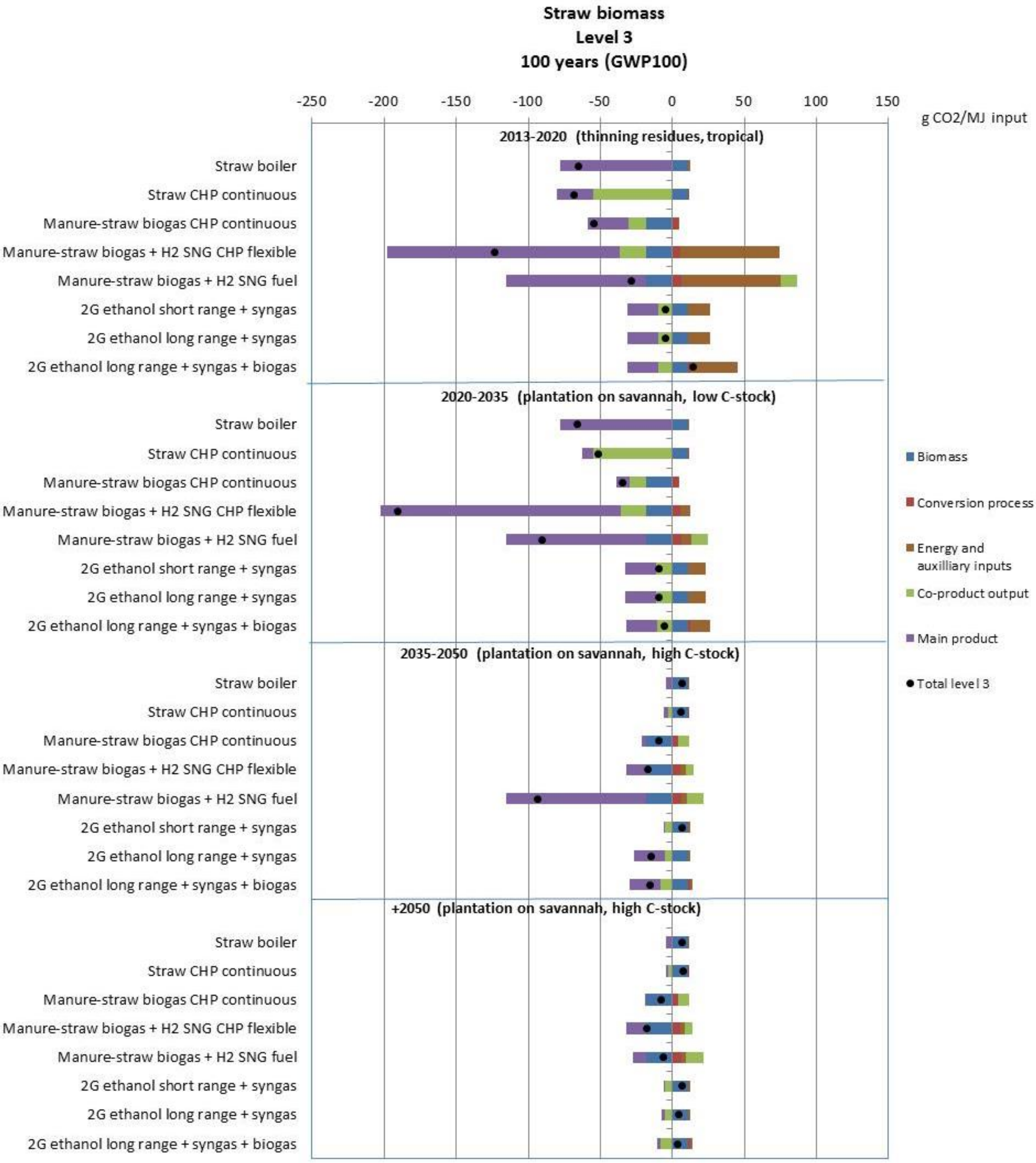


Figure 5-45 Comparing straw biomass pathways at level 3 in the 100y horizon

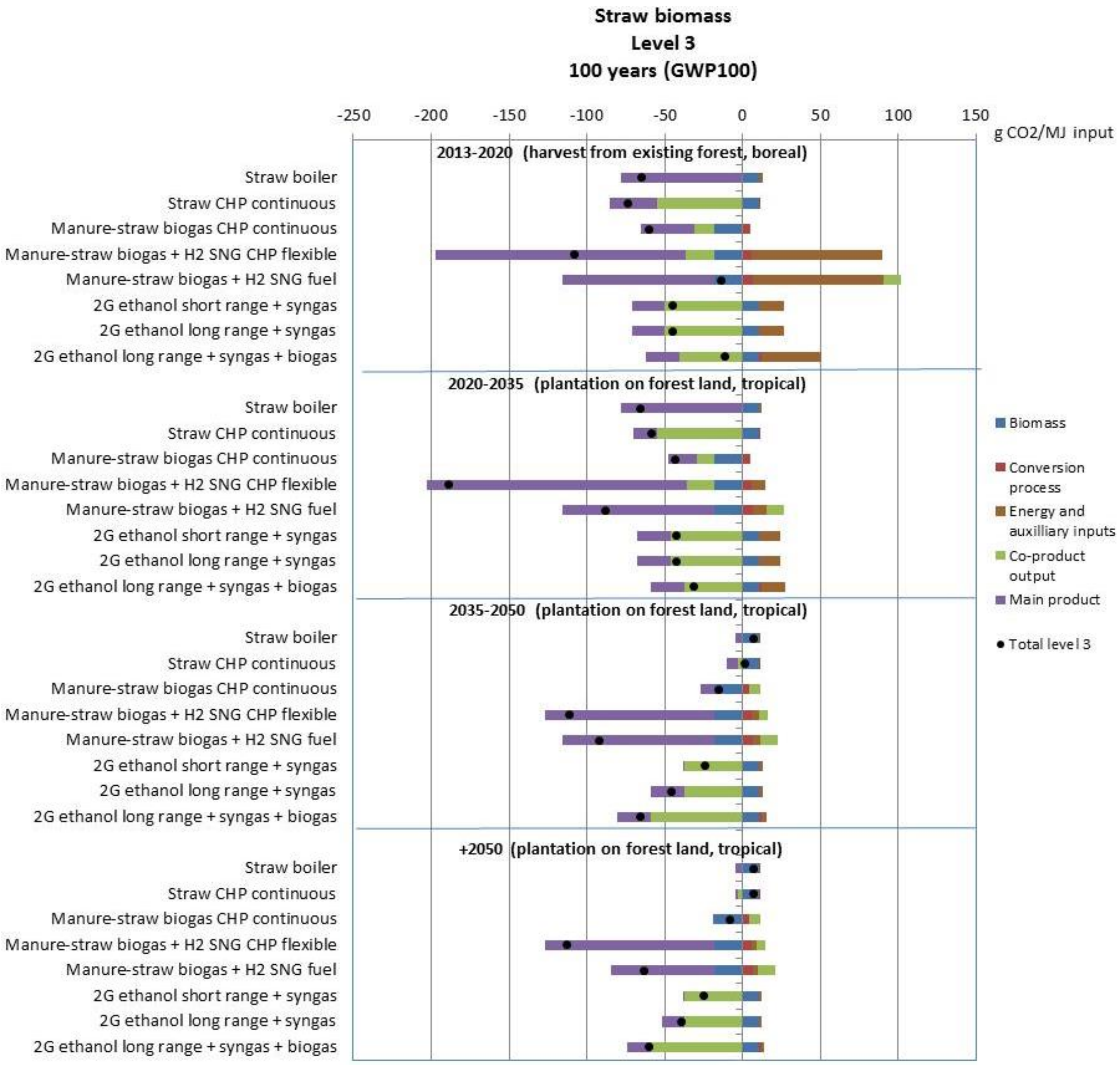


Figure 5-46 Comparing straw biomass pathways at level 3 in the 100y horizon

From Figure 5-43 to Figure 5-46, it is seen that biogas may have a slightly lower carbon footprint than the ethanol pathways, but that they are both performing quite well and better than the combustion pathways. Moreover, the difference between the mono-digestion and co-digestion pathway is more or less eliminated, because level 3 shows result per MJ input, thus allowing for a better comparison and prioritization. What this comparison at level 3 does not support is, however, an understanding of the implication of soil carbon equivalence between pathways, as described under the section on uncertainty and sensitivity. This is, however, revealed in the next section on the level 4 comparisons.

5.8 Overview of results from individual conversion pathways

Table 5-1 Overview of carbon footprint totals at Level 2 for the 100 year time horizon, GWP 100

Pathway	Unit	2013 – 2020				2020 – 2035				2035 – 2050		2050+	
		Thinning residues, tropical	Plantation on tropical grassland, low ILUC	Plantation on temperate cropland, high ILUC	Harvest from existing boreal forest	Plantation on savannah, low C-stock	Plantation on savannah, high C-stock	Plantation on tropical grassland, high ILUC	Plantation on tropical forest land	Plantation on savannah, high C-stock	Plantation on tropical forest land	Plantation on savannah, high C-stock	Plantation on tropical forest land
Heat													
Wood boiler	g CO2-eq./MJ output	1,4	-3,9	19,4	79,6	3,6	10,0	17,4	71,4	9,6	70,9	9,5	70,6
Straw boiler	g CO2-eq./MJ output	12,6	12,6	12,7	13,0	11,6	11,6	11,7	12,1	11,3	11,6	11,2	11,2
CHP continuous													
Wood CHP continuous	g CO2-eq./kWh output	-272,6	-317,8	-122,1	385,1	-235,2	-184,3	-124,9	307,8	59,9	519,9	58,1	503,5
Straw CHP continuous	g CO2-eq./kWh output	-558,2	-558,2	-558,2	-558,2	-558,2	-558,2	-558,2	-558,2	109,4	109,4	109,4	109,4
Manure biogas CHP continuous	g CO2-eq./kWh output	-904,7	-905,0	-903,7	-900,3	-863,2	-862,6	-861,9	-856,9	-636,2	-632,1	-637,6	-637,6
Manure-straw biogas CHP continuous	g CO2-eq./kWh output	-291,1	-291,2	-290,7	-289,5	-272,1	-271,9	-271,7	-270,0	-67,0	-65,8	-67,4	-67,4
CHP flexible													
Wood + H2 SNG CHP flexible	g CO2-eq./kWh output	-92,3	-142,0	76,4	642,2	-59,7	-2,9	63,5	546,7	80,4	630,0	80,4	630,0
Manure biogas + H2 SNG CHP flexible	g CO2-eq./kWh output	19,9	13,7	41,1	112,1	-336,9	-335,6	-334,1	-323,1	-363,8	-355,2	-366,6	-366,6
Manure-straw biogas + H2 SNG CHP flexible	g CO2-eq./kWh output	226,5	220,4	247,3	317,0	-134,7	-133,6	-132,4	-123,1	-18,3	-11,0	-20,6	-20,6
Fuels													
Wood + H2 methanol&DME	g CO2-eq./MJ output	25,7	20,5	43,3	102,5	-24,1	-18,8	-12,6	32,5	8,8	59,8	8,6	58,8
Manure biogas + H2 SNG fuel	g CO2-eq./MJ output	-17,3	-18,1	-14,7	-6,0	-65,8	-65,8	-65,9	-66,4	-65,3	-65,7	-65,2	-65,2
Manure-straw biogas + H2 SNG fuel	g CO2-eq./MJ output	60,8	59,9	63,8	74,1	6,2	6,3	6,5	7,9	3,4	4,5	3,0	3,0
2G ethanol short range + syngas	g CO2-eq./MJ output	65,8	76,5	29,5	-92,3	49,7	37,0	22,2	-85,6	27,7	-96,0	26,8	-99,6
2G ethanol long range + syngas	g CO2-eq./MJ output	65,8	76,5	29,5	-92,3	49,7	37,0	22,2	-85,6	27,7	-96,0	26,8	-99,6
2G ethanol long range + syngas + biogas	g CO2-eq./MJ output	144,6	151,7	120,4	39,4	63,0	53,3	42,1	-39,6	24,5	-176,3	23,5	-180,4

Table 5-2 Overview of carbon footprint totals at Level 3 for the 100 year time horizon, GWP 100

		2013 – 2020				**2020 – 2035**				**2035 – 2050**		**2050+**	
Pathway	Unit	Thinning residues, tropical	Plantation on tropical grassland, low ILUC	Plantation on temperate cropland, high ILUC	Harvest from existing boreal forest	Plantation on savannah, low C-stock	Plantation on savannah, high C-stock	Plantation on tropical grassland, high ILUC	Plantation on tropical forest land	Plantation on savannah, high C-stock	Plantation on tropical forest land	Plantation on savannah, high C-stock	Plantation on tropical forest land
Heat													
Wood boiler	g CO2-eq./MJ input	-73,3	-78,3	-56,2	1,0	-71,2	-65,2	-58,1	-6,8	5,0	63,2	4,9	62,9
Straw boiler	g CO2-eq./MJ input	-65,3	-65,3	-65,2	-64,9	-66,3	-66,3	-66,2	-65,8	6,8	7,1	6,7	6,7
CHP continuous													
Wood CHP continuous	g CO2-eq./MJ input	-66,7	-71,1	-51,6	-0,8	-39,6	-34,7	-28,9	12,9	3,3	53,6	5,7	63,7
Straw CHP continuous	g CO2-eq./MJ straw input	-68,3	-67,9	-69,6	-73,9	-51,2	-52,0	-52,8	-58,8	5,9	1,1	7,4	7,4
Manure biogas CHP continuous	g CO2-eq./MJ manure VS input	-75,0	-74,7	-75,9	-79,1	-61,8	-62,4	-63,0	-67,7	-44,9	-48,7	-43,7	-43,7
Manure-straw biogas CHP continuous	g CO2-eq./MJ straw input	-54,1	-53,7	-55,6	-60,4	-34,5	-35,4	-36,3	-43,4	-9,7	-15,5	-7,9	-7,9
CHP flexible													
Wood + H2 SNG CHP flexible	g CO2-eq./MJ input	-101,2	-106,3	-83,9	-26,0	-106,5	-100,3	-93,1	-40,8	0,6	1,6	0,2	0,2
Manure biogas + H2 SNG CHP flexible	g CO2-eq./MJ manure VS input	-101,0	-101,7	-98,6	-90,6	-147,5	-147,3	-147,2	-145,9	-46,4	-109,7	-46,7	-111,0
Manure-straw biogas + H2 SNG CHP flexible	g CO2-eq./MJ straw input	-123,3	-124,3	-119,8	-108,2	-190,5	-190,3	-190,1	-188,5	-17,1	-111,0	-17,5	-112,7
Fuels													
Wood + H2 methanol&DME	g CO2-eq./MJ input	-69,5	-75,5	-49,1	19,1	-127,0	-120,9	-113,7	-61,6	-89,0	-30,1	-	-
Manure biogas + H2 SNG fuel	g CO2-eq./MJ manure VS input	-60,5	-60,9	-58,9	-53,8	-88,8	-88,9	-88,9	-89,2	-43,2	-72,7	-43,2	-72,7
Manure-straw biogas + H2 SNG fuel	g CO2-eq./MJ straw input	-28,5	-29,5	-25,0	-13,4	-90,4	-90,2	-90,0	-88,4	-93,6	-92,3	-6,3	-63,3
2G ethanol short range + syngas	g CO2-eq./MJ input	-5,0	-2,3	-14,1	-44,5	-9,1	-12,2	-15,9	-42,9	6,6	-24,3	6,4	-25,2
2G ethanol long range + syngas	g CO2-eq./MJ input	-5,0	-2,3	-14,1	-44,5	-9,1	-12,2	-15,9	-42,9	-14,6	-45,5	4,6	-39,6
2G ethanol long range + syngas + biogas	g CO2-eq./MJ input	14,7	16,4	8,6	-11,6	-5,7	-8,1	-10,9	-31,4	-15,4	-65,5	3,7	-59,8

Table 5-3 Overview of carbon footprint totals at Level 2 for the 20 year time horizon, GWP 20

Pathway	Unit	2013 – 2020				2020 – 2035				2035 – 2050		2050+	
		Thinning residues, boreal	Plantation on tropical grassland, low ILUC	Plantation on temperate cropland, high ILUC	Harvest from existing boreal forest	Plantation on savannah, low C-stock	Plantation on savannah, high C-stock	Plantation on tropical grassland, high ILUC	Plantation on tropical forest land	Plantation on savannah, high C-stock	Plantation on tropical forest land	Plantation on savannah, high C-stock	Plantation on tropical forest land
Heat													
Wood boiler	g CO2-eq./MJ output	70,1	-17,6	33,1	163,1	15,3	46,0	88,4	406,2	45,6	405,1	45,3	403,2
Straw boiler	g CO2-eq./MJ output	26,1	25,7	25,9	26,5	24,8	25,0	25,3	27,5	24,6	26,3	24,3	24,3
CHP continuous													
Wood CHP continuous	g CO2-eq./kWh output	305,8	-432,7	-5,6	1.088,8	-141,1	101,7	444,3	2.989,5	330,3	3.026,7	319,8	2.931,2
Straw CHP continuous	g CO2-eq./kWh output	-391,0	-391,0	-391,0	-391,0	-391,0	-398,4	-391,0	-391,0	276,6	276,6	276,6	276,6
Manure biogas CHP continuous	g CO2-eq./kWh output	-1.196,6	-1.201,6	-1.198,7	-1.191,4	-1.144,9	-1.142,0	-1.138,1	-1.108,8	-904,7	-880,3	-908,4	-908,4
Manure-straw biogas CHP continuous	g CO2-eq./kWh output	-191,4	-193,2	-192,1	-189,4	-177,7	-176,8	-175,5	-165,7	23,8	31,2	22,7	22,7
CHP flexible													
Wood + H2 SNG CHP flexible	g CO2-eq./kWh output	552,9	-271,0	205,5	1.426,5	44,5	319,3	698,3	3.541,1	402,5	3.624,3	402,5	3.624,3
Manure biogas + H2 SNG CHP flexible	g CO2-eq./kWh output	-171,4	-274,8	-215,0	-61,8	-579,9	-573,6	-565,0	-500,6	-604,1	-553,5	-612,0	-612,0
Manure-straw biogas + H2 SNG CHP flexible	g CO2-eq./kWh output	380,7	279,2	337,9	488,3	-60,8	-55,6	-48,4	5,9	57,9	100,5	51,3	51,3
Fuels													
Wood + H2 methanol&DME	g CO2-eq./MJ output	93,2	7,0	56,8	184,5	-14,4	11,3	46,7	312,0	38,7	337,6	38,0	332,6
Manure biogas + H2 SNG fuel	g CO2-eq./MJ output	-109,2	-121,9	-114,6	-95,7	-167,7	-168,0	-168,4	-171,2	-167,4	-169,6	-167,1	-167,1
Manure-straw biogas + H2 SNG fuel	g CO2-eq./MJ output	84,8	69,8	78,5	100,6	18,7	19,5	20,6	28,9	16,3	22,8	15,3	15,3
2G ethanol short range + syngas	g CO2-eq./MJ output	-21,0	156,3	53,7	-209,1	78,4	17,1	-67,4	-701,3	7,2	-718,2	4,7	-736,5
2G ethanol long range + syngas	g CO2-eq./MJ output	-21,0	156,3	53,7	-209,1	78,4	17,1	-67,4	-701,3	7,2	-718,2	4,7	-736,5
2G ethanol long range + syngas + biogas	g CO2-eq./MJ output	112,4	230,3	162,1	-12,6	105,5	59,0	-5,1	-485,9	-33,1	-1.209,7	-679,9	-1.230,8

Table 5-4 Overview of carbon footprint totals at Level 3 for the 20 year time horizon, GWP 20

Pathway	Unit	2013 – 2020				2020 – 2035				2035 – 2050		2050+	
		Thinning residues, boreal	Plantation on tropical grassland, low ILUC	Plantation on temperate cropland, high ILUC	Harvest from existing boreal forest	Plantation on savannah, low C-stock	Plantation on savannah, high C-stock	Plantation on tropical grassland, high ILUC	Plantation on tropical forest land	Plantation on savannah, high C-stock	Plantation on tropical forest land	Plantation on savannah, high C-stock	Plantation on tropical forest land
Heat													
Wood boiler	g CO2-eq./MJ input	-8,0	-91,4	-43,2	80,3	-60,1	-31,0	9,3	311,2	39,1	380,6	38,9	378,9
Straw boiler	g CO2-eq./MJ input	-52,0	-52,4	-52,1	-51,6	-53,2	-53,0	-52,7	-50,6	20,0	21,7	19,7	19,7
CHP continuous													
Wood CHP continuous	g CO2-eq./MJ input	-8,8	-82,7	-40,0	69,5	-30,6	-6,8	26,0	272,2	32,8	327,5	39,7	379,7
Straw CHP continuous	g CO2-eq./MJ straw input	-60,3	-53,9	-57,6	-67,0	-39,6	-43,0	-47,7	-83,2	16,1	-11,9	20,4	20,4
Manure biogas CHP continuous	g CO2-eq./MJ manure VS input	-96,8	-92,1	-94,8	-101,7	-81,0	-83,6	-87,3	-114,7	-65,3	-87,9	-61,8	-61,8
Manure-straw biogas CHP continuous	g CO2-eq./MJ straw input	-51,0	-43,9	-48,0	-58,4	-27,4	-31,4	-36,9	-78,3	-4,4	-38,4	0,8	0,8
CHP flexible													
Wood + H2 SNG CHP flexible	g CO2-eq./MJ input	-35,1	-119,5	-70,7	54,3	-95,2	-65,4	-24,4	283,2	1,2	7,1	0,2	0,2
Manure biogas + H2 SNG CHP flexible	g CO2-eq./MJ manure VS input	-107,6	-119,2	-112,5	-95,2	-163,0	-162,3	-161,2	-153,7	-99,3	-470,4	-100,2	-477,2
Manure-straw biogas + H2 SNG CHP flexible	g CO2-eq./MJ straw input	-97,5	-114,5	-104,7	-79,6	-177,7	-176,8	-175,5	-166,1	-59,7	-610,3	-60,8	-618,9
Fuels													
Wood + H2 methanol&DME	g CO2-eq./MJ input	8,4	-91,0	-33,5	113,8	-115,8	-86,1	-45,3	261,0	-54,5	290,5	-	-
Manure biogas + H2 SNG fuel	g CO2-eq./MJ manure VS input	-114,3	-121,7	-117,4	-106,4	-148,6	-148,7	-148,9	-150,6	-120,2	-292,7	-120,2	-292,7
Manure-straw biogas + H2 SNG fuel	g CO2-eq./MJ straw input	-1,3	-18,2	-8,4	16,7	-76,2	-75,2	-74,0	-64,6	-78,9	-71,5	-25,8	-359,8
2G ethanol short range + syngas	g CO2-eq./MJ input	-26,7	17,6	-8,0	-73,7	-1,9	-17,2	-38,3	-196,8	1,5	-179,9	0,9	-184,4
2G ethanol long range + syngas	g CO2-eq./MJ input	-26,7	17,6	-8,0	-73,7	-1,9	-17,2	-38,3	-196,8	-19,7	-201,0	-8,3	-267,3
2G ethanol long range + syngas + biogas	g CO2-eq./MJ input	6,6	36,1	19,1	-24,6	4,9	-6,7	-22,8	-143,0	-29,7	-323,9	-179,5	-390,9

5.9 Key conversion pathway assumptions, uncertainties and sensitivity

Overall scope: The most essential parts of the biomass conversion pathway systems are included. The biomass supply is the dominant source of GHG emissions, and it is dealt with in a holistic way, striving to include direct as well as indirect effects (DLUC and ILUC). Both high and low estimates on ILUC have been included, and the DLUC of land conversion has been expressed in both a 20y and 100y time horizon. The time and scale dependency of biomass marginal has been elaborated and candidates for biomass marginal identified in a transparent way.

The future variations of the energy system marginals have been considered and an elaborate approach taken to assessing conversion pathways against varying energy system marginals.

System expansion on co-product outputs including varying assumptions on the fate of these (in the 2G ethanol case) have been done, and on level 3, also system expansion on the alternative displaced by the main product output from the pathway is done.

However, there are also parts of the systems which have been omitted.

Capital goods: Capital goods are included in parts of the systems, but not all. As described earlier, however, there is documentation that capital goods do not contribute significantly in systems like this. An illustration of this can be seen from the fact that wind power production has a much lower carbon footprint than the fossil and many biomass pathways have. As shown in the many result Figures, the significance of a co-product or main product displacing a wind power based alternative is very small. The same insignificance is found within any individual pathway – maybe except solar cell production – and for e.g. a large CHP plant, the construction and demolition of the plant will have minor contribution compared to the life time emissions from operating the plant. Another way to look at this is the energy payback time of the plant. For a wind turbine, this is today less than a year, and the same holds true for CHP plants, boilers etc.

Transport: Transport has been omitted. In order to show the significance of this omission, a small sensitivity check has been carried out. If biomass is transported from South America by ship and by truck from a Danish harbor, assuming 12,000 km of ship transport and 200 km of truck transport, we get the following data on energy consumption and GHG emission:

- 0,086 MJ fuel/MJ biomass transported, if the fuel is oil
- 1,7 g CO_2-eq./MJ biomass transported, if the fuel is oil

This confirms our experience that transport of fuels is insignificant in an energy system or energy conversion pathway carbon footprint.

Biomass marginals: Several approaches to identifying candidates for being the biomass marginal for an incremental Danish demand on the international market for solid biofuels have been included. The outcome of the GLOBIOM model is found to be quite unambiguous in the way it points to the key candidates for a large scale biomass demand in the longer term future.

Energy system marginals: The study is, as mentioned, quite elaborate on identifying varying energy system marginal on heat, continuous power, flexible power (input and output), and short and long range transport fuels. Due to time constraints, however, some potential marginals, have been omitted. This concerns the choice of the time period in which a flexible power marginal changes from a mixed or average to e.g. wind power. A choice has been taken here that reflects a belief the pace of penetration of wind power into the system and the pace of building larger heat storage capacities. However, situations reflecting other developments over time can most probably be seen from the results figures in one or more of the time periods. It also concerns, for example, the inclusion of import/export of electricity, i.e. the fact that also in the longer term future, the marginal electricity may be fossil, if traded across the border. But also this situation can been extracted from the result figures by looking at an early time period in which the marginal is in fact fossil.

Conversion process data: The uncertainty on conversion process data e.g. in terms of conversion efficiencies on electricity, heat and transport fuels is believed to mean only little in most pathways. The key issue will almost always be the assumptions on the origin of the biomass, and the nature of the displaced energy system marginal from the co-products and main product outputs. For a few of the pathways, however, there are some key issues.

For the biogas conversion pathways, methane emissions are found to be of high significance. We have set the methane emission to be 1% of total methane production in the conversion including any upgrading by hydrogen. State-of-the-art technology is probably more like 2% from a gas engine and 1% diffuse emissions from the biogas facility. Assuming this would very significantly influence the carbon footprint of the biogas pathways. In the future, however, such emissions are believed to be reduced significantly. The standard for manure storage (including digestate storage) may soon be concrete cover/lid on the storage tank. This is already required by law in The Netherlands and may derive as a future requirement from the ongoing revision of the BREF document for Intensive Rearing of Pigs and Poultry. Moreover, the future SNG conversion may be in fuel cells or other technology with a much lower emission that today’s gas engines.

As already mentioned, the 2G Ethanol yield assumptions may be optimistic. The first full scale 2G facility was taken into operation in Italy this year, and the reported yield is about 26% ethanol (MJ ethanol : MJ straw), which is the same as we have assumed here, but in the Italian process, the molasses fraction is internally converted to ethanol, and the majority of the lignin is used for heat. So there is almost no co-products. This will change the carbon footprint of the 2G ethanol significantly. From the result figures, it can immediately be seen what the implication of not having the co-products would be.

Manure management: In the biogas pathways, the avoided conventional manure management is dominating – or rather the net difference between the carbon footprint of the conventional manure management and the digestate management. We have used the latest IPCC consensus data for these models. Methane emissions comprise around 60% of the net benefit related to this shift in manure management, whereas N_2O emissions comprise 40%. The uncertainty on N_2O emission estimates is found to be very large, around 300% according to IPCC, but on methane emissions they are much smaller. We find it well documented that there is a large emission reduction when taking the manure through biogas. In a fully renewable energy system, this GHG emission aspect becomes quite significant, see the section on energy system scenarios.

It has been decided to account for GHG emissions in both a 20y and a 100y time horizon, i.e. annualizing emissions over 20 and 100 years and normalizing them to the biomass harvested from the land use in question over this same time period. In doing that, we have refrained from going into more sophisticated dynamic accounting models, as there seem to be no consensus on the influence of time variations of emissions on the climate and temperature impacts (IPCC AR5, 2013). We have, thus, found it best to just include the conventional GPW20 and GWP 100 impact assessment approach to express data in a 20 and 100 year time horizon.

Omitting other impact categories implies, of course, that caution should be taken in the interpretation of the results from this study as an *environmental* assessment. This, however, is more important for some impact categories than for others. For the traditionally energy system related impacts categories like acidification (from NO_x and SO_2 emissions), nutrient enrichment (from NH_3, NO_3, NO_x and P emissions), photochemical ozone formation (from hydrocarbon emissions and NO_x) and particles, we believe the caution to be lower. This relates to the character of the decisions to be supported by this study. The study is meant for strategic decisions on the longer term design of the Danish energy system. The aspects of the above mentioned types of environmental impact are typically handled at a later stage, when facilities are implemented and is dealt with by flue gas treatment, wastewater treatment etc. GHG emissions, on the other hand, relate more to the backbone – or conceptual design and resource dependency – of the system, unless of course the strategy is to follow a carbon capture and storage approach, which it is not in Denmark, following as we do a renewable energy approach.

A few other impact categories/concerns do, however, call for high caution, especially the aspect of biodiversity impacts and the concern for supply security. If, as we have found, one of the most probably candidates for a larger scale and longer term biomass supply is indeed plantation on savannah and other similar biomes, the issue of biodiversity may well prove to be a more decisive concern than global warming. Especially as the carbon footprint from plantation on the savannah in a longer time perspective is not that large, i.e. around 9 g CO_2-eq./MJ in a 100 year perspective and even lower in a longer perspective. We recommend looking further into this issue before designing the Danish energy system for a large long term dependency on such biomass provision.

In each case, the pathways will be compared under two different sets of biomass marginals, in order to reveal the dependency of the comparison on the assumption of marginal biomass. In Appendix I, an even more elaborate comparison is made, including in all four set of assumptions on the biomass marginal. The two sets, selected here, cover the range of high and low carbon footprint marginal.

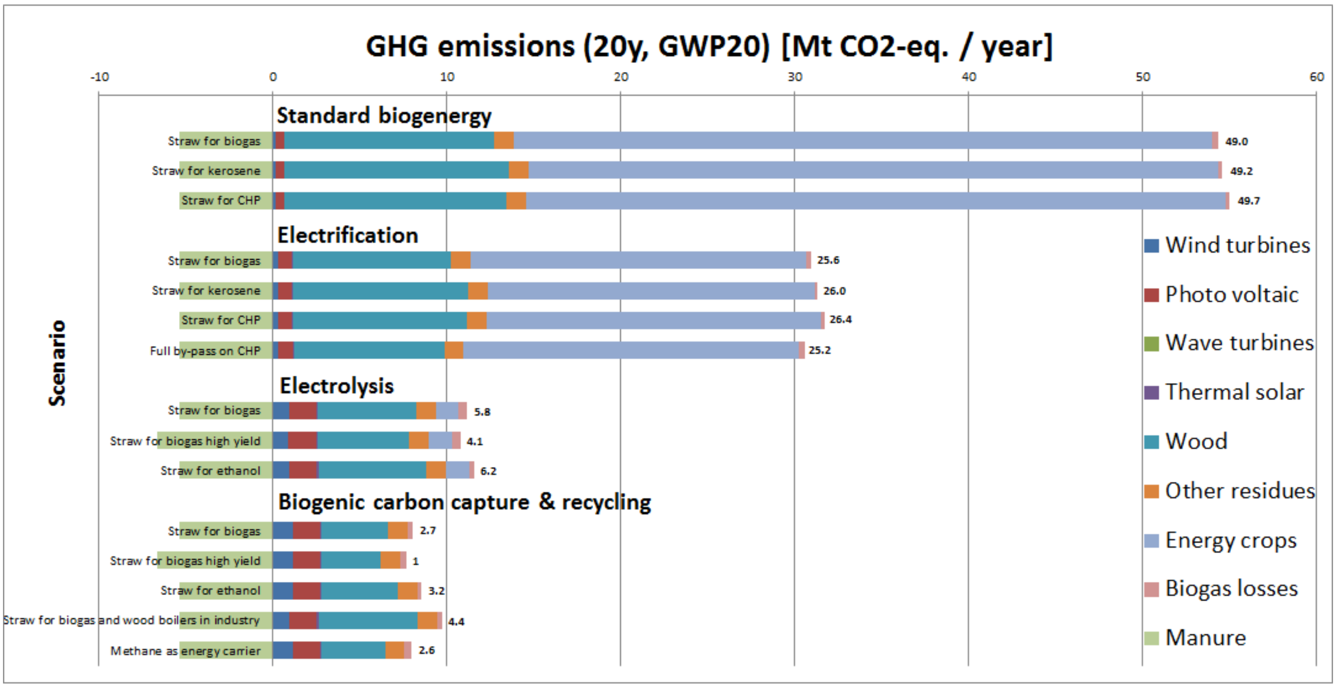
5.10 Comparing full systems design – level 4

Based on emission factors determined either in level 3 or found in the tables above, as well as the supplementary emissions factors presented in Table 4-1, it is possible to quantify the whole-system emission of GHG under different conditions. In the event that wood marginal is found to be plantation on savannah, the GHG emission of each of the whole-system designs is given in Figure 5-47. Compared to the GHG emission of a Danish fossil energy system, which is found to be around 70 Mt CO_2-eq. / year in 2050, all renewable energy systems perform better, albeit both the standard bioenergy and the electrification scenarios come quite close to this projected fossil system. It is also evident that the increased emission of GHGs in the standard bioenergy and electrification scenarios is predominantly linked to the use of energy crops, whereas an increase in the consumption of wood only brings about a minor increase in the release of GHG in the case of the biomass marginal being plantation on savannah.

In Figure 5-48 the GHG emission of the 15 alternative scenarios is given with the assumption that the wood marginal is a plantation on tropical forest lands. In contrast to the results from the marginal wood from plantation on savannah discussed above, the GHG emissions from the consumption of wood are in this case predominant in all scenarios and the emission of GHG, measured as GWP20 in a 20 year time horizon, is in the standard bioenergy and electrification scenarios higher than that of a fossil energy system.

It should be noted that a high end emission factor was assumed for the photovoltaic electricity production, and even so this contributes only minor to total electricity supply in the systems, the GHG emission contribution from it is significant. This emission is due to speciality chemicals with a very high CO2 equivalence factor, and the probability is, of course, that the use of such chemicals is eliminated before 2050.

In Figure 5-49 the excess electricity, RES, hydrogen, 20 year GWP 20 and 100 year GWP 100 in each of the scenarios is depictured as a function of biomass consumption. It is evident that with increasing bioenergy demand, the penetration of RES drops, while the emission of greenhouse gasses rises. This is true regardless of the choice of marginal land for wood. A substantial reduction in the emission of greenhouse gases can only be achieved reducing the biomass demand considerably.



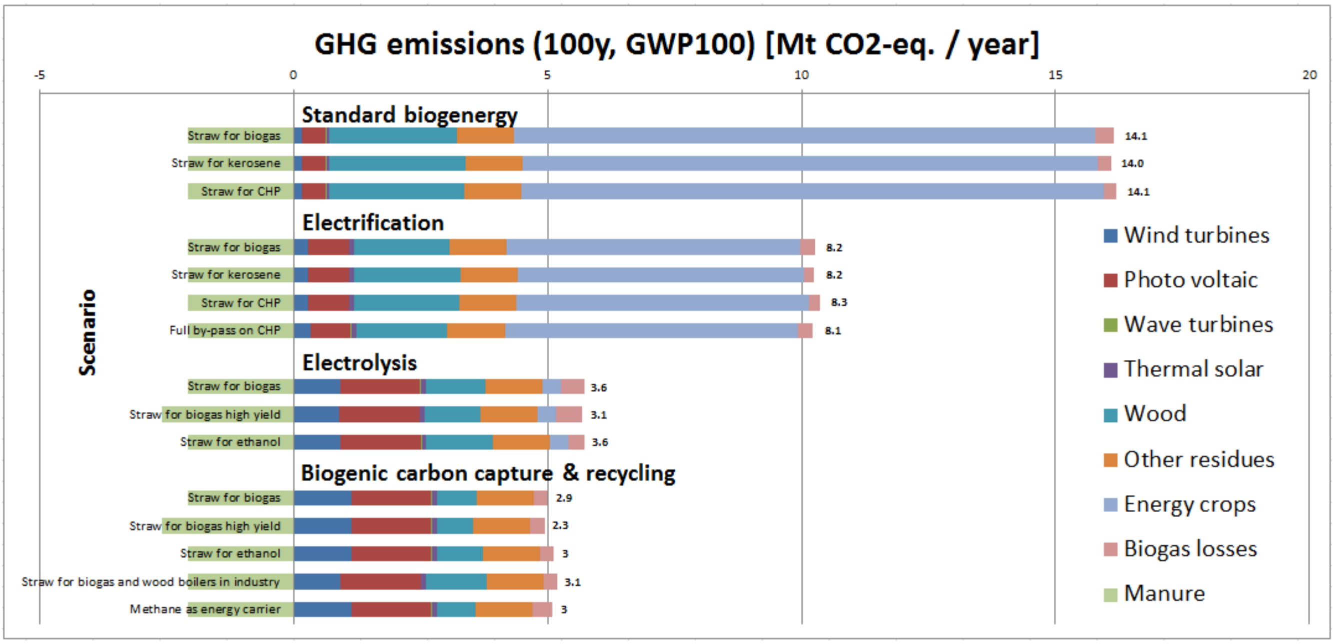
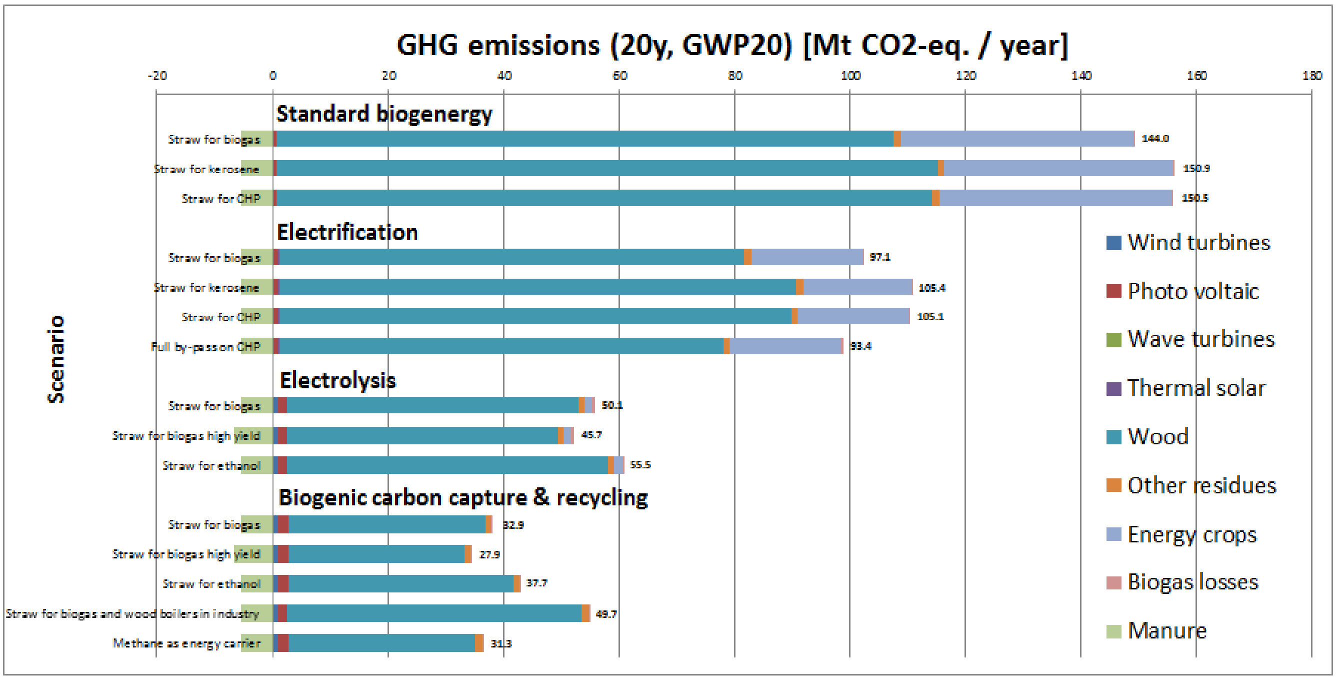


Figure 5-47 *Carbon footprint assessment of the renewable energy system designs for the Danish energy system 2050. Wood marginal assumed to be plantation on savannah with a high carbon stock*



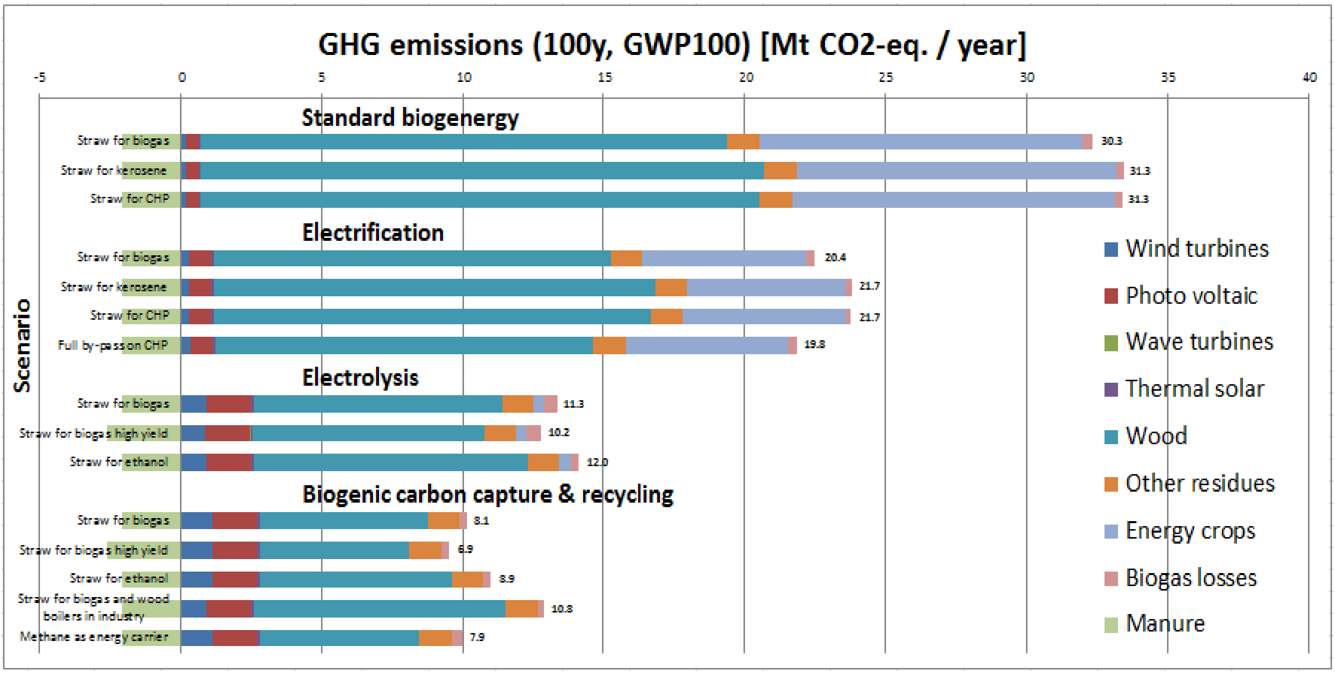
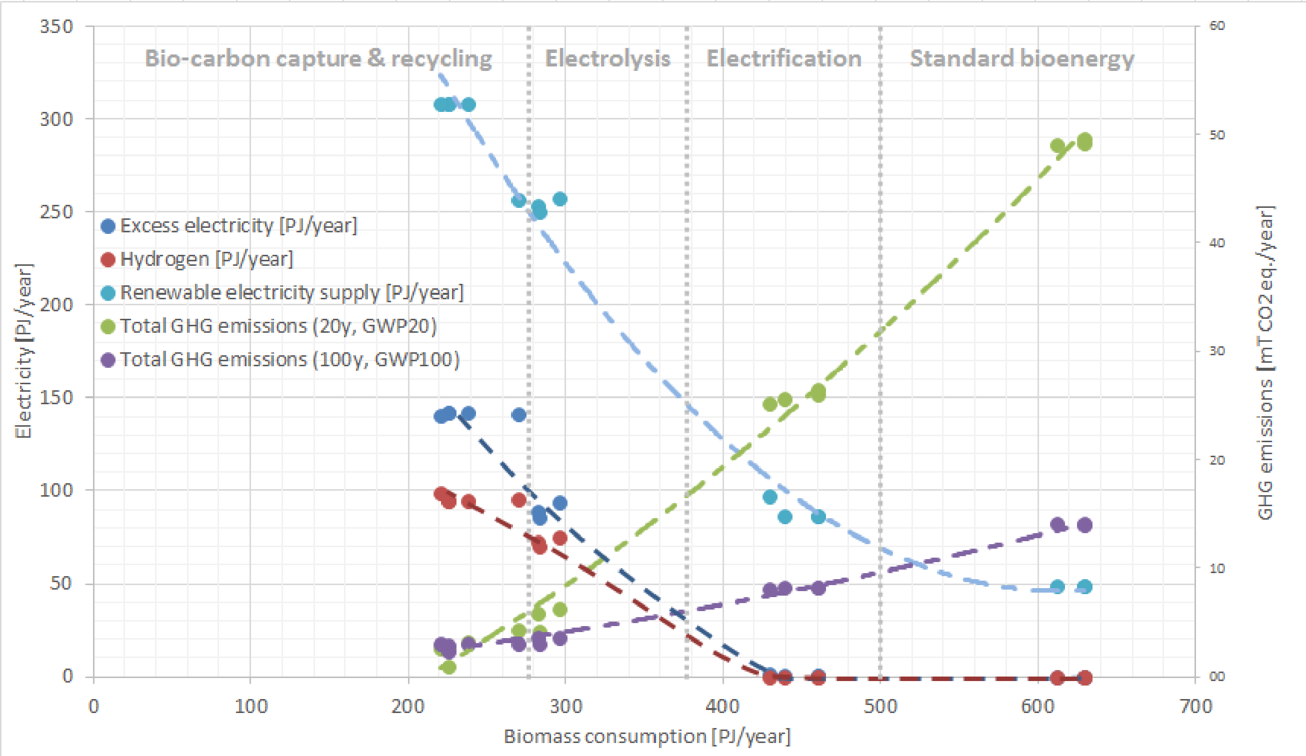


Figure 5-48. *Carbon footprint assessment of the renewable energy system designs for the Danish energy system 2050. Wood marginal assumed to be plantation on tropical forest land*



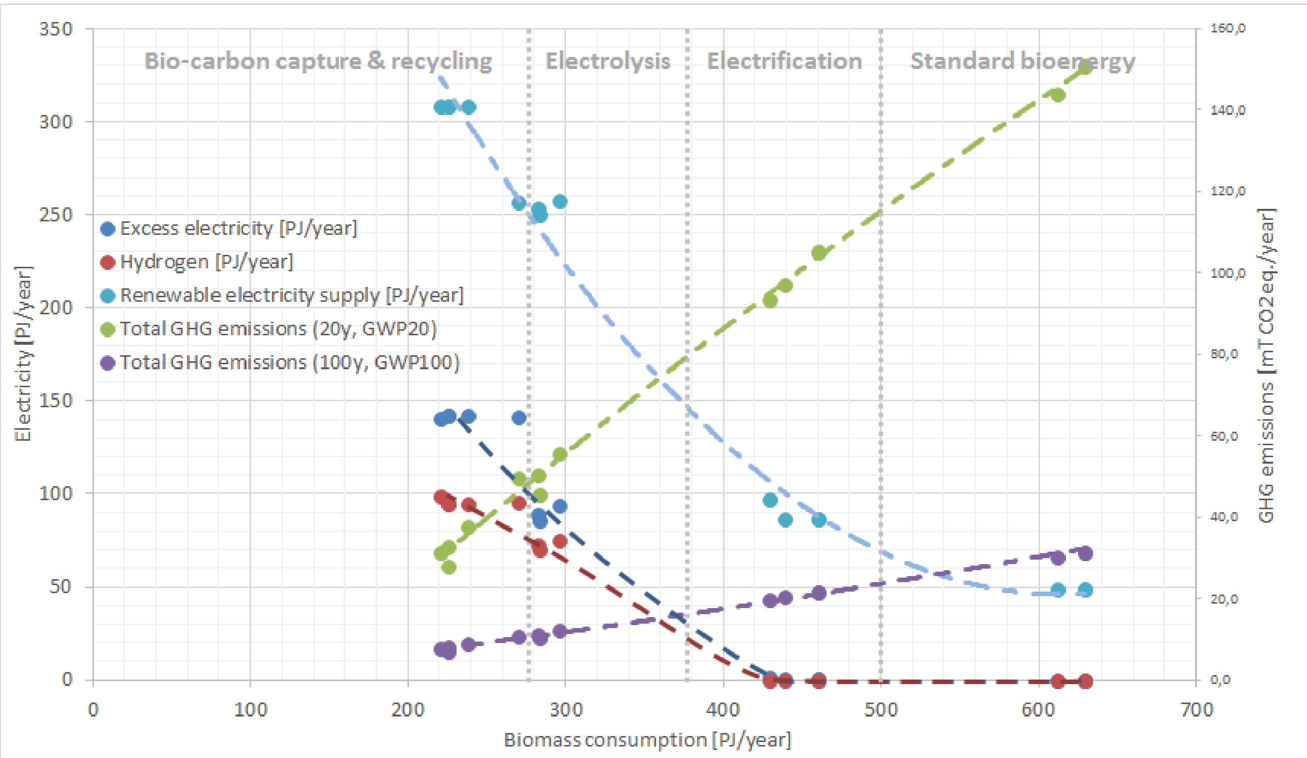


Figure 5-49 *Total renewable electricity supply (RES), Excess electricity (=RES minus conventional consumption – approximately equal to electrolysis input), , hydrogen,20 year GWP 20 and 100 year GWP 100 as a function of bioenergy demand*

6 Interpretation

In conclusion, the carbon footprint of bioenergy per functional output is found to vary greatly. At one end, woody biomass from deforestation may under certain conditions emit more GHG per delivered MJ than the relevant fossil fuel comparator, whereas some pathways assuming plantation on low-carbon land may result in net removal of GHG from the atmosphere.

The main determinants of the footprint have been found to be:

- the nature and origin of the marginal biomass supply which in turn is judged to depend on background conditions, such as the global scale of biomass demand and the type and enforcement of land governance and GHG emission governance, and

- the nature and composition of the energy system in which the biomass conversion pathway is applied

As a result of these contextual dependencies, the footprints also vary over time, as e.g. the energy system develops and changes. A pathway and biomass type attractive in the near future may therefore very well become less attractive at a later point in time within the studied time frame.

6.1.1 Summarizing key aspects of the scope and assumptions of the study

It is part of the goal definition of the study to assess the carbon footprint of the various bioenergy pathways as applied in the changing Danish energy system as defined by the aforementioned milestones in the Danish energy policy. This development of the energy system is, thus, a key assumption in the study, and it is essential to the results.

The global-scale bioenergy demand has been assumed to develop towards a demand range of 100 – 200 EJ/year or more by 2050, corresponding to around 10 – 20 GJ/person/year with an estimate of above 9 billion people on Earth by 2050. This development of the global demand represents a background scenario with increasing global interest in bioenergy, assuming the world adapting a climate agenda aiming to stay below 2 degree C temperature increase and/or assuming increasing cost of fossil fuels rendering bioenergy more attractive. Against this scenario, the per capita Danish biomass demand for a fully renewable energy system will be comparatively higher, i.e. 45 – 120 GJ/person/year, and to depend on the degree of sophistication of the energy and transport system infrastructure as follows:

- 120 GJ/person/year in a renewable energy system of a 'conventional' infrastructure, i.e. in a system without significant electricity storage or electrochemical electricity conversion and without significant electrification of heat and transport infrastructure, and in which biomass is used for heat and power (in boilers and conventional combustion CHP and PP plants) and in transport (conventional biofuels, i.e. 1G biodiesel and 1G ethanol)

- 90 GJ/person/year in a more advanced system involving a maximum degree of electrification of transport (electric trains and battery cars for short distance person transport on road) and heat (heat pumps for almost all individual heating and district heating), as the electrification allows a higher share of wind and other renewable power production in the system. Biomass is in this system used in power production (conventional combustion CHP and PP plants) and transport (conventional biofuels)

- 60 GJ/person/year in the even more advanced system, in which hydrogen is used as a system integrator in power-to-gas or power-to-liquid-fuel scenarios through electrolysis. The reduced biomass demand in this system is due to a high degree of synergy in using excess fluctuating power for electrolysis, using the produced hydrogen to upgrade bio-carbon to energy dense fuels like methane or methanol, and using the waste heat of electrolysis, of biomass-to-fuel conversion (like thermal gasification) and of bio-C hydrogenation for heating purposes. Biomass is in this system prioritized for biogas fermentation and thermal gasification, and biogas and syngas are upgraded by hydrogen to methane or liquid fuels for transport. Very little biomass for combustion CHP, PP and boilers.

- 45 GJ/person/year in the most advanced system design, in which bio-C is further captured (as CO_2) from stationary facilities like fuel cells for flexible power production and hydrogenated again to methane or liquid fuels, thereby recycling part of the bio-C. Biomass is also in this system prioritized for biogas fermentation and thermal gasification, and biogas and syngas are upgraded by hydrogen to methane or liquid fuels for transport. Very little biomass for combustion CHP, PP and boilers. This system implies a demand for hydrogen as high as 20 GJ H_2/person/year.

These acknowledgements of the scale of biomass demand in design of a Danish renewable energy system are in line with the findings of a range of similar studies carried out by the Danish Energy Agency, the Danish electricity transmission system operator (energinet.dk), the Danish Climate Commission and a consortium of leading Danish universities in renewable energy system solutions (Lund et al., 2011).

6.1.2 Interpretation related to each main biomass category

The key biomass resources for a Danish renewable energy strategy, assessed in this study, are domestic agricultural residues of manure and straw, and domestic and imported woody biomass:

6.1.3 Manure conversion pathways (biogas)

The GHG emissions from using manure for energy through biogas conversion are net negative or close to zero throughout all time periods and irrespective of the dependencies on the energy system. The reason for this is that emissions of methane from storage and N_2O from storage and field application are larger for raw manure than from biogas digestate. From a carbon footprint perspective, therefore, using manure for biogas is attractive, and as the results of this study show, manure biogas conversion pathways in all cases come out with a carbon footprint in the lowest end compared to all other alternatives. This conclusion is found to be robust, but it should be noted that the benefit may decrease somewhat, as GHG emissions from both raw manure and digestate management may decrease in the future due to cleaner technology and better emission control from both storage and field application.

The carbon footprint of manure biogas does depend on the nature of the energy system and the global woody biomass marginal, as it is evident that it becomes less beneficial – for GHG reduction – to produce electricity and heat from biogas on a continuous basis as the wind power share of electricity increases. At some point, the benefit of converting biogas to pure methane as SNG, either by removing or hydrogenating CO_2 and storing it for the use in flexible power production or transport becomes very significant. Assuming the Danish energy policy milestone plan, this will be the case already after 2020. The reason for this is two-fold: firstly due to the *decreasing* GHG benefit of avoiding continuous power production compared to avoiding flexible power production or transport fuel, secondly due to the *increasing* GHG benefit of flexible power consumption by electrolysis, as this can derive increasingly from wind power.

A total of 1 % emission of produced methane throughout all conversion processes including fermentation and upgrading or CHP production has been assumed in the analysis. This emission can, however, at present reach levels around 2 % being reported as average (Nielsen et al., 2007) and up to 4 % in worst case, and this will significantly increase the carbon footprint from biogas conversion. It is, however, assumed that by future emission control and reduction from biogas reactors and of engines and fuel cells, total process emissions can be kept at levels of 1 % or below.

6.1.4 Straw conversion pathways

When straw residues are ploughed down, a part of the carbon stays in the soil, i.e. around 10-15% in a long term perspective. Incorporating straw carbon into the soil is the marginal alternative to using it for energy, which is reflected in the carbon footprint of straw, calculated at 24 g CO_2-eq./MJ in the 20 year horizon and 11 g CO_2-eq./MJ in the 100 year horizon. It is, however, important to note that this is very significantly reduced when the straw is used in a fermentation pathway that allows the hard bio-degradable part of the straw carbon to go back to the soil – as it does in case of using straw in biogas conversion e.g. as co-digestion with manure. Around 75% of the soil carbon will, in this case, be maintained compared to ploughing down the raw straw. This is a significant difference from using the straw in combustion or gasification pathways in which no carbon goes back to soil. In the whole-system designs, it is assumed that the functional output of the whole system includes maintaining a constant (and sufficient) soil carbon level. This approach renders the available straw potential (for energy purposes) a function of the conversion pathway. The straw available for energy in Denmark was, thus, found to vary significantly: when using the straw in biogas conversion, the Danish potential available for energy was around 50 PJ/year, whereas the potential was only 12.5 PJ/year when taking straw through combustion for CHP – as the balance of 37.5 PJ/year would have to be ploughed down directly in the CHP scenarios in order to maintain the same soil carbon level as in the biogas scenarios.

Comparing the use of straw for biogas and 2G ethanol, indicates the carbon footprint of the biogas co-digestion with manure pathways to be lower than the 2G ethanol pathway. The reason for this is two-fold. One reason is that the use of straw to add more carbon to the very dilute manure in practice makes it possible to get more manure into biogas, i.e. the conventional storage and field application of manure is assumed as an avoided marginal of using straw in biogas co-digestion with manure. Another reason is that the ethanol pathway has a somewhat lower fermentation yield plus a use of thermal energy for distillation, compared to biogas for which the gas escapes the liquor without any energy demand. Moreover, the manure-straw biogas pathways inherently ensures that the digestate, including the non-degraded straw, goes back to soil, which is possible but not equally likely in the case of the 2G ethanol pathway. It should be noted, however, that 2G ethanol & biogas combination with manure-straw co-fermentation is also an option (under implementation in Denmark, 2014). This pathway was not included in the study.

Prioritizing straw conversion pathways, there is a significant dependency on the nature and composition of the energy system in which the pathway is applied. As long as the district heating marginal and continuous power marginal are mainly based on fossil fuels, there is still a large GHG benefit of using straw in boilers and conventional combustion CHP and PP plants. But this benefit largely falls away, when the system marginals for heat and continuous power become increasingly based on wind power.

6.1.5 Wood conversion pathways

A relatively large potential, compared to today's scale of global, commercial bioenergy demand, exist for optimizing forestry for multiple outputs, i.e. increasing the biomass yield and using more thinnings and other biomass co-products from higher value timber production. Except for boreal forest thinnings in the 20 year horizon, thinning residues has a carbon footprint close to zero, and if forest intensification can become part of the response to a Danish biomass demand, the carbon footprint from this part becomes even negative.

Based on the scale of biomass harvest from forestry for timber, however, the limits of the scale at which thinnings and yield intensification of multi-output forestry can be the marginal biomass supply for bioenergy is judged to be around 5-10 EJ/year. Beyond this scale, increased biomass demand is judged more likely to derive from single-output short-rotation plantations, because the markets for the higher value products from multi-output forestry will, then, be saturated.

Developing an increasing market for wood pellets or chips, however, also call for caution, if it is to be avoided that woody biomass of other origin with higher carbon footprint enter the market, such as plantation on agricultural cropland or harvest from existing forest.

Plantation on cropland has become part of the marginal biomass supply for bioenergy policies already, e.g. in the case of biogas policies in both Denmark and Germany. In these policies, energy crops are allowed as part of the input – at a scale implying that the majority of the produced biogas may derive from the crop. If there is no regulation preventing this from happening, a similar situation may arise also for woody biomass, i.e. that woody energy crops from agriculture to some extent enter the wood pellet or wood chip market. On the other hand, a conscious policy of increasing the agricultural carbon stock by planting carbon rich, above and below ground, woody energy crops (e.g. miscanthus) at the expense of lower carbon stock/lower yield food or feed crops (e.g. barley) may result in a relatively small carbon footprint even including an ILUC factor. There is, however, still a large uncertainty involved in the estimation of such ILUC effects.

Regarding roundwood harvest from existing forest, statistics show that a minor but not negligible share finds use for energy purposes either directly as fuel wood in a household boiler, as chips or at wood pellet plants, predominantly when traded locally. This cannot be explained from a long term economic optimization perspective of a well-managed forest, as the profit margin of the higher value roundwood production for timber is much larger than for wood fuel, and it thus indicates that shorter term or private economy considerations, inheritance or self-dependency may guide management and harvest decisions for some forest owners. It also indicates that the price signal on a global international market may not direct local or informal wood markets in certain locations. As a result, this biomass may find its way to the global market, implying in this case a high carbon footprint, and that this implication should be given attention when discussing wood conversion pathways.

Balancing the findings, thinning and harvesting residues together with forest intensification are found to be able to constitute the predominant biomass supply on the shorter term up to a scale of 5-10 EJ/year of commercial global bioenergy demand, when supported by a conscious policy and governance for ensuring it. Also above 5-10 EJ/year of global biomass demand for bioenergy, there are still options for biomass supply hand-in-hand with increasing carbon stocks. Plantations on low carbon grassland, or intensifying grass yields, are such options likely to be candidates for a marginal biomass supply. Together with a policy of intensifying animal production and including ILUC from displaced animal grazing, it is found that the carbon footprint of supplying biomass from such plantation can be quite low, even though there is a risk of a high carbon footprint if displacing future high yielding tropical grasslands. Looking at the simulation results of the partial equilibrium econometric model, GLOBIOM, it is found that framework conditions of CO_2 price from 0 to 50 US$/ton and biomass prices from 1.5 to 5 US$/GJ from an economic perspective will limit the supply of biomass from plantation on grassland to something between 10 and below 40 EJ/year (on top of the supply of thinning and harvesting residues). Further, in a gradual development towards a global commercial biomass demand of just above 100 EJ/year in 2050, this limit will be reached somewhere between 2020 and 2030.

Therefore, at a scale of global commercial biomass demand for bioenergy of 50 EJ/year and beyond, plantation on other land like savannah is a more likely candidate for being the biomass marginal supply. The carbon footprint of biomass from plantation on savannah is found to be between 3 and 9 g CO_2-eq./MJ in the 100 year horizon and between 14 and 43 g CO_2-eq./MJ in the 20 year horizon. This is still significantly lower than the carbon footprint of fossil fuels and increasingly so when looking at even longer time horizons than 100 years. However, in this context, the carbon footprint is not necessarily the most decisive concern – compared to other issues like biodiversity. Also, at this large scale of biomass supply, aspects of supply security become a concern. At even higher scales of 100 – 200 EJ/year, the probability that wood derives from conversion of natural/high standing forests into plantations or from harvesting in existing forest increases, which in turn can lead to very high carbon footprints.

Prioritizing wood conversion pathways, there is a significant dependency on the nature and composition of the energy system in which the pathway is applied. As long as the district heating marginal and continuous power marginal are mainly based on fossil fuels, there is still a large benefit of using wood in boilers and conventional combustion CHP and PP plants. But as for straw conversion pathways, this benefit largely falls away when the system marginal for heat and continuous power become increasingly based on wind power.

6.1.6 Road map considerations

For some years ahead, there is judged to be a large potential for supplying a Danish biomass demand with biomass having a low or even negative carbon footprint, given good forest governance and optimized management. Moreover, as long as the Danish energy system allows the displacement of fossil fuels in continuous (base load) electricity production as well as heat supply, biomass including imported wood can be used in both conventional combustion CHP and PP plants and boilers. Already in 2020, however, wind power will supply 50 percent of electricity and using biomass for continuous power production becomes less attractive for GHG emission reduction. Biomass for heat still has the potential, although decreasingly, to substitute fossil based heat until 2035, but beyond that heat is assumed to be supplied by renewable energy and increasingly wind power via electric boilers and heat pumps. There is known to be economic and technological incentives for using woody biomass in boilers and combustion CHP and PP plants, and up to 2020 and also some years towards 2030, the carbon footprint of doing so appears to be low, when supported by governance to ensure the aforementioned origin of wood from pre-commercial thinnings and harvesting residues.

Manure biogas is an attractive way of ensuring GHG reduction throughout all periods of time, and prioritizing this to the extent economy allows seems recommendable. Time will show at which point an upgrading of the biogas to SNG is attractive, thereby being able to store the gas for flexible power or transport fuels, but it is judged to be within the next 5-10 years given the assumed development of the Danish energy system. With respect to prioritizing the use of straw, there are high incentives for manure-straw biogas co-digestion allowing both an increased use of manure biogas as such, and ensuring a sustainable soil carbon quality. Converting the easily bio-degradable carbon of the straw – that would have degraded in the soil anyway – to biogas is a very efficient way of using biogenic carbon in the systems perspective. This may also be an option for combinations of 2G ethanol and biogas, but the concrete carbon footprint aspects of this have not been analyzed in this study. Should such 2G bioethanol pathways at a later stage become attractive, it should be ensured that ethanol as transport fuel does not compete with electric transportation, but is targeted towards long distance transport substituting other carbon based fuels.

At the larger scale of global biomass demand, it becomes less certain if a low carbon footprint of wood can be ensured. Moreover, from concerns for biodiversity and from a supply security point of view, it does not seem recommendable to aim for large scale bioenergy dependency of much above 40 GJ/person/year equivalent to around 200 PJ/year. To keep biomass demand at a realistic scale, moreover, a gradual introduction of hydrogen as system integrator seems to be a possible solution. This involves prioritizing biomass conversion pathways that support an assimilation of hydrogen in the system, and biogas pathways as well as thermal gasification pathways can be such pathways. Also ethanol fermentation allows for capturing CO_2 for further hydrogenation.

An important acknowledgement of this study is this shift in prioritizing biomass supply and conversion pathways at some point in time in the development of the system. From larger scale combustion based CHP, PP and boilers being attractive in the first coming years, a development towards a full renewable energy strategy seem to involve a shift towards limiting biomass demand and prioritizing it for biogas fermentation (of manure and straw) and thermal gasification (of woody biomass) pathways at a later point in time. To manage this shift, special attention is required in order to create the necessary incentives and regulatory framework and to avoid technology lock-in into biomass combustion pathways.

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Appendix A Emissions from converting primary forest bioenergy plantations

A.1 Description

A.1.1 Bioenergy system

In the bioenergy system it is assumed that the biomass that is used for bioenergy production comes initially from primary forests and all biomass (including branches and tops) is used for energy. Subsequent to the clearing of the primary forest, a coppice plantation is established.

A.1.2 Reference system

If the reference system, it is assumed that the primary forest is in dynamic equilibrium.

A.2 Model

The model is a combination of the plantation model with the primary forest model. However additional information on the ratio of biomass in the plantation to primary forest is necessary. This has a wide range of values because it depends on the rotation length plantation. Different net calorific values are applied to the biomass from the primary and plantation forests

A.2.1 Correction for cyclicity

A simple correction for cyclicity as previously applied does not work in this example, because the plantation produces less energy per harvest than the clearing of the primary forest. Instead, an inverse operator is calculated so that when it is convolved[16] with the “raw” energy stream the output produces a single pulse of energy at t=0.

The same operator is convolved with the “raw” emissions series to produce the corrected emission series.

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[16] See http://en.wikipedia.org/wiki/Convolution for details

A.3 Data

	Boreal	Temperate	Tropical
Plantation biomass (t d.m. / ha)	20 – 200[17]	20 - 200[17]	50-200[18]
Primary forest biomass (t d.m. / ha)	200 - 600[17, 19]	200 - 600[17, 19]	100 – 400[19]
Plantation / Primary	0.1 – 0.5	0.1 – 0.5	0.1 – 0.5

A.4 Results

Given that the exact values of the required parameters above are not known. The emission profile is estimated using the mean of a Monte Carlo simulation using 500 different locations. The provided spreadsheet calculates the mean and standard deviation of emissions profiles in the three biomes. The results are shown in the following diagrams.

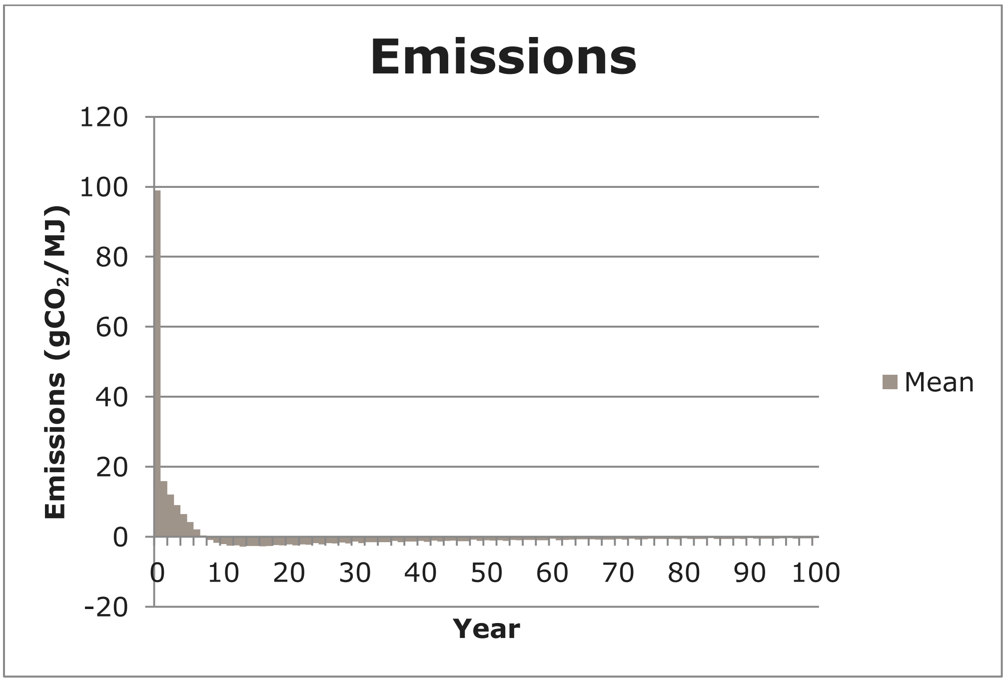

Figure A-1: Emissions from using primary forest converted to bioenergy plantation (boreal biome).

[17] Joint Research Centre. 2013. European forest yield table database
[18] Tiarks A, Nambiar EKS, and Cossalter C. 1998. Site Management and Productivity in Tropical Forest Plantations. CIFOR: Occasional paper no. 16
[19] IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

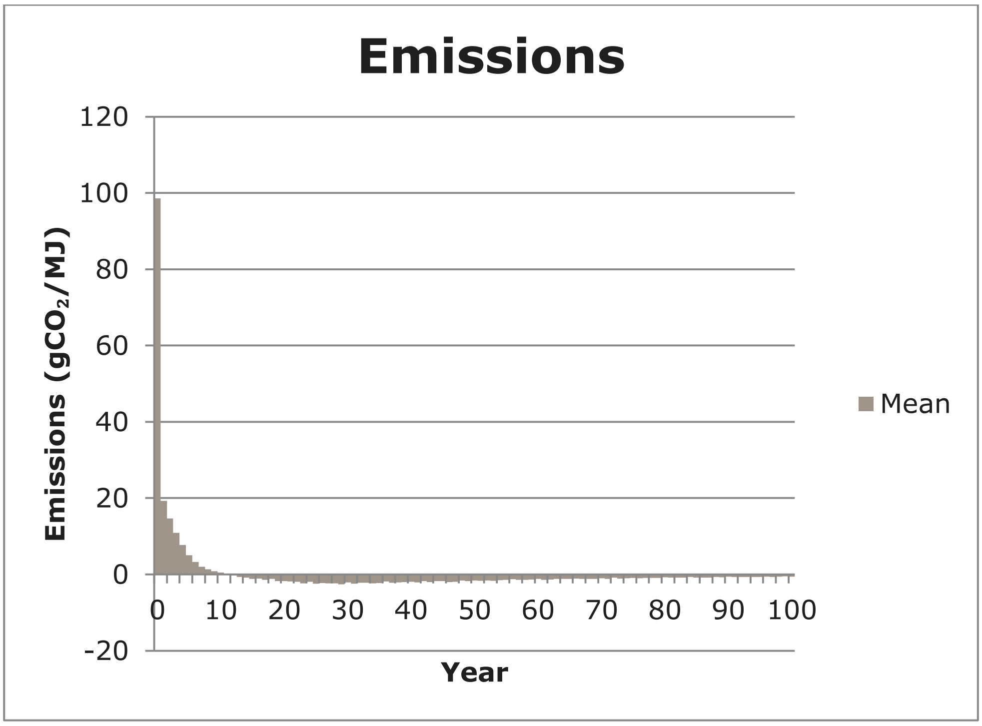

Figure A-2: Emissions from using primary forest for bioenergy (temperate biome).

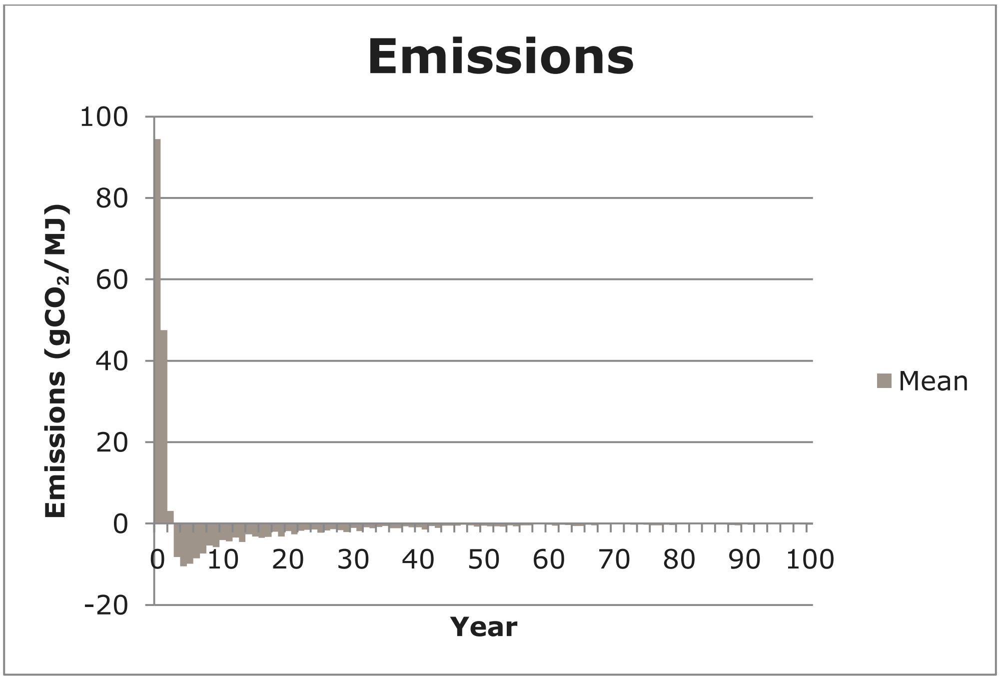

Figure A-3: Emissions from using primary forest for bioenergy (tropical biome).

Appendix B Emissions from primary forest remaining primary forest

B.1 Description

B.1.1 Bioenergy system

In the bioenergy system it is assumed that the biomass that is used for bioenergy production comes from primary forests.

1. The biomass is extracted at the "optimal" time when the mean annual increment is a maximum. This assumption may be challenged because it is more likely in forest in developed countries that the forest is older than this age. The assumption makes a pessimistic estimate of the emissions from bioenergy use because the forest will grow more in the reference system.
2. All biomass (including branches and tops) is used for energy. This assumption may also be challenged. When one speaks with foresters the say that this scenario is not very likely since the forest always have more value as lumber than as biomass for energy. They claim that only processing residues will end up as biomass for energy. However, biomass for pulp is already in competition with biomass for energy in Austria (Schwarzbauer 2010)[20].
3. The biomass is not "de-barked". For this reason, the net calorific value used for the conversion of mass to energy will be a weighted mixture of forest residues and clean wood.

B.1.2 Reference system

If the reference system, it is assumed that forest if not harvested for bioenergy would continue to grow. This assumption may also be challenged because the forest will be subject to natural disturbances such as windthrow, fire (boreal forests), and pests.

B.2 Model

B.2.1 Above-ground live biomass (AGB)

To model the biomass growth of the forest a "logistic" curve[21] is used.

$$B(t) = \frac{B_o B_{mx}}{B_o + (B_{mx} - B_o)e^{-ct}}$$

[20] Schwarzbauer, P and Stern T. 2010. Energy vs. material: Economic impacts of a "wood-for-energy scenario" on the forest-based sector in Austria — A simulation approach. Forest Policy and Economics, 12, 31–38

[21] Zweitering MH, Jogenburger I, Rombouts FM and van't Riet K. 1990. Modeling of bacterial growth curve. Applied and Environmental Microbiology. 56 / 6, 1875-1881

Where B_o = biomass at t=0, B_{mx} = maximum biomass and c is a constant that scales the time axis. If we assume that B_o = 0.01 B_{mx}, we can simplify the equation to

$$B(t) = \frac{0.01B_{mx}}{0.01 + 0.99e^{-ct}}$$

In this situation the maximum of the mean annual increment occurs when ct = 6.26. Therefore

$$c = \frac{6.26}{T_{rotation}}$$

This is the time at which the biomass would be harvested. At this time $B_{harvest}$ = 0.84 B_{mx}

So the biomass equation can be rewritten in terms of the harvest biomass as:

$$B(t) = \frac{0.01B_{harvest}}{0.84 * (0.01 + 0.99e^{-ct})}$$

B.2.2 Below-ground live biomass (BGB)

I will assume a constant root-to-shot ratio, *R*.

Li et al[22] suggest that fine-root biomass is a proportion of total root biomass using the equation

$$\frac{FR}{R} = 0.072 + 0.354e^{-0.060R}$$

However, this equation is not very conducive to the model formulation used (normalized to harvest biomass), so a simpler formula is applied:

$$FR = kR$$

And calculate an average value from the Li equation for the range of root biomass expected.

B.2.3 Above-ground dead biomass

Litter

Every year the forest produces litter which decays following simple exponential decay. Litter is typically about 4% of above ground biomass. The decay rate of litter is temperature and biome following an equation derived by Brovkin et al (2012)[23]. In this paper they suggest

$$k_{litter} = k_{litter10} Q_{10}^{\left(\frac{T-10}{10}\right)}$$

And have studied a global compilation of reports to attain values for $k_{litter10}$ and Q_{10}. They suggest:

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[22] Li Z., Kurz W., Apps S. and Beukema S. l, 2003, Belowground biomass dynamics in the Carbon Budget Model of the Canadian Forest Sector: recent improvements and implications for the estimation of NPP and NEP. Can. J. For. Res. 33: 126-136.

[23] Brovkin V, van Bodegom PM, Kleinen T, Wirth C, Conrwell WK, Cornelissen JHC and Kattge J. 2012. Plant-driven variation in decomposition rates improves projections of global litter stock distribution. Biogeosciences 9, 565-576

Table B-1: Parameters for the estimation of litter decay-rates

Biome	$K_{litter10}$	Q_{10}
Trop. Broadleaved evergreen	0.93	2.75
Trop. Broadleaved raingreen	1.17	2.75
Temp. needleleaved evergreen	0.70	1.97
Temp. broadleaved	0.95	1.37
Boreal needleleaved	0.76	1.97
Boreal broadleaved	0.94	1.37

Dead wood

In addition the forest produces dead wood due to mortality. Typical mortality rates are shown in Table B-2. It is assumed that dead wood is harvested for bioenergy when the stems are harvested.

Table B-2: Average mortality rates

Biome	Average mortality rate (fraction of standing biomass per year)
Tropical forests	0.0177
Evergreen forests	0.0116
Deciduous forests	0.0117

Source[24]

I assume that dead wood will decay exponentially following Brovkin's relationship for wood

$$k_{wood} = k_{wood10} Q_{10}^{\left(\frac{T-10}{10}\right)}$$

They have studied a global compilation of reports to attain values for k_{wood10} and Q_{10}. They suggest:

Table B-3: Parameters for the estimation of decay-rate for wood

Biome	k_{wood10}	Q_{10}
Trop. Broadleaved evergreen	0.039	2.75
Trop. Broadleaved raingreen	0.039	2.75
Temp. needleleaved evergreen	0.041	1.97
Temp. broadleaved	0.104	1.37
Boreal needleleaved	0.041	1.97
Boreal broadleaved	0.104	1.37

For the purpose of this study, it is assumed that temperate forests are predominantly broadleaved and boreal forests are predominantly needle leaved.

[24] IPCC. (2003). Good practice guidance for land use, land-use change and forestry. (J. Penman, M. Gytarsky, T. Hiraishi, T. Krug , D. Kruger, R. Pipatti, et al., Hrsg.) Hayama, Kanagawa, Japan: The Institute for Global Environmental Strategies for the IPCC and IPCC National Greenhouse Gas Inventories Programme

B.2.4 Below-ground dead biomass

Below-ground dead biomass comes from two sources: decaying roots post-harvest and fine root litter. The latter is a bit of a problem to model. The IPCC default method has soil organic carbon on a per hectare basis depending on soil type, forest type and management.

Coarse roots post-harvest

I will assume that all dead roots decay following Brovkin's relationship for wood.

Fine roots

Brunner et al[25] have recently published root turnover rates for European forests. They found that fine root turnover = 1.11 mean fine root biomass. This value is used for an estimate of fine root turnover for both temperate and boreal forests.

For tropical forest a relationship based on that derived by Finér et al[26] is used. They found that

$$Ln(FRP) = 0.515 * ln(FR) + 2.51$$

Where FRP= fine-root production and FRB = fine-root biomass. This equation is simplified to

$$FRP \approx FRBe^{0.515}$$

And the fine root turnover

$$FRT = FRP - FRB = FRB * (e^{0.515} - 1) = 0.673$$

Fine-roots are assumed to decay following Brovkin's relationship for wood.

Initial biomass in dead biomass pools

One must estimate the initial biomass in the dead biomass pools. To do so, it is assumed that the forest is in dynamic equilibrium. This means that the initial biomass in each of the dead biomass pools is the same as in the year of harvest.

B.2.5 Emissions per kg biomass harvested

The emissions per kg of biomass in a specific year are given

$$Emission_i = \frac{44}{12} * 0.5 * (Biomass_{i-1} - Biomass_i)$$

Finally, one can this in terms of emissions per MJ of energy through the net calorific value (NCV) since NCV = MJ/kg harvested

B.2.6 Correction for cyclicity

The fits energy produced by this type of land management change occurs at the end of the first rotation. As well, once the land management change has happened the land produces multiple batches of energy. Both these factors must be corrected for,

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[25] Brunner I, Bakker MR, Björk RG, Hirano Y et al. 2013. Fine root turnover rates for European forests revisited: an analysis of data from sequential coring and ingrowth cores. Plant Soil. 362: 357-372

[26] Finér L, Ohashi M, Noguchi K, Hirano Y. 2011. Fine root production and turnover in forest ecosystems in relation to stand and environmental characteristics. Forest Ecology and Management. 262: 2008-2023

if one is to use the emission stream with an energy demand steam. This correction is applied in two steps:

1) the negative of the energy series, time delayed by a rotation is added to the original energy series. This corrects for the cyclic nature; and
2) The resulting time series from the first step is shifted back in time so that the first energy produced occurs at t=0.

The same operations are performed on the emissions series.

B.3 Data

	Boreal	Temperate	Tropical
Rotation length (years)	40 – 140[27]	40 – 120[17]	10 – 70[28]
R-to-S ratio[29]	0.15 – 0.37	0.12 – 0.93	0.29 – 0.81
Fine-root / total roots[30]	17% - 30%	10% - 15%	12% - 20%
Fine-root turnover ($year^{-1}$)	1.11[25]	1.11[25]	0.673[26]
Average temperature (deg. C)	-5 – 5	5 – 16	16 - 30
Annual rainfall (mm)	200 – 2000	500 – 1500	500 – 16000
Net calorific value (MJ/kg)	18.6 – 21.1[31]	18.6 – 20.7[31]	Eucalyptus 19.0 – 19.6

B.4 Results

Given that the exact values of the required parameters above are not known. The emission profile is estimated using the mean of a Monte Carlo simulation using 500 different locations. The provided spreadsheet calculates the mean and standard deviation of emissions profiles in the three biomes. The results are shown in the following diagrams.

The three curves have very similar shape (Figure, Figure, Figure). The differences are caused by the differences in rotation lengths. The time until the bioenergy

[27] Joint Research Centre. 2013. European forest yield table database
[28] Tiarks A, Nambiar EKS, and Cossalter C. 1998. Site Management and Productivity in Tropical Forest Plantations. CIFOR: Occasional paper no. 16
[29] IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan
[30] Values calculated from the Li equation
[31] Oak Ridge National Laboratory. 2011. Heat Content Ranges for Various Biomass Fuels. http://cta.ornl.gov/bedb/appendix_a/Heat_Content_Ranges_for_Various_Biomass_Fuels.xls Accessed 15 July 2013

system has less emissions than the corresponding fossil energy system that it replaces will also be proportional to rotation length.

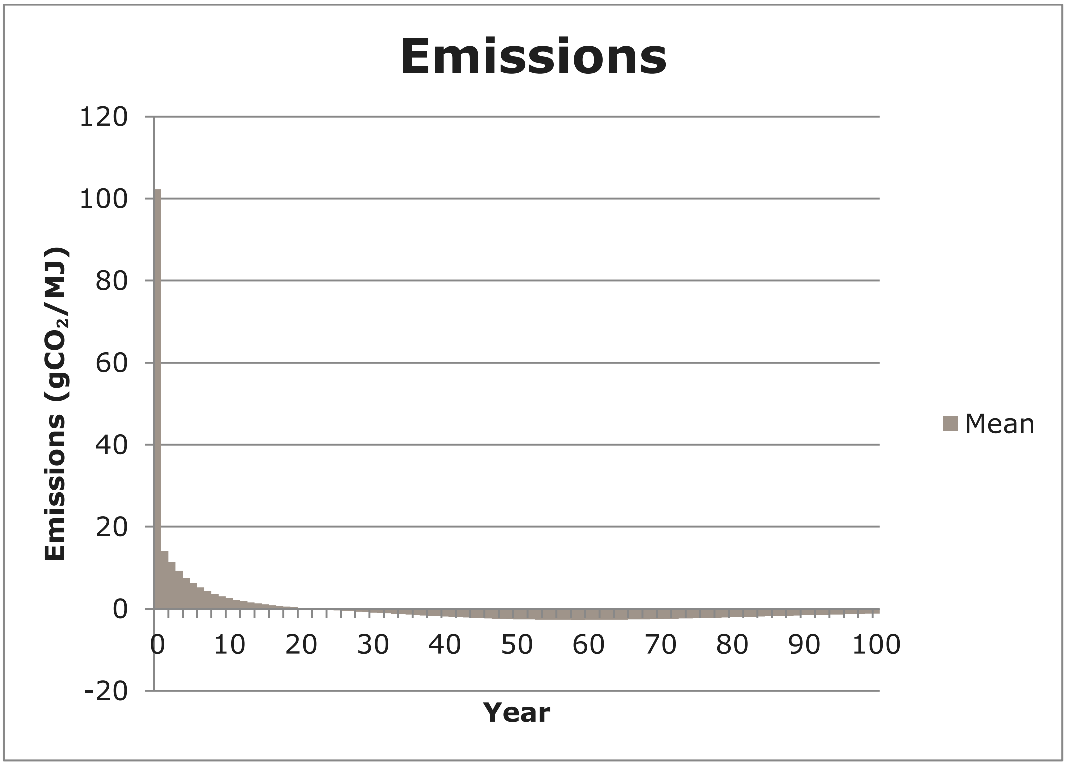

Figure B-1: Emissions from using primary forest for bioenergy (boreal biome).

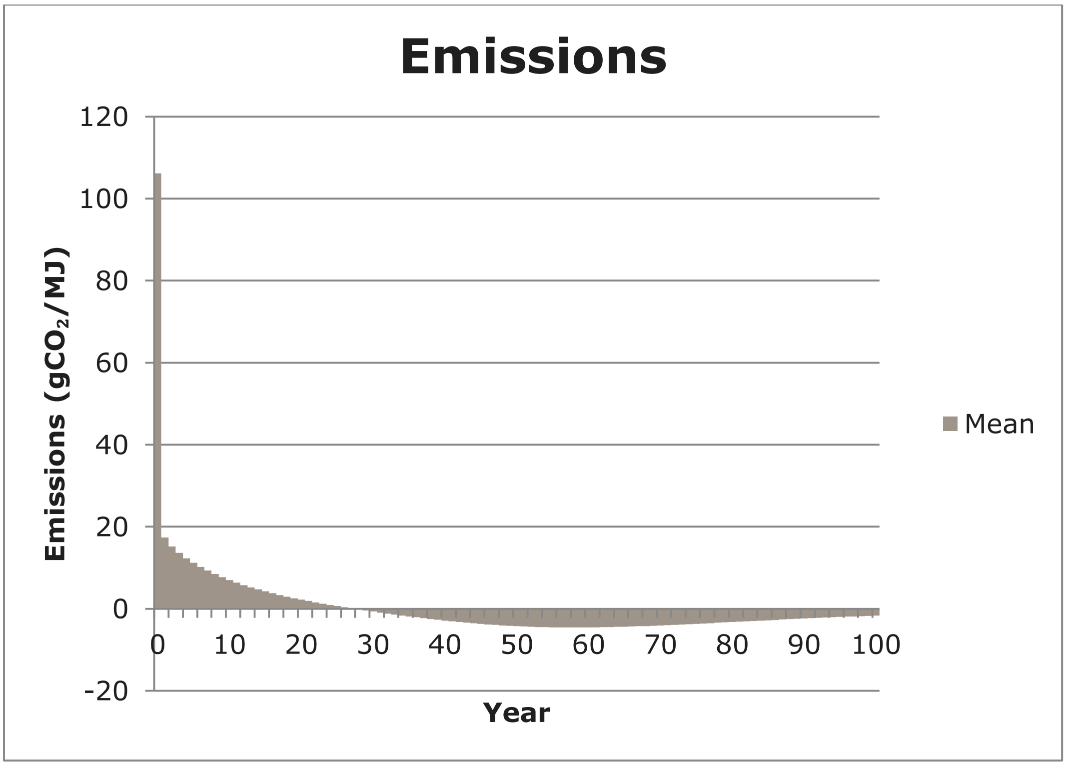

Figure B-2: Emissions from using primary forest for bioenergy (temperate biome).

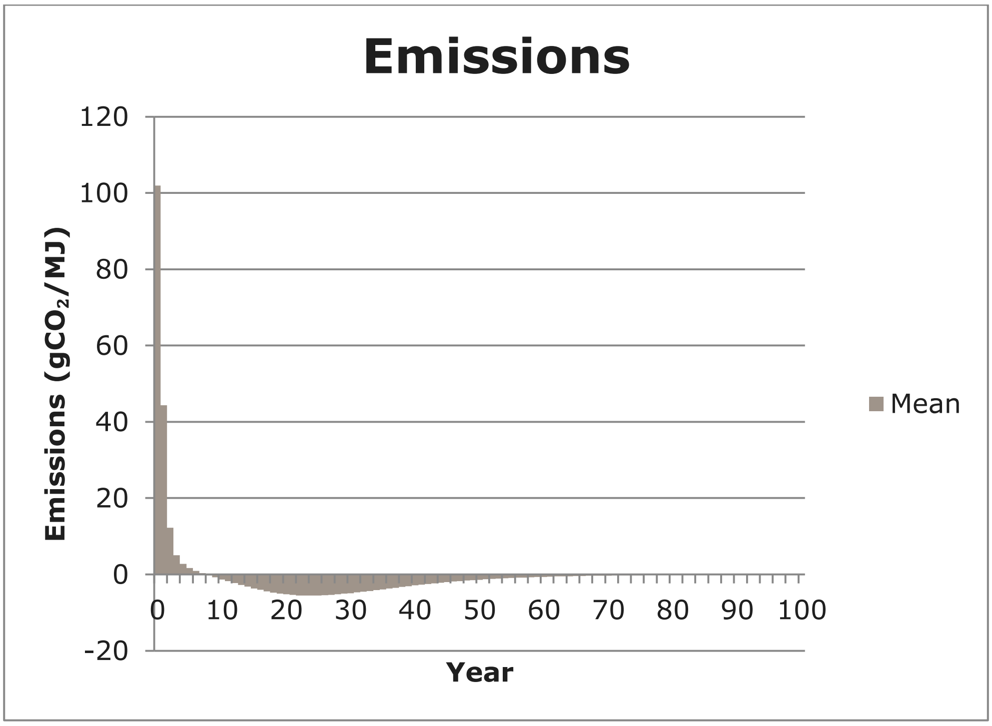

Figure B-3: Emissions from using primary forest for

Appendix C Emissions from new plantations on marginal land and grassland

C.1 Description

C.1.1 Bioenergy system

In the bioenergy system it is assumed that the biomass that is used for bioenergy production comes from short-rotation forests planted specifically for this purpose on marginal land and grassland. All biomass (including branches and tops) is used and the biomass is not “de-barked”. For this reason, the net calorific value used for the conversion of mass to energy will be a weighted mixture of forest residues and clean wood.

The species planted coppices (e.g. willow, poplar, black locust) which means that there is no root die-back at harvest.

C.1.2 Reference system

If the reference system, it is assumed that the marginal and grassland is in steady-state (i.e. there is no net gain or loss of biomass). The lands may be used for other purposes (e.g. subsistence agriculture or grazing) and as such conversion to plantation may cause indirect land use change (iLUC). This is not calculated.

C.2 Model

C.2.1 Above-ground live biomass (AGB)

To model the biomass growth of the plantation a “logistic” curve[32] is used.

$$B(t) = \frac{B_o B_{mx}}{B_o + (B_{mx} - B_o)e^{-ct}}$$

Where B_o = biomass at t=0, B_{mx} = maximum biomass and c is a constant that scales the time axis. If we assume that B_o = 0.01 B_{mx}, we can simplify the equation to

$$B(t) = \frac{0.01B_{mx}}{0.01 + 0.99e^{-ct}}$$

In this situation the maximum of the mean annual increment occurs when ct = 6.26. Therefore

$$c = \frac{6.26}{T_{rotation}}$$

This is the time at which the biomass would be harvested. At this time $B_{harvest}$ = 0.84 B_{mx}

So the biomass equation can be rewritten in terms of the harvest biomass as:

$$B(t) = \frac{0.01B_{harvest}}{0.84 * (0.01 + 0.99e^{-ct})}$$

[32] Zweitering MH, Jogenburger I, Rombouts FM and van’t Riet K. 1990. Modeling of bacterial growth curve. Applied and Environmental Microbiology. 56 / 6, 1875-1881

C.2.2 Below-ground live biomass (BGB)

Since we have assumed that the planted species coppices, we will assume a constant root-to-shot ratio, *R*, during the first rotation and a constant value = $B_{harvest}*R$ thereafter.

C.2.3 Above-ground dead biomass

Every year the plantation produces litter which decays following simple exponential decay. Litter is typically about 4% of above ground biomass. The decay rate of litter is temperature and biome following an equation derived by Brovkin et al (2012)[33]. In this paper they suggest

$$k_{litter} = k_{litter10} Q_{10}^{\left(\frac{T-10}{10}\right)}$$

And have studied a global compilation of reports to attain values for $k_{litter10}$ and Q_{10}. They suggest:

Table C-1: Parameters for the estimation of litter decay-rates

Biome	$K_{litter10}$	Q_{10}
Trop. Broadleaved evergreen	0.93	2.75
Trop. Broadleaved raingreen	1.17	2.75
Temp. needleleaved evergreen	0.70	1.97
Temp. broadleaved	0.95	1.37
Boreal needleleaved	0.76	1.97
Boreal broadleaved	0.94	1.37

C.2.4 Below-ground dead biomass

Below-ground dead biomass (including soil organic carbon) is a bit of a problem. The IPCC default method has soil organic carbon on a per hectare basis depending on soil type, forest type and management.

Marginal lands

As such it is not explicitly dependant on the amount of biomass growing or harvested. A slightly different approach is used. Berhougaray et al (2013) report fine root production as a proportion, k, of net primary productivity (NPP). Therefore:

$$FineRoot_{prod} = \frac{k}{(1-k)} * (\Delta AGB + \Delta BGB)$$

Where $3.9\% \leq k \leq 10\%$

They also estimate fine root biomass turnover rate, t_r, as the ratio of fine root production to mean fine root biomass. Therefore, if we assume that the difference between the production and the mean biomass is the amount that dies per year, we have

[33] Brovkin V, van Bodegom PM, Kleinen T, Wirth C, Conrwell WK, Cornelissen JHC and Kattge J. 2012. Plant-driven variation in decomposition rates improves projections of global litter stock distribution. Biogeosciences 9, 565-576

$$FineRoot_{mort} = \frac{(t_r - 1)}{t_r} * FineRoot_{prod}$$

Where $1.9 \leq t_r \leq 2.7$

And combining the two equations we arrive at

$$FineRoot_{mort} = \frac{(t_r - 1)k}{t_r(1-k)} * (\Delta AGB + \Delta BGB)$$

This, it is assumed, will decay exponentially following Brovkin's relationship for wood

$$k_{wood} = k_{wood10} Q_{10}^{\left(\frac{T-10}{10}\right)}$$

They have studied a global compilation of reports to attain values for k_{wood10} and Q_{10}. They suggest:

Table C-2: Parameters for the estimation of decay-rate for wood

Biome	k_{wood10}	Q_{10}
Trop. Broadleaved evergreen	0.039	2.75
Trop. Broadleaved raingreen	0.039	2.75
Temp. needleleaved evergreen	0.041	1.97
Temp. broadleaved	0.104	1.37
Boreal needleleaved	0.041	1.97
Boreal broadleaved	0.104	1.37

For the purpose of this study, it is assumed that temperate forests are predominantly broadleaved and boreal forests are predominantly needleleaved.

Grasslands

For grasslands it is assumed that there is no change in soil organic carbon.

C.2.5 Emissions per kg biomass harvested

The emissions per kg of biomass in a specific year are given

$$Emission_i = \frac{44}{12} * 0.5 * (Biomass_{i-1} - Biomass_i)$$

Finally, one can this in terms of emissions per MJ of energy through the net calorific value (NCV) since NCV = MJ/kg harvested

C.2.6 Correction for delayed production and cyclicity

The fits energy produced by this type of land management change occurs at the end of the first rotation. As well, once the land management change has happened the land produces multiple batches of energy. Both these factors must be corrected for, if one is to use the emission stream with an energy demand steam. This correction is applied in two steps:

3) the negative of the energy series, time delayed by a rotation is added to the original energy series. This corrects for the cyclic nature; and

4) The resulting time series from the first step is shifted back in time so that the first energy produced occurs at t=0.

The same operations are performed on the emissions series.

C.3 Data

	Boreal	Temperate	Tropical
Rotation length (years)	10 – 30[34]	3 – 20[35 36 37 38]	3 – 10
R-to-S ratio[39]	0.15 – 0.37	0.12 – 0.93	0.29 – 0.81
Fine-root production / NPP	3.9% - 10%	3.9% - 10%	3.9% - 10%
Fine-root turnover (year^{-1})	1.9 – 2.7	1.9 – 2.7	1.9 – 2.7
Average temperature (deg. C)	-5 – 5	5 – 16	16 - 30
Annual rainfall (mm)	200 – 2000	500 – 1500	500 – 16000
Net calorific value (MJ/kg)	Short Rotation Coppice (SRC): 17.3 – 19.7[40 41]	SRC: 17.3 – 19.7	Eucalyptus 19.0 – 19.6

[34] Weih M. 2004. Intensive short rotation forestry in boreal climates: present and future perspectives. Can. J. For. Res. 34: 1369–1378

[35] Drake-Brockman GR. 1996. Establishment and Maintenance Of A Woodfuel Resource. Forestry Research Technical note 17/96. http://www.biomassenergycentre.org.uk/pls/portal/docs/PAGE/RESOURCES/REF_LIB_RES/PUBLICATIONS/GUIDANCE/ESTABLISHMENT%20AND%20MAINTENANCE%20OF%20A%20WOODFUEL%20RESOURCE%20TDB_TN1796.PDF

[36] Pontailler JY, Ceulemans R, and Guittet J. 1999. Biomass yield of poplar after five 2-year rotations. Forestry 72 / 2, 157-163

[37] Aylott MJ, Casella E, Tubby I, Street NR, Smith P and Taylor G. 2008. Yield and spatial supply of bioenergy poplar and willow short-rotation coppice in the UK. New Phytologist 178: 358–370

[38] Evans S (coordinator), Baldwin M, Henshall P, Matthews R, Morgan G, Poole J, Taylor P, and Tubby I. 2007. Final Report: Yield models for Energy: Coppice of Poplar and willow. Volume A – Empirical Models. Report to DTI (B/W2/00624/00/00URN). Ed: I Tubby and J Poole. 91pp

[39] IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan

[40] McKendry P. 2002. Energy production from biomass (part 1): overview of biomass. Bioresource Technology 83 (2002) 37–46

[41] OMAFRA. 2001. Biomass Burn Characteristics Factsheet. Ontario Ministry of Agriculture and Food. http://www.omafra.gov.on.ca/english/engineer/facts/11-033.htm#3. Accessed 17 June 2013

C.4 Results

Given that the exact values of the required parameters above are not known. The emission profile is estimated using the mean of a Monte Carlo simulation using 500 different locations. The provided spreadsheet calculates the mean and standard deviation of emissions profiles in the three biomes. The results are shown in the following diagrams.

There are minor differences between plantation established on marginal land or on grasslands within the same biome. This is due to the increase in soil organic carbon when planted on marginal lands.

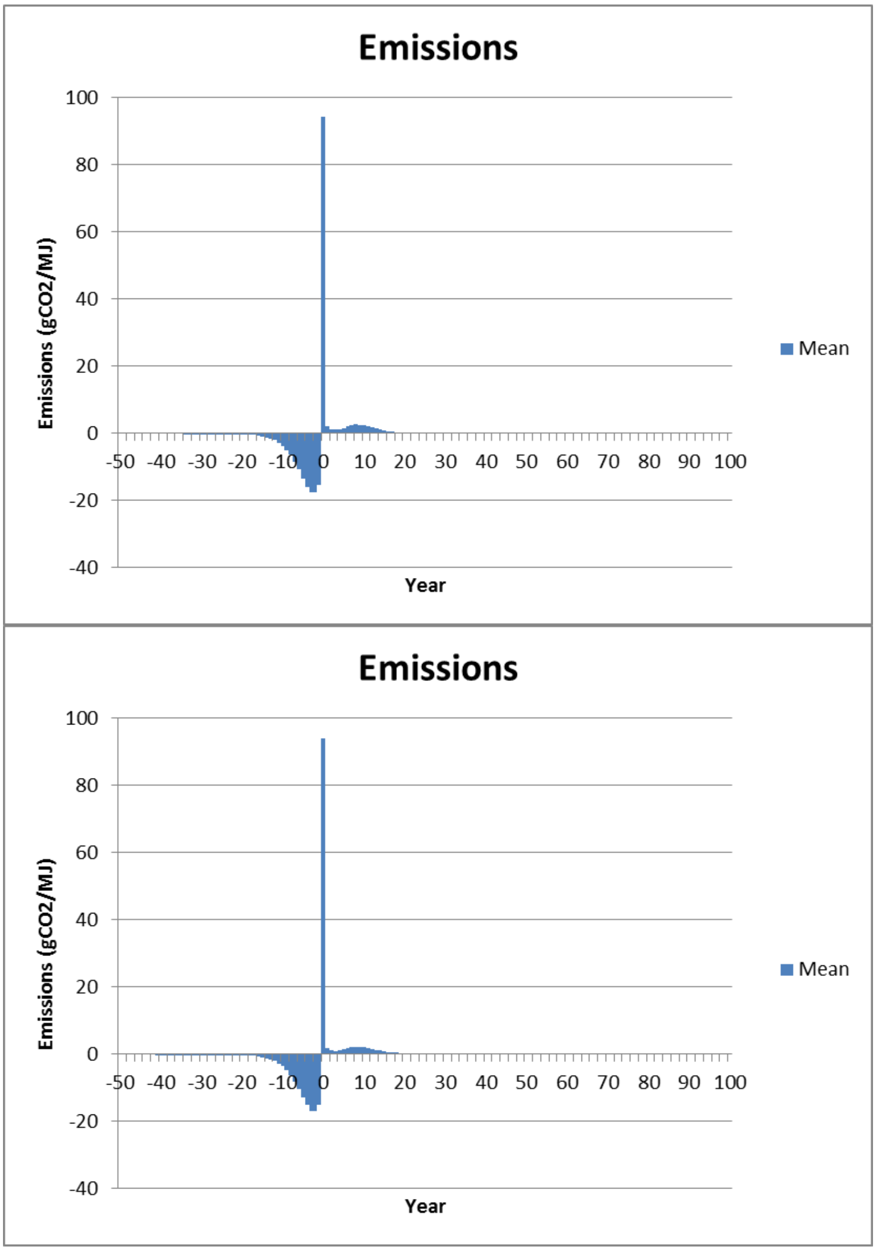

Figure C-1: Emissions from short rotation forestry on marginal lands (boreal biome).

Left image is for on marginal lands. Right image is for grassland. There is a slight net removal on the marginal land due to an increase in soil organic carbon

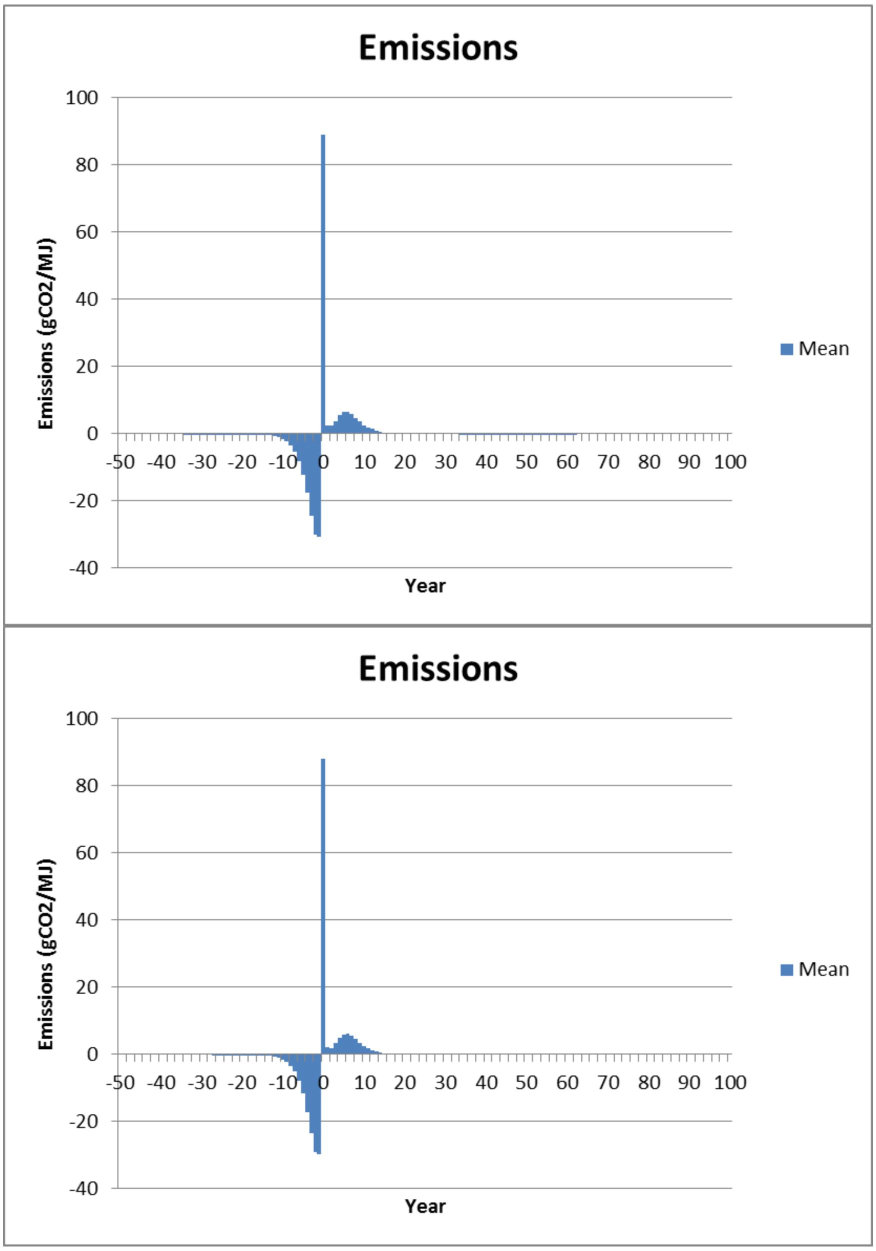

Figure C-2: Emissions from short rotation forestry on marginal lands (temperate biome). Left image is for marginal lands. Right image is for grassland.

Left image is for marginal lands. Right image is for grassland. There is a slight net removal on the marginal land due to an increase in soil organic carbon

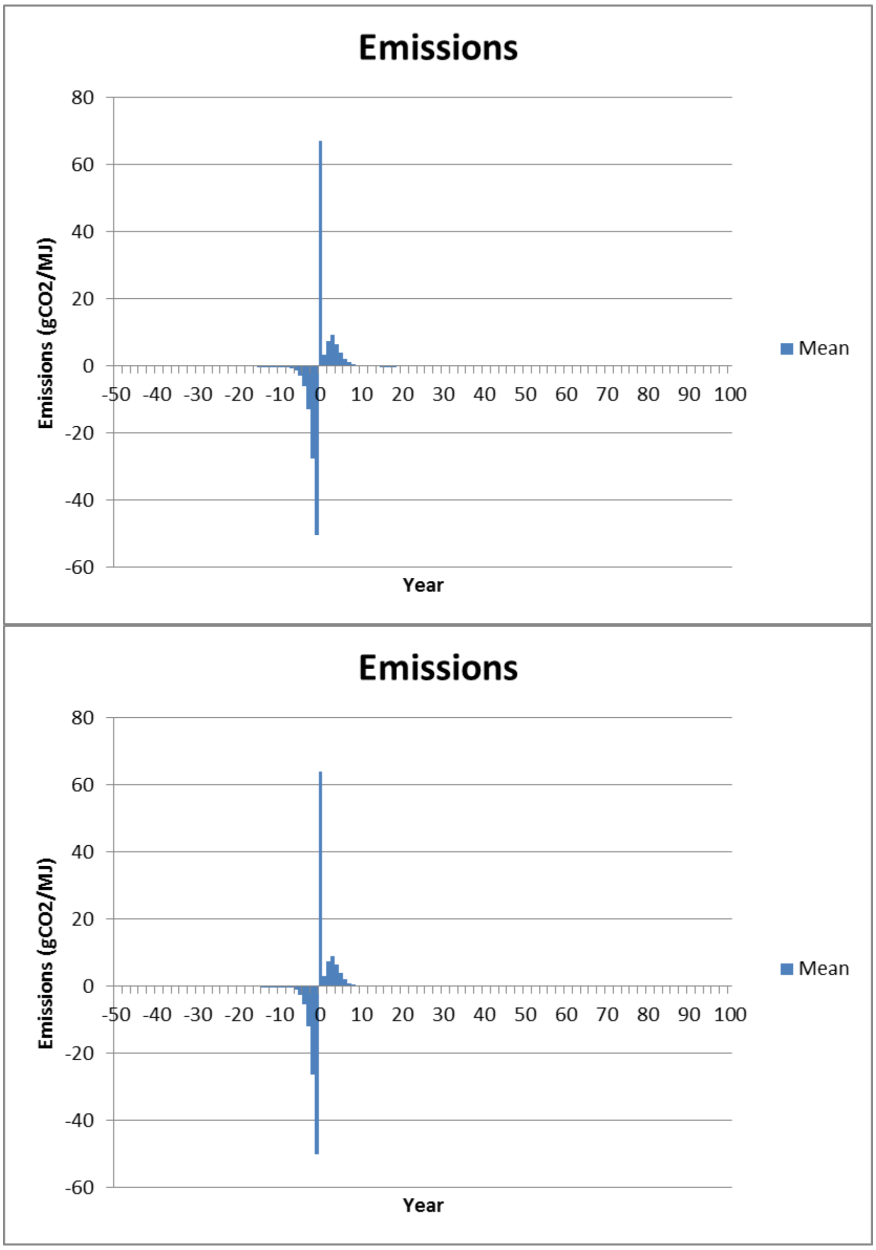

Figure C-3: Emissions from short rotation forestry on marginal lands (tropical biome)

Left image is for marginal lands. Right image is for grassland. There is a slight net removal on the marginal land due to an increase in soil organic carbon.

Appendix D Emissions from the use of forest residues

D.1 Description

D.1.1 Bioenergy system

In the bioenergy system it is assumed that the biomass that is used for bioenergy production is composed of branches, tops, and standing dead wood. The biomass is not “de-barked”. For this reason, the net calorific value used for the conversion of mass to energy must be specifically for forest residues and not for clean wood.

D.1.2 Reference system

If the reference system, it is assumed that the biomass is left on site where it decays following simple exponential decay.

D.2 Model

Therefore the emissions from the use of residues are given by

$$Emission(t) = [B_o\delta(t) - kB_oe^{-kt}] * \frac{44}{12} * 0.5$$

Where the first term is the emission from burning the biomass, B_o[42], and the second term is the displaced emissions from the decay of the biomass (hence the negative sign). The 0.5 is the carbon fraction of dry biomass and the 44/12 is used to convert mass C into mass CO_2.

The emissions in the first year are given by

$$Emission_1 = [B_oe^{-k}] * \frac{44}{12} * 0.5$$

Emissions in year 2 are given by:

$$Emission_2 = Emissions_1(e^{-k} - 1)$$

Emissions in all other years are

$$Emission_j = Emissions_{j-1}e^{-k}$$

The decay constant has been shown to be a function of temperature and rainfall[43]. Moore et al (1999) established a linear relationship between the amount of biomass remaining after three years and rainfall and temperature.

$$\frac{B_3}{B_o} = 0.887 - 0.0163(T - 2.4) - 0.00015(P - 778)$$

Therefore

$$k = -\frac{1}{3}\ln(\frac{B_3}{B_o})$$

However, as this relationship was derived for Canadian forests, another relationship derived by Brovkin et al (2012)[44] is used. In this paper they suggest

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[42] δ(t) is the dirac function. It equals 1 when t = 0, and = 0 when t ≠ 0

[43] Moore et al. (1999). Litter decomposition rates in Canadian forests. Global Change Biology 5, 75-82

$$k_{wood} = k_{wood10} Q_{10}^{\left(\frac{T-10}{10}\right)}$$

And have studied a global compilation of reports to attain values for k_{wood10} and Q_{10}. They suggest:

Table D-1: Parameters for the estimation of decay-rate

Biome	k_{wood10}	Q_{10}
Trop. Broadleaved evergreen	0.039	2.75
Trop. Broadleaved raingreen	0.039	2.75
Temp. needleleaved evergreen	0.041	1.97
Temp. broadleaved	0.104	1.37
Boreal needleleaved	0.041	1.97
Boreal broadleaved	0.104	1.37

For the purpose of this study, it is assumed that temperate forests are predominantly broadleaved and boreal forests are predominantly needleleaved.

Finally, one can express B_o in terms of emissions per MJ of energy through the net calorific value (NCV) since NCV = MJ/kg
Therefore

$$Eintensity_1 = \frac{e^{-k}}{NCV} * \frac{44}{12} * 0.5$$
$$Eintensity_2 = Eintensity_1 \left(e^{-k} - 1\right)$$
$$Eintensity_j = Eintensity_{j-1} e^{-k}$$

Where *Eintensity* has the units kg CO_2/MJ

D.3 Data

	Boreal	Temperate	Tropical
Average temperature (deg C)	-5 – 5	5 – 16	16 – 30
Annual rainfall (mm)	200 – 2000	500 – 1500	500 – 16000
Net calorific value	18.5 – 20.7[45] [46]	19.0 – 20.0[47]	17.2 – 17.8[50]

[44] Brovkin V, van Bodegom PM, Kleinen T, Wirth C, Conrwell WK, Cornelissen JHC and Kattge J. 2012. Plant-driven variation in deomposition rates improves projections of global litter sotck distribution. Biogeosciences 9, 565-576

[45] European Bioenergy Networks (EUBIONET). 2003. Biomass Co-Firing - An Efficient Way To Reduce Greenhouse Gas Emissions. http://ec.europa.eu/energy/renewables/studies/doc/bioenergy/2003_cofiring_eu_bionet.pdf

[46] Oak Ridge National Laboratory. 2011. Heat Content Ranges for Various Biomass Fuels. http://cta.ornl.gov/bedb/index.shtml. Accessed 17 June 2013

	Boreal	Temperate	Tropical
(MJ/kg)		SRC: 17.3 – 19.7[48] [49]	Eucalyptus 19.0 – 19.6

D.4 Results

Given that the exact climate conditions at the location where the residues are collected and their net calorific value is not known. The emission profile is estimated using the mean of a Monte Carlo simulation using 500 different locations. The provided spreadsheet calculates the mean and standard deviation of emissions profiles in the three biomes. The results are shown in the following diagrams.

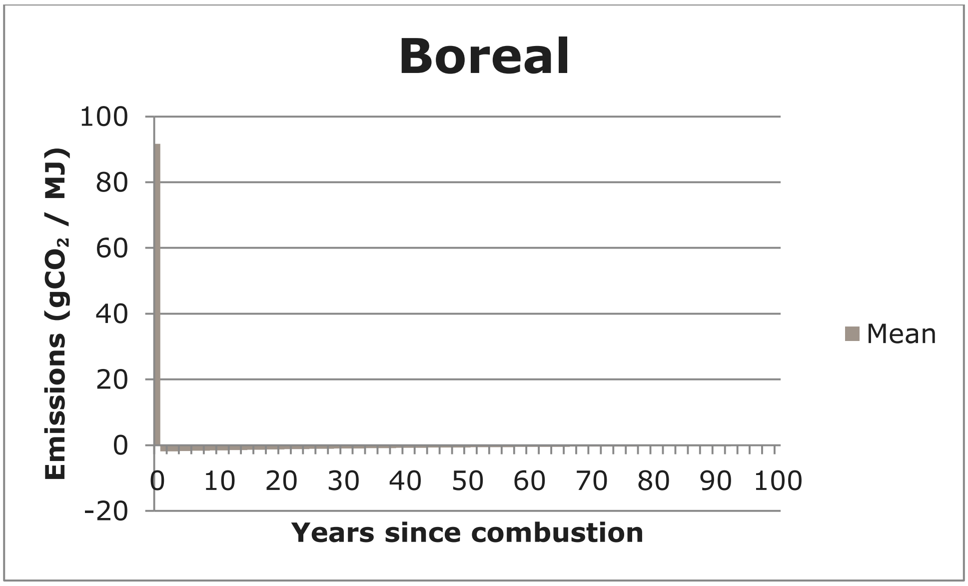

Figure D-1: Emissions from use of boreal residues

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[47] Gravalos I, Kateris D, Xyradakis P, Gialamas T et al. 2010. A Study On Calorific Energy Values Of Biomass Residue Pellets For Heating Purposes. FORMEC 2010. Forest Engineering: Meeting the Needs of the Society and the Environment. July 11 – 14, 2010, Padova – Italy

[50] Thek G, Obernberger I. 2010. The Pellet Handbook. Earthscan Ltd. London. 549 pp.

[48] McKendry P. 2002. Energy production from biomass (part 1): overview of biomass. Bioresource Technology 83 (2002) 37–46

[49] OMAFRA. 2001. Biomass Burn Characteristics Factsheet. Ontario Ministry of Agriculture and Food. http://www.omafra.gov.on.ca/english/engineer/facts/11-033.htm#3. Accessed 17 June 2013

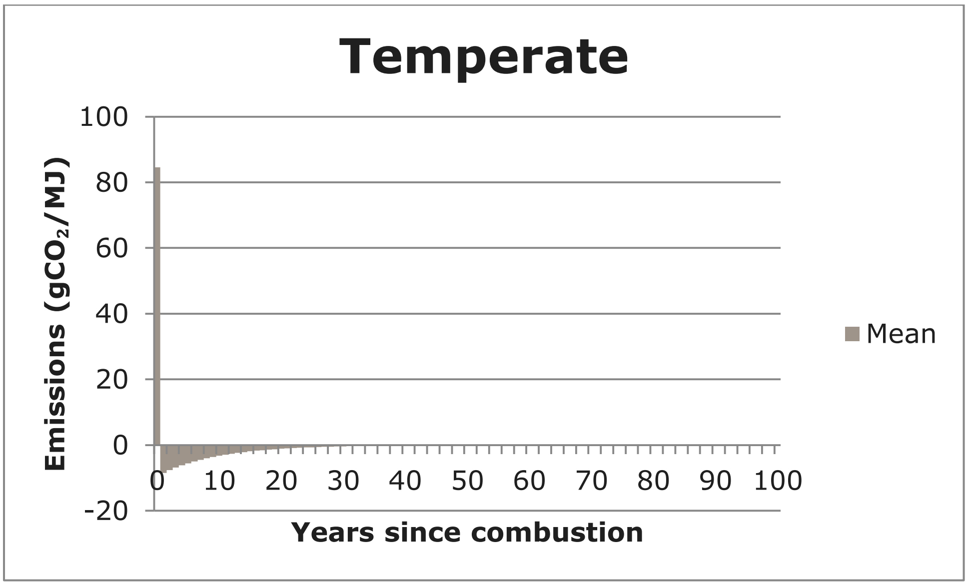

Figure D-2: Emissions from the use of temperate residues

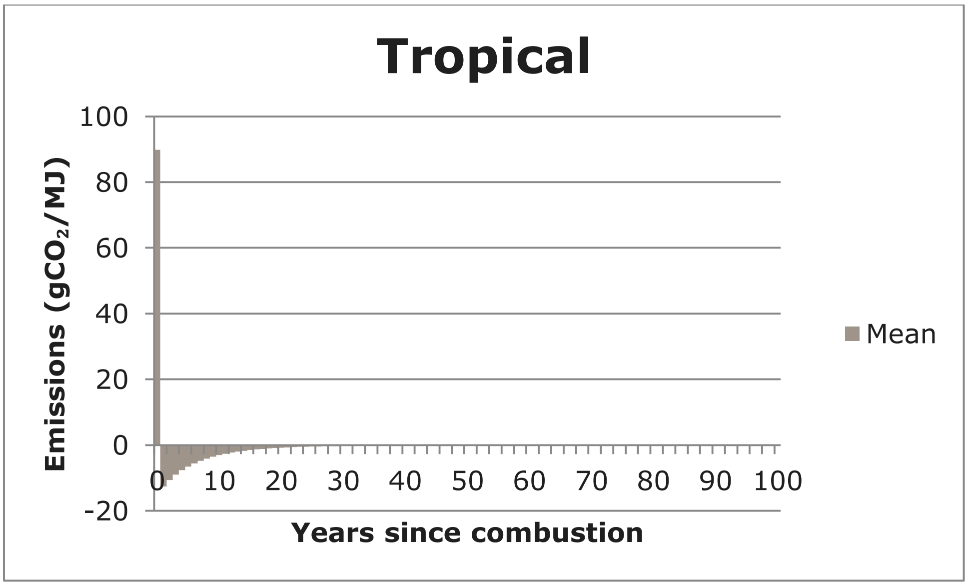

Figure D-3: Emissions from the use of tropical residues

Appendix E Emissions from converting savannah bioenergy plantations

E.1 Description

Reference system

If the reference system, I assume that the savannah[51] is in dynamic equilibrium.

E.2 Model

The model is a combination of the plantation model with the savannah model. However additional information on the ratio of biomass in the plantation to savannah is necessary. This has a wide range of values because it depends on the rotation length plantation. Different net calorific values are applied to the biomass from the primary and plantation forests

E.3 Data

	Plantation	Savannah
Above ground biomass (t d.m. / ha)	50-200[52]	50 – 200[53] Dry forests 133 ± 76[54] Woodlands: 62 ± 28 Savannah: 18 ± 8
Below ground biomass (t d.m. / ha)	15 – 110	15 – 110
Soil organic carbon (tC/ha)	31 – 38[53]	Woodlands: 11.8 ± 5.34 Grassy savannah: 5.65 ± 4.60 Occasionally as high as 115 tC/ha[55]
Total (tC/ha)	**60 - 193**	**36 - 270**
Total (tC/t above ground plantation)	**0.97 - 1.2** Middle value: 1.1	**0.18 – 5.4** Middle value: 3.6

[51] You'll see from the table that there is a large range of values

[52] Tiarks A, Nambiar EKS, and Cossalter C. 1998. Site Management and Productivity in Tropical Forest Plantations. CIFOR: Occasional paper no. 16

[53] IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan

[54] Scholes RJ and Hall DO. 1996. The Carbon Budget of Tropical Savannas, Woodlands and Grasslands http://www.scopenvironment.org/downloadpubs/scope56/Chapter04.html. Accessed 21 October 2013

[55] Chen X, Hutley L, Eamus D. 2003. Carbon balance of a tropical savanna of northern Australia. Oecologia 137:405–416

Note: ranges of 30 tC/ha are equal to 0.1 – 1.0 kg biomass/kg harvested. This requires a fine-to-coarse root ratio of as high a 1. For this, I would use a ratio of 1.0 ± 0.5. A more realistic value of between this and typical forests is 0.58 ± 0.5

High carbon savannah is modelled as 127 ton C/ha as total AGB, BGB and soil C, whereas low C is half of that. Plantation C-stock at max value is modelled as 70 ton C/ha.

Appendix F iLUC model

F.1 Approach

A deterministic approach to modelling iLUC, as e.g. described in Schmidt (2008), was used. This section details how emissions were estimated for land expansion (iLUC) and intensification.

F.2 Plantation on grassland

F.2.1 Establishing the model and overall figures needed

Establishing a woody plantation on grassland involves that grassland is displaced.

The starting point for the analysis was to consider that the grass was used as feed for grazing animals. In terms of nutritional value, grass supplies essentially carbohydrates and protein (66% and 20% of the DM, respectively, the rest being ashes and fat; Møller et al. (2000)). For the purpose of this study, it was considered that grass DM supplies 77% carbohydrates and 23% protein (values of Møller, normalized to carbohydrates and protein only).

As a consequence of a new plantation on grassland, the nutritional value that was provided by the grass now has to be supplied by the marginal source of protein and carbohydrates. This is illustrated in Figure F-1 (example for tropical biome), where the boundary conditions considered are shown.

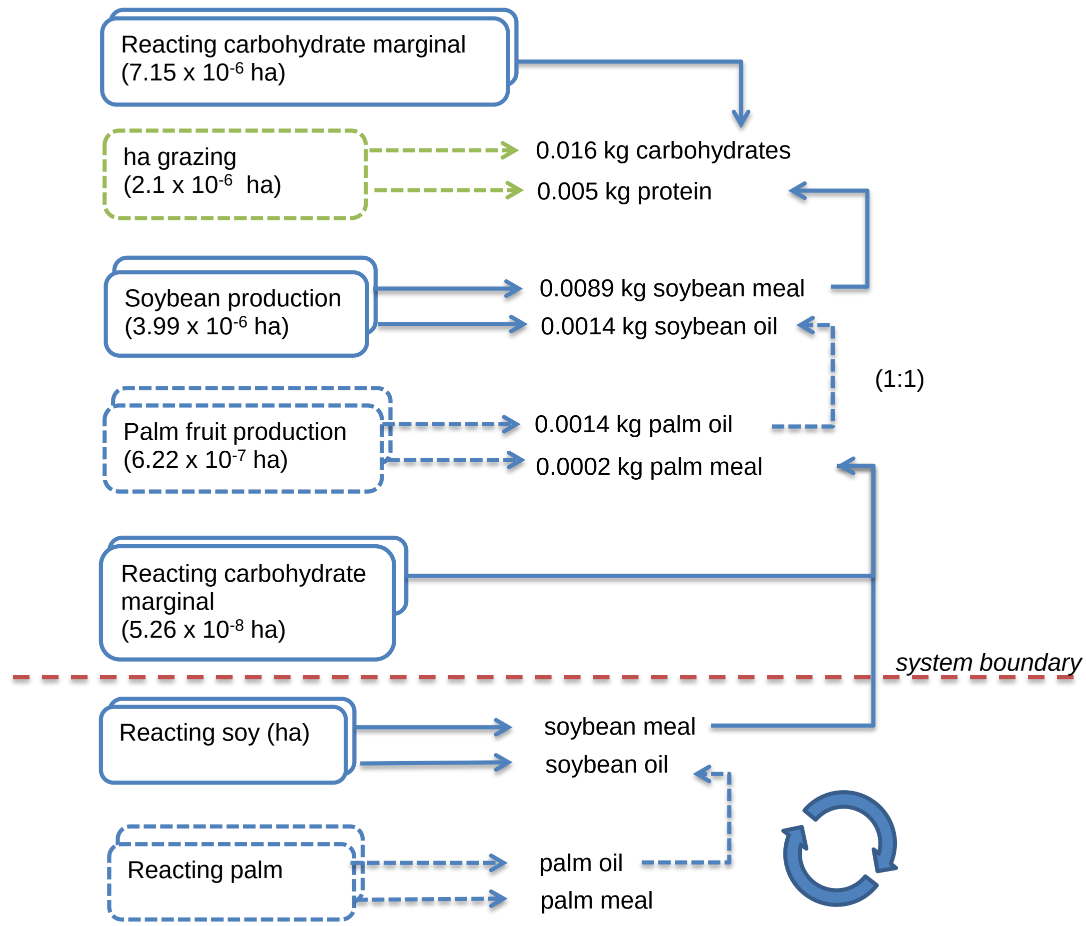

Figure F-1: Process flow diagram considered for modelling the consequences of establishing a plantation on grassland. The flows are expressed per MJ wood and represent the case of a plantation on tropical biome, for the "high" interval (see text). Full lines represent induced flows and dotted lines avoided flows. The boxes on the second plan represent intensification. The system boundary considered here excludes, for simplicity, the protein share of the palm fruit meal, which would involve a continuous soybean loop. It is therefore assumed that considering this would yield no further information that is significant for decision making. For more details on the soybean loop illustrated herein, see Dalgaard et al. (2008).

The first step to this analysis is thus to determine how much carbohydrates and protein are displaced, in each biome. This can be done on the basis of the information shown in Table F-1, and the above-mentioned proportions of carbohydrates and protein in grass DM.

Table F-1. LHV and yield considered for the woody plantations as well as the yield of the displaced grass, for each biome

Biome	LHV, wood from plantation (1) (MJ / kg DM)	Yield, wood from plantation (t DM / ha*y)	Yield of grass(5) (t DM / ha*y)
Tropical	19.9	22.8(2)	1.7 – 10.9
Boreal	19.8	4.5(3)	1.3 – 3.0
Temperate	19.5	12.0(4)	1.3 – 4.2

(1) Same data as used for the dLUC model, Appendixes A-E
(2) Considering a mean annual increment of 25 t ha^{-1} y^{-1} (Stape et al., 2010), and a DM content of 91% (Phyllis database; ecn.nl/phyllis2)
(3) Taken as an average of SRC and willow in Finland and Sweden, from Don et al. (2012)
(4) Don et al. (2012; average for Europe); Sannigrahi et al. (2010)
(5) IPCC (2006), page 27, Table 6.4.

Of course, not all of the grass that is generated in a given biome would necessarily be used for grazing, depending on the stocking density, as well as the grazing losses. For the latter, losses of ca. 15% appears as a realistic figure[56]. Therefore, an interval of grass displacement of 50 (low displacement) to 85% (high displacement) has been considered. The upper range is to be seen as a situation with grazing losses only, while the lower range would reflect a situation with a more extensive stocking density. Considering an average consumption of 16 kg DM ha^{-1} d^{-1} for cattle[1], it appears that rather low stocking densities are necessary if the yields presented in Table F-1 are to support grazing (i.e. below 1 cow per ha; except for upper range of the tropical biome where a density slightly above 1.5 cow per ha is obtained). On this basis, a "low" grass displacement below 50% appears difficult to justify, so the lower displacement interval was limited to 50%. These "low" and "high" ranges were used for all biomes, as shown in Table F-2.

Table F-2: Proportion of the grass that is really displaced

	Tropical	Boreal	Temperate
HIGH DISPLACEMENT (%)	85%	85%	85%
LOW DISPLACEMENT (%)	50%	50%	50%

The resulting amount of carbohydrates and protein displaced in all biome is shown in Table F-3.

[56] Personal communication with Dr. Heiko Georg, Johann Heinrich von Thunen-Institute (vTI), Federal Research Institute for Rural Areas, Forestry and Fisheries, Institute of Organic Farming. October 21st, 2013.

Table F-3: Amount of carbohydrates and protein displaced in all biome(1, 2)

Biome	kg carbohydrate/MJ wood		kg protein/MJ wood	
	HIGH DISPLACEMENT, HIGH GRASS YIELD	LOW DISPLACEMENT, LOW GRASS YIELD	HIGH DISPLACEMENT, HIGH GRASS YIELD	LOW DISPLACEMENT, LOW GRASS YIELD
Tropical	0.015719	0.001442	0.004756	0.000436
Boreal	0.022014	0.005611	0.006661	0.001698
Temperate	0.011722	0.002134	0.003547	0.000646

(1) Numbers are presented with many digits for the transparency of calculation only, but these are not to be seen as significant digits.

(2) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

Considering soybean meal as the marginal protein source (Schmidt, 2007) and a mix of maize, wheat and barley as the marginal carbohydrate source (Hamelin, 2013), the next step consists to determine the amount of soy meal (and co-produced soybean oil) and marginal cereals that are produced as a reaction to the amount of carbohydrates and protein no longer supplied by the grass (Table F-3). This is presented in Table F-4.

Table F-4: Amount of soybean meal, soybeal oil and marginal cereals produced as a reaction to the grass no longer supplied(1, 5)

Biome	Soybean meal(2)		Soybean oil(3)		Cereals(4)	
	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield
tropical (kg DM/ MJ wood)	0.008857048	0.000812573	0.0014	0.000128266	0.018758182	0.001720934
boreal (kg DM/ MJ wood)	0.012403588	0.003161699	0.001957922	0.000499078	0.026269334	0.006696105
temperate (kg DM/ MJ wood)	0.006604903	0.001202573	0.001042592	0.000189828	0.013988404	0.002546908

(1) Numbers are presented with many digits for the transparency of calculation only, but these are not to be seen as significant digits; displ. stands for displacement
(2) 0.54 kg protein per kg soybean meal DM (Møller et al., 2000)
(3) 0.16 kg soybean oil per kg soybean meal (Dalgaard et al., 2008)
(4) 0.84 kg carbohydrate per kg marginal cereal DM (average of spring barley, winter barley, maize and wheat in Møller et al., 2000)

(5) Results can be normalized by ha through multiplying by (1 / 2.21 x 10-6) (tropical biome); (1 / 1.12 x 10-5) (boreal biome) and (4.28 x 10-5) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

Based on an analysis of the historical data available in FAOstat, it appears that soybean meal from Argentina and Brazil is the one most likely to react to an increase in demand for soy (Figure F-2).

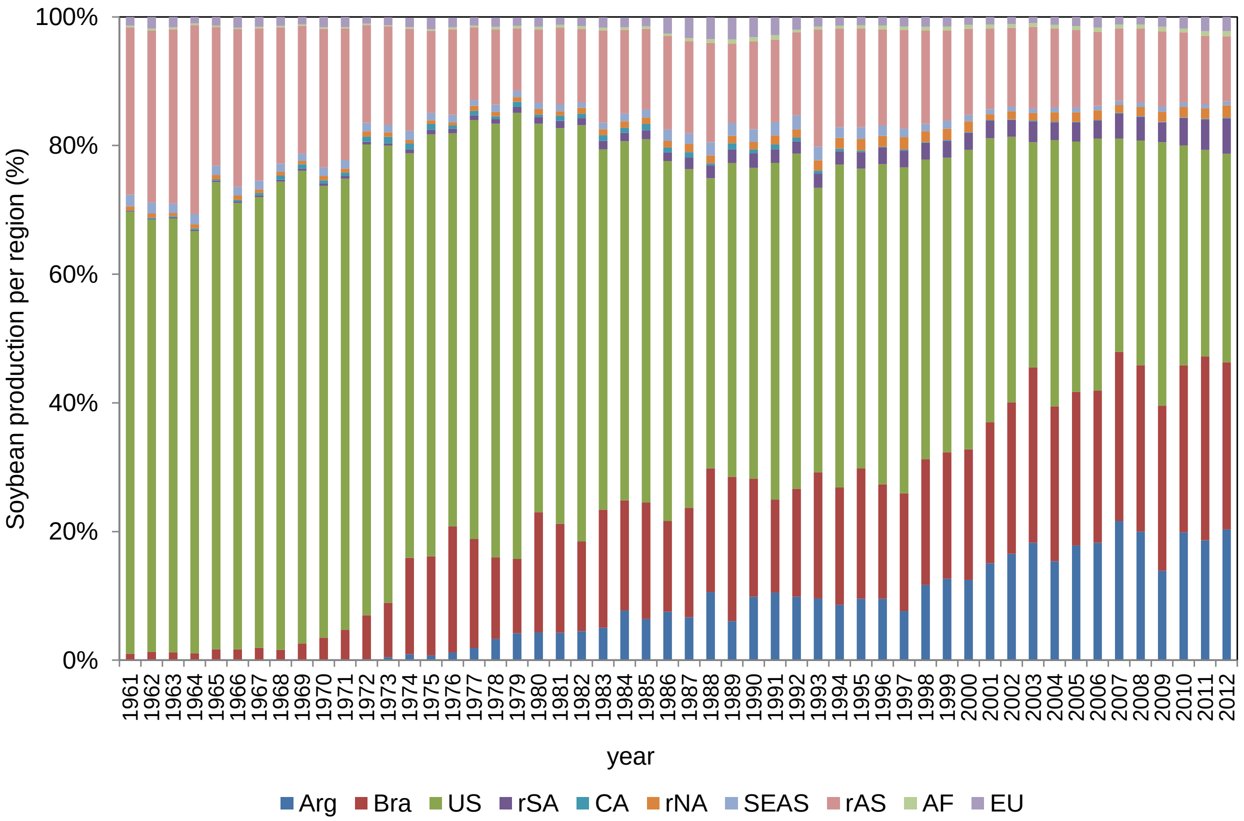

Figure F-2: Soybean production per region (1961-2012). Data extracted from FAOstat. Arg: Argentina; Bra: Brazil; US: United States; rSA: rest of South America; CA: central America; rNA: rest of North America; SEAS: South-east Asia; rAS: rest of Asia; AF: Africa; EU: Europe.

Considering, on the basis of Kløverpris (2008), that an increased demand for carbohydrates would lead to land expansion in Sub-Saharan Africa (24%)[57], European Union (EU-15) (24%), Brazil (14%), Former Soviet Union[58] (12%), Australia (9%), Canada (7%), South America (6%)[59] and United States (4%), and considering the major carbohydrate crops (i.e. wheat, maize, rice, barley, sorghum, millet, rye and oats) as well as the regional production volumes of these crops in the last 10 years, a marginal "reacting carbohydrate crop mix" can be derived. This procedure is described in Hamelin (2013), and the results are shown in Table F-5.

Table F-5: Marginal reacting carbohydrate crop mix

Crop Country	Maize Botswana	maize Brazil	maize Argentina	wheat France	wheat Kazakhstan	wheat Australia	wheat USA	barley Canada
% in the mix	22%	13%	5%	22%	11%	9%	4%	6%
kg DM/kg FM[(1)]	86%	86%	86%	85%	85%	85%	85%	85%

(1) Møller et al. (2000)

[57] See Hamelin (2013) for details on how these proportions were derived from the results of Kløverpris (2008).

[58] Excluding Baltic States

[59] Excluding Brazil and Peru

The data for "cereals" in Table F-4 can thus be detailed according to the information presented in Table F-5. This is presented in Table F-6.

Part of the amount of crops shown in Table F-6 will be provided by land expansion (iLUC), and part will be provided by intensification. In this study, a "low" and "high" range was considered for the land expansion share, as shown in Table F-7. These ranges are based on recent studies indicating that the share of the intensification response is likely to be of at least 15% (Kløverpris, 2008; Marelli et al., 2011) and may potentially be as high as 70% (Marelli et al., 2011).

Table F-6: Land conversion, low and high iLUC(1, 2)

	Tropical		Boreal		Temperate	
	high iLUC, low intensif	low iLUC, high intensif	high iLUC, low intensif	low iLUC, high intensif	high iLUC, low intensif	low iLUC, high intensif
Portion supplied by land expansion	85%	30%	85%	30%	85%	30%
Proportion supplied by intensification	15%	70%	15%	70%	15%	70%

(1) Intensif stands for intensification

(2) For soy, 85% land expansion is considered for both "high" and "low" iLUC, as the production cannot be increased much by an increased N supply from mineral fertilizers (soy being a N-fixing crop).

The next step in calculating the area of land expanded and the amount of crop (i.e. soy and marginal cereals) produced by intensification is to determine the yield of these crops. In Table F-8, both the "historical" yield (2001-2010) and the projected yield (2025; from FAPRI outlook[60]) are presented for these crops. Based on Laborde (2011), a ratio of 0.75 between the yield on new cropland and the average yield is considered, and applied to the FAPRI values. The yield considered for this study where the highest value among the "historical yield" and the "FAPRI-adjusted" yield. Of course, it is here intended to use values that would best represent the yield of "the future". When "historical yield" are used (e.g. for soy in Argentina/Brazil), it is thus to be interpreted that it is considered that significant increases in yield for that crop (in that specific region) are unlikely.

60 http://www.fapri.iastate.edu/tools/outlook.aspx

Table F-7: Amount of soy and marginal cereals produced as a reaction to the grass no longer supplied (kg DM / MJ wood)[(2)]

Biome	Soy[(1)] (Latin America)		maize Botswana		maize Brazil		maize argentina		wheat France		wheat Kazakhstan		wheat Australia		wheat USA		Barley Canada	
	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield
Tropi-cal	1.2 X 10^{-2}	1.1 X 10^{-3}	4.8 X 10^{-3}	4.4 X 10^{-4}	2.8 X 10^{-3}	2.6 X 10^{-4}	1.1 X 10^{-3}	1.0 X 10^{-4}	4.9 X 10^{-3}	4.5 X 10^{-4}	2.4 X 10^{-3}	2.2 X 10^{-4}	2.0 X 10^{-3}	1.8 X 10^{-4}	8.8 X 10^{-4}	8.1 X 10^{-5}	1.3 X 10^{-3}	1.2 X 10^{-4}
boreal	1.7 X 10^{-2}	4.4 X 10^{-3}	6.7 X 10^{-3}	1.7 X 10^{-3}	4.0 X 10^{-3}	1.0 X 10^{-3}	1.5 X 10^{-3}	3.9 X 10^{-4}	6.8 X 10^{-3}	1.7 X 10^{-3}	3.4 X 10^{-3}	8.7 X 10^{-4}	2.8 X 10^{-3}	7.1 X 10^{-4}	1.2 X 10^{-3}	3.2 X 10^{-4}	1.9 X 10^{-3}	4.7 X 10^{-4}
Tempe-rate	9.2 X 10^{-3}	1.7 X 10^{-3}	3.6 X 10^{-3}	6.5 X 10^{-4}	2.1 X 10^{-3}	3.8 X 10^{-4}	8.1 X 10^{-4}	1.5 X 10^{-4}	3.6 X 10^{-3}	6.6 X 10^{-4}	1.8 X 10^{-3}	3.3 X 10^{-4}	1.5 X 10^{-3}	2.7 X 10^{-4}	6.6 X 10^{-4}	1.2 X 10^{-4}	9.9 X 10^{-4}	1.8 X 10^{-4}

(1) Considering 0.87 kg DM per kg FM (Møller et al., 2000), and 0.83 kg soymeal per kg soybean (Dalgaard et al., 2008).

(2) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

Table F-8: Yield of crops considered in this study (t FM per ha per y)

	soy (S. America)	Maize Botswana	maize Brazil	Maize Argentina	wheat France	wheat Kazakhstan	wheat Australia	wheat USA	barley Canada	palm fruit Malaysia / Indonesia
Historical (2001-2010)[(1)]	2.6[(4)]	0.22	3.59	6.52	6.95	1.04	1.55	2.82	2.96	18.98
2025 (FAPRI)[(2)]	3.21[(4)]	1.76[(5)]	5	8.35	5.69[(6)]	2.86[(7)]	2.09	3.16	3.87	34.1[(8)]
FAPRI-adjusted[(3)]	2.40	1.32	3.75	6.26	4.27	2.15	1.57	2.37	2.90	25.58
This study	2.63	1.32	3.75	6.52	6.95	2.15	1.57	2.82	2.96	25.58

(1) FAOstat (faostat.fao.org)
(2) http://www.fapri.iastate.edu/tools/outlook.aspx
(3) Based on Laborde (2011), see text.
(4) Average for Argentina and Brazil.
(5) Figure for "Africa, other"
(6) Figure for European Union
(7) Taken as the average for Ukraine and Russia
(8) Taken from Laborde (2011; Table 2, p.25), as no data for this in FAPRI.

F.2.2 Land expansion/intensification resulting from the protein share of the grass displaced (soy in South America)

Land expanded and amounts from intensification

Based on the figures presented in Tables F- 6-8, the amount of land expanded can be calculated. Results are shown in Table F-9.

*Table F-9: Land expansion for the extra soy needed, in Argentina/Brazil (m^2*y/MJ wood)(1, 2)*

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield
Land expanded	0.040	0.004	0.056	0.014	0.030	0.005

(1) Only a "high" land expansion (or iLUC) is considered for soy, see text.

(2) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

From this, the amount of soy that has to be provided by intensification can be calculated as the missing amount (Table F-10).

Table F-10: Amount of soy supplied from intensification (kg FM/MJ wood)(1)

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield
Soy supplied by intensification	0.00185	0.00017	0.00259	0.00066	0.00138	0.00025

(1) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to land expansion

In order to quantify the releases of C due to the land conversion presented in Table F-9, the soil and vegetation carbon data from the Woods Hole Research Centre, as published in the "supporting online material" of Searchinger et al. (2008) was used. From this database, the amount of C in the soil and vegetation of all affected land types in the region "Latin America" could be extracted. This allowed the calculation of the CO_2 emitted during land conversion, where the following has been considered:

› 25% of the C in the soil is released as CO_2 for all types of land use conversion, except when forests are converted to grassland, where 0% is released;

› 100% of the C in vegetation is released as CO_2 for all forest types as well as for tropical grassland conversions[61], while 0% is released for the remaining biome types (e.g. shrub land, non-tropical grassland, chaparral).

The results of this calculation are shown in Table F-11.

[61] This is to be seen as a simplifying assumption (personal communication with Miguel Brandão, ILCA, January 2013, and with David Laborde, IFPRI, February 2013). In fact, from the data of Earles et al. (2012), whom detailed, for 169 countries, the fate of the above-ground residues when forest are cleared, it can be seen that even after 100 years, it is not exactly 100% of the C that is returned to the atmosphere, although the gap is negligible in most cases.

Table F-11: CO_2 releases from land expansion in Latin America[(3)]

					Tropical		Boreal		Temperate	
Data from Woodshole database, in Searchinger et al. 2008 (SI) (Appendix D of Searchinger et al.)					25% of soil C; 100% of vegetation C[(1)]		25% of soil C; 100% of vegetation C[(1)]		25% of soil C; 100% of vegetation C[(1)]	
Biomes converted	**% conversion**	Region	C in vegetation (ton/ha)	C in soil (ton/ha)	CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)	
					High ILUC	Low ILUC	High ILUC	Low ILUC	High ILUC	Low ILUC
Tropical evergreen forest	3%	LA[(2)]	200	98	93.78	8.60	131.33	33.48	69.94	12.73
Tropical seasonal forest	22%	LA	140	98	525.71	48.23	736.22	187.66	392.04	71.38
Tropical open forest	47%	LA	55	69	495.00	45.41	693.21	176.70	369.13	67.21
Temperate evergreen forest	3%	LA	168	134	84.17	7.72	117.88	30.05	62.77	11.43
Temperate seasonal forest	1%	LA	100	134	16.73	1.53	23.43	5.97	12.47	2.27
Grassland	24%	LA	10	42	71.51	6.56	100.14	25.53	53.33	9.71
Desert	1%	LA	6	58	2.57	0.24	3.60	0.92	1.92	0.35
TOTAL CO_2 (g CO_2*y/MJ)					**1289.48**	**118.30**	**1805.81**	**460.30**	**961.59**	**175.08**
TOTAL ANNUALIZED CO_2 (20 y) (g CO_2/MJ)					**64.47**	**5.92**	**90.29**	**23.02**	**48.08**	**8.75**
TOTAL ANNUALIZED CO_2 (100 y) (g CO_2/MJ)					**12.89**	**1.18**	**18.06**	**4.60**	**9.62**	**1.75**

(1) Except exceptions, see text.
(2) LA: Latin America (selected as the closest region in the Woodshole database to represent Argentina and Brazil)
(3) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to intensification

The emissions induced from input-driven intensification were calculated as described in (Schmidt, 2007), where yield responses to an increased level of N-fertilizer application of 5% are presented, for various crops in various regions of the world (Tables 18.2 to 18.4).

As of now, the inventory data of Schmidt (2007) for intensified crop production are used (Table F-12). It is however foreseen to adjust these data, among other the inventory of ammonium nitrate based on an updated inventory for the N_2O emissions related to nitric acid production[62]. The yield data and yield responses will also be adjusted in function of the yields used in this study (Table F-8).

Table F-12: Inventory data considered for intensified crop production (fertilizer-driven), based on Schmidt (2007; Tables 18.6, 18.7, 18.9)

	Ammonium nitrate, as N kg / ha*y	NH_3 kg / ha*y	N_2O kg / ha*y	NO_3 kg / ha*y	CO_2 kg / ha*y	Ammonium sulfate (as N) kg / ha*y	urea (as N) kg / ha*y	yield kg fm/ha*y
Barley, Canada, intensified(1)	70.4	7.8	2.4	60				2858
Soybean, Brazil, intensified	0	0	4.9	0				3341
Palm, Indonesia/Malaysia, intensified (FFB)		18.9	10.4	375	1500	80.3	29.7	19199

(1) Used as a representative for all intensified cereals

Based on Table F-12 and Table F- 10, the emissions induced from the intensification (input-driven) response of soybean can be calculated. Results are presented in Table F-13.

[62] 0.00248 kg N_2O per kg nitric acid based on an average of plants applying catalytic N_2O decomposition in the oxidation reactor (European Commission, 2007, Table 3.12) (instead of the figure of 0.00839 kg N_2O per kg nitric acid presented in the Ecoinvent v.2.2 database). The BAT level for new plants is however stated to a much lower level, i.e. 0.00012 to 0.00060 kg N_2O per kg nitric acid.

Table: F-13: Emissions induced from the intensification response of soybean (multi-cropping), in kg / MJ wood (1)

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW"	"HIGH"	"LOW"	"HIGH"	"LOW"
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield
NH_3	0	0	0	0	0	0
N_2O	2.71×10^{-6}	2.49×10^{-7}	3.80×10^{-6}	9.67×10^{-7}	2.02×10^{-6}	3.68×10^{-7}
NO_3	0	0	0	0	0	0
CO_2	0	0	0	0	0	0

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

F.2.1 Land expansion/intensification resulting from the carbohydrates share of the grass displaced

Land expanded and amounts from intensification

Based on the figures presented in Tables F-6-8, the amount of land expanded can be calculated. Results are shown in Table F-14.

*Table F-14: Land expansion for the extra cereals needed (m^2*y/MJ wood)(1)*

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW"	"HIGH"	"LOW"	"HIGH"	"LOW"
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
Maize, Botswana	0.0309	0.0010	0.0433	0.0039	0.0230	0.0015
Maize, Brazil	0.0064	0.0002	0.0090	0.0008	0.0048	0.0003
Maize, Argentina	0.0014	0.0000	0.0020	0.0002	0.0011	0.0001
Wheat, France	0.0059	0.0002	0.0083	0.0007	0.0044	0.0003
Wheat, Kazakhstan	0.0096	0.0003	0.0135	0.0012	0.0072	0.0005
Wheat, Australia	0.0108	0.0003	0.0151	0.0014	0.0080	0.0005
Wheat, USA	0.0027	0.0001	0.0037	0.0003	0.0020	0.0001
Barley, Canada	0.0038	0.0001	0.0053	0.0005	0.0028	0.0002

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area

of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

From this, the amount of cereals that has to be provided by intensification can be calculated as the missing amount (Table F-15).

Table F-15: Amount of cereals supplied from intensification (kg FM/MJ wood)(1)

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW"	"HIGH"	"LOW"	"HIGH"	"LOW"
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
Maize, Botswana	0.00072	0	0.00101	0.00120	0.00054	0.00046
Maize, Brazil	0.00043	0	0.00060	0.00071	0.00032	0.00027
Maize, Argentina	0.00016	0	0.00023	0.00027	0.00012	0.00010
Wheat, France	0.00073	0	0.00102	0.00121	0.00054	0.00046
Wheat, Kazakhstan	0.00036	0	0.00051	0.00061	0.00027	0.00023
Wheat, Australia	0.00030	0	0.00042	0.00050	0.00022	0.00019
Wheat, USA	0.00013	0	0.00019	0.00022	0.00010	0.00008
Barley, Canada	0.00020	0	0.00028	0.00033	0.00015	0.00013
Total	0.00303	0	0.00424	0.00505	0.00226	0.00192

(1) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to land expansion

GHG from land expansion were calculated as described in 2.2.2, and on the basis of the regional repartition presented in Table F-5. The biome converted in each region was selected on the basis of the results from Kløverpris (2008). Results are shown in Table F-16.

Table F-16: CO_2 releases from land due to cereals (carbohydrates displaced from grass)(3)

From Kløverpris (2008)					Data from Woodshole database, in Searchinger et al. 2008 (SI) (Appendix D of Searchinger et al.)		Tropical 25% of soil C; 100% of vegetation C(1)		Boreal 25% of soil C; 100% of vegetation C(1)		Temperate 25% of soil C; 100% of vegetation C(1)	
Biomes converted	**Reacting crop**	Region (2)	Share of biome	Final share	C in vegetation (ton/ha)	C in soil (ton/ha)	CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)	
							High	Low	High	Low	High	Low
Savanna (taken as shrub land)	maize	xss	50%	12.0%	4.6	30	12.79	0.41	17.91	1.61	9.54	0.61
African tropical evergreen forest (taken as tropical rain forest)	maize	xss	50%	12.0%	127	190	297.00	9.62	415.93	37.42	221.48	14.23
Tropical evergreen forest	maize	bra	100%	14.0%	200	98	446.56	14.46	625.37	56.26	333.01	21.40
Grassland/steppe (taken as grassland)	maize	xla	50%	3.00%	10	42	4.48	0.14	6.27	0.56	3.34	0.21
Tropical evergreen forest	maize	xla	50%	3.00%	200	98	95.69	3.10	134.01	12.06	71.36	4.59
Temperate evergreen forest	wheat	xeu15	24%	5.76%	160	134	118.47	3.84	165.90	14.93	88.34	5.68
Temperate deciduous forest	wheat	xeu15	24%	5.76%	120	134	93.98	3.04	131.61	11.84	70.08	4.50
Dense shrubland (taken as temperate grassland)	wheat	xeu15	52%	12.48%	7	189	62.68	2.03	87.77	7.90	46.74	3.00
Grassland/steppe (taken as temperate grassland)	wheat	xsu	100%	12.00%	10	189	60.27	1.95	84.40	7.59	44.94	2.89
Savanna (taken as tropical grassland)	wheat	aus	100%	9.00%	18	42	27.26	0.88	38.18	3.43	20.33	1.31
Open shrubland (talen as chaparral)	wheat	usa	100%	4.00%	40	80	8.50	0.28	11.91	1.07	6.34	0.41
Boreal deciduous forest (taken as temperate deciduous forest)	barley	can	100%	7.00%	135	134	16.44	0.53	23.03	2.07	12.26	0.79
TOTAL CO_2 (g CO_2*y/MJ wood)							**1244.117**	**40.284**	**1742.286**	**156.745**	**927.766**	**59.619**
TOTAL ANNUALIZED CO_2 (20 y) (g CO_2/MJ wood)							**62.206**	**2.014**	**87.114**	**7.837**	**46.388**	**2.981**
TOTAL ANNUALIZED CO_2 (100 y) (g CO_2/MJ wood)							**12.441**	**0.403**	**17.423**	**1.567**	**9.278**	**0.596**

(1) Except exceptions, see text.

(2) With xss: Sub-Saharan Africa, excluding Botswana, Lesotho, Namibia, South Africa and Swaziland; xeu15: EU-15, excluding Denmark; bra: Brazil; xsu: Former Soviet Union, excluding the Baltic States; aus: Australia; can: Canada; xla: South America, excluding Brazil and Peru; usa: United States.

(3) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to intensification

The emissions induced from input-driven intensification were calculated as described in section F.2.2. Results are presented in Table F-17.

Table F-17. Emissions induced from the intensification response of cereals (displaced carbohydrates from grass; input-driven), in kg / MJ wood(1)

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
NH_3	8.27×10^{-6}	0	1.16×10^{-5}	1.38×10^{-5}	6.17×10^{-6}	5.24×10^{-6}
N_2O	2.54×10^{-6}	0	3.56×10^{-6}	4.24×10^{-6}	1.90×10^{-6}	1.61×10^{-6}
NO_3	6.36×10^{-5}	0	8.91×10^{-5}	1.06×10^{-4}	4.74×10^{-5}	4.03×10^{-5}
CO_2	0	0	0	0	0	0

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

F.2.2 Land expansion/intensification avoided from the avoided palm plantation (as a result of extra soy oil)

Land expanded and amounts from intensification

Based on the figures presented in Tables F-6 and F-8, the amount of land expanded, palm oil (and fruits) avoided and palm meal displaced can be calculated. Results are shown in Table F-18.

*Table F-18: Land expansion avoided due to the increase for palm fruit avoided (m^2*y/MJ wood)[(6)]*

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
Amount of palm fruits avoided, kg DM / MJ wood[(1,2)]	6.24×10^{-3}	5.72×10^{-4}	8.73×10^{-3}	2.23×10^{-3}	4.65×10^{-3}	8.47×10^{-4}
Area of increased palm plantation avoided, m^2*y / MJ wood[(3)]	6.22×10^{-3}	2.19×10^{-3}	8.71×10^{-3}	3.06×10^{-3}	4.64×10^{-3}	1.63×10^{-3}
Amount of palm meal avoided, kg DM / MJ wood[(4)]	1.68×10^{-4}	1.54×10^{-5}	2.36×10^{-4}	6.01×10^{-5}	1.26×10^{-4}	2.29×10^{-5}
Amount of carbohydrates to be replaced, kg / MJ wood[(5)]	1.15×10^{-4}	1.06×10^{-5}	1.62×10^{-4}	4.12×10^{-5}	8.61×10^{-5}	1.57×10^{-5}
Amount of palm oil avoided, kg DM / MJ wood[(2)]	1.40×10^{-3}	1.28×10^{-4}	1.96×10^{-3}	4.99×10^{-4}	1.04×10^{-3}	1.90×10^{-4}

(1) Assuming that 1 kg of soybean oil displaces 1 kg palm oil
(2) 0.224 kg palm oil per kg palm fruit (Dalgaard et al., 2008)
(3) 0.333 kg palm fruit DM per kg palm fruit FM (Goh & Härdter, p.194)
(4) 0.027 kg palm meal per kg palm fruit (Dalgaard et al., 2008; figure 1)
(5) 0.686 kg carbohydrate per kg meal (Møller et al., 2000)
(6) Results can be normalized by ha through multiplying by (1 / 2.21×10^{-6}) (tropical biome); (1 / 1.12×10^{-5}) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

From this, the amount of palm fruit no longer provided by intensification can be calculated as the missing amount (Table F-19).

Table F-19: Amount of palm fruit no longer supplied from intensification (kg FM/MJ wood)[(1)]

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
	0.000935	0	0.001310	0	0.000698	0

(1) Results can be normalized by ha through multiplying by (1 / 2.21×10^{-6}) (tropical biome); (1 / 1.12×10^{-5}) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to land expansion

GHG from land expansion were calculated as described in F.2.2. Results are shown in Table F-20.

Table F-20: CO_2 releases (avoided) from land expansion due to avoided palm fruit[4]

						Tropical		Boreal		Temperate	
Data from Woodshole database, in Searchinger et al. 2008 (SI) (Appendix D of Searchinger et al.)						25% of soil C; 100% of vegetation C[1]		25% of soil C; 100% of vegetation C[1]		25% of soil C; 100% of vegetation C[1]	
Biomes converted	**% conversion**[2]	Region	C in vegetation (ton/ha)	C in soil (ton/ha)	Emission factor peat (ton CO_2/ha)	CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)	
						High ILUC	Low ILUC	High ILUC	Low ILUC	High ILUC	Low ILUC
Tropical evergreen forest	53%	South & SouthEast Asia	250	120		-340	-120	-476	-167	-253	-89
Tropical seasonal forest	13%	South & SouthEast Asia	150	80		-52	-18	-72	-25	-38	-14
Tropical open forest	4%	South & SouthEast Asia	60	50		-6	-2	-8	-3	-4	-2
Peatland	30%	South & SouthEast Asia			1100[3]	-205	-72	-287	-101	-153	-54
TOTAL CO_2 (g CO_2*y/MJ wood)						-602	-212	-843	-297	-449	-158
TOTAL ANNUALIZED CO_2 (20 y) (g CO_2/MJ wood)						-30	-11	-42	-15	-22	-8
TOTAL ANNUALIZED CO_2 (100 y) (g CO_2/MJ wood)						-6	-2	-8	-3	-4	-2

(1) Except exceptions, see text.
(2) Based on Laborde (2011; footnote p.53), it can be assumed that 30% of the palm extension would occur on peatland. The repartition given by Searchinger et al. (2008), which does not involve peatland, has thus been adjusted accordingly.
(3) Based on Laborde (2011; footnote p.53): 55 t CO_2/ha*y, 20y annualization

(4) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to intensification

The emissions induced from input-driven intensification were calculated as described in section F.2.2. Results are presented in Table F-21. Negative signs indicate that the intensification is avoided.

Table F-21: Emissions avoided from the intensification response of avoided palm fruit), in kg / MJ wood[(1)]

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
NH_3	-9.12×10^{-7}	0	-1.29×10^{-6}	0	-6.87×10^{-7}	0
N_2O	-5.07×10^{-7}	0	-7.10×10^{-7}	0	-3.78×10^{-7}	0
NO_3	-1.83×10^{-5}	0	-2.56×10^{-5}	0	-1.36×10^{-5}	0
CO_2	-7.31×10^{-5}	0	-1.02×10^{-4}	0	-5.45×10^{-5}	0

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

F.2.3 Land expansion/intensification resulting from the induced demand for carbohydrates (as a result of missing palm meal)

Based on the figures presented in Tables 5, 6, 8 and 18, the amount of land expanded can be calculated. Results are shown in Table F-22.

*Table F-22: Land expansion for the extra cereals needed, as a reaction to the missing palm meal (m^2*y/MJ wood)[(1)]*

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
Maize, Botswana	2.27×10^{-4}	2.08×10^{-5}	3.18×10^{-4}	8.10×10^{-5}	1.69×10^{-4}	3.08×10^{-5}
Maize, Brazil	4.72×10^{-5}	4.33×10^{-6}	6.61×10^{-5}	1.69×10^{-5}	3.52×10^{-5}	6.41×10^{-6}
Maize, Argentina	1.4×10^{-5}	9.58×10^{-7}	1.46×10^{-5}	3.73×10^{-6}	7.79×10^{-6}	1.42×10^{-6}
Wheat, France	4.36×10^{-5}	4.00×10^{-6}	6.11×10^{-5}	1.56×10^{-5}	3.25×10^{-5}	5.92×10^{-6}
Wheat, Kazakhstan	7.07×10^{-5}	6.48×10^{-6}	9.90×10^{-5}	2.52×10^{-5}	5.27×10^{-5}	9.60×10^{-6}
Wheat, Australia	7.91×10^{-5}	7.26×10^{-6}	1.11×10^{-4}	2.82×10^{-5}	5.90×10^{-5}	1.07×10^{-5}
Wheat, USA	1.95×10^{-5}	1.79×10^{-6}	2.74×10^{-5}	6.98×10^{-6}	1.46×10^{-5}	2.65×10^{-6}
Barley, Canada	2.79×10^{-5}	2.56×10^{-6}	3.91×10^{-5}	9.97×10^{-6}	2.08×10^{-5}	3.79×10^{-6}

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

From this, the amount of cereals that has to be provided by intensification can be calculated as the missing amount (Table F-23).

Table F-23: Amount of cereals supplied from intensification, as a result of the missing palm meal (kg FM/MJ wood) [(1)]

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
Maize, Botswana	5.29×10^{-6}	4.85×10^{-7}	7.41×10^{-6}	1.89×10^{-6}	3.94×10^{-6}	7.18×10^{-7}
Maize, Brazil	3.12×10^{-6}	2.87×10^{-7}	4.38×10^{-6}	1.12×10^{-6}	2.33×10^{-6}	4.24×10^{-7}
Maize, Argentina	1.20×10^{-6}	1.10×10^{-7}	1.68×10^{-6}	4.29×10^{-7}	8.96×10^{-7}	1.63×10^{-7}
Wheat, France	5.35×10^{-6}	4.91×10^{-7}	7.49×10^{-6}	1.91×10^{-6}	3.99×10^{-6}	7.26×10^{-7}
Wheat, Kazakhstan	2.68×10^{-6}	2.45×10^{-7}	3.75×10^{-6}	9.55×10^{-7}	2.00×10^{-6}	3.63×10^{-7}
Wheat, Australia	2.19×10^{-6}	2.01×10^{-7}	3.7×10^{-6}	7.81×10^{-7}	1.63×10^{-6}	2.97×10^{-7}
Wheat, USA	9.73×10^{-7}	8.93×10^{-8}	1.36×10^{-6}	3.47×10^{-7}	7.25×10^{-7}	1.32×10^{-7}
Barley, Canada	1.46×10^{-6}	1.34×10^{-7}	2.04×10^{-6}	5.21×10^{-7}	1.09×10^{-6}	1.98×10^{-7}
Total	2.23×10^{-5}	2.04×10^{-6}	3.12×10^{-5}	7.95×10^{-6}	1.66×10^{-5}	3.02×10^{-6}

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to land expansion

GHG from land expansion were calculated as described in section F.2.2. Results are shown in Table F-24.

Table F-24: CO_2 releases from land expansion due to cereals (carbohydrates displaced from no longer available palm meal)[(3)]

From Kløverpris (2008)					Data from Woodshole database, in Searchinger et al. 2008 (SI) (Appendix D of Searchinger et al.)		Tropical: 25% of soil C; 100% of vegetation C[(1)]		Boreal: 25% of soil C; 100% of vegetation C[(1)]		Temperate: 25% of soil C; 100% of vegetation C[(1)]	
Biomes converted	**Reacting crop**	Region [(2)]	Share of biome	Final share	C in vegetation (ton/ha)	C in soil (ton/ha)	CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)	
							High	Low	High	Low	High	Low
Savanna (taken as shrub land)	maize	xss	50%	12.0%	4.6	30	0.094	0.009	0.132	0.034	0.070	0.013
African tropical evergreen forest (taken as tropical rain forest)	maize	xss	50%	12.0%	127	190	2.182	0.014	3.056	0.779	1.627	0.296
Tropical evergreen forest	maize	bra	100%	14.0%	200	98	3.281	0.014	4.595	1.171	2.447	0.445
Grassland/steppe (taken as grassland)	maize	xla	50%	3.00%	10	42	0.033	0.009	0.046	0.012	0.025	0.004
Tropical evergreen forest	maize	xla	50%	3.00%	200	98	0.703	0.014	0.985	0.251	0.524	0.095
Temperate evergreen forest	wheat	xeu15	24%	5.76%	160	134	0.870	0.010	1.219	0.311	0.649	0.118
Temperate deciduous forest	wheat	xeu15	24%	5.76%	120	134	0.690	0.010	0.967	0.246	0.515	0.094
Dense shrubland (taken as temperate grassland)	wheat	xeu15	52%	12.48%	7	189	0.461	0.006	0.645	0.164	0.343	0.063
Grassland/steppe (taken as temperate grassland)	wheat	xsu	100%	12.00%	10	189	0.443	0.006	0.620	0.158	0.330	0.060
Savanna (taken as tropical grassland)	wheat	aus	100%	9.00%	18	42	0.200	0.010	0.281	0.072	0.149	0.027
Open shrubland (talen as chaparral)	wheat	usa	100%	4.00%	40	80	0.062	0.006	0.087	0.022	0.047	0.008
Boreal deciduous forest (taken as temperate deciduous forest)	barley	can	100%	7.00%	135	134	0.121	0.001	0.169	0.043	0.090	0.016
TOTAL CO_2 (g CO_2*y/MJ wood)							**9.141**	**0.111**	**12.801**	**3.263**	**6.816**	**1.241**
TOTAL ANNUALIZED CO_2 (20 y) (g CO_2/MJ wood)							**0.457**	**0.006**	**0.640**	**0.163**	**0.341**	**0.062**
TOTAL ANNUALIZED CO_2 (100 y) (g CO_2/MJ wood)							**0.091**	**0.001**	**0.128**	**0.033**	**0.068**	**0.012**

(1) Except exceptions, see text.

(2) With xss: Sub-Saharan Africa, excluding Botswana, Lesotho, Namibia, South Africa and Swaziland; xeu15: EU-15, excluding Denmark; bra: Brazil; xsu: Former Soviet Union, excluding the Baltic States; aus: Australia; can: Canada; xla: South America, excluding Brazil and Peru; usa: United States.

(3) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to intensification

The emissions induced from input-driven intensification were calculated as described in section F.2.2. Results are presented in Table F-25.

Table F-25: Emissions induced from the intensification response of cereals (displaced carbohydrates from no longer available palm meal; input-driven), in kg / MJ wood[(1)]

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
NH_3	6.08×10^{-8}	5.57×10^{-9}	8.15×10^{-8}	2.17×10^{-8}	4.53×10^{-8}	8.25×10^{-9}
N_2O	1.87×10^{-8}	1.72×10^{-9}	2.62×10^{-8}	6.67×10^{-9}	1.39×10^{-8}	2.54×10^{-9}
NO_3	4.67×10^{-7}	4.29×10^{-8}	6.55×10^{-7}	1.67×10^{-7}	3.49×10^{-7}	6.35×10^{-8}
CO_2	0	0	0	0	0	0

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

F.2.4 Final iLUC / intensification figures for plantation of grassland

The final iLUC and intensification figures (i.e. summing up the effect over the whole system, as illustrated in Figure F-1) occurring as a result of a plantation on grassland are presented in Table F-25.

The intensification figures shown in Table F-25 present the net global warming impact in g CO_2 eq. per MJ wood, considering IPCC AR4's GWP_{100}[63]. Further, the figures presented in Tables F-13, F-17, F-21 and F-25 are for the input-driven (here fertilizer) share of intensification. Here, it was considered that this effect would account for a maximal of 75% of the intensification response, the rest of the share being considered GHG-negligible (e.g. improved breeds, irrigation, mechanization improvement, etc.). Accordingly, the GHG figures from the above-mentioned Tables were multiplied by 75%.

[63] Involving, among others, a factor of 289 kg CO_2 eq. per kg N_2O. AR4 stands for assessment report 4.

Table F-26: Final iLUC/intensification aggregated GHG figures for plantation on grassland, in g CO_2 eq. per MJ wood)(1,2, 4)

	ILUC						INTENSIFICATION			TOTAL (ILUC + INTENSIFICATION)					
	20 years annualization(3)			100 years annualization(3)						20 years annualization(3)			100 years annualization(3)		
	Tro	Bor	Tem	Tro	Bor	Tem	Tro	Bor	Tem	Tro	Bor	Tem	Tro	Bor	Tem
HIGH	97	136	72	19	27	14	1	1	1	98	137	73	20	29	15
LOW	-3	16	4	-1	3	1	0	1	0	-3	17	4	0	4	1

(1) all figures were calculated with IPCC AR4's GWP_{100}
(2) Tro: tropical; Bor: boreal; Tem: temperate
(3) The same approach as applied and described in Chapter 5.3.2
(4) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

F.3 Plantation on cropland

Establishing a woody plantation on cropland involves that a crop is displaced. In order to determine how much land expansion would take place as a result of such cropland displacement, a deterministic approach was used, as in section F.2.

The starting point for the analysis was to consider wheat as the crop displaced, in all biomes. This involves that it is considered that it is this crop that farmers would give up, if less land is available. Wheat is thus here considered as a representative of the crop with the lowest marginal returns. It can be argued whether this is a realistic choice of not. Yet, based on an analysis of historical data in FAOstat, it appears that cereals and coarse grains do respond more strongly to a price change than most other crops. Further, according to Weidema, (2003), this, i.e. wheat as the marginal displaced crop, is a realistic case for EU (along with barley). One important aspect of this choice, for the present analysis, of course lies in the crop yield. In fact, the higher is the yield of the crop displaced, the higher is the nutritional value (e.g. carbohydrates) displaced, and thus the higher is the iLUC likely to be. For this reason, an important yield range was selected for the wheat displaced in each biome.

In terms of nutritional value, wheat supplies essentially carbohydrates (84% of the DM, based on Møller et al., 2000). As a consequence of a new plantation on grassland, the nutritional value that was provided by the wheat now has to be supplied by the marginal source of carbohydrates. This is illustrated in Figure F-3 (example for tropical biome), where the boundary conditions considered are shown.

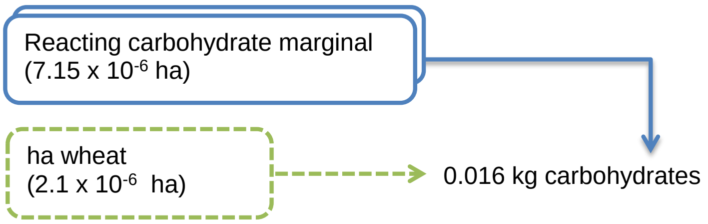

Figure F-3: Process flow diagram considered for modeling the consequences of establishing a plantation on grassland. The flows are expressed per MJ wood and represent the case of a plantation on tropical biome, for the "high" interval (see text). Full lines represent induced flows and dotted lines avoided flows. The boxes on the second plan represent intensification.

The first step to this analysis is thus to determine how much carbohydrates are displaced, in each biome. This can be done on the basis of the information shown in Table F-27.

Table F-27: LHV and yield considered for the woody plantations as well as the yield of the displaced wheat, for each biome

Biome	LHV, wood from plantation (1) (MJ / kg DM)	Yield, wood from plantation (t DM / ha*y)	Yield of wheat(5) (t DM / ha*y)
Tropical	19.9	22.8(2)	2.4 – 9.0
Boreal	19.8	4.5(3)	1.8 – 3.8
Temperate	19.5	12.0(4)	3.1 – 8.0

(1) Same data as used for the dLUC model, Appendixes A-E
(2) Considering a mean annual increment of 25 t ha^{-1} y^{-1} (Stape et al., 2010), and a DM content of 91% (Phyllis database; ecn.nl/phyllis2)
(3) Taken as an average of SRC and willow in Finland and Sweden, from Don et al. (2012)
(4) Don et al. (2012; maximal range of average yields reported for Europe); Sannigrahi et al. (2010)
(5) Selected based on the FAPRI outlook. For tropical, the lower interval represents the yield of Africa and Australia in 2010, while the higher interval represents the yield of Egypt in 2025. For boreal, the lower interval represents the yield of Russia in 2010, while the higher interval represents the yield of Canada in 2025. For temperate, the lower interval represents the yield of Ukraine in 2010, while the highest interval represents the yield of Denmark today, taken from Hamelin et al. (2012). This higher interval was selected as above the values predicted in FAPRI (yet, it should be realistic to consider such high yields in the future for wheat, if these are already achieved today in Denmark, where allowed fertilization levels are below the economical optimum). For all cases, a DM content of 85% was considered for wheat (i.e. 0.85 kg DM per kg FM).

The resulting amount of carbohydrates and protein displaced in all biome is shown in Table F-28.

Table F-28: Amount of carbohydrates displaced in all biome(1, 3)

Biome	kg carbohydrate/MJ wood(2)	
	HIGH wheat yield	LOW wheat yield
Tropical	0.016727	0.004373
Boreal	0.035603	0.017468
Temperate	0.028776	0.011172

(1) Numbers are presented with many digits for the transparency of calculation only, but these are not to be seen as significant digits.
(2) 0.84 kg carbohydrates per kg DM were considered, based on Møller et al. (2000).
(3) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

As in the case of plantation on grassland, the amount of reacting marginal cereals can now be calculated (Table F- 29).

Table F-29: Amount of marginal cereals produced as a reaction to the wheat no longer supplied[1, 3]

Biome	Cereals[2]	
	HIGH wheat yield	LOW wheat yield
tropical (kg DM/ MJ wood)	0.019961148	0.005218601
boreal (kg DM/ MJ wood)	0.042485195	0.020844299
temperate (kg DM/ MJ wood)	0.034338999	0.013331611

(1) Numbers are presented with many digits for the transparency of calculation only, but these are not to be seen as significant digits; displ. stands for displacement

(2) 0.84 kg carbohydrate per kg marginal cereal DM (average of spring barley, winter barley, maize and wheat in Møller et al., 2000)

(3) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

Based on the same approach as presented in section F. 2.3, and on the distribution and marginal cereal yields presented in Tables F-5 and F-8 respectively, the amount of extra marginal cereal needed can be calculated (Table F-30), as well as the amount of land expansion (Table F-31) and the amount of cereals produced by intensification (Table F-32).

The GHG from land expansion and intensification were also calculated as described in section F.2.3, and results are presented in Table F-33 and F-34, respectively.

Table F-30: Amount of marginal cereals produced as a reaction to the wheat no longer supplied (kg DM / MJ wood)(1)

Biome	Maize Botswana		maize Brazil		Maize Argentina		Wheat France		wheat Kazakhstan		wheat Australia		wheat USA		barley Canada	
	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield
Tropi-cal	5.11 X 10^{-3}	1.33 X 10^{-3}	3.02 X 10^{-3}	7.89 X 10^{-4}	1.16 X 10^{-3}	3.03 X 10^{-4}	5.17 X 10^{-3}	1.35 X 10^{-3}	2.58 X 10^{-3}	6.75 X 10^{-4}	2.11 X 10^{-3}	5.53 X 10^{-4}	9.39 X 10^{-4}	2.46 X 10^{-4}	1.41 X 10^{-3}	3.68 X 10^{-4}
boreal	1.09 X 10^{-2}	5.33 X 10^{-3}	6.42 X 10^{-3}	3.15 X 10^{-3}	2.47 X 10^{-3}	1.21 X 10^{-3}	1.10 X 10^{-2}	5.39 X 10^{-3}	5.50 X 10^{-3}	2.70 X 10^{-3}	4.50 X 10^{-3}	2.21 X 10^{-3}	2.00 X 10^{-3}	9.81 X 10^{-4}	3.00 X 10^{-3}	1.47 X 10^{-3}
Tempe-rate	8.78 X 10^{-3}	3.41 X 10^{-3}	5.19 X 10^{-3}	2.02 X 10^{-3}	2.00 X 10^{-3}	7.75 X 10^{-4}	8.89 X 10^{-3}	3.45 X 10^{-3}	4.44 X 10^{-3}	1.73 X 10^{-3}	3.64 X 10^{-3}	1.41 X 10^{-3}	1.62 X 10-3	6.27 X 10-4	2.42 X 10^{-3}	9.41 X 10^{-4}

(1) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

*Table F-31: Land expansion for the extra cereals needed (m^2*y/MJ wood)(1)*

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH wheat yield	Low iLUC (high intensif), LOW wheat yield	High iLUC (low intensif), HIGH wheat yield	Low iLUC (high intensif), LOW wheat yield	High iLUC (low intensif), HIGH wheat yield	Low iLUC (high intensif), LOW wheat yield
Maize, Botswana	3.29 X 10-2	3.03 X 10-3	7.00 X 10-2	1.21 X 10-2	5.66 X 10-2	7.75 X 10-3
Maize, Brazil	6.84 X 10-3	6.31 X 10-4	1.46 X 10-2	2.52 X 10-3	1.18 X 10-2	1.61 X 10-3
Maize, Argentina	1.51 X 10-3	1.40 X 10-4	3.22 X 10-3	5.58 X 10-4	2.60 X 10-3	3.57 X 10-4
Wheat, France	6.32 X 10-3	5.83 X 10-4	1.34 X 10-2	2.33 X 10-3	1.09 X 10-2	1.49 X 10-3
Wheat, Kazakhstan	1.02 X 10-2	9.45 X 10-4	2.18 X 10-2	3.77 X 10-3	1.76 X 10-2	2.41 X 10-3
Wheat, Australia	1.15 X 10-2	1.06 X 10-3	2.44 X 10-2	4.22 X 10-3	1.97 X 10-2	2.70 X 10-3
Wheat, USA	2.83 X 10-3	2.61 X 10-4	6.03 X 10-3	1.04 X 10-3	4.87 X 10-3	6.67 X 10-4
Barley, Canada	4.05 X 10-3	3.73 X 10-4	8.61 X 10-3	1.49 X 10-3	6.96 X 10-3	9.54 X 10-4

(1) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

Table F-32: Amount of cereals supplied from intensification (kg FM/MJ wood)[(1)]

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH wheat yield	Low iLUC (high intensif), LOW wheat yield	High iLUC (low intensif), HIGH wheat yield	Low iLUC (high intensif), LOW wheat yield	High iLUC (low intensif), HIGH wheat yield	Low iLUC (high intensif), LOW wheat yield
Maize, Botswana	7.66E-04	0	1.63E-03	3.73E-03	1.32E-03	2.39E-03
Maize, Brazil	4.53E-04	0	9.63E-04	2.21E-03	7.79E-04	1.41E-03
Maize, Argentina	1.74E-04	0	3.71E-04	8.48E-04	2.99E-04	5.43E-04
Wheat, France	7.75E-04	0	1.65E-03	3.78E-03	1.33E-03	2.42E-03
Wheat, Kazakhstan	3.87E-04	0	8.25E-04	1.89E-03	6.67E-04	1.21E-03
Wheat, Australia	3.17E-04	0	6.75E-04	1.54E-03	5.45E-04	9.88E-04
Wheat, USA	1.41E-04	0	3.00E-04	6.87E-04	2.42E-04	4.39E-04
Barley, Canada	2.11E-04	0	4.50E-04	1.03E-03	3.64E-04	6.59E-04
Total	3.22E-03	0	6.86E-03	1.57E-02	5.55E-03	1.00E-02

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

Table F-33: CO_2 releases from land expansion due to cereals (carbohydrates displaced from wheat no longer produced at the plantation location)[(3)]

From Kløverpris (2008)					Data from Woodshole database, in Searchinger et al. 2008 (SI) (Appendix D of Searchinger et al.)		Tropical: 25% of soil C; 100% of vegetation C[(1)]		Boreal: 25% of soil C; 100% of vegetation C[(1)]		Temperate: 25% of soil C; 100% of vegetation C[(1)]	
Biomes converted	**Reacting crop**	Region [(2)]	Share of biome	Final share	C in vegetation (ton/ha)	C in soil (ton/ha)	CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)	
							High	Low	High	Low	High	Low
Savanna (taken as shrub land)	maize	xss	50%	12.0%	4.6	30	13.6	1.3	29.0	5.0	23.4	3.2
African tropical evergreen forest (taken as tropical rain forest)	maize	xss	50%	12.0%	127	190	316.1	29.2	672.7	116.5	543.7	74.5
Tropical evergreen forest	maize	bra	100%	14.0%	200	98	475.2	43.8	1011.4	175.1	817.5	112.0
Grassland/steppe (taken as grassland)	maize	xla	50%	3.00%	10	42	4.8	0.4	10.1	1.8	8.2	1.1
Tropical evergreen forest	maize	xla	50%	3.00%	200	98	101.8	9.4	216.7	37.5	175.2	24.0
Temperate evergreen forest	wheat	xeu15	24%	5.76%	160	134	126.1	11.6	268.3	46.5	216.9	29.7
Temperate deciduous forest	wheat	xeu15	24%	5.76%	120	134	100.0	9.2	212.8	36.9	172.0	23.6
Dense shrubland (taken as temperate grassland)	wheat	xeu15	52%	12.48%	7	189	66.7	6.2	142.0	24.6	114.7	15.7
Grassland/steppe (taken as temperate grassland)	wheat	xsu	100%	12.00%	10	189	64.1	5.9	136.5	23.6	110.3	15.1
Savanna (taken as tropical grassland)	wheat	aus	100%	9.00%	18	42	29.0	2.7	61.7	10.7	49.9	6.8
Open shrubland (talen as chaparral)	wheat	usa	100%	4.00%	40	80	9.0	0.8	19.3	3.3	15.6	2.1
Boreal deciduous forest (taken as temperate deciduous forest)	barley	can	100%	7.00%	135	134	17.5	1.6	37.2	6.4	30.1	4.1
TOTAL CO_2 (g CO_2*y/MJ wood)							**1324**	**122**	**2818**	**488**	**2278**	**312**
TOTAL ANNUALIZED CO_2 (20 y) (g CO_2/MJ wood)							**66.2**	**6.1**	**140.9**	**24.4**	**113.9**	**15.6**
TOTAL ANNUALIZED CO_2 (100 y) (g CO_2/MJ wood)							**13.2**	**1.2**	**28.2**	**4.9**	**22.8**	**3.1**

(1) Except exceptions, see text.

(2) With xss: Sub-Saharan Africa, excluding Botswana, Lesotho, Namibia, South Africa and Swaziland; xeu15: EU-15, excluding Denmark; bra: Brazil; xsu: Former Soviet Union, excluding the Baltic States; aus: Australia; can: Canada; xla: South America, excluding Brazil and Peru; usa: United States.

(3) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

Table F-34: Emissions induced from the intensification response of cereals (displaced carbohydrates from no longer available wheat at plantation location; input-driven), in kg / MJ wood [(1)]

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield
NH_3	6.08×10^{-8}	5.57×10^{-9}	8.15×10^{-8}	2.17×10^{-8}	4.53×10^{-8}	8.25×10^{-9}
N_2O	1.87×10^{-8}	1.72×10^{-9}	2.62×10^{-8}	6.67×10^{-9}	1.39×10^{-8}	2.54×10^{-9}
NO_3	4.67×10^{-7}	4.29×10^{-8}	6.55×10^{-7}	1.67×10^{-7}	3.49×10^{-7}	6.35×10^{-8}
CO_2	0	0	0	0	0	0

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

The final iLUC/intensification figures for this scenario are summarized in Table F-35. These were calculated as in the grassland case, i.e. considering that the fertilizer-driven response accounts for 75% of the intensification response.

Table F-35: Final iLUC/intensification aggregated GHG figures for plantation on cropland, in g CO_2 eq. per MJ wood)[(1,2, 3, 4)]

	ILUC						INTENSIFI-CATION			TOTAL (ILUC + INTENSIFICATION)					
	20 years annualization[(3)]			100 years annualization[(3)]						20 years annualization[(3)]			100 years annualization[(3)]		
	Tr	Bo	Te	Tr	Bo	Te	Tr	Bo	Te	Tr	Bo	Te	Tr	Bo	Te
HIGH	66	141	114	13	28	23	1	1	1	67	142	115	14	29	24
LOW	6	24	16	1	5	3	0	3	2	6	27	17	1	8	5

(1) all figures were calculated with IPCC AR4's GWP_{100}
(2) Tr: tropical; Bo: boreal; Te: temperate
(3) The same approach as applied and described in Chapter 5.3.2
(4) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

F.4 Limitations

The main limitation of the approach used for estimating land expansion and intensification lies in the data quality and assumption. Particularly critical (sensitive) data are[64]:

- Future yields:
    - Of the plantation
    - Of the grass / crop displaced*
    - Of the reacting marginal crops
- The stock of soil and vegetation C used[65,66]
- The assumptions regarding the identification of the marginal crops
- The proportions considered for:
    - "high" and "low" expansion*
    - "high" and "low" grass displacement*
    - How much of the intensification response is due to an increase of N-fertilizers

Further, it should be highlighted that the environmental impacts due to the fertilization of the plantation itself have not been included anywhere in this study (although this is not related with the iLUC and intensification calculations). This should be taken into account when interpreting the results as absolute values. Similarly, the impacts related to the harvest and transport of the woody biomass were also excluded, although this can be expected to be of more minor importance (at least in comparison to the global warming contribution from ILUC/intensification).

One other weak point of the approach presented herein relates to the carbohydrates portion of the feedstock to be replaced (here modelled as a corresponsing increased demand for carbohydrates). For this, a mix carbohydrate marginal was derived from the results of Kløverpris (2008). On the basis of that same study, it was considered that land expansion would occur according to specific proportions in specific biomes. This could be seen as a slight inconsistency, since the study of Kløverpris (2008) is based on economic equilibrium modelling. Instead, the same

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64 Parameters marked with a * are those that were taken into account through the use of range.

65 For instance, the peatland emission factor used is 55 t CO_2 per ha per y, while recent studies suggested higher values (for example, Marelli et al., 2011, proposed 86 t CO_2 per ha per y)

66 C stock data from the Woods Hole database, as published in Searchinger et al. (2008), were used for ILUC. Yet, for the DLUC calculations (Appendixes A-E), IPCC data were used. Ideally, the same C stock database should have been used. However, it should be highlighted that important uncertainty exists in relation to both these databases. Nevertheless, using another data source for C stock would change the value of the absolute ILUC figures derived.

approach as used for the protein share could have been used, i.e. determining a single marginal carbohydrate crop and the region from which it is likely to come from based on historical data and best available knowledge. The impact of this (i.e. the method to determine the affected biomes for land expansion due to the carbohydrate share of the increased demand) on the results is however foreseen to be rather insignificant, but the actual sensitivity of the ILUC results to this have not been tested.

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Appendix G Straw and manure inventory

Introduction

This appendix presents the inventory data considered for:

- The conventional manure management of fattening pig slurry
- Wheat straw management (with and without ploughing)
- Mono-digestion of fattening pig slurry (excluding use of the biogas, and energy input data)
- Co-digestion of fattening pig slurry and wheat straw (excluding use of the biogas, and energy input data)

The reason why the energy input and use of biogas are excluded from the 2 latter is that these parameters will be dependent upon the scenario considered for the marginal energy. Similarly, these data do not include any specific energy pathway for of the use of wheat straw, and are simply "cradle-to-gate", the gate being the harvest of the straw.

G.1 Biogenic CO_2

Soils have an equilibrium C content which is the result of a balance between inflows (e.g. plant matter from above- and below- ground residues, manure, etc.) and outflows (e.g. decomposition, erosion, leaching of soluble C, etc.) to the soil pool. If outflows are greater than inflows, soil C decreases, while soil C increases if inflows are greater than outflows.

When manure (or digesate) and straw are applied/plough down to/into land, part of the C in it enters the soil C pool, and part ends up emitted as CO_2. This was modelled on a year per year basis, with the dynamic soil C model C-TOOL, developed to calculate the soil carbon dynamics in relation to the Danish commitments to UNFCCC (Petersen, 2010a; Petersen et al., 2002).

In the inventory tables presented here (i.e. Tables 6-8, which are to be used for the full bioenergy pathways), it is, however, only the net biogenic CO_2 flows that are presented (sequestration in soils or loss of native soil C), as this is in conformity to the structure of the bioenergy pathways.

G.2 Characterized results

Tables 5-8 also present, besides emission flows themselves, some characterized results for the following impact categories:

- Global warming (time horizon of 20 y an 100 y)
- Aquatic eutrophication (when N is the limiting element for growth)

The methodology used for the former is the one described in IPCC AR4 (Forster et al., 2007), while the methodology used for the latter is the Danish EDIP 2003 life cycle impact assessment method (Hauschild, 2005).

The characterization factors shown in Table 1 were used:

Table G-1: Characterization factors used for the global warming and eutrophication impact

	Global warming, 100 y	Global warming, 20 y	Eutrophication-N
CO_2	1 kg CO_2 eq. / kg CO_2	1 kg CO_2 eq. / kg CO_2	
N_2O	298 CO_2 eq. / kg N_2O	289 CO_2 eq. / kg N_2O	
CH_4	25 CO_2 eq. / kg CH_4	72 CO_2 eq. / kg CH_4	
NH_3			0.1886 kg N eq. / kg NH_3
NO_X			0.096 kg N eq. / kg NOx
NO_3			0.1357 kg N eq. / kg NO_3

G.3 Conventional manure management

The reference pig slurry management considered in this study is based on the reference system described in Hamelin et al. (in press; Supporting Information, p. S2-S4), and assume the same pre-conditions. It a nutshell, this process consists to store the excreted manure (first in the housing system, then in an outdoor storage facility) until it can be applied on land, where it is used as a source of N, P and K fertilizer. By using manure as a fertilizer, it involves that marginal mineral N, P and K fertilizers do not need to be produced and used.

As in Hamelin et al. (in press), outdoor storage is assumed to take place in a concrete tank, covered by a straw floating layer and slurry is applied to fields with a trail-hose slurry tanker. The same reference crop rotation as described in Hamelin et al. (in press; Table S63) is considered here.

The reference slurry composition is based on the Danish manure standards (Poulsen, 2011). Table 2 presents the slurry composition considered, and Table 3, the life cycle inventory data considered for reference slurry management (emission flows). State-of-the-art mass balances were performed to ensure consistency between the slurry composition, and the emission flows. Based on Table 2, there is 1.002 tonne of manure ex-housing (i.e. manure as it leaves the housing unit) per tonne manure ex-animal (i.e. manure as "freshly" excreted). It is the slurry ex-housing (or ex pre-tank) which is the input into the digester[67].

When manure is used for biogas, its conventional storage and application on land is avoided (as well as the mineral fertilizer replacement that it would have generated). Table 4 shows the aggregated environmental impact of this for some selected flows and characterized impacts, per kg VS.

Table G-2: Reference pig slurry composition (from Hamelin et al., in press)

Parameter	Slurry ex-animal[a]	Slurry ex-housing[b]	Slurry ex-storage[c]	Source and assumptions
Mass ($t\ pig^{-1}$)	0.47	0.47[d]	0.48	Data needed to ensure correspondence between each manure stage. Values ex-animal and ex-storage based on Poulsen (2011). Value ex-housing based on mass balance[d]. A net water addition of 0.02 m^3 per tonne manure is considered during outdoor storage.
Total N ($kg\ t^{-1}$)	6.00	5.26	5.03	N ex-animal from Poulsen (2011). Losses considered (during housing and during storage): NH_3, N_2O, N_2, NO. Details on N losses are in Table 3. The N from straw addition[e] in-house and as a floating layer during outdoor storage is estimated as 0.009 kg per tonne manure ex-animal and 0.011 kg per tonne manure ex-storage, respectively.
P ($kg\ t^{-1}$)	1.21	1.21	1.19	P ex-animal from Poulsen (2011). No losses considered during housing and storage. The P from straw addition[e] in-house and as a floating layer during outdoor storage is estimated as 0.001 kg per tonne manure ex-animal and 0.002 kg per tonne manure ex-storage, respectively.
K ($kg\ t^{-1}$)	2.83	2.85	2.83	K ex-animal from Poulsen (2011). No losses considered during housing and storage. The K from straw addition[e] in-house and as a floating layer during outdoor storage is estimated as 0.02 kg per tonne manure ex-animal and 0.03 kg per tonne manure ex-storage, respectively.
DM ($kg\ t^{-1}$)	74.8	68.7	66.0	DM ex-storage from Poulsen (2011). Losses during storage: 5 % of the ex-housing values; losses during housing: 10 % of the ex-animal value. Assumptions for losses during storage and housing based on (Poulsen, 2008).
VS ($kg\ t^{-1}$)	60.7	54.6	52.1	VS are assumed to constitute 79 % of the DM content. Losses considered during storage and housing (absolute values) are the same as for DM (i.e. it is assumed that all DM lost was VS).
C ($kg\ t^{-1}$)	34.5	34.2	31.6	C ex-storage = 47.9 % of DM ex-storage for pigs, based on the ratio C: DM obtained by (Knudsen and Birkmose, 2005). Losses considered (during housing and during storage): CH_4 and CO_2. Details on C losses are in Table 3. The C from straw addition[e] in-house and as a floating layer during outdoor storage is estimated as 0.75 kg per tonne manure ex-animal and 0.95 kg per tonne manure ex-storage, respectively.
Cu ($g\ t^{-1}$)	31.0	31.0	30.4	Cu ex-storage = 0.0453 % of DM ex-storage, based on the ratio Cu: DM obtained by (Knudsen and Birkmose, 2005). No losses considered during housing and storage. The Cu from straw addition[e] in-house and as a floating layer during outdoor storage is estimated as 4.92 mg per tonne manure ex-animal and 6.25

[67] The slurry is pumped from the pre-tank before to be transferred to a biogas plant. Since it remains there rather temporarily, the manure is assumed to have the same composition as it leaves the animal house – towards the pre-tank – and as it leaves the pre-tank.

Parameter	Slurry ex-animal[a]	Slurry ex-housing[b]	Slurry ex-storage[c]	Source and assumptions
				mg per tonne manure ex-storage, respectively.
Zn ($g\ t^{-1}$)	90.8	90.7	89.1	Zn ex-storage = 0.135 % of DM ex-storage, based on the ratio Zn: DM obtained by (Knudsen and Birkmose, 2005). No losses considered during housing and storage. The Zn from straw addition[e] in-house and as a floating layer during outdoor storage is estimated as 75.5 mg per tonne manure ex-animal and 95.9 mg per tonne manure ex-storage, respectively.
NH_4-N ($kg\ t^{-1}$)	4.20	3.94	3.07	Value ex-storage based on Poulsen (2011). Value ex-housing assuming 0.75 kg NH_4-N per kg manure ex-housing (Poulsen, 2008), and value ex-animal assuming 0.70 kg NH_4-N per kg manure ex-animal (EMEP/EEA, 2010).

[a] All values of this column are expressed per tonne slurry ex-animal. [b] All values of this column are expressed per tonne slurry ex-housing. [c] All values of this column are expressed per tonne slurry ex-storage. [d] The non-rounded value ex-housing is 0.47089 t pig^{-1}, and considers a net water addition in-house of 3.57 kg water per pig, the straw addition described below and DM losses as in this Table. [e] The N, P and K addition from straw added in the stable considers, based on (Poulsen, 2008), an addition of 3 kg of straw per animal per year, 3.3 rotations per year, and the above-mentioned amount of manure ex-animal and ex-housing, yielding a total of 0.0019 t straw per tonne manure ex-housing. For the floating layer, the amount considered is based on (Wesnæs et al., 2009), i.e. 2.5 kg per tonne manure ex-housing. The straw DM content is 85 % (Møller et al., 2000). The N, P, K, Cu and Zn content of straw per kg of DM is 0.00528 kg, 0.0009 kg, 0.015 kg, 3 mg and 46 mg, respectively, based on (Møller et al., 2000). The C content is taken as 0.4563 kg C per kg DM, based on an average of 13 values from the Biolex database (FORCE Technology, 2013).

Table G-3: Life cycle inventory data for the reference manure management (from Hamelin et al., in press). All values in kg (per t manure ex-animal, ex-housing or ex-storage).

Substances	Life cycle stage			Comments		
	in-house per tonne ex-animal manure	outdoor storage per tonne ex-housing manure	Field[c] per tonne ex-storage manure	in-house	outdoor storage	field
NH_3-N	0.71	0.099	0.60	0.17 kg NH_3-N per kg TAN[a] (Poulsen, 2008), with 0.7 kg TAN/kg N (EMEP/EEA, 2010).	2.5 % of TAN[a] ex-housing (Poulsen, 2008); the N ex-housing being estimated according to (Poulsen, 2008), i.e.: N ex-animal minus NH_3-N losses in-house (and not accounting for other losses).	12% of N applied (Hansen et al., 2008) (this is an average for application by trail hose tanker, excluding illegal dates).
NH_3-N, at application			0.015			0.5% of TAN applied, for application by trail hoses, (Hansen et al., 2008).
N_2O-N	0.012	0.030	0.050	0.002 kg N_2O-N per kg N ex-animal (IPCC, 2006a) (pit storage below animal)	0.005 kg N_2O-N per kg N ex-animal (IPCC, 2006a) (liquid/slurry storage)	1% of N applied, (IPCC, 2006b).
NO-N (representing NO_x)	1.96×10^{-4}	1.84×10^{-4}	0.005	0.0001 kg NO per kg TAN ex-animal (EMEP/EEA, 2010).	0.0001 kg NO per kg TAN ex-housing (EMEP/EEA, 2010).	0.1 × N_2O-N, based on (Nemecek and Kägi, 2007).
NO_3-N	0	0	1.68	No leaching from housing, based on (Hamelin et al., 2011).	No leaching from outdoor storage, based on (Hamelin et al., 2011).	Based on Danish $NLES_4$ model (Kristensen et al., 2008).
N_2-N	0.013	0.012		0.003 kg NO per kg TAN ex-animal (EMEP/EEA, 2010).	0.003 kg NO per kg TAN ex-housing (EMEP/EEA, 2010).	
CO_2-C	0.36*	1.20*	31.3* (31.1)*	1.83 kg CO_2 per kg CH_4[b]	1.83 kg CO_2 per kg CH_4[b]	Based on the Danish dynamic soil C model C-TOOL (Petersen, 2010a; Petersen et al., 2002).
CH_4-C	0.54	1.80	0	IPCC algorithm (IPCC, 2006a); MCF of 3% and B_0 of 0.40 kg CH_4/kg VS, with the density of CH_4 at 0°C.	IPCC algorithm (IPCC, 2006a); MCF of 10% and B_0 of 0.40 kg CH_4/kg VS, with the density of CH_4 at 0°C.	Assumed negligible, based on (Hamelin et al., 2011).
P leaching	0	0	0.060			5% of surplus, based on (Hamelin et al., 2012). See details in Hamelin et al. (in press), p. S65-66.
indirect N_2O-N (volatilization)	7.14×10^{-3}	9.91×10^{-4}	0.006	1% of N loss as NH_3 and as NO_x, (ex-animal) (IPCC, 2006b).	1% of N loss as NH_3 and as NO_x, (ex-housing) (IPCC, 2006b).	1% of N loss as NH_3 and as NO_x, (ex-storage) (IPCC, 2006b).
indirect N_2O-N (leaching)	0	0	0.013	0.75% of N lost through leaching (ex-animal) (IPCC, 2006b).	0.75% of N lost through leaching (ex-animal) (IPCC, 2006b).	0.75% of N lost through leaching (ex-animal) (IPCC, 2006b).

[a] Ammonium-N (NH_4^+-N) and compounds readily broken down to NH_4^+-N are referred to as total ammoniacal N (TAN).
[b] Details on how this figure was derived are available in Hamelin et al. (in press), p. S60-61.
[c] For CO_2-C, the amount shown is for a 100 y annualization, while the amount between parenthesis is for a 20 y annualization

*These releases are presented for transparency only, but only the net biogenic CO_2 flows were considered in this study (Table 4)

Table G-4: Inventory data for avoided conventional fattening pig slurry management, expressed per kg VS manure

Cradle : Manure ex-housing (see remark a)
Gate : Application of raw manure on land (including the avoided mineral fertilizers substituted by applying manure)
Processes included : Outdoor storage; manure spreading (application process itself and field processes); (avoided) production of mineral N, P and K**; (avoided) application of mineral N, P and K‡
Remark : a) Process considers that the conventional management of 1 tonne manure ex-animal is avoided (housing stage excluded, as independent of whether manure is used for biogas or not)
kg VS, slurry ex pre-tank: 54.6 kg VS/t ex pre-tank (used to express values per kg VS) (Table 2)
Slurry ex pre-tank : 1002 kg slurry ex pre-tank per 1000 kg slurry ex-animal (can be derived from Table 2)

Substance / parameter	Unit	System expansion process: Conventional manure management (outdoor storage, spreading, mineral fertilizers avoided)δ	Total, for use in bioenergy pathways (avoided conventional manure management)†
CO_2, biogenic*	kg / kg VS	-2.10 x 10^{-2} (3.58 x 10^{-2})	2.10 x 10^{-2} (-3.58 x 10^{-2})
CO_2, fossil	kg / kg VS	-2.00 x 10^{-1}	2.00 x 10^{-1}
CH_4, biogenic	kg / kg VS	4.39 x 10^{-2}	-4.39 x 10^{-2}
CH_4, fossil	kg / kg VS	-4.31 x 10^{-4}	4.31 x 10^{-4}
N_2O	kg / kg VS	2.50 x 10^{-3}	-2.50 x 10^{-3}
NO_3-	kg / kg VS	-1.99 x 10-^{10}	1.99 x 10-^{10}
NH_3	kg / kg VS	1.56 x 10^{-2}	-1.56 x 10^{-2}
NO_x	kg / kg VS	-7.59 x 10^{-4}	7.59 x 10^{-4}
SO_2	kg / kg VS	-5.84 x 10^{-4}	5.84 x 10^{-4}
GWP_{100}*	kg CO_2 eq. / kg VS	1.61 x 10^{0} (1.60 x 10^{0})	-1.61 x 10^{0} (-1.60 x 10^{0})
GWP_{20}*	kg CO_2 eq. / kg VS	3.63 x 10^{0} (3.61 x 10^{0})	-3.63 x 10^{0} (-3.61 x 10^{0})
Eutrophication (N)	kg N eq. / kg VS	-2.59 x 10^{-4}	2.59 x 10^{-4}

* Annualization over 100 years, whenever it applies. In parenthesis are the values for a 20 years annualization, for the **net** C flow (i.e. soil C changes) involved as a result of manure spreading.

** 3.8 kg CAN (as N), 0.59 kg DAP (as N), 1.56 kg K_2O (as K) avoided, as a result of manure spreading. All calculations details to determine the exact quantity of avoided mineral fertilizers is available in Hamelin et al. (in press), Supporting Information, Table S64. CAN, DAP and K_2O are considered to be the marginal mineral fertilizers, as described in Hamelin (2013), p. 15-20. The inventory for the fertilizers is from the Ecoinvent database (Nemecek and Kägi, 2007), but the inventory for nitric acid has been corrected to 0.00248 kg N_2O per kg nitric acid, as explained in Appendix F.

‡ Modeled with the Ecoinvent database (process “fertilizing, by broadcaster”), but diesel consumption adjusted for soil JB3 of the Danish classification system (sandy soil), as described in Hamelin et al. (2012)

†Values from previous column multiplied by -1, as the process is avoided.

δ The inventory for outdoor storage and spreading (field processes part) is as detailed in Table 3.

G.4 Straw

The straw reference used in this study is represented by winter wheat straw (as being the most abundant in Denmark) with a yield of 3.09 t DM per ha (Hamelin et al., 2012)[68].

The harvest process involves swath, baling and loading (of the bales), and these were modelled as described in (Hamelin et al., 2012). The straw composition considered is shown in Table G-5.

Table G-5: Straw composition

	Straw "as harvested"
Unit	kg/1 000.0 kg straw "as harvested"
Total mass	1 000.0
DM	850.0[a]
VS	810.6[c]
Total N	4.49[a]
Phosphorus (P)	0.77[a]
Potassium (K)	12.75[a]
Carbon (C)	382.50[b]
Cupper (Cu)	0.003[a]
Zinc (Zn)	0.039[a]

[a] Based on (Møller et al., 2000);
[b] Based on (Petersen, 2010a), 0.45 kg C/kg DM;
[c] Taken as 95 % of DM, according to (Møller et al., 2004; Triolo et al., 2011; Wang et al., 2009).

If not used for bioenergy, it is considered that straw would have been incorporated to the soil instead. Part of the C of the straw would have entered the soil C pool, building up soil C stock, while most of it would have end up as a CO_2 emission to the atmosphere.

The net difference between straw harvest and incorporation was modelled on the basis of the wheat life cycle inventory presented in Hamelin et al. (2012)[69], where the flows of C and N are presented for systems with and without the harvest of the straw. According to this, the soil C change is:

- Straw removal system[70]: -79.8 (-132.5) kg C per ha per y
- Straw incorporation system: 51.1 (128) kg C per ha per y

Additional inventory details are presented in Table G- 6.

[68] Sandy soil (JB3), "wet" climate (964 mm per y).
[69] Same soil type as above, case without application of manure (as manure, being a waste product from another activity, cannot be a marginal fertilizer)
[70] Value annualized over 100 y, unless presented between parenthesis

Table G-6: Inventory data for wheat straw

Cradle : Straw is generated
Gate : Harvest of straw
LHV straw : 16.8 MJ / kg DM (0.85 kg DM per kg FM)
Yield straw : 3.09 t DM / ha
(1 tonne of wheat straw)

Substance / parameter	Unit	Additional emissions due to harvesting of straw instead of ploughing, biogenic flows only(2)	Straw harvest (swath, baling and loading)(8)	Avoided stubble harrowing(8, 9)	Total, for use in bioenergy pathways
CO_2, biogenic(1)	kg / MJ_{straw}	1.28 x 10^{-2} (2.55 x 10^{-2})	0	0	1.28 x 10^{-2} (2.55 x 10^{-2})
CO_2, fossil	kg / MJ_{straw}	-	1.02 x 10^{-3}	-5.12 x 10^{-4}	5.07 x 10^{-4}
CH_4, biogenic	kg / MJ_{straw}	Negligible(3)	0	0	0
CH_4, fossil	kg / MJ_{straw}	-	2.44 x 10^{-6}	-6.72 x 10^{-7}	1.77 x 10^{-6}
N_2O	kg / MJ_{straw}	-6.87 x 10^{-6}(4)	2.65 x 10^{-8}	-1.58 x 10^{-8}	-6.86 x 10^{-6}
NO_3-	kg / MJ_{straw}	0(5)	1.71 x 10^{-8}	-7.77 x 10^{-9}	9.36 x 10^{-9}
NH_3	kg / MJ_{straw}	0(6)	1.77 x 10^{-8}	-1.00 x 10^{-8}	7.68 x 10^{-9}
NO_x	kg / MJ_{straw}	9.64 x 10^{-6}(7)	8.33 x 10^{-6}	-3.55 x 10^{-6}	1.44 x 10^{-5}
SO_2	kg / MJ_{straw}	-	1.75 x 10^{-6}	-7.51 x 10^{-7}	1.00 x 10^{-6}
Global warming impact (100 y horizon)	kg CO_2 eq. / MJ_{straw}	1.07 x 10^{-2} (2.34 x 10^{-2})	1.09 x 10^{-3}	-5.37 x 10^{-4}	1.13 x 10^{-2} (2.40 x 10^{-2})
Global warming impact (20 y horizon)	kg CO_2 eq. / MJ_{straw}	1.08 x 10^{-2} (2.35 x 10^{-2})	1.24 x 10^{-3}	-5.82 x 10^{-4}	1.15 x 10^{-2} (2.40 x 10^{-2})
Eutrophication (N)	kg N eq. / MJ_{straw}	9.25 x 10^{-7}	8.06 x 10^{-7}	-3.44 x 10^{-7}	1.39 x 10^{-6}

(1) Annualization over 100 years, whenever it applies. In parenthesis are the values for a 20 years annualization, for the net C flow (i.e. soil C changes) involved as a result of straw harvesting.
(2) Value represent the emission (or changes in soil C) in the wheat system when straw is incorporated minus emission (or changes in soil C) when straw is harvested. Soil C changes and emissions considered for the wheat system are as described in Hamelin et al. (2012), where all inventory data are available.
(3) The CH_4 sink as a result of microbial oxidation is considered negligible in annual crop systems and has not been included in this study, for the reasons explained in Hamelin (2013), p. 56.
(4) In Hamelin et al. (2012), N_2O were calculated based on the IPCC guidelines (IPCC, 2006b). In this case, only “direct” N_2O applies (because NH_3 and NO_3 are the same whether straw is incorporated or not, see below), and this is calculated as 0.01 kg N_2O-N per kg N in straw.
(5) Many studies reported, from a short-term perspective, a decrease in NO_3 losses with increasing straw incorporation (e.g. Beaudoin et al., 2005; Gabrielle and Gagnaire, 2008), due to a temporary immobilization of mineral N by soil microflora. When the microbes die, this immobilized N is

remobilized and as a result, the net effect is simply to postpone the straw-N losses by a few years. For this reason, the empirical model used in this study for predicting nitrate leaching (N-LES4) does not consider any effects from the straw incorporation (Kristensen et al., 2008). In the longer term, however, an increase in soil organic matter through incorporation of straw may lead to higher levels of NO_3 leaching than shown here.

(6) NH_3 due to straw degradation was, in Hamelin et al. (2012), considered insignificant, on the basis of de Ruijter et al. (2010). This part of the inventory should be reviewed, although this flow is expected to be rather small.

(7) Hamelin et al. (2012) used, based on Haenel et al. (2010) an emission factor of 0.007 kg NO-N per kg N, for crop residues (where NO-N was used to represented NOx)

(8) Inventory for these was drawn from the Ecoinvent database. For the exact process used, see Hamelin et al. (2012), Appendix 2 (available online free of charges).

(9) The negative sign applies as the process is "avoided".

G.5 Mono- and co-digestion of fattening pig slurry and straw

Tables G-7 and G-8 present the necessary inventory data for mono-digestion of fattening pig slurry and co-digestion of fattening pig slurry with straw, respectively. Figures G-1 and G-2 illustrate the system boundary considered for these 2 systems. In both cases, the use of the biogas is not included within the inventory data, as the idea is to use these data as an input to a given energy conversion pathway.

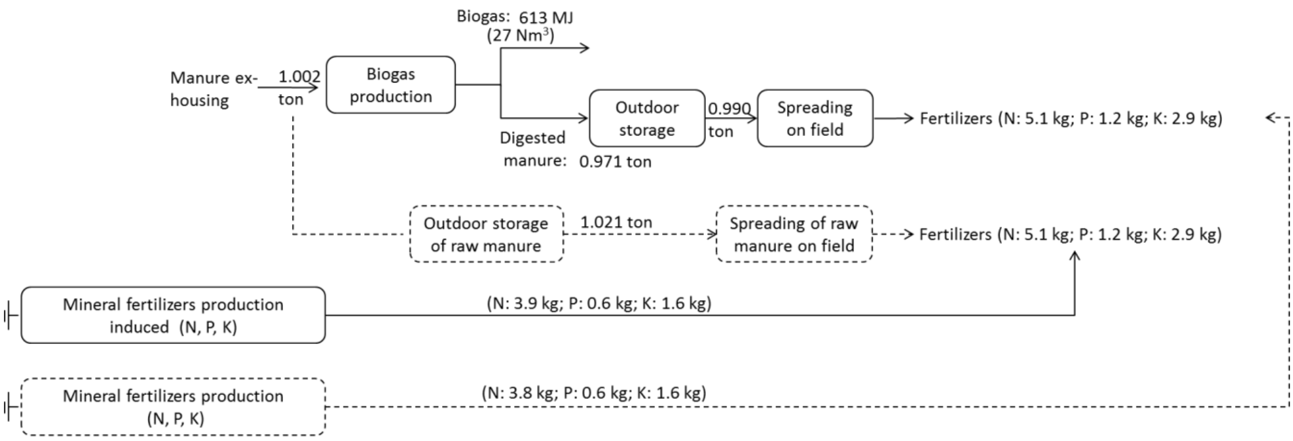

Figure G-1: System boundary considered for the inventory data of mono-digestion of fattening pig slurry. Dotted lines indicate an avoided process while full lines indicate an induced process.

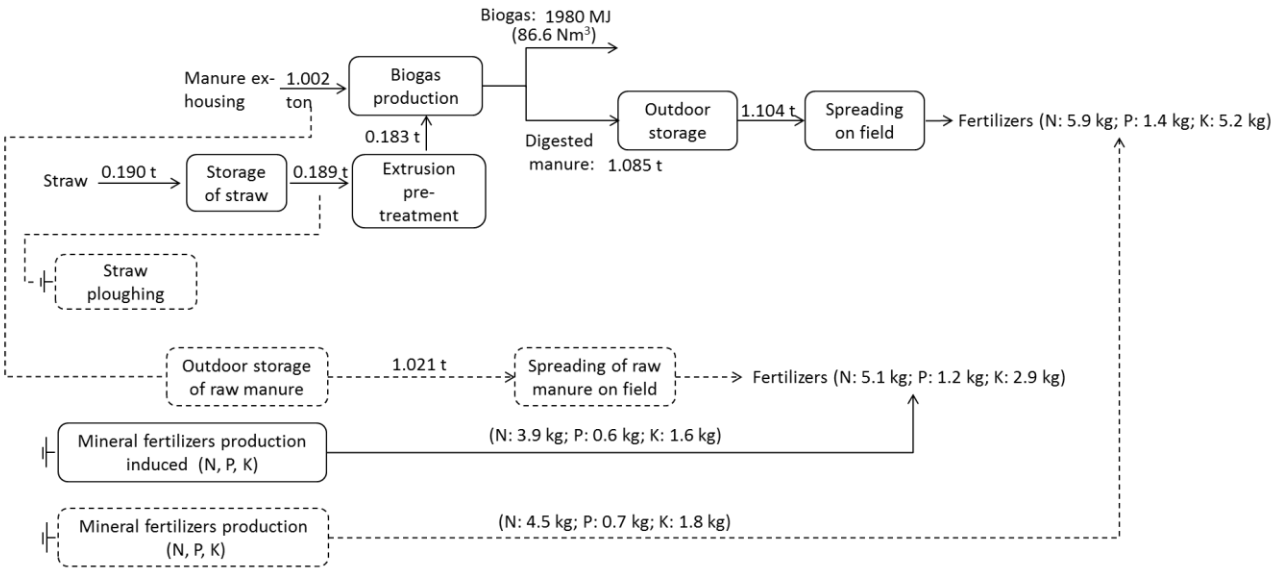

Figure G-2: System boundary considered for the inventory data of mono-digestion of fattening pig slurry. Dotted lines indicate an avoided process while full lines indicate an induced process.

The inventory data presented in Tables G-7 and G-8 are essentially based on a recent study (Hamelin et al., 2014), although a few modifications from this were performed:

- The internal energy consumption needed for the anaerobic digestion process was taken out, as this is adjusted in the pathway assessment, depending on the scenario used for the energy marginal;
- Only the net biogenic CO_2 emissions are accounted for (although the mass balances still take into account the losses of biogenic CO_2 occurring at each individual process

Table G-7: Manure-biogas (mono-digestion of fattening pigs slurry) inventory, all process up to biogas production (use of the biogas, and thereby the energy replaced, are not included)

Cradle : Manure excretion
Gate : a) for the biogas part: biogas
b) for the digestate part: application on land and substitution of mineral fertilizers
Remark : a) This process draws on Hamelin et al. (2014).
b) This process does **not** include the internal energy consumption, nor the use of the biogas.
Amount of manure ex-animal : 1 tonne
kg VS, slurry ex pre-tank : 54.6 kg VS/t ex pre-tank (used to express values per kg VS) (Table G-2)
Slurry ex pre-tank : 1002 kg slurry ex pre-tank per 1000 kg slurry ex-animal (can be derived from Table G-2)
CH_4 yield, pig slurry : 319 Nm^3 CH_4 per t VS (based on Hamelin et al., 2014)
LHV of CH_4 : 35.9 MJ per Nm^3 CH_4 (Energinet.dk and DEA, 2012)

Substance / parameter	Unit	Biogas production (fugitive losses) (3)	Digestate handling (storage, field application and avoided mineral fertilizers)(9)	Avoided conventional slurry handling (outdoor storage, spreading, mineral fertilizers avoided)(2)	Total pathway, excluding energy input and biogas use
CO_2, biogenic(1)	kg / MJ biogas	0	8.29×10^{-3} (1.54×10^{-2})	1.83×10^{-3} (-3.12×10^{-3})	1.01×10^{-2} (1.85×10^{-2})
CO_2, fossil	kg / MJ biogas	0	-2.07×10^{-2}	1.75×10^{-2}	-3.26×10^{-3}
CH_4, biogenic	kg / MJ biogas	2.00×10^{-4}	9.76×10^{-4}(4)	-3.84×10^{-3}	-2.66×10^{-3}

Substance / parameter	Unit	Biogas production (fugitive losses) [(3)]	Digestate handling (storage, field application and avoided mineral fertilizers)[(9)]	Avoided conventional slurry handling (outdoor storage, spreading, mineral fertilizers avoided)[(2)]	Total pathway, excluding energy input and biogas use
CH_4, fossil	kg / MJ biogas	0	-4.31×10^{-5}	3.77×10^{-5}	-5.47×10^{-6}
N_2O	kg / MJ biogas	0	1.60×10^{-4}(5)	-2.18×10^{-4}	-5.89×10^{-5}
NO_3-	kg / MJ biogas	0	-1.99×10^{-11}(6)	1.74×10^{-11}	-2.52×10^{-12}
NH_3	kg / MJ biogas	0	1.38×10^{-3}(7)	-1.37×10^{-3}	1.08×10^{-5}
NO_x	kg / MJ biogas	0	-8.73×10^{-5}(8)	6.63×10^{-5}	-2.10×10^{-5}
SO_2	kg / MJ biogas	0	-1.14×10^{-4}	5.10×10^{-5}	-6.32×10^{-5}
Global warming impact (100 y horizon)	kg CO_2 eq. / MJ biogas	5.00×10^{-3}	5.86×10^{-2} (6.57×10^{-2})	-1.41×10^{-1} (-1.39×10^{-1})	-7.70×10^{-2} (-6.87×10^{-2})
Global warming impact (20 y horizon)	kg CO_2 eq. / MJ biogas	1.44×10^{-2}	1.01×10^{-1} (1.08×10^{-1})	-3.17×10^{-1} (-3.15×10^{-1})	-2.02×10^{-1} (-1.93×10^{-1})
Eutrophication (N)	kg N eq. MJ biogas	0.00×10^{0}	1.89×10^{-3}	2.26×10^{-5}	1.92×10^{-3}

(1) Annualization over 100 years, whenever it applies. In parenthesis are the values for a 20 years annualization, for the net C flow (i.e. soil C changes) involved as a result of manure/digestate spreading. Soil C changes were calculated with the dynamic soil C model C-TOOL.

(2) As in Table G-2, but units are different

(3) Fugitive losses of CH_4 during the digestion process: 1% of the methane content of the biogas is assumed to be emitted to the environment, based on recent studies (Börjesson and Berglund, 2006; Jungbluth et al., 2007). This is judged to be realistic for future state-of-the-art biogas plants to be built.

(4) For storage: IPCC algorithm (IPCC, 2006a); MCF of 10% and B_0 of 0.400 kg CH_4/kg VS. To this, an "emission reduction potential" factor of 60 % is applied, accounting for the lower emissions of digestates (Nielsen et al., 2009); At field, biogenic CH_4 are considered negligible, as for raw manure application

(5) Storage: Storage: Calculated as for raw manure; At field: Calculated as for raw manure (Table G-3)

(6) Based on the N-LES4 model, as described in Hamelin et al. (2014), p. S65-66.

(7) Calculated as for raw manure (Table G-3), but for storage, it was considered that TAN is 77% of the total N, and for field application, 79% of the total N

(8) Calculated as for raw manure (Table G-3), but for storage, it was considered that TAN is 77% of the total N

(9) Processes related to the production and application of marginal mineral fertilizers were taken from the Ecoinvent database, with the same specifications as indicated in Table G-4 for raw manure

Table G-8: Co-digestion of fattening pig slurry with wheat straw, all process up to biogas production (use of the biogas, and thereby energy replaced, not included)

Cradle : Straw generation
Gate : a) for the biogas part: biogas
b) for the digestate part: application on land and substitution of mineral fertilizers
Remark : a) This process draws on Hamelin et al. (2014)
b) This process does **not** include the internal energy consumption, nor the use of the biogas.
LHV straw : 16.8 MJ / kg DM (0.85 kg DM per kg FM)
Yield straw : 3.09 t DM / ha
Amount of manure ex-animal in input mixture : 1 tonne (1002 kg slurry ex pre-tank per 1000 kg slurry ex-animal)
Amount of straw ex-storage in input mixture : 0.1886 tonne (990.7 kg straw ex-storage per kg straw ex-harvest; Hamelin et al., 2014)
CH_4 yield, extruded straw : 263 Nm^3 / t VS (Hamelin et al., 2014)
LHV of CH_4 : 35.9 MJ per Nm^3 CH4 (Energinet.dk & DEA, 2012)

Substance / parameter	Unit	Biogas production (fugitive losses) (3)	Digestate handling (storage, field application and avoided mineral fertilizers(9))	Straw handling (harvest, storage, and extrusion pre-treatment)(10)	Additional emissions due to straw harvest instead of ploughing(11) (20 y annualization)	Avoided conventional slurry handling (outdoor storage, spreading, mineral fertilizers avoided) (2)	Total pathway, excluding energy input and biogas use
CO_2, biogenic(1)	kg / MJ_{straw}	0	-1.33×10^{-2} (-2.19×10^{-2})	0	1.29×10^{-2} (2.57×10^{-2})	4.90×10^{-4} (7.90×10^{-4})	1.19×10^{-3} (5.79×10^{-3})
CO_2, fossil	kg / MJ_{straw}	0	-5.61×10^{-3}	2.00×10^{-3}	-5.18×10^{-4}	4.06×10^{-3}	-6.92×10^{-5}
CH_4, biogenic	kg / MJ_{straw}	1.50×10^{-4}	7.26×10^{-4}(4)	0	0	-8.92×10^{-4}	-1.66×10^{-5}
CH_4, fossil	kg / MJ_{straw}	0	-1.17×10^{-5}	6.66×10^{-6}	0	8.76×10^{-6}	3.76×10^{-6}
N_2O	kg / MJ_{straw}	0	4.29×10^{-5}(5)	7.28×10^{-8}	-6.96×10^{-6}	-5.08×10^{-5}	-1.48×10^{-5}
NO_3-	kg / MJ_{straw}	0	3.27×10^{-3}(6)	4.07×10^{-8}	-7.86×10^{-9}	-2.83×10^{-3}	4.38×10^{-4}
NH_3	kg / MJ_{straw}	0	3.70×10^{-4}(7)	5.49×10^{-6}	-1.01×10^{-8}	-3.18×10^{-4}	5.80×10^{-5}
NO_x	kg / MJ_{straw}	0	-2.40×10^{-5}(8)	9.40×10^{-6}	6.16×10^{-6}	1.54×10^{-5}	7.00×10^{-6}
SO_2	kg / MJ_{straw}	0	-3.08×10^{-5}	3.38×10^{-6}	-7.60×10^{-7}	1.19×10^{-5}	-1.63×10^{-5}
Global warming impact (100 y horizon)	kg CO_2 eq. / MJ_{straw}	3.74×10^{-3}	1.17×10^{-2} (3.20×10^{-3})	3.28×10^{-3}	1.03×10^{-2} (2.31×10^{-2})	-3.27×10^{-2} (-3.24×10^{-2})	-3.65×10^{-3} (9.49×10^{-4})
Global warming impact (20 y horizon)	kg CO_2 eq. / MJ_{straw}	1.08×10^{-2}	4.48×10^{-2} (3.63×10^{-2})	3.66×10^{-3}	1.03×10^{-2} (2.32×10^{-2})	-7.37×10^{-2} (-7.34×10^{-2})	-4.13×10^{-3} (4.66×10^{-4})
Eutrophication (N)	kg N eq. / MJ_{straw}	0	5.10×10^{-4}	1.94×10^{-6}	5.88×10^{-7}	-4.42×10^{-4}	7.10×10^{-5}

(1) Annualization over 100 years, whenever it applies. In parenthesis are the values for a 20 years annualization, for the net C flow (i.e. soil C changes) involved as a result of manure/digestate spreading. Soil C changes were calculated with the dynamic soil C model C-TOOL.

(2) As in Table G-2, but units are different

(3) Fugitive losses of CH_4 during the digestion process: 1% of the methane content of the biogas is assumed to be emitted to the environment, based on recent studies (Börjesson and Berglund, 2006; Jungbluth et al., 2007). This is judged to be realistic for future state-of-the-art biogas plants to be built.

(4) For storage: IPCC algorithm (IPCC, 2006a); MCF of 10% and B_0 of 0.475 kg CH_4/kg VS. To this, an "emission reduction potential" factor of 60 % is applied, accounting for the lower emissions of digestates (Nielsen et al., 2009); At field, biogenic CH_4 are considered negligible, as for raw manure application

(5) Storage: Calculated as for raw manure; At field: Calculated as for raw manure (Table G-3)

(6) Based on the N-LES4 model, as described in Hamelin et al. (2014), p. S65-66.

(7) Calculated as for raw manure (Table G-3), but for storage, it was considered that TAN is 77% of the total N, and for field application, 79% of the total N

(8) Calculated as for raw manure (Table G-3), but for storage, it was considered that TAN is 77% of the total N

(9) Processes related to the production and application of marginal mineral fertilizers were taken from the Ecoinvent database, with the same specifications as indicated in Table 4 for raw manure.

(10) Harvest process is as in Table G-6; storage process considers that 1.1% of the initial DM is lost on the basis of (Kreuger et al., 2011), and NH_3-N losses of 0.077 kg per t of harvested straw (Hamelin et al., 2014, p.S28-S30); extrusion pre-treatment only considers an input of 14.5 kWh per t of straw ex-storage, which has here been taken as coal-based electricity (on the basis of the Ecoinvent process "electricity, hard coal, at power plant/NORDEL U"). The latter should of course be made consistent with the pathway scenario considered.

(11) Biogenic flows, as in Table G-6, plus avoided stubble harrowing (Table G-6)

G.6 Limitation

One clear limitation of the inventories presented in this Appendix, in the perspective of direct use for the modeling of several energy pathways, lies in the use of the data from the Ecoinvent v2.2 database for background processes. In fact, many of these processes require electricity/heat/fuel input, and these often involve fossil fuels, and as such may not necessarily always be consistent with the pathways under analysis, especially for the scenarios with 100% renewable energy.

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Appendix H Conversion process inventory data

When a specific conversion technology is combined with a specific biomass feed or combination of biomass feeds, this is referred to as a pathway. This appendix provides an overview of which biomass types are relevant for which conversion technology.

Since only conversion technologies which to some extend are able to convert available and accessible fractions of biomass to useful products are considered in this study, this defines the boundaries of the study and whether a specific technology or pathway is relevant or not.

The study breaks the products from different technologies into four different categories which are defined by their functional output; Conversion of biomass, heat, heat and power and biofuels.

Each pathway is given a pathway ID which consists of three separate identification marks. The first letter refers to the type of output, while the second refer to the conversion technology. The number refers to the number in the given category, which is supplying the same output using the same conversion technology. Usually this is used whenever two or more types of biomass can be used in the same conversion technology giving the same type of output.

Glossary:

- *Output*
  - *IH – Industrial heat*
  - *DH – district heating*
  - *HP – Heat and power (combined)*
  - *F – Fuel*
  - *AF – Advanced fuel (BtL or biogas upgrading assisted by an electrolyser)*
  - *CC – Carbon capture to fuel*
- *Conversion technology*
  - *B – Boiler*
  - *DC – direct combustion (for CHP)*
  - *FC – Fuel cell (for CHP)*
  - *U – upgrading (of biogas)*
  - *BM – Biomass/CO_2 to SNG*
  - *BE – Bioethanol (1^{st} and 2^{nd} generation)*
  - *BD – Biodiesel*
  - *M – Biomass/CO_2 to Methanol or DME*
  - *K – Biomass to Kerosene*
  - *HM – hydromethanation of biogas*

Pathway ID	HP.DC.1					
Conversion technology	Direct combustion in a boiler, producing combined heat and power in back pressure mode					
						Comments / references
Plant capacity [MW]	10 - 50					/ Energinet.dk & DEA, 2012
Biomass characterisation	Straw					
Carbon content (just before conversion)	-					
Dry Matter content (just before conversion)	85%					/ Birkmose, 2013
Content of volatile solids (just before conversion) (as a % of Dry Matter)	95%					/ Birkmose, 2013
Nitrogen content (just before conversion)	-					
Lower Heating Value (LHV) (MJ/kg Dry Matter)	16,8					/ Domalski et al., 1987 & Videncenter for halm og flisfyring, 1999
CH4 yield (Nm3/ton VS) (when available)	278					Birkmose, 2013
Carbon Conversion Efficiency (%)	-					
Change during handling (gain or loss: "handling" can be storage, drying or any pre-treatment)	-					

		Unit	2013	2020	2035	2050	Comments / References
Inputs							
	Electricity, peak load (specify*)	MWh	-	-	-	-	
	Electricity,base load (specify*)	MWh	-	-	-	-	
	Heat (specify*)	GJ	-	-	-	-	
	Steam (specify*)	GJ	-	-	-	-	
	Oil (fossil origin)	GJ	-	-	-	-	
	Coal	GJ	-	-	-	-	
	Natural gas	GJ	-	-	-	-	
	Manure (specified category*)	Ton	-	-	-	-	
	Waste (specified category*)	Ton	-	-	-	-	
	Hydrogen	Ton	-	-	-	-	
	Biomass (specified category*)**	GJ	100	100	100	100	
	Other (specify*)	-	-	-	-	-	
Intermediate conversion (if any)							
	Biogas upgrading efficiency	%	-	-	-	-	
	Cold gas efficiency	%	-	-	-	-	
	Torrefaction efficiency	%	-	-	-	-	
	Other (specify*)	%	-	-	-	-	
Outputs							
	Aviation fuel (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Other transport fuels (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Electricity		-	-	-	-	
	• Balancing	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	• Continuous	GJ	28	28	28	28	
	Conversion efficiency	%	29%	29%	29%	29%	Energinet.dk & DEA, 2012
	Heat		-	-	-	-	
	• Industry	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	• District heating	GJ	70	70	70	70	
	Conversion efficiency	%	72%	72%	72%	72%	With fluegas condensation / Energinet.dk & DEA, 2012
	Food/feed (specify*)	Ton	-	-	-	-	
	Other (specify*)		-	-	-	-	
Emissions							
	CO_2, biogenic upper treshold	kg	10200	10200	10200	10200	
	CO_2, biogenic lower treshold	kg	10200	10200	10200	10200	
	CO_2, fossil upper treshold	kg					
	CO_2, fossil lower treshold	kg					
	CH4, biogenic upper treshold	g	47	47	47	47	
	CH4, biogenic lower treshold	g	47	47	47	47	
	CH4, fossil upper treshold	g					
	CH4, fossil lower treshold	g					
	N2O, upper treshold	g	190	190	190	190	
	N2O, lower treshold	g	80	80	80	80	
	NH_3, upper treshold	g					
	NH_3, lower treshold	g					
	Particles, upper treshold	g	13,3	13,3	13,3	13,3	
	Particles, lower treshold	g	13,3	13,3	13,3	13,3	
	SO_2, upper treshold	g	7800	7800	7800	7800	
	SO_2, lower treshold	g	2400	2400	2400	2400	
	NOx, upper treshold	g	17800	17800	17800	17800	
	NOx, lower treshold	g	9800	9800	9800	9800	
Other implications and outputs							
	Land occupation	m^2					
	Global warming	g CO_2-eq.					
	Eutrophication	g NO3-eq.					

*To be selected from default list
**Lower Heating Value of dry matter

Pathway ID		HP.PF.7					
Conversion technology		Central advanced pulverized fuel power plant operating in extraction mode					
							Comments / References
Plant capacity [MW]		250 - 400					Energinet.dk & DEA, 2012
Biomass characterisation		Dried wood					
Carbon content (just before conversion)		-					
Dry Matter content (just before conversion)		90%					Koppejan et al., 2012
Content of volatile solids (just before conversion)		-					
Nitrogen content (just before conversion)		-					
Lower Heating Value (LHV) (MJ/kg Dry Matter)		19					Koppejan et al., 2012
CH4 yield (Nm3/ton VS) (when available)		0					
Carbon Conversion Efficiency (%)		-					
Change during handling (gain or loss: "handling"		-					
		Unit	2013	2020	2035	2050	Comments / References
Inputs							
	Electricity, peak load (specify*)	MWh	-	-	-	-	
	Electricity,base load (specify*)	MWh	-	-	-	-	
	Heat (specify*)	GJ	-	-	-	-	
	Steam (specify*)	GJ	-	-	-	-	
	Oil (fossil origin)	GJ	-	-	-	-	
	Coal	GJ	-	-	-	-	
	Natural gas	GJ	-	-	-	-	
	Manure (specified category*)	Ton	-	-	-	-	
	Waste (specified category*)	Ton	-	-	-	-	
	Hydrogen	Ton	-	-	-	-	
	Biomass (specified category*)**	GJ	100	100	100	100	
	Other (specify*)	-	-	-	-	-	
Intermediate conversion (if nany)							
	Biogas upgrading efficiency	%	-	-	-	-	
	Cold gas efficiency	%	-	-	-	-	
	Torrefaction efficiency	%	-	-	-	-	
	Other (specify*)	%	-	-	-	-	
Outputs							
	Aviation fuel (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Other transport fuels (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Electricity		-	-	-	-	
	• Balancing	GJ	0	0	0	0	
	Conversion efficiency	%	46%	49%	52%	54%	/ Energinet.dk & DEA, 2012
	• Continuous	GJ	40	42	45	47	
	Conversion efficiency	%	41%	43%	46%	48%	/ Energinet.dk & DEA, 2012
	Heat		-	-	-	-	
	• Industry	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	• District heating	GJ	39	39	39	39	
	Conversion efficiency	%	40%	40%	40%	40%	/ Energinet.dk & DEA, 2012
	Food/feed (specify*)	Ton	-	-	-	-	
	Other (specify*)		-	-	-	-	
Emissions							
	CO_2, biogenic upper treshold	kg	10200	10200	10200	10200	
	CO_2, biogenic lower treshold	kg	10200	10200	10200	10200	
	CO_2, fossil upper treshold	kg					
	CO_2, fossil lower treshold	kg					
	CH4, biogenic upper treshold	g	200	200	200	200	
	CH4, biogenic lower treshold	g	200	200	200	200	
	CH4, fossil upper treshold	g					
	CH4, fossil lower treshold	g					
	N2O, upper treshold	g	80	80	80	80	
	N2O, lower treshold	g	80	80	80	80	
	NH_3, upper treshold	g					
	NH_3, lower treshold	g					
	Particles, upper treshold	g	194	194	194	194	
	Particles, lower treshold	g	194	194	194	194	
	SO_2, upper treshold	g	174	174	174	174	
	SO_2, lower treshold	g	174	174	174	174	
	NOx, upper treshold	g	6900	6900	6900	6900	
	NOx, lower treshold	g	3800	3500	3500	3500	
Other implications and outputs							
	Land occupation	m^2					
	Global warming	g CO_2-eq.					
	Eutrophication	g NO3-eq.					

*To be selected from default list
**Lower Heating Value of dry matter

Pathway ID		PP.FC.2-S.G.1					
Conversion technology		Biomass to SNG followed by a solid oxide fuel cell for power production					
							Comments / References
Plant capacity [MW]		10 - 100					/ Energinet.dk & DEA, 2012
Biomass characterisation		Dried wood					
Carbon content (just before conversion)		-					
Dry Matter content (just before conversion)		90%					/ Koppejan et al., 2012
Content of volatile solids (just before conversion) (as a % of Dry Matter)		-					
Nitrogen content (just before conversion)		-					
Lower Heating Value (LHV) (MJ/kg Dry Matter)		19					/ Koppejan et al., 2012
CH4 yield (Nm3/ton VS) (when available)		0					
Carbon Conversion Efficiency (%)		-					
Change during handling (gain or loss: "handling" can be storage, drying or any pre-treatment) (% Dry Matter) (% Carbon) (%Nitrogen)		-					
		Unit	2013	2020	2035	2050	Comments / References
Inputs							
	Electricity, peak load (specify*)	MWh	-	-	-	-	
	Electricity,base load (specify*)	MWh	1,7	1,7	1,7	1,7	The gasifier consumes 6 % of fuel input / Meijden et al., 2010 & Evald et al., 2013
	Heat (specify*)	GJ	-	-	-	-	
	Steam (specify*)	GJ	-	-	-	-	
	Oil (fossil origin)	GJ	-	-	-	-	
	Coal	GJ	-	-	-	-	
	Natural gas	GJ	-	-	-	-	
	Manure (specified category*)	Ton	-	-	-	-	
	Waste (specified category*)	Ton	-	-	-	-	
	Hydrogen	Ton	-	-	-	-	
	Biomass (specified category*)**	GJ	100	100	100	100	
	Other (specify*)	-	-	-	-	-	
Intermediate conversion (if any)							
	Biogas upgrading efficiency	%	-	-	-	-	
	Biomass to gas efficiency	%	70%	70%	70%	70%	/ Meijden et al., 2010
	Torrefaction efficiency	%	-	-	-	-	
	Other (specify*)	%	-	-	-	-	
Outputs							
	Aviation fuel (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Other transport fuels (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Electricity		-	-	-	-	
	• Balancing	GJ	36	38	38	38	
	Conversion efficiency	%	53%	55%	55%	55%	/ Energinet.dk & DEA, 2012
	• Continuous	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Heat		-	-	-	-	
	• Industry	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	• District heating	GJ	12	12	12	12	
	Conversion efficiency	%	12%	12%	12%	12%	From the gasifier / Evald et al., 2013
	Food/feed (specify*)	Ton	-	-	-	-	
	Other (specify*)		-	-	-	-	
Emissions							
	CO_2, biogenic upper treshold	kg	10200	10200	10200	10200	It is assumed that half of the biogenic CO_2 is released at the SNG plant
	CO_2, biogenic lower treshold	kg	10200	10200	10200	10200	It is assumed that half of the biogenic CO_2 is released at the SNG plant
	CO_2, fossil upper treshold	kg					
	CO_2, fossil lower treshold	kg					
	CH4, biogenic upper treshold	g	0	0	0	0	
	CH4, biogenic lower treshold	g	0	0	0	0	
	CH4, fossil upper treshold	g					
	CH4, fossil lower treshold	g					
	N2O, upper treshold	g	0	0	0	0	
	N2O, lower treshold	g	0	0	0	0	
	NH_3, upper treshold	g					
	NH_3, lower treshold	g					
	Particles, upper treshold	g	0	0	0	0	
	Particles, lower treshold	g	0	0	0	0	
	SO_2, upper treshold	g	0	0	0	0	
	SO_2, lower treshold	g	0	0	0	0	
	NOx, upper treshold	g	7	7	7	7	
	NOx, lower treshold	g	7	7	7	7	
Other implications and outputs							
	Land occupation	m^2					
	Global warming	g CO_2-eq.					
	Eutrophication	g NO3-eq.					

*To be selected from default list
**Lower Heating Value of dry matter

Pathway ID	HP.DC.16-B.AD.2		
Conversion technology	Anaerobic digestion followed by combustion in gas engine		
			Comments / References
Plant capacity [MW]	1 - 10		/ Energinet.dk & DEA, 2012
Biomass characterisation	Straw	Slurry	
Carbon content (just before conversion)	-	-	
Dry Matter content (just before conversion)	85%	7%	/ Birkmose, 2013
Content of volatile solids (just before	95%	80%	/ Birkmose, 2013
Nitrogen content (just before conversion)	-	-	
Lower Heating Value (LHV) (MJ/kg Dry Matter)	16,8	0	/ Domalski et al., 1987 & Videncenter for halm og flisfyring, 1999
CH4 yield (Nm3/ton VS) (when available)	278	319	/ Birkmose, 2013, Hamelin, 2013
Carbon Conversion Efficiency (%)	-	-	
Change during handling (gain or loss:	-	-	

		Unit	2013	2020	2035	2050	Comments / References
Inputs							
	Electricity, peak load (specify*)	MWh	-	-	-	-	
	Electricity,base load (specify*)	MWh	0,2	0,2	0,2	0,2	5 kWh pr. ton biomass / Energinet.dk & DEA, 2012
	Heat (specify*)	GJ	6	6	6	6	34 kWh pr. m3 of raw biomass. Assumed density / Energinet.dk & DEA, 2012
	Steam (specify*)	GJ	-	-	-	-	
	Oil (fossil origin)	GJ	-	-	-	-	
	Coal	GJ	-	-	-	-	
	Natural gas	GJ	-	-	-	-	
	Manure (specified category*)	Ton	32,6	32,6	32,6	32,6	/ Hamelin, 2013
	Waste (specified category*)	Ton	-	-	-	-	
	Hydrogen	Ton	-	-	-	-	
	Biomass (specified category*)**	GJ	100	100	100	100	Requires extrusion
	Other (specify*)	-	-	-	-	-	
Intermediate conversion (if any)							
	Biogas upgrading efficiency	%	-	-	-	-	
	Cold gas efficiency	%	-	-	-	-	
	Torrefaction efficiency	%	-	-	-	-	
	Other (specify*)	%	-	-	-	-	
Outputs							
	Aviation fuel (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Other transport fuels (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Electricity		-	-	-	-	
	● Balancing	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	● Continuous	GJ	33	34	36	36	
	Conversion efficiency	%	44%	46%	48%	48%	/ Energinet.dk & DEA, 2012
	Heat		-	-	-	-	
	● Industry	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	● District heating	GJ	36	34	32	32	
	Conversion efficiency	%	48%	46%	43%	43%	/ Energinet.dk & DEA, 2012
	Food/feed (specify*)	Ton	-	-	-	-	
	Other (specify*)		-	-	-	-	
Emissions							
	CO_2, biogenic upper treshold	kg	6279	6279	6279	6279	
	CO_2, biogenic lower treshold	kg	6279	6279	6279	6279	
	CO_2, fossil upper treshold	kg					
	CO_2, fossil lower treshold	kg					
	CH4, biogenic upper treshold	g	75701	75701	75701	75701	It is assumed that 1% of the biogas is emitted at the plant due to leakage
	CH4, biogenic lower treshold	g	26771	26771	26771	26771	It is assumed that 1% of the biogas is emitted at the plant due to leakage
	CH4, fossil upper treshold	g					
	CH4, fossil lower treshold	g					
	N2O, upper treshold	g	158	158	158	158	
	N2O, lower treshold	g	38	38	38	38	
	NH_3, upper treshold	g					
	NH_3, lower treshold	g					
	Particles, upper treshold	g	34	34	34	34	
	Particles, lower treshold	g	34	34	34	34	
	SO_2, upper treshold	g	1442	1442	1442	1442	
	SO_2, lower treshold	g	1442	1442	1442	1442	
	NOx, upper treshold	g	40561	40561	40561	40561	
	NOx, lower treshold	g	8187	8187	8187	8187	
Other implications and outputs							
	Land occupation	m^2					
	Global warming	g CO_2-eq.					
	Eutrophication	g NO3-eq.					

*To be selected from default list
**Lower Heating Value of dry matter

Pathway ID	HP.DC.16-B.AD.3					
Conversion technology	Anaerobic digestion followed by combustion in gas engine					
						Comments / References
Plant capacity [MW]	1 - 10					Energinet.dk & DEA, 2012
Biomass characterisation	Pig slurry					
Carbon content (just before conversion)	-					
Dry Matter content (just before conversion)	7%					Birkmose, 2013
Content of volatile solids (just before	80%					Birkmose, 2013
Nitrogen content (just before conversion)	-					
Lower Heating Value (LHV) (MJ/kg Dry	0					
CH4 yield (Nm3/ton VS) (when available)	319					Hamelin, 2013
Carbon Conversion Efficiency (%)	-					
Change during handling (gain or loss:	-					

	Unit	2013	2020	2035	2050	Comments / References
Inputs						
Electricity, peak load (specify*)	MWh	-	-	-	-	
Electricity,base load (specify*)	MWh	0,8	0,8	0,8	0,8	5 kWh pr. ton biomass / Energinet.dk & DEA, 2012
Heat (specify*)	GJ	20	20	20	20	34 kWh pr. m3 of raw biomass, assumed density of 1 ton/m³ / Energinet.dk & DEA, 2012
Steam (specify*)	GJ	-	-	-	-	
Oil (fossil origin)	GJ	-	-	-	-	
Coal	GJ	-	-	-	-	
Natural gas	GJ	-	-	-	-	
Manure (specified category*)	Ton	162	162	162	162	
Waste (specified category*)	Ton	-	-	-	-	
Hydrogen	Ton	-	-	-	-	
Biomass (specified category*)**	GJ	-	-	-	-	
Other (specify*)	-	-	-	-	-	
Intermediate conversion (if any)						
Biogas upgrading efficiency	%	-	-	-	-	Without the addition of hydrogen
Cold gas efficiency	%	-	-	-	-	
Torrefaction efficiency	%	-	-	-	-	
Other (specify*)	%	-	-	-	-	
Outputs						
Aviation fuel (specify*)	GJ	-	-	-	-	
Conversion efficiency	%	-	-	-	-	
Other transport fuels (specify*)	GJ	-	-	-	-	
Conversion efficiency	%	-	-	-	-	
Electricity		-	-	-	-	
• Balancing	GJ					
Conversion efficiency	%					Energinet.dk & DEA, 2012
• Continuous	GJ	44	46	48	48	
Conversion efficiency	%	44%	46%	48%	48%	
Heat		-	-	-	-	
• Industry	GJ	-	-	-	-	
Conversion efficiency	%	-	-	-	-	
• District heating	GJ	48	46	43	43	
Conversion efficiency	%	48%	46%	43%	43%	Energinet.dk & DEA, 2012
Food/feed (specify*)	Ton	-	-	-	-	
Other (specify*)		-	-	-	-	
Emissions						
CO_2, biogenic upper treshold	kg	8360	8360	8360	8360	
CO_2, biogenic lower treshold	kg	8360	8360	8360	8360	
CO_2, fossil upper treshold	kg					
CO_2, fossil lower treshold	kg					
CH4, biogenic upper treshold	g	100784	100784	100784	100784	It is assumed that 1% of the biogas is emitted at the plant due to leakage
CH4, biogenic lower treshold	g	35642	35642	35642	35642	It is assumed that 1% of the biogas is emitted at the plant due to leakage
CH4, fossil upper treshold	g					
CH4, fossil lower treshold	g					
N2O, upper treshold	g	210	210	210	210	
N2O, lower treshold	g	50	50	50	50	
NH_3, upper treshold	g					
NH_3, lower treshold	g					
Particles, upper treshold	g	45	45	45	45	
Particles, lower treshold	g	45	45	45	45	
SO_2, upper treshold	g	1920	1920	1920	1920	
SO_2, lower treshold	g	1920	1920	1920	1920	
NOx, upper treshold	g	54000	54000	54000	54000	
NOx, lower treshold	g	10900	10900	10900	10900	
Other implications and outputs						
Land occupation	m²					
Global warming	g CO_2-eq.					
Eutrophication	g NO3-eq.					

*To be selected from default list
**Lower Heating Value of dry matter

Pathway ID	AF.CB.1-B.AD.2					
Conversion technology	Biogasification and upgrading via hydromethanation to SNG followed by compression					
						Comments / References
Plant capacity [MW]	2 - 10					Energinet.dk & DEA, 2012
Biomass characterisation	Straw	Slurry				
Carbon content (just before conversion)	-	-				
Dry Matter content (just before conversion)	50%	7%				Birkmose, 2013
Content of volatile solids (just before	95%	80%				Birkmose, 2013
Nitrogen content (just before conversion)	-	-				
Lower Heating Value (LHV) (MJ/kg Dry Matter)	16,8	0				Domalski et al., 1987 & Videncenter for halm og flisfyring, 1999
CH4 yield (Nm3/ton VS) (when available)	278	319				Birkmose, 2013, Hamelin, 2013
Carbon Conversion Efficiency (%)	-	-				
Change during handling (gain or loss:	-	-				

		Unit	2013	2020	2035	2050	Comments
Inputs							
	Electricity, peak load (specify*)	MWh	19	19	19	19	Electrolyser consumes 90 % of biogas output (assuming 70 % electrolyser efficiency) / Calculated based on Specht et al., 2010, Clausen et al., 2010
	Electricity,base load (specify*)	MWh	0,6	0,6	0,6	0,6	AD: 5 kWh pr. ton biomass. Upgrading of biogas: 2 % of biogas production. Compression to use in vehicle: 4,5 % of energycontent in the methane. / Energinet.dk & DEA, 2012, Specht et al., 2010
	Heat (specify*)	GJ	2	2	2	2	AD: 34 kWh pr. m3 of raw biomass, assumed density of 500 kg/m3 for straw and 1 ton/m3 for slurry. Energy equivalent to 6 % of biogas input into the upgrading proces is ecovered as heat for the biogasification. / Energinet.dk & DEA, 2012, Specht et al., 2010
	Steam (specify*)	GJ	-	-	-	-	
	Oil (fossil origin)	GJ	-	-	-	-	
	Coal	GJ	-	-	-	-	
	Natural gas	GJ	-	-	-	-	
	Manure (specified category*)	Ton	32,6	32,6	32,6	32,6	Hamelin, 2013
	Waste (specified category*)	Ton	-	-	-	-	
	Hydrogen	Ton	-	-	-	-	
	Biomass (specified category*)**	GJ	100	100	100	100	Straw (requires extrusion)
	Other (specify*)	-	-	-	-	-	
Intermediate conversion (if any)							
	Biogas upgrading efficiency	%	93%	93%	93%	93%	With the addition of hydrogen / Calculated based on Specht et al., 2010
	Cold gas efficiency	%	-	-	-	-	
	Torrefaction efficiency	%	-	-	-	-	
	Other (specify*)	%	70%	70%	70%	70%	Clausen et al., 2010
Outputs							
	Aviation fuel (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Other transport fuels (specify*)	GJ					
	Conversion efficiency	%					
	Electricity		-	-	-	-	
	● Balancing	GJ	-	-	-	-	
	Conversion efficiency	%	53%	55%	55%	55%	
	● Continuous	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Heat		-	-	-	-	
	● Industry	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	● District heating	GJ	-	-	-	-	
	Conversion efficiency	%	38%	37%	37%	37%	
	Food/feed (specify*)	Ton	-	-	-	-	
	Other (specify*)		-	-	-	-	
Emissions							
	CO_2, biogenic upper treshold	kg	0	0	0	0	
	CO_2, biogenic lower treshold	kg	0	0	0	0	
	CO_2, fossil upper treshold	kg					
	CO_2, fossil lower treshold	kg					
	CH4, biogenic upper treshold	g	15022	15022	15022	15022	It is assumed that 1% of the biogas is emitted at the plant due to leakage
	CH4, biogenic lower treshold	g	15022	15022	15022	15022	It is assumed that 1% of the biogas is emitted at the plant due to leakage
	CH4, fossil upper treshold	g					
	CH4, fossil lower treshold	g					
	N2O, upper treshold	g					
	N2O, lower treshold	g					
	NH_3, upper treshold	g					
	NH_3, lower treshold	g					
	Particles, upper treshold	g					
	Particles, lower treshold	g					
	SO_2, upper treshold	g	0	0	0	0	Assuming that sulphur is removed prior to upgrading
	SO_2, lower treshold	g	0	0	0	0	Assuming that sulphur is removed prior to upgrading
	NOx, upper treshold	g					
	NOx, lower treshold	g					
Other implications and outputs							
	Land occupation	m²					
	Global warming	g CO_2-eq.					
	Eutrophication	g NO3-eq.					

*To be selected from default list
**Lower Heating Value of dry matter

Pathway ID		AF.CB.1-B.AD.3					
Conversion technology		Biogasification and upgrading via hydromethanation to SNG followed by compression					
							Comments / References
Plant capacity [MW]		2 - 10					Energinet.dk & DEA, 2012
Biomass characterisation		Slurry					
Carbon content (just before conversion)		-					
Dry Matter content (just before conversion)		7%					Birkmose, 2013
Content of volatile solids (just before		80%					Birkmose, 2013
Nitrogen content (just before conversion)		-					
Lower Heating Value (LHV) (MJ/kg Dry		0					
CH4 yield (Nm3/ton VS) (when available)		319					Hamelin, 2013
Carbon Conversion Efficiency (%)		-					
Change during handling (gain or loss:		-					
		Unit	2013	2020	2035	2050	Comments
Inputs							
	Electricity, peak load (specify*)	MWh	25	25	25	25	Electrolyser consumes 90 % of biogas output (assuming 70 % electrolyser efficiency) / Calculated based on Specht et al., 2010, Clausen et al., 2010
	Electricity,base load (specify*)	MWh	3,3	3,3	3,3	3,3	AD: 5 kWh pr. ton biomass. Upgrading of biogas: 2 % of biogas production. Compression to use in vehicle: 4,5 % of energycontent in the methane. / Energinet.dk & DEA, 2012, Specht et al., 2010
	Heat (specify*)	GJ	14	14	14	14	AD: 34 kWh pr. m3 of raw biomass, assumed density of 500 kg/m3 for straw and 1 ton/m3 for slurry. Energy equivalent to 6 % of biogas input into the upgrading proces is recovered as heat for the biogasification. / Energinet.dk & DEA, 2012, Specht et al., 2010
	Steam (specify*)	GJ	-	-	-	-	
	Oil (fossil origin)	GJ	-	-	-	-	
	Coal	GJ	-	-	-	-	
	Natural gas	GJ	-	-	-	-	
	Manure (specified category*)	Ton	162	162	162	162	
	Waste (specified category*)	Ton	-	-	-	-	
	Hydrogen	Ton	-	-	-	-	
	Biomass (specified category*)**	GJ	-	-	-	-	
	Other (specify*)	-	-	-	-	-	
Intermediate conversion (if any)							
	Biogas upgrading efficiency	%	93%	93%	93%	93%	With the addition of hydrogen / Calculated based on Specht et al., 2010
	Cold gas efficiency	%	-	-	-	-	
	Torrefaction efficiency	%	-	-	-	-	
	Other (specify*)	%	70%	70%	70%	70%	Clausen et al., 2010
Outputs							
	Aviation fuel (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Other transport fuels (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Electricity		-	-	-	-	
	● Balancing	GJ	-	-	-	-	
	Conversion efficiency	%	53%	55%	55%	55%	
	● Continuous	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Heat		-	-	-	-	
	● Industry	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	● District heating	GJ	-	-	-	-	
	Conversion efficiency	%	38%	37%	37%	37%	
	Food/feed (specify*)	Ton	-	-	-	-	
	Other (specify*)		-	-	-	-	
Emissions							
	CO_2, biogenic upper treshold	kg	0	0	0	0	
	CO_2, biogenic lower treshold	kg	0	0	0	0	
	CO_2, fossil upper treshold	kg					
	CO_2, fossil lower treshold	kg					
	CH4, biogenic upper treshold	g	20000	20000	20000	20000	It is assumed that 1% of the biogas is emitted at the plant due to leakage
	CH4, biogenic lower treshold	g	20000	20000	20000	20000	It is assumed that 1% of the biogas is emitted at the plant due to leakage
	CH4, fossil upper treshold	g					
	CH4, fossil lower treshold	g					
	N2O, upper treshold	g					
	N2O, lower treshold	g					
	NH_3, upper treshold	g					
	NH_3, lower treshold	g					
	Particles, upper treshold	g					
	Particles, lower treshold	g					
	SO_2, upper treshold	g	0	0	0	0	Assuming that sulphur is removed prior to upgrading
	SO_2, lower treshold	g	0	0	0	0	Assuming that sulphur is removed prior to upgrading
	NOx, upper treshold	g					
	NOx, lower treshold	g					
Other implications and outputs							
	Land occupation	m^2					
	Global warming	g CO_2-eq.					
	Eutrophication	g NO3-eq.					

*To be selected from default list
**Lower Heating Value of dry matter

Pathway ID		PP.FC.2-S.G.1					
Conversion technology		Biomass to SNG followed by a solid oxide fuel cell for power production					
							Comments / References
Plant capacity [MW]		10 - 100					Energinet.dk & DEA, 2012
Biomass characterisation		Dried wood					
Carbon content (just before conversion)		-					
Dry Matter content (just before conversion)		90%					Koppejan et al., 2012
Content of volatile solids (just before conversion) (as a % of Dry Matter)		-					
Nitrogen content (just before conversion)		-					
Lower Heating Value (LHV) (MJ/kg Dry		19					Koppejan et al., 2012
CH4 yield (Nm3/ton VS) (when available)		0					
Carbon Conversion Efficiency (%)		-					
Change during handling (gain or loss: "handling" can be storage, drying or any pre-treatment)		-					
		Unit	2013	2020	2035	2050	Comments / References
Inputs							
	Electricity, peak load (specify*)	MWh	-	-	-	-	
	Electricity,base load (specify*)	MWh	0,47	0,47	0,47	0,47	The gasifier consumes 6 % of fuel input Meijden et al., 2010 & Evald et al., 2013
	Heat (specify*)	GJ	-	-	-	-	
	Steam (specify*)	GJ	-	-	-	-	
	Oil (fossil origin)	GJ	-	-	-	-	
	Coal	GJ	-	-	-	-	
	Natural gas	GJ	-	-	-	-	
	Manure (specified category*)	Ton	-	-	-	-	
	Waste (specified category*)	Ton	-	-	-	-	
	Hydrogen	Ton	-	-	-	-	
	Biomass (specified category*)	GJ	100	100	100	100	
	Other (specify*)	-	-	-	-	-	
Intermediate conversion (if any)							
	Biogas upgrading efficiency	%	-	-	-	-	
	Biomass to gas efficiency	%					Meijden et al., 2010
	Torrefaction efficiency	%	-	-	-	-	
	Other (specify*)	%	-	-	-	-	
Outputs							
	Aviation fuel (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Other transport fuels (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Electricity		-	-	-	-	
	• Balancing	GJ	0	0	0	0	
	Conversion efficiency	%					Energinet.dk & DEA, 2012
	• Continuous	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Heat		-	-	-	-	
	• Industry	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	• District heating	GJ	99	99	99	99	
	Conversion efficiency	%					From the gasifier / Evald et al., 2013
	Food/feed (specify*)	Ton	-	-	-	-	
	Other (specify*)		-	-	-	-	
Emissions							
	CO_2, biogenic upper treshold	kg	10200	10200	10200	10200	It is assumed that half of the biogenic CO_2 is released at the SNG plant
	CO_2, biogenic lower treshold	kg	10200	10200	10200	10200	It is assumed that half of the biogenic CO_2 is released at the SNG plant
	CO_2, fossil upper treshold	kg					
	CO_2, fossil lower treshold	kg					
	CH4, biogenic upper treshold	g	0	0	0	0	
	CH4, biogenic lower treshold	g	0	0	0	0	
	CH4, fossil upper treshold	g					
	CH4, fossil lower treshold	g					
	N2O, upper treshold	g	0	0	0	0	
	N2O, lower treshold	g	0	0	0	0	
	NH_3, upper treshold	g					
	NH_3, lower treshold	g					
	Particles, upper treshold	g	0	0	0	0	
	Particles, lower treshold	g	0	0	0	0	
	SO_2, upper treshold	g	0	0	0	0	
	SO_2, lower treshold	g	0	0	0	0	
	NOx, upper treshold	g	0	0	0	0	
	NOx, lower treshold	g	0	0	0	0	
Other implications and outputs							
	Land occupation	m^2					
	Global warming	g CO_2-eq.					
	Eutrophication	g NO3-eq.					

*To be selected from default list
**Lower Heating Value of dry matter

Pathway ID		PP.FC.2-S.G.1					
Conversion technology		Biomass to SNG followed by a solid oxide fuel cell for power production					
							Comments / References
Plant capacity [MW]		10 - 100					Energinet.dk & DEA, 2012
Biomass characterisation		Dried wood					
Carbon content (just before conversion)		-					
Dry Matter content (just before conversion)		90%					Koppejan et al., 2012
Content of volatile solids (just before conversion) (as a % of Dry Matter)		-					
Nitrogen content (just before conversion)		-					
Lower Heating Value (LHV) (MJ/kg Dry Matter)		19					Koppejan et al., 2012
CH4 yield (Nm3/ton VS) (when available)		0					
Carbon Conversion Efficiency (%)		-					
Change during handling (gain or loss: "handling" can be storage, drying or any pre-treatment) (% Dry Matter) (% Carbon) (%Nitrogen)		-					
		Unit	2013	2020	2035	2050	Comments / References
Inputs							
	Electricity, peak load (specify*)	MWh	-	-	-	-	
	Electricity,base load (specify*)	MWh	0,42	0,42	0,42	0,42	The gasifier consumes 6 % of fuel input / Meijden et al., 2010 & Evald et al., 2013
	Heat (specify*)	GJ	-	-	-	-	
	Steam (specify*)	GJ	-	-	-	-	
	Oil (fossil origin)	GJ	-	-	-	-	
	Coal	GJ	-	-	-	-	
	Natural gas	GJ	-	-	-	-	
	Manure (specified category*)	Ton	-	-	-	-	
	Waste (specified category*)	Ton	-	-	-	-	
	Hydrogen	Ton	-	-	-	-	
	Biomass (specified category*)**	GJ	100	100	100	100	
	Other (specify*)	-	-	-	-	-	
Intermediate conversion (if any)							
	Biogas upgrading efficiency	%	-	-	-	-	
	Biomass to gas efficiency	%					Meijden et al., 2010
	Torrefaction efficiency	%	-	-	-	-	
	Other (specify*)	%	-	-	-	-	
Outputs							
	Aviation fuel (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Other transport fuels (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Electricity		-	-	-	-	
	● Balancing	GJ	0	0	0	0	
	Conversion efficiency	%					Energinet.dk & DEA, 2012
	● Continuous	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Heat		-	-	-	-	
	● Industry	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	● District heating	GJ	95	95	95	95	
	Conversion efficiency	%					From the gasifier / Evald et al., 2013
	Food/feed (specify*)	Ton	-	-	-	-	
	Other (specify*)		-	-	-	-	
Emissions							
	CO_2, biogenic upper treshold	kg	10200	10200	10200	10200	It is assumed that half of the biogenic CO_2 is released at the SNG plant
	CO_2, biogenic lower treshold	kg	10200	10200	10200	10200	It is assumed that half of the biogenic CO_2 is released at the SNG plant
	CO_2, fossil upper treshold	kg					
	CO_2, fossil lower treshold	kg					
	CH4, biogenic upper treshold	g	0	0	0	0	
	CH4, biogenic lower treshold	g	0	0	0	0	
	CH4, fossil upper treshold	g					
	CH4, fossil lower treshold	g					
	N2O, upper treshold	g	0	0	0	0	
	N2O, lower treshold	g	0	0	0	0	
	NH_3, upper treshold	g					
	NH_3, lower treshold	g					
	Particles, upper treshold	g	0	0	0	0	
	Particles, lower treshold	g	0	0	0	0	
	SO_2, upper treshold	g	0	0	0	0	
	SO_2, lower treshold	g	0	0	0	0	
	NOx, upper treshold	g	0	0	0	0	
	NOx, lower treshold	g	0	0	0	0	
Other implications and outputs							
	Land occupation	m^2					
	Global warming	g CO_2-eq.					
	Eutrophication	g NO3-eq.					
*To be selected from default list							
**Lower Heating Value of dry matter							

Pathway ID		**AF.M.2-S.G.1**					
Conversion technology		Electrolyser assisted biomass to methanol					
							Comments / References
Plant capacity [MW]		125 - 500					
Biomass characterisation		Dried wood					
Carbon content (just before conversion)		-					
Dry Matter content (just before conversion)		90%					Koppejan et al., 2012
Content of volatile solids (just before conversion) (as a % of Dry Matter)		-					
Nitrogen content (just before conversion)		-					
Lower Heating Value (LHV) (MJ/kg Dry		19					Koppejan et al., 2012
CH4 yield (Nm3/ton VS) (when available)		0					
Carbon Conversion Efficiency (%)		-					
Change during handling (gain or loss: "handling" can be storage, drying or any pre-treatment)		-					
		Unit	2013	2020	2035	2050	Comments
Inputs							
	Electricity, peak load (specify*)	MWh	19	19	19	19	MeOH synthesis hydrogen/syngas ratio: 55.8 % / Calculated based on Mortensgaard et al., 2011 & Clausen et al., 2010
	Electricity,base load (specify*)	MWh	2,2	2,2	2,2	2,2	Biomass-to-SNG: 8 % of fuel input. / Evald et al., 2013, Mortensgaard et al., 2011
	Heat (specify*)	GJ	-	-	-	-	
	Steam (specify*)	GJ	-	-	-	-	
	Oil (fossil origin)	GJ	-	-	-	-	
	Coal	GJ	-	-	-	-	
	Natural gas	GJ	-	-	-	-	
	Manure (specified category*)	Ton	-	-	-	-	
	Waste (specified category*)	Ton	-	-	-	-	
	Hydrogen	Ton	-	-	-	-	
	Biomass (specified category*)**	GJ	100	100	100	100	
	Other (specify*)	-	-	-	-	-	
Intermediate conversion (if any)							
	Biogas upgrading efficiency	%	-	-	-	-	
	Biomass to gas efficiency	%	86%	86%	86%	86%	Mortensgaard et al., 2011
	Torrefaction efficiency	%	-	-	-	-	
	Other (specify*)	%	70%	70%	70%	70%	Clausen et al., 2010
Outputs							
	Aviation fuel (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Other transport fuels (specify*)	GJ	115	115	115	115	Methanol
	Conversion efficiency	%	87%	87%	87%	87%	Clausen et al., 2010, Mortensgaard et al., 2011
	Electricity		-	-	-	-	
	● Balancing	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	● Continuous	GJ	3	3	3	3	
	Conversion efficiency	%	2%	2%	2%	2%	Mortensgaard et al., 2011
	Heat		-	-	-	-	
	● Industry	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	● District heating	GJ	44	44	44	44	
	Conversion efficiency	%	34%	34%	34%	34%	Clausen et al., 2010, Mortensgaard et al., 2011
	Food/feed (specify*)	Ton	-	-	-	-	
	Other (specify*)		-	-	-	-	
Emissions							
	CO_2, biogenic upper treshold	kg	0	0	0	0	
	CO_2, biogenic lower treshold	kg	0	0	0	0	
	CO_2, fossil upper treshold	kg					
	CO_2, fossil lower treshold	kg					
	CH4, biogenic upper treshold	g	0	0	0	0	
	CH4, biogenic lower treshold	g	0	0	0	0	
	CH4, fossil upper treshold	g					
	CH4, fossil lower treshold	g					
	N2O, upper treshold	g	0	0	0	0	
	N2O, lower treshold	g	0	0	0	0	
	NH_3, upper treshold	g					
	NH_3, lower treshold	g					
	Particles, upper treshold	g	0	0	0	0	
	Particles, lower treshold	g	0	0	0	0	
	SO_2, upper treshold	g	0	0	0	0	
	SO_2, lower treshold	g	0	0	0	0	
	NOx, upper treshold	g	0	0	0	0	
	NOx, lower treshold	g	0	0	0	0	
Other implications and outputs							
	Land occupation	m^2					
	Global warming	g CO_2-eq.					
	Eutrophication	g NO3-eq.					

*To be selected from default list
**Lower Heating Value of dry matter

Pathway ID	AF.CB.1-B.AD.2					
Conversion technology	Biogasification and upgrading via hydromethanation to SNG followed by compression					
						Comments / References
Plant capacity [MW]	2 - 10					Energinet.dk & DEA, 2012
Biomass characterisation	Straw	Slurry				
Carbon content (just before conversion)	-	-				
Dry Matter content (just before conversion)	50%	7%				Birkmose, 2013
Content of volatile solids (just before	95%	80%				Birkmose, 2013
Nitrogen content (just before conversion)	-	-				
Lower Heating Value (LHV) (MJ/kg Dry Matter)	16,8	0				Domalski et al., 1987 & Videncenter for halm og flisfyring, 1999
CH4 yield (Nm3/ton VS) (when available)	278	319				Birkmose, 2013, Hamelin, 2013
Carbon Conversion Efficiency (%)	-	-				
Change during handling (gain or loss:	-	-				

		Unit	2013	2020	2035	2050	Comments
Inputs							
	Electricity, peak load (specify*)	MWh	19	19	19	19	Electrolyser consumes 90 % of biogas output (assuming 70 % electrolyser efficiency) / Calculated based on Specht et al., 2010, Clausen et al., 2010
	Electricity,base load (specify*)	MWh	2,1	2,1	2,1	2,1	AD: 5 kWh pr. ton biomass. Upgrading of biogas: 2 % of biogas production. Compression to use in vehicle: 4,5 % of energycontent in the methane. / Energinet.dk & DEA, 2012, Specht et al., 2010
	Heat (specify*)	GJ	2	2	2	2	AD: 34 kWh pr. m3 of raw biomass, assumed density of 500 kg/m3 for straw and 1 ton/m3 for slurry. Energy equivalent to 6 % of biogas input into the upgrading proces is recovered as heat for the biogasification. / Energinet.dk & DEA, 2012, Specht et al., 2010
	Steam (specify*)	GJ	-	-	-	-	
	Oil (fossil origin)	GJ	-	-	-	-	
	Coal	GJ	-	-	-	-	
	Natural gas	GJ	-	-	-	-	
	Manure (specified category*)	Ton	32,6	32,6	32,6	32,6	Hamelin, 2013
	Waste (specified category*)	Ton	-	-	-	-	
	Hydrogen	Ton	-	-	-	-	
	Biomass (specified category*)**	GJ	100	100	100	100	Requires extrusion
	Other (specify*)	-	-	-	-	-	
Intermediate conversion (if any)							
	Biogas upgrading efficiency	%	93%	93%	93%	93%	With the addition of hydrogen / Calculated based on Specht et al., 2010
	Cold gas efficiency	%	-	-	-	-	
	Torrefaction efficiency	%	-	-	-	-	
	Other (specify*)	%	70%	70%	70%	70%	Clausen et al., 2010
Outputs							
	Aviation fuel (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Other transport fuels (specify*)	GJ	113	113	113	113	SNG
	Conversion efficiency	%	100%	100%	100%	100%	
	Electricity		-	-	-	-	
	• Balancing	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	• Continuous	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Heat		-	-	-	-	
	• Industry	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	• District heating	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Food/feed (specify*)	Ton	-	-	-	-	
	Other (specify*)		-	-	-	-	
Emissions							
	CO_2, biogenic upper treshold	kg	0	0	0	0	
	CO_2, biogenic lower treshold	kg	0	0	0	0	
	CO_2, fossil upper treshold	kg					
	CO_2, fossil lower treshold	kg					
	CH4, biogenic upper treshold	g	15022	15022	15022	15022	It is assumed that 1% of the biogas is emitted at the plant due to leakage
	CH4, biogenic lower treshold	g	15022	15022	15022	15022	It is assumed that 1% of the biogas is emitted at the plant due to leakage
	CH4, fossil upper treshold	g					
	CH4, fossil lower treshold	g					
	N2O, upper treshold	g					
	N2O, lower treshold	g					
	NH_3, upper treshold	g					
	NH_3, lower treshold	g					
	Particles, upper treshold	g					
	Particles, lower treshold	g					
	SO_2, upper treshold	g	0	0	0	0	Assuming that sulphur is removed prior to upgrading
	SO_2, lower treshold	g	0	0	0	0	Assuming that sulphur is removed prior to upgrading
	NOx, upper treshold	g					
	NOx, lower treshold	g					
Other implications and outputs							
	Land occupation	m^2					
	Global warming	g CO_2-eq.					
	Eutrophication	g NO3-eq.					

*To be selected from default list
**Lower Heating Value of dry matter

Pathway ID		AF.CB.1-B.AD.3					
Conversion technology		Biogasification and upgrading via hydromethanation to SNG followed by compression					
							Comments / References
Plant capacity [MW]		2 - 10					Energinet.dk & DEA, 2012
Biomass characterisation		Slurry					
Carbon content (just before conversion)		-					
Dry Matter content (just before conversion)		7%					Birkmose, 2013
Content of volatile solids (just before		80%					Birkmose, 2013
Nitrogen content (just before conversion)		-					
Lower Heating Value (LHV) (MJ/kg Dry		0					
CH4 yield (Nm3/ton VS) (when available)		319					Hamelin, 2013
Carbon Conversion Efficiency (%)		-					
Change during handling (gain or loss:		-					
		Unit	2013	2020	2035	2050	Comments / References
Inputs							
	Electricity, peak load (specify*)	MWh	25	25	25	25	Electrolyser consumes 90 % of biogas output (assuming 70 % electrolyser efficiency) / Calculated based on Specht et al., 2010,Clausen et al., 2010
	Electricity,base load (specify*)	MWh	3,3	3,3	3,3	3,3	AD: 5 kWh pr. ton biomass. Upgrading of biogas: 2 % of biogas production. Compression to use in vehicle: 4,5 % of energy content in the methane. / Energinet.dk & DEA, 2012, Specht et al., 2010
	Heat (specify*)	GJ	14	14	14	14	AD: 34 kWh pr. m3 of raw biomass, assumed density of 500 kg/m3 for straw and 1 ton/m3 for slurry. Energy equivalent to 6 % of biogas input into the upgrading proces is ecovered as heat for the biogasification. / Energinet.dk & DEA, 2012, Specht et al., 2010
	Steam (specify*)	GJ	-	-	-	-	
	Oil (fossil origin)	GJ	-	-	-	-	
	Coal	GJ	-	-	-	-	
	Natural gas	GJ	-	-	-	-	
	Manure (specified category*)	Ton	162	162	162	162	
	Waste (specified category*)	Ton	-	-	-	-	
	Hydrogen	Ton	-	-	-	-	
	Biomass (specified category*)**	GJ	-	-	-	-	
	Other (specify*)	-	-	-	-	-	
Intermediate conversion (if any)							
	Biogas upgrading efficiency	%	93%	93%	93%	93%	With the addition of hydrogen / Calculated based on Specht et al., 2010
	Cold gas efficiency	%	-	-	-	-	
	Torrefaction efficiency	%	-	-	-	-	
	Other (specify*)	%	70%	70%	70%	70%	Clausen et al., 2010
Outputs							
	Aviation fuel (specify*)	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Other transport fuels (specify*)	GJ	151	151	151	151	SNG
	Conversion efficiency	%	100%	100%	100%	100%	
	Electricity		-	-	-	-	
	● Balancing	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	● Continuous	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Heat		-	-	-	-	
	● Industry	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	● District heating	GJ	-	-	-	-	
	Conversion efficiency	%	-	-	-	-	
	Food/feed (specify*)	Ton	-	-	-	-	
	Other (specify*)		-	-	-	-	
Emissions							
	CO_2, biogenic upper treshold	kg	0	0	0	0	
	CO_2, biogenic lower treshold	kg	0	0	0	0	
	CO_2, fossil upper treshold	kg					
	CO_2, fossil lower treshold	kg					
	CH4, biogenic upper treshold	g	20000	20000	20000	20000	It is assumed that 1% of the biogas is emitted at the plant due to leakage
	CH4, biogenic lower treshold	g	20000	20000	20000	20000	It is assumed that 1% of the biogas is emitted at the plant due to leakage
	CH4, fossil upper treshold	g					
	CH4, fossil lower treshold	g					
	N2O, upper treshold	g					
	N2O, lower treshold	g					
	NH_3, upper treshold	g					
	NH_3, lower treshold	g					
	Particles, upper treshold	g					
	Particles, lower treshold	g					
	SO_2, upper treshold	g	0	0	0	0	Assuming that sulphur is removed prior to upgrading
	SO_2, lower treshold	g	0	0	0	0	Assuming that sulphur is removed prior to upgrading
	NOx, upper treshold	g					
	NOx, lower treshold	g					
Other implications and outputs							
	Land occupation	m^2					
	Global warming	g CO_2-eq.					
	Eutrophication	g NO3-eq.					

*To be selected from default list
**Lower Heating Value of dry matter

Appendix I Pathway comparisons at levels 2 and 3

This appendix holds the complete set of graphics presenting carbon footprints comparisons in three different ways: First 'Biomass types and conversion pathways', second 'Conversion pathways and energy supply, and third 'Biomass types'. The specific graphics numbered 1 to 54 can be found by using the overview tables below in the first subsection. Graphics numbered 56 – 102 are found in the secon subsection and are supplementary to 'Conversion pathways and energy supply' and ''Biomass types'.

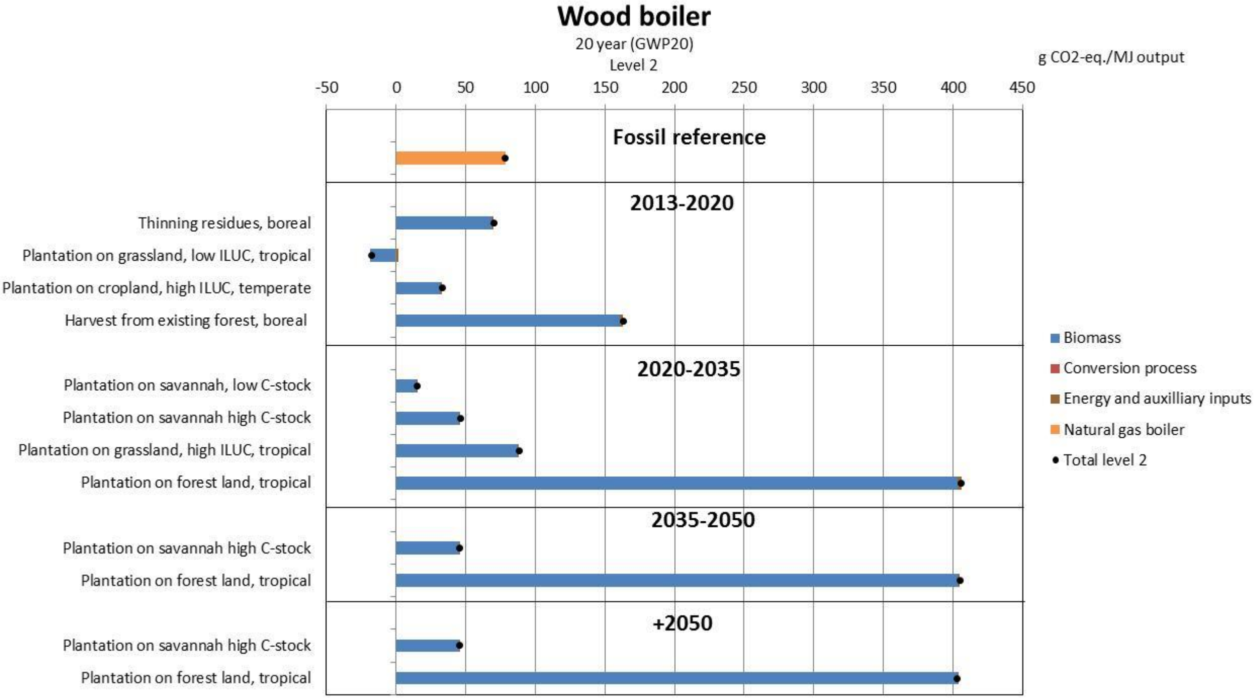
I.1 Subsection

Biomass types and conversion pathways	**Type of energy supply**	**20 and 100 year time horizons Level 2**	**20 and 100 year time horizons Level 3**
Wood boiler	Heat	1	2
Straw boiler	Heat	3	4
Wood CHP continuous	Power	5	6
Straw CHP continuous	Power	7	8
Manure biogas CHP continuous	Power	9	10
Manure-straw biogas CHP continuous	Power	11	12
Wood SNG CHP flexible	Power	13	14
Manure biogas + H2 CHP flexible	Power	15	16
Manure-straw biogas + H2 SNG CHP flexible	Power	17	18
Wood + H2 methanol & DME fuel	Transport fuel	19	20

Manure biogas + H2 SNG fuel	Transport fuel	21	22
Manure-straw biogas + H2 SNG fuel	Transport fuel	23	24
2G ethanol short range + syngas	Transport fuel	25	26
2G ethanol long range + syngas	Transport fuel	27	28
2G eth long range + syngas + biogas	Transport fuel	29	30

Conversion pathways, energy supply	**20 year time horizon Level 2**	**100 Year time horizon Level 2**
Boiler, heat	31, 32	33, 34
CHP continuous, power	35, 36	37, 38
CHP flexible, power	39, 40	41, 42
Fermentation +, transport fuel	43, 44	45, 46

Biomass types	**20 year time horizon Level 3**	**100 Year time horizon Level 3**
Woody biomass	47, 48	49, 50
Straw biomass	51, 52	53, 54


Wood boiler
20 year (GWP20)
Level 2
g CO2-eq./MJ output
-50
0
50
100
150
200
250
300
350
400
450
Fossil reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Natural gas boiler
Total level 2

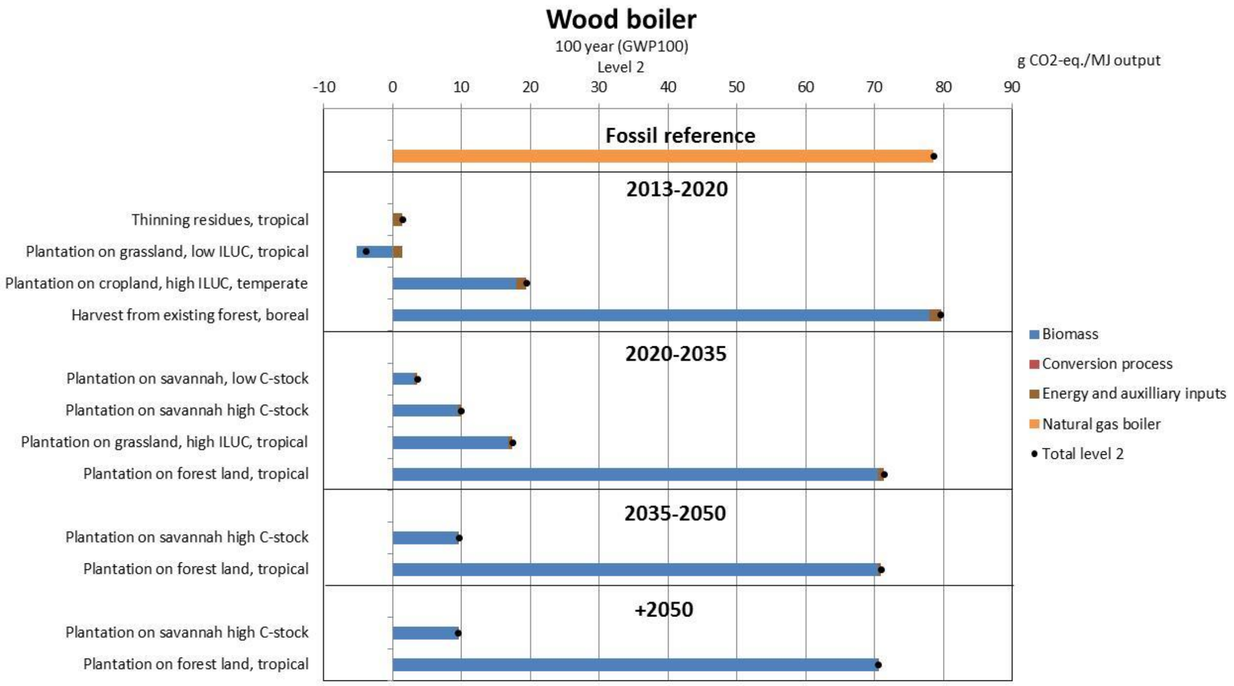
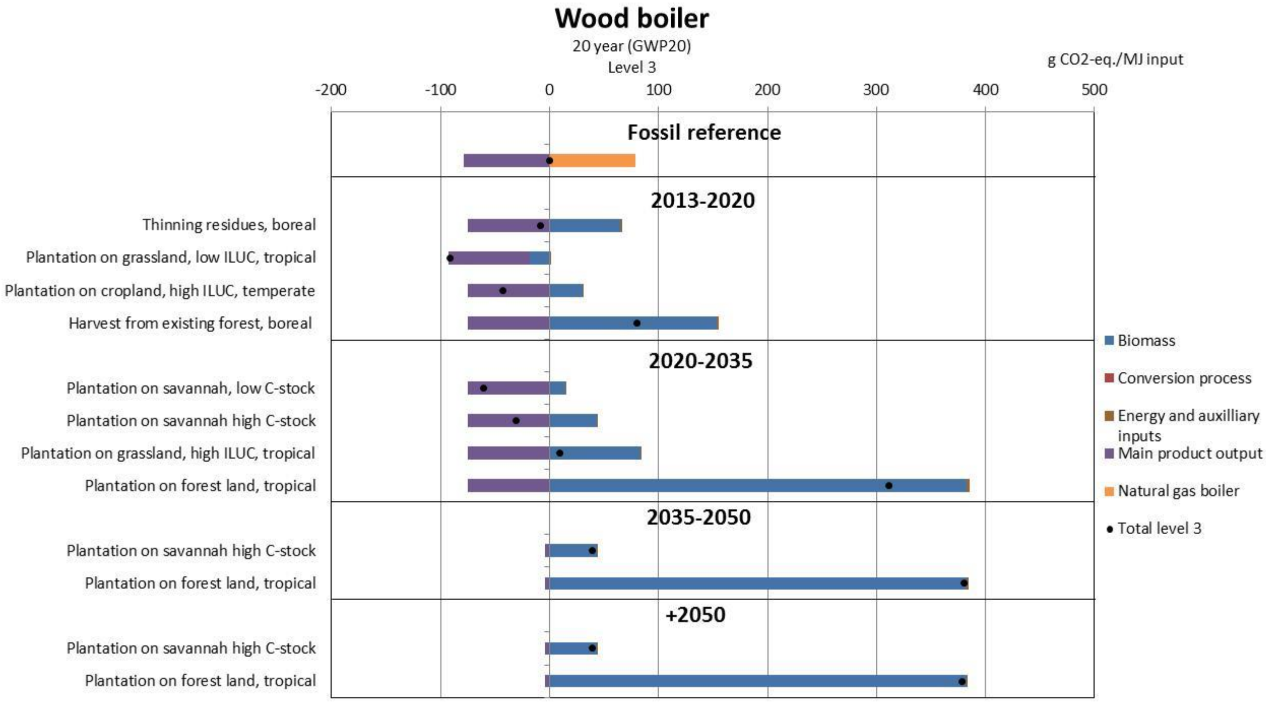

Wood boiler
100 year (GWP100)
Level 2
g CO2-eq./MJ output
-10
0
10
20
30
40
50
60
70
80
90
Fossil reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Natural gas boiler
Total level 2

Figure 0-1


Wood boiler
20 year (GWP20)
Level 3
g CO2-eq./MJ input
-200
-100
0
100
200
300
400
500
Fossil reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Main product output
Natural gas boiler
Total level 3

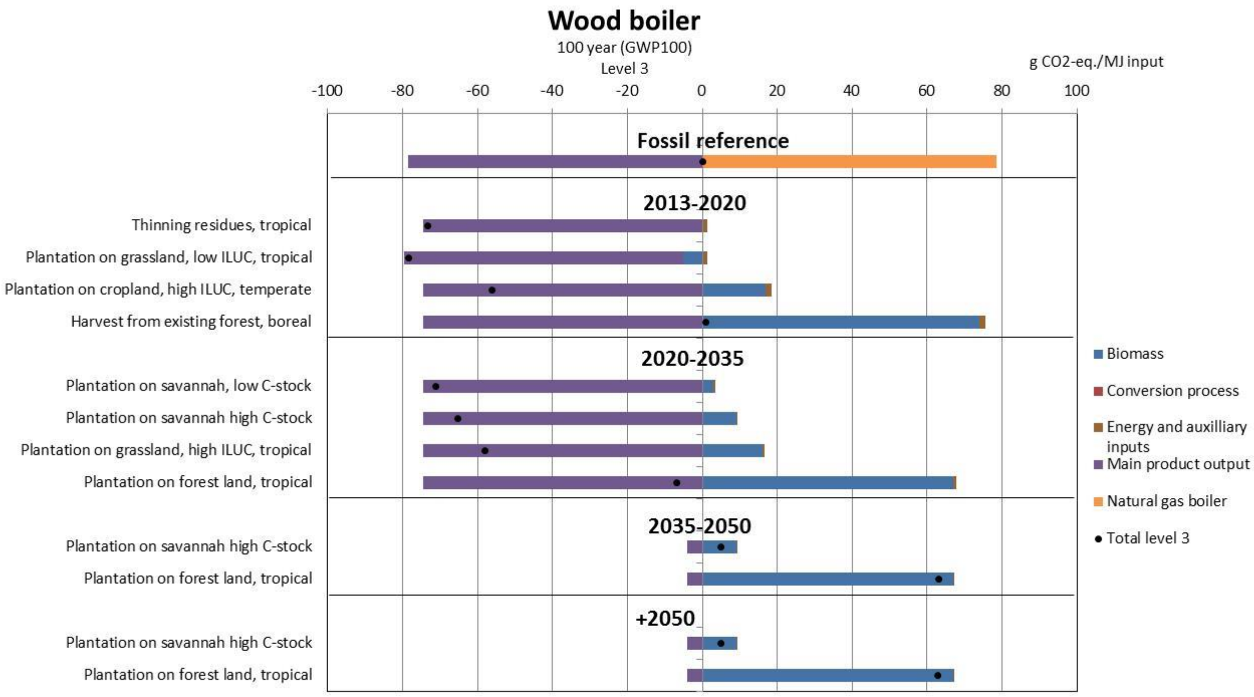
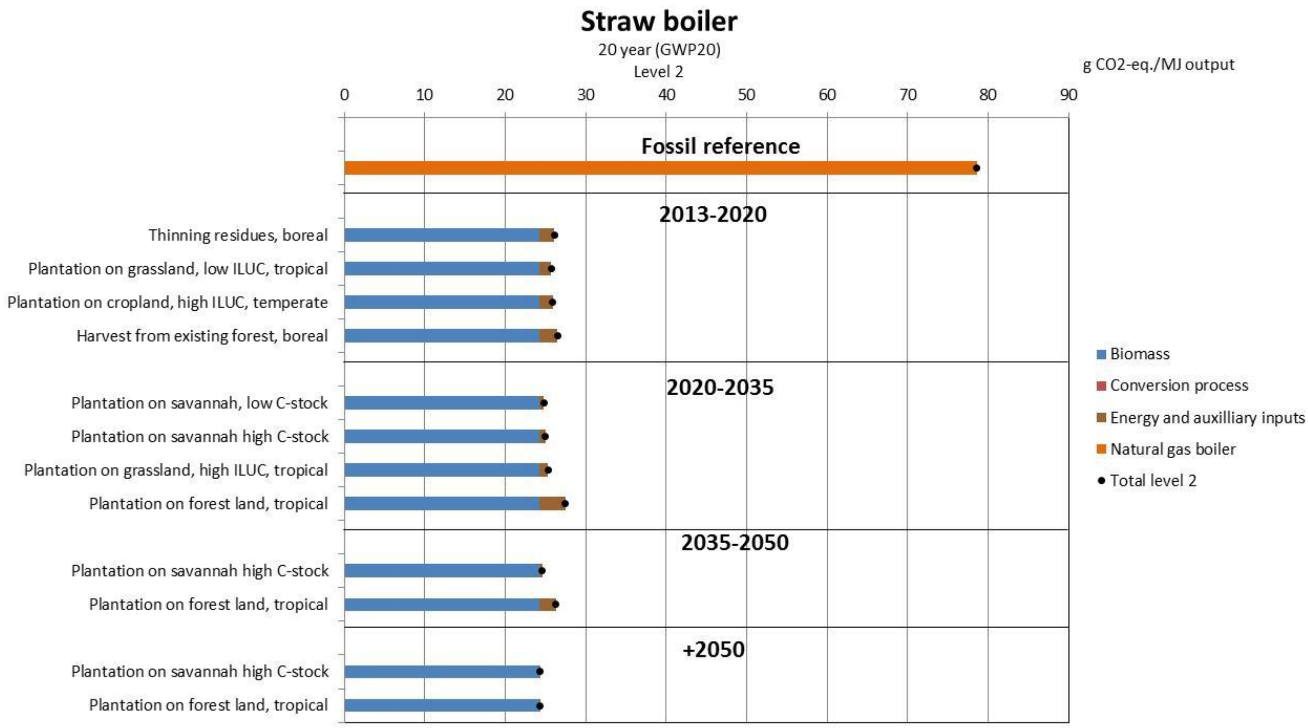

Wood boiler
100 year (GWP100)
Level 3
g CO2-eq./MJ input
-100
-80
-60
-40
-20
0
20
40
60
80
100
Fossil reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Main product output
Natural gas boiler
Total level 3

Figure 0-2


Straw boiler
20 year (GWP20)
Level 2
g CO2-eq./MJ output
0
10
20
30
40
50
60
70
80
90
Fossil reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Natural gas boiler
Total level 2

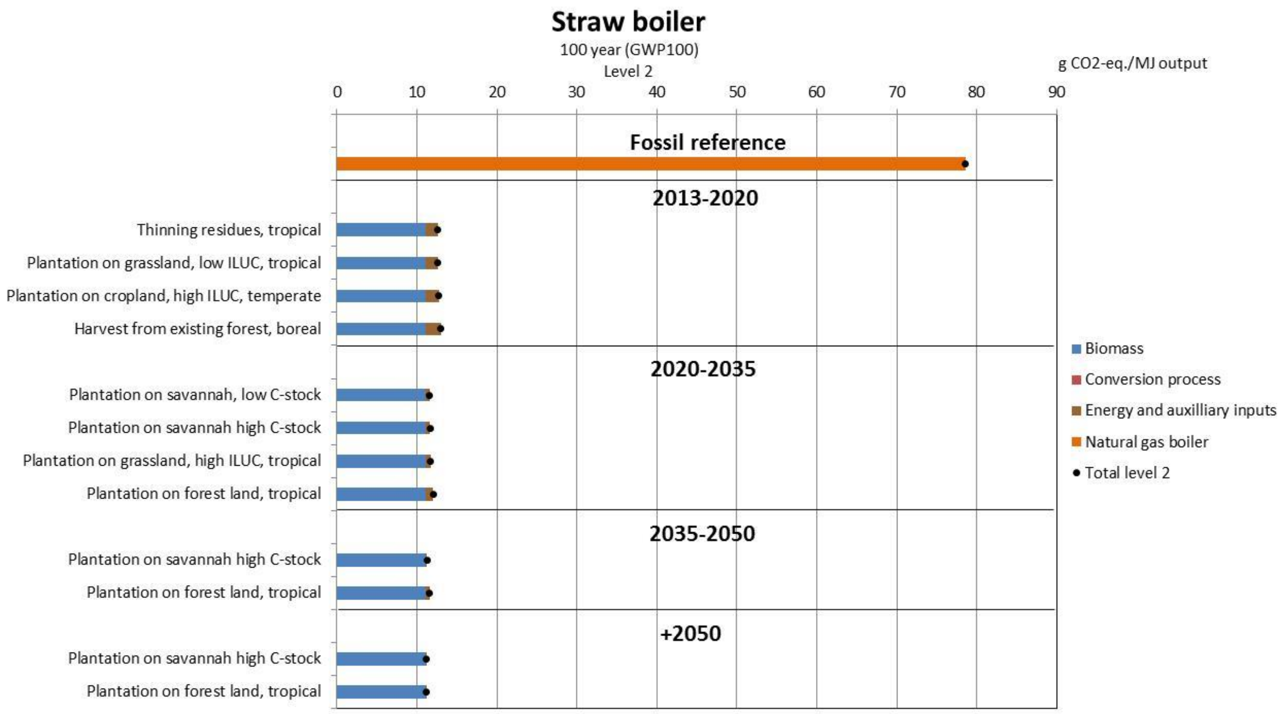
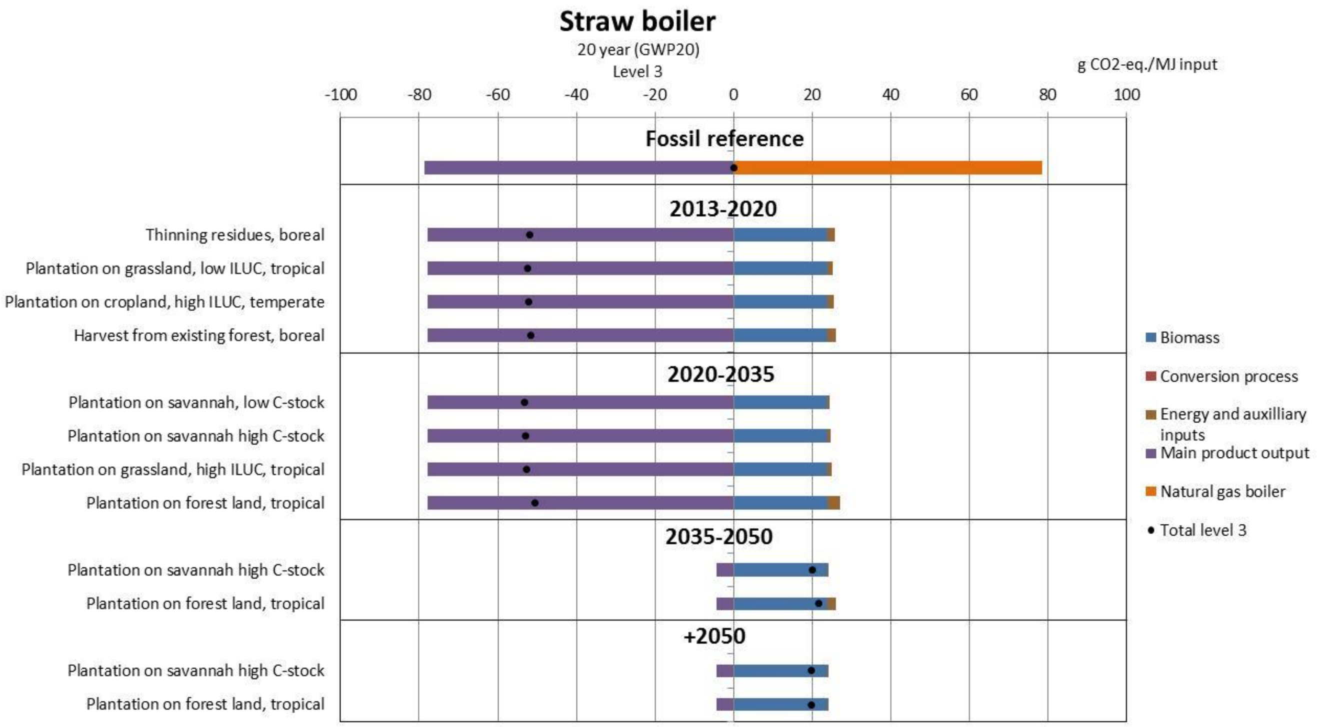

Straw boiler
100 year (GWP100)
Level 2
g CO2-eq./MJ output
0
10
20
30
40
50
60
70
80
90
Fossil reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Natural gas boiler
Total level 2

Figure 0-3


Straw boiler
20 year (GWP20)
Level 3
g CO2-eq./MJ input
-100
-80
-60
-40
-20
0
20
40
60
80
100
Fossil reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Main product output
Natural gas boiler
Total level 3

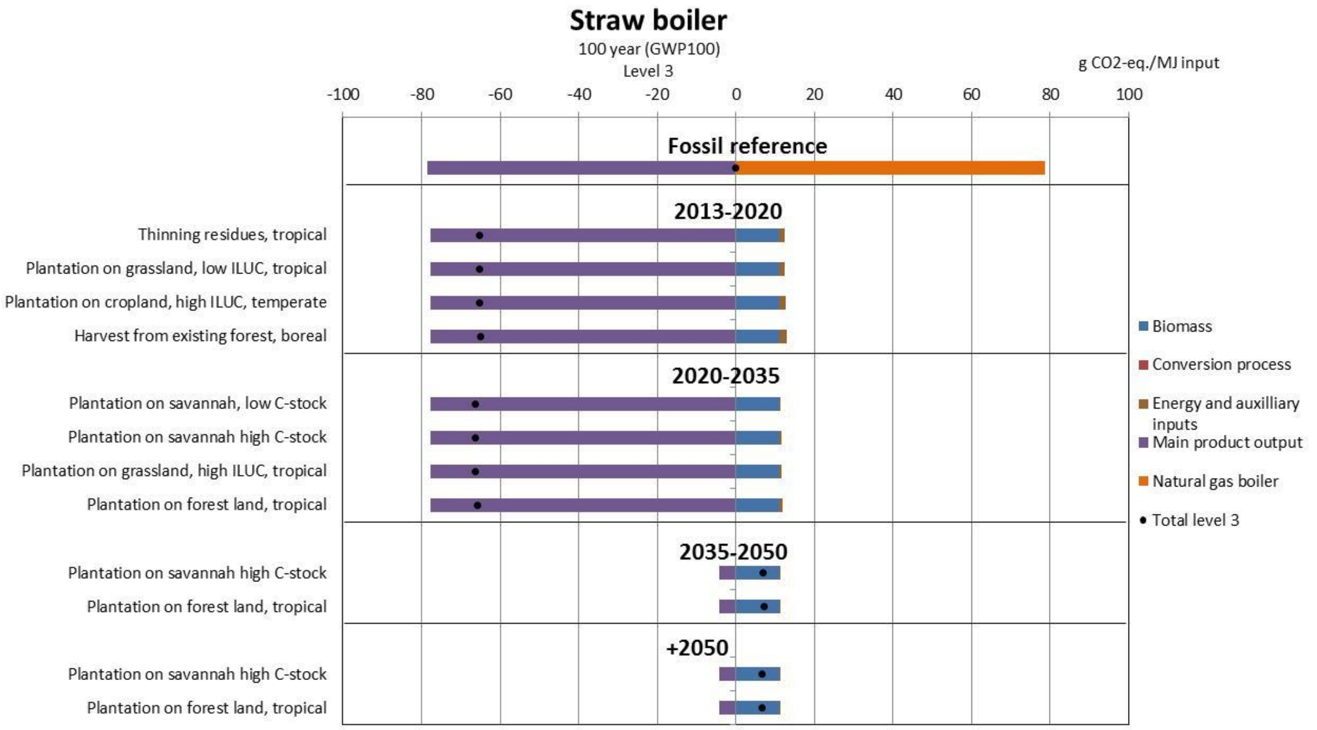
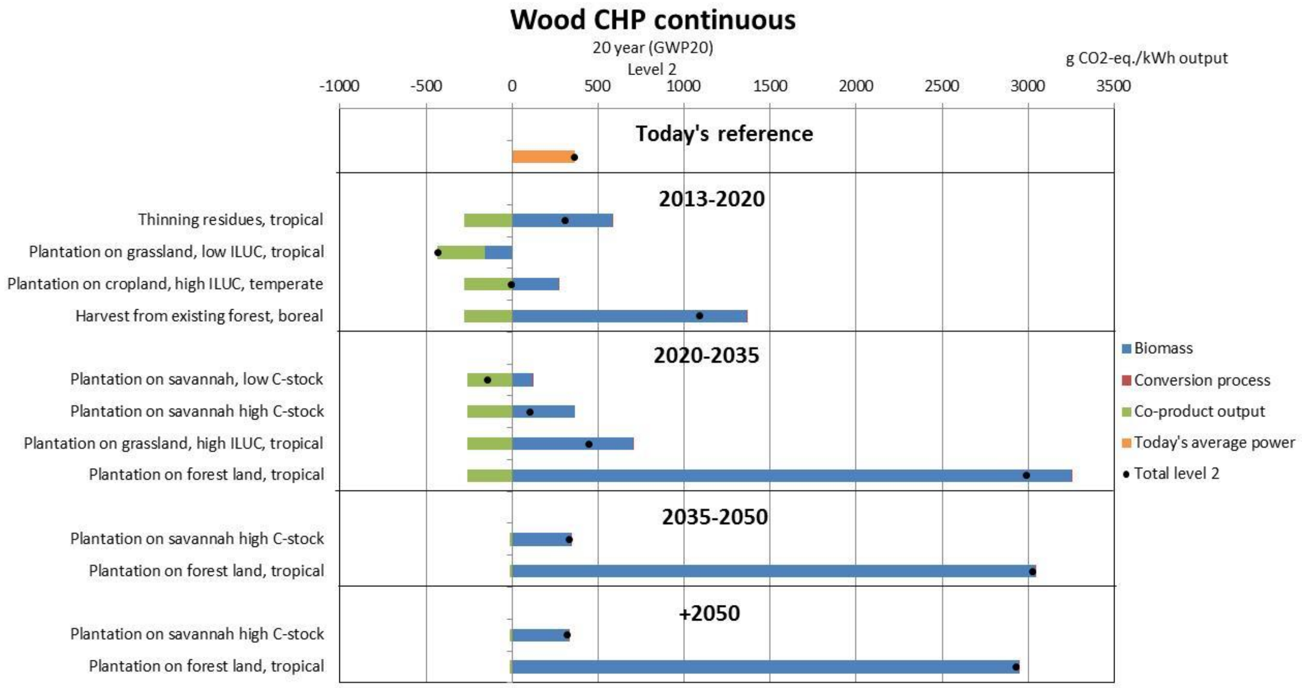

Straw boiler
100 year (GWP100)
Level 3
g CO2-eq./MJ input
-100
-80
-60
-40
-20
0
20
40
60
80
100
Fossil reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Main product output
Natural gas boiler
Total level 3

Figure 0-4


Wood CHP continuous
20 year (GWP20)
Level 2
g CO2-eq./kWh output
-1000
-500
0
500
1000
1500
2000
2500
3000
3500
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Co-product output
Today's average power
Total level 2

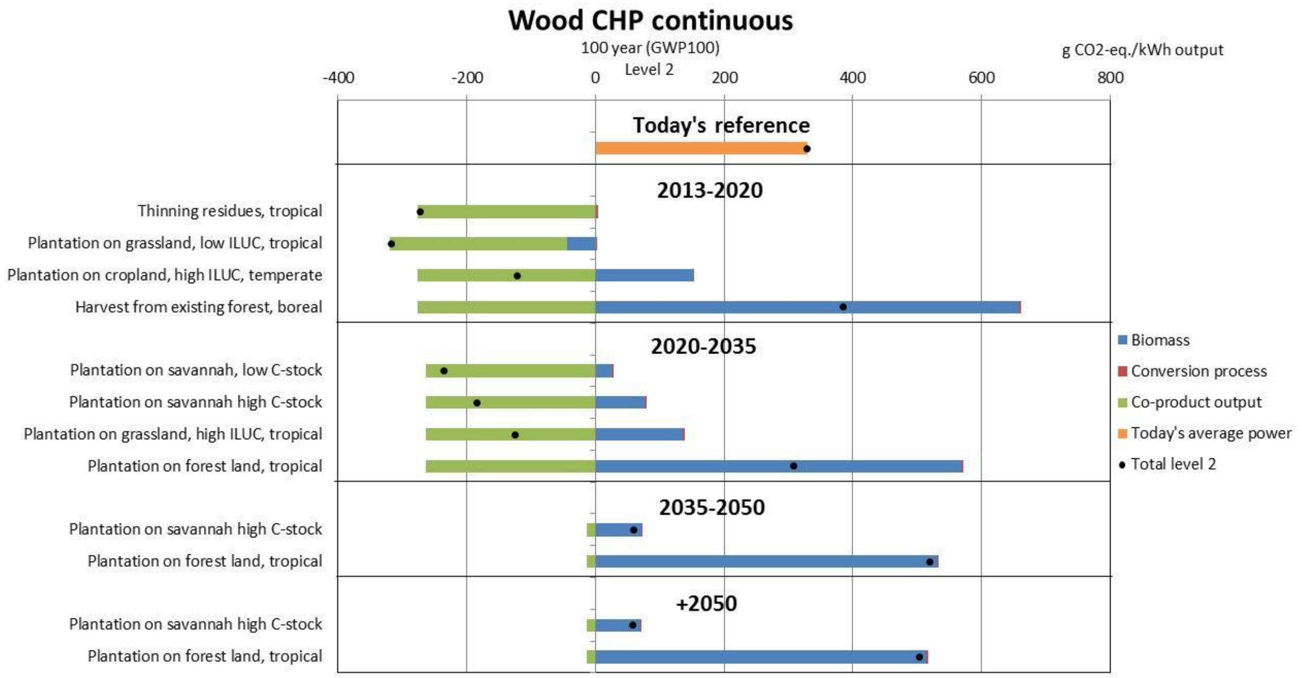
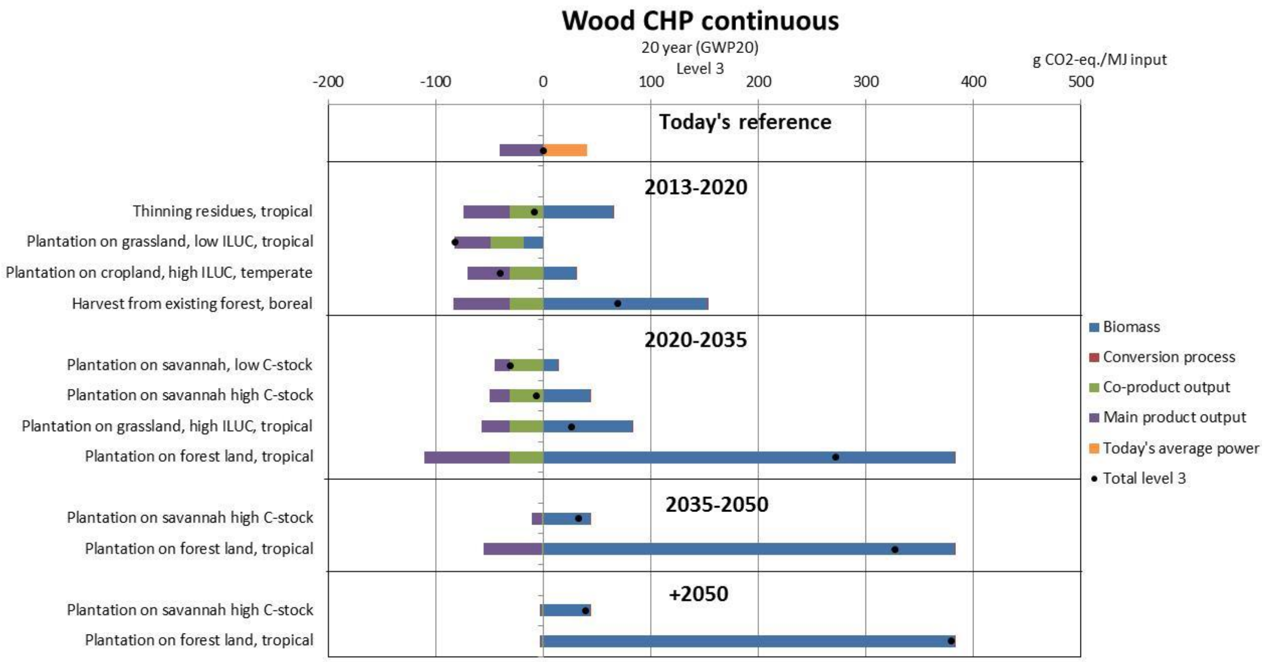

Wood CHP continuous
100 year (GWP100)
Level 2
g CO2-eq./kWh output
-400
-200
0
200
400
600
800
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Co-product output
Today's average power
Total level 2

Figure 0-5


Wood CHP continuous
20 year (GWP20)
Level 3
g CO2-eq./MJ input
-200
-100
0
100
200
300
400
500
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Co-product output
Main product output
Today's average power
Total level 3

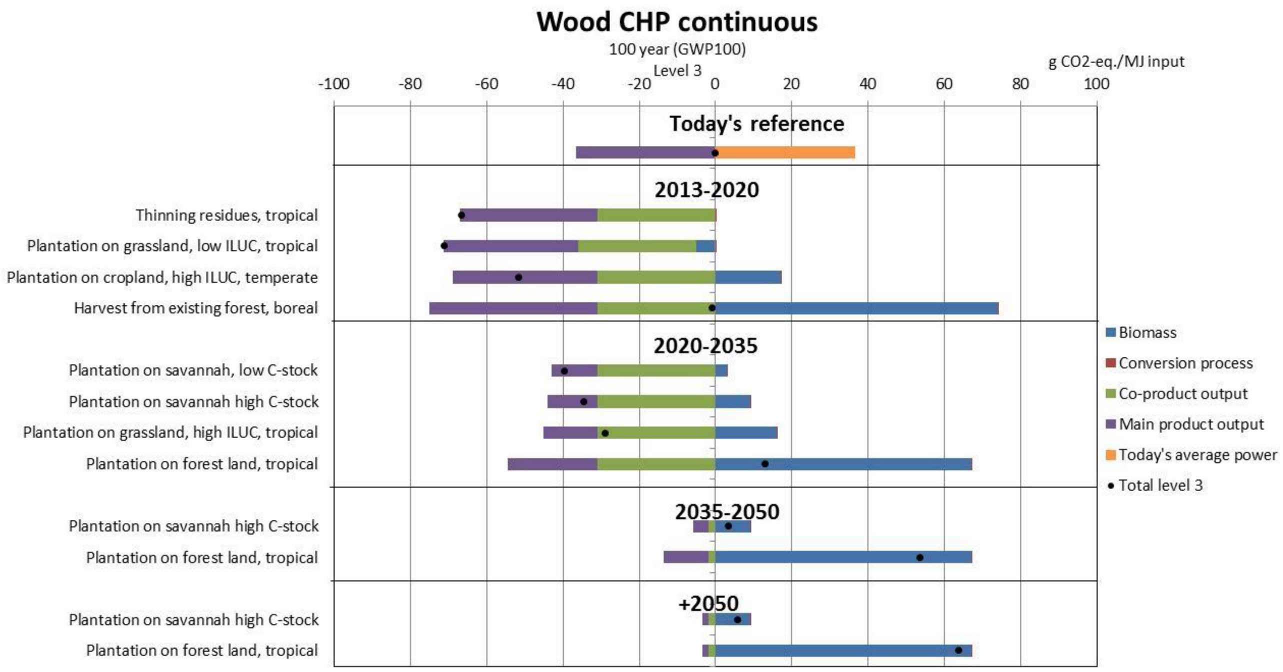

Wood CHP continuous
100 year (GWP100)
Level 3
g CO2-eq./MJ input
-100
-80
-60
-40
-20
0
20
40
60
80
100
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Co-product output
Main product output
Today's average power
Total level 3

Figure 0-6

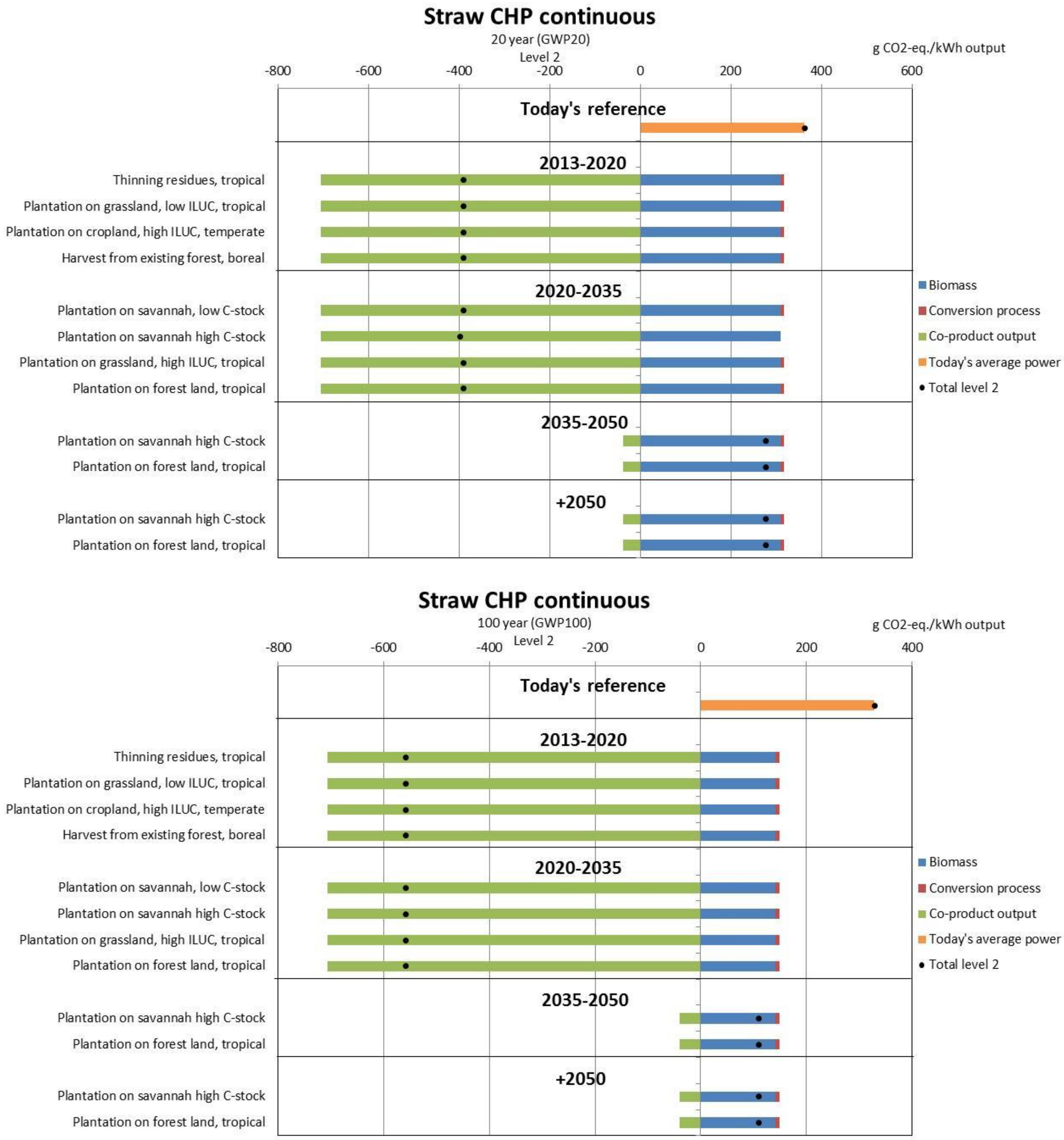
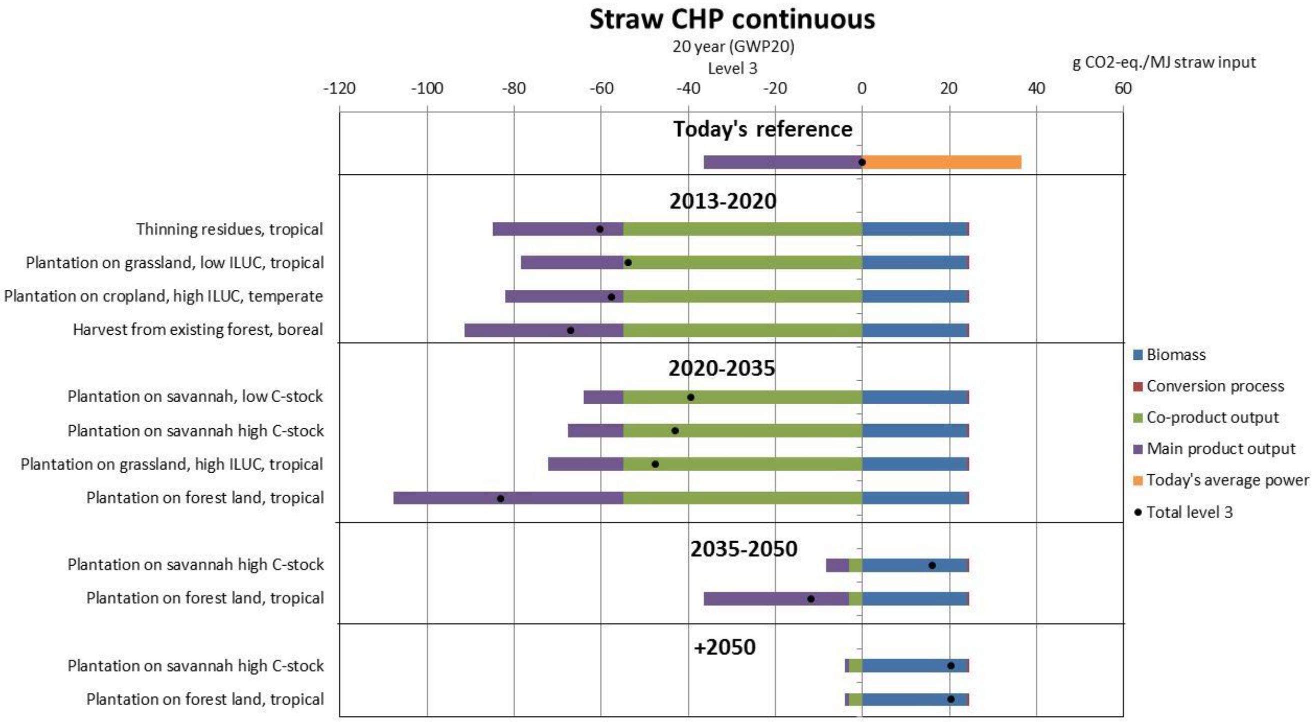

Straw CHP continuous
20 year (GWP20)
Level 2
g CO2-eq./kWh output
-800
-600
-400
-200
0
200
400
600
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Co-product output
Today's average power
Total level 2
Straw CHP continuous
100 year (GWP100)
Level 2
g CO2-eq./kWh output
-800
-600
-400
-200
0
200
400
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Co-product output
Today's average power
Total level 2

Figure 0-7


Straw CHP continuous
20 year (GWP20)
Level 3
g CO2-eq./MJ straw input
-120 -100 -80 -60 -40 -20 0 20 40 60
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Co-product output
Main product output
Today's average power
Total level 3

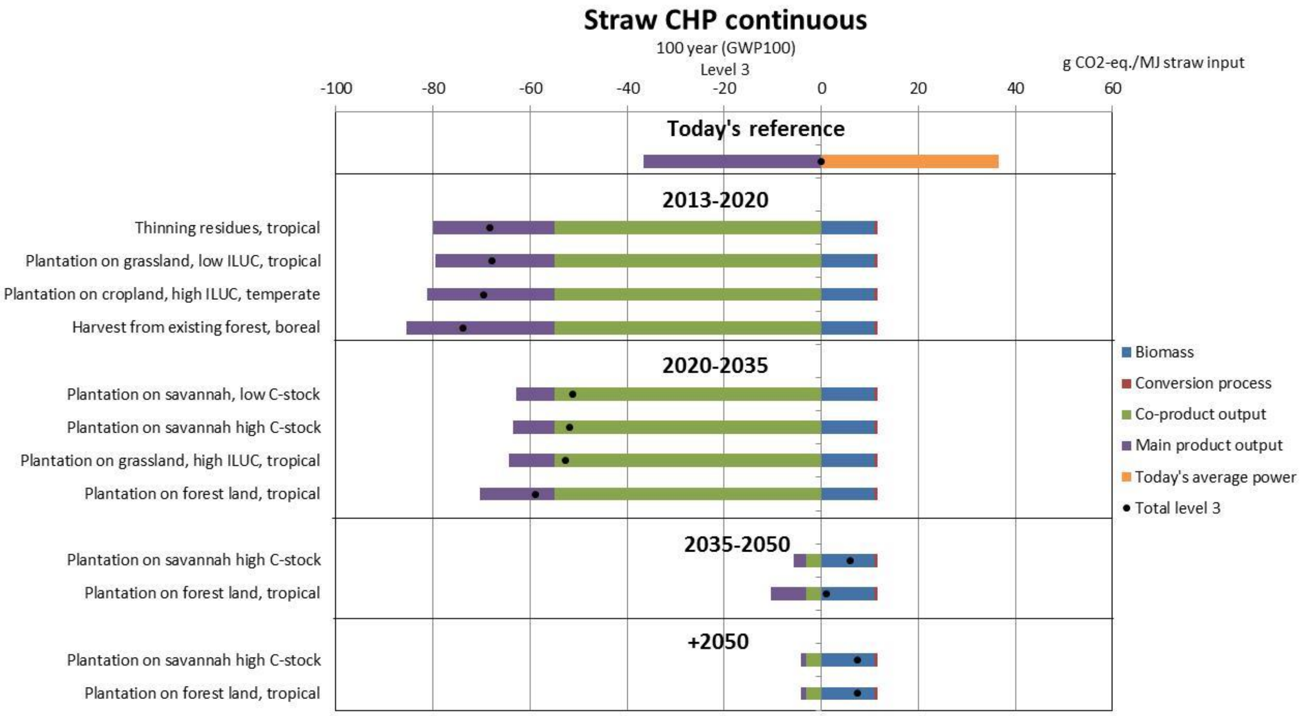
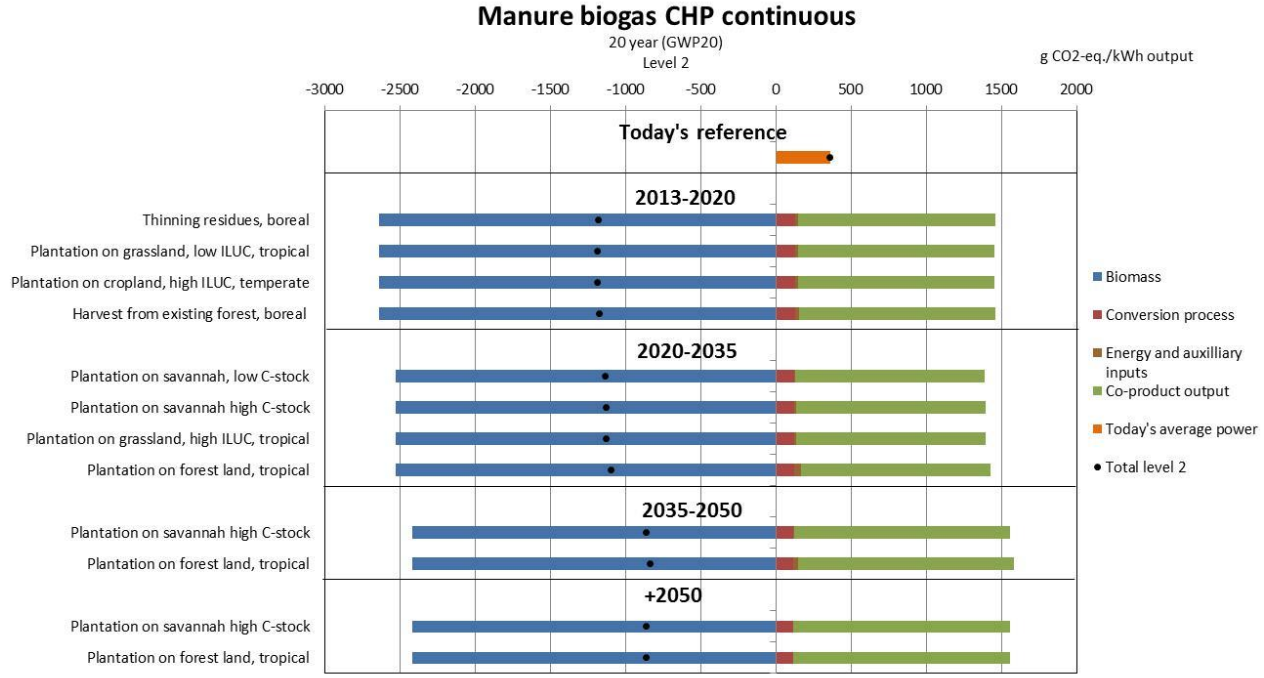

Straw CHP continuous
100 year (GWP100)
Level 3
g CO2-eq./MJ straw input
-100 -80 -60 -40 -20 0 20 40 60
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Co-product output
Main product output
Today's average power
Total level 3

Figure 0-8


Manure biogas CHP continuous
20 year (GWP20)
Level 2
g CO2-eq./kWh output
-3000 -2500 -2000 -1500 -1000 -500 0 500 1000 1500 2000
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Today's average power
Total level 2

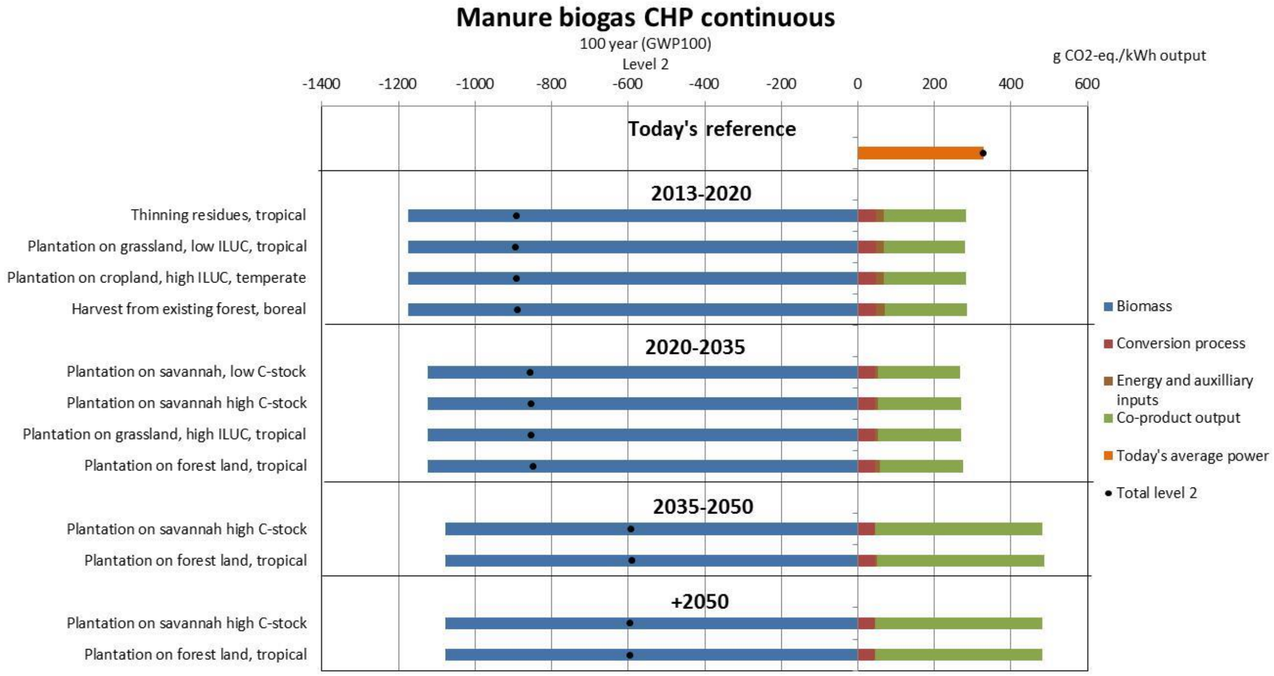
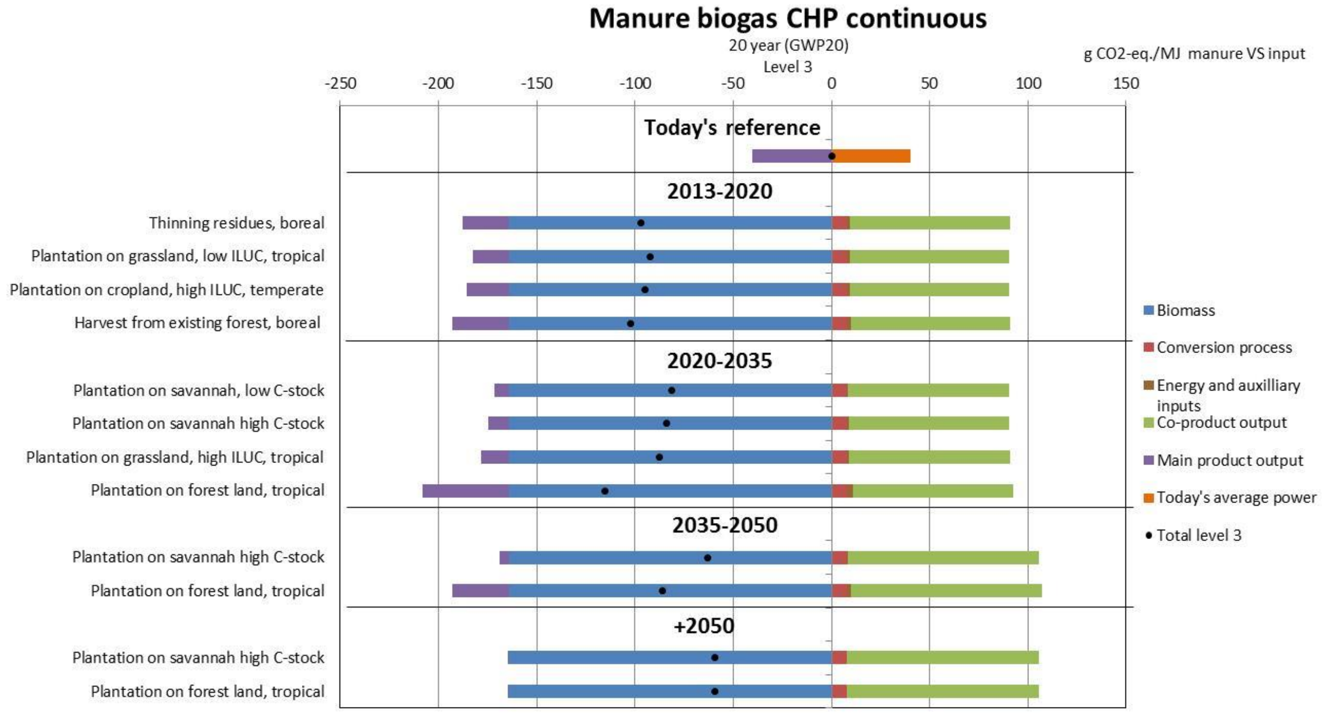

Manure biogas CHP continuous
100 year (GWP100)
Level 2
g CO2-eq./kWh output
-1400 -1200 -1000 -800 -600 -400 -200 0 200 400 600
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Today's average power
Total level 2

Figure 0-9


Manure biogas CHP continuous
20 year (GWP20)
Level 3
g CO2-eq./MJ manure VS input
-250
-200
-150
-100
-50
0
50
100
150
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product output
Today's average power
Total level 3

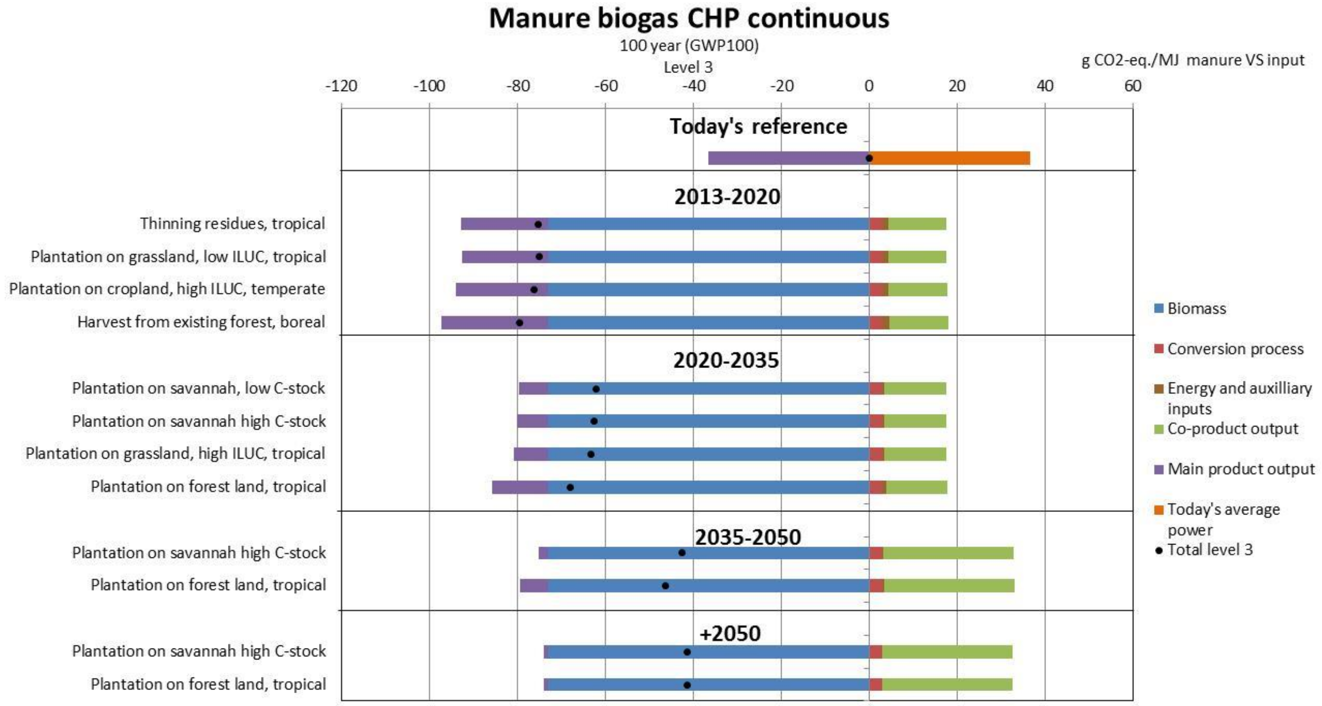
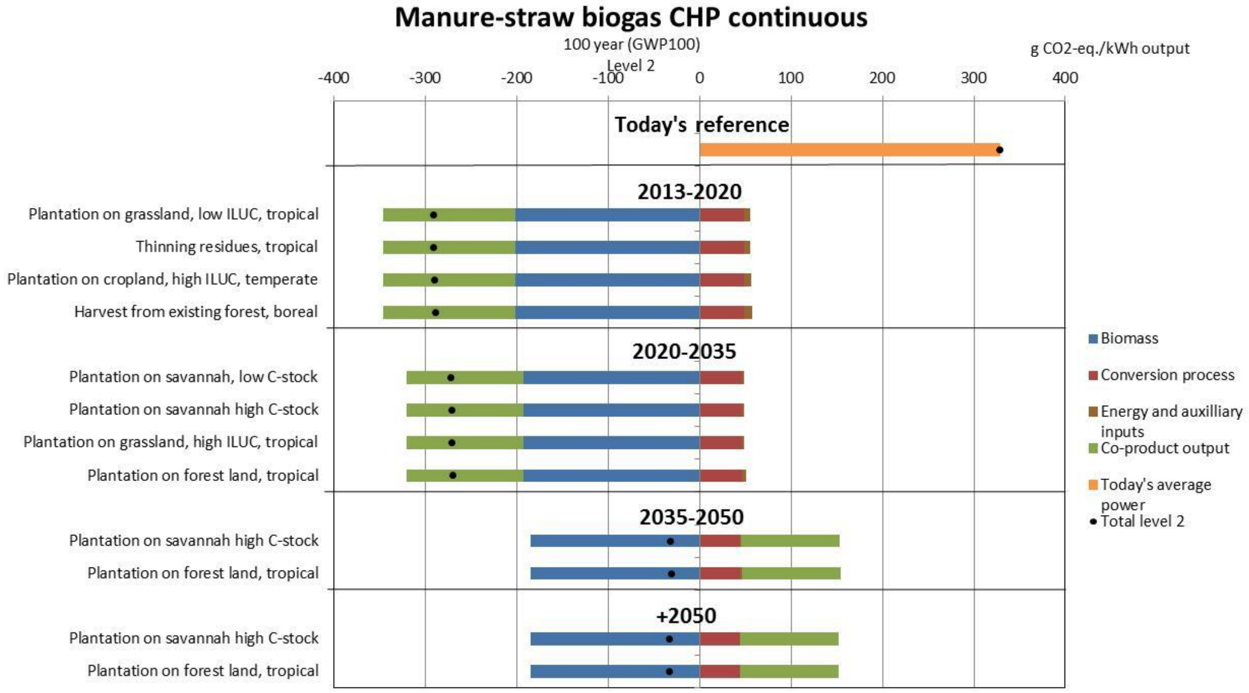

Manure biogas CHP continuous
100 year (GWP100)
Level 3
g CO2-eq./MJ manure VS input
-120
-100
-80
-60
-40
-20
0
20
40
60
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product output
Today's average power
Total level 3

Figure 0-10


Manure-straw biogas CHP continuous
100 year (GWP100)
Level 2
g CO2-eq./kWh output
-400
-300
-200
-100
0
100
200
300
400
Today's reference
2013-2020
Plantation on grassland, low ILUC, tropical
Thinning residues, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Today's average power
Total level 2

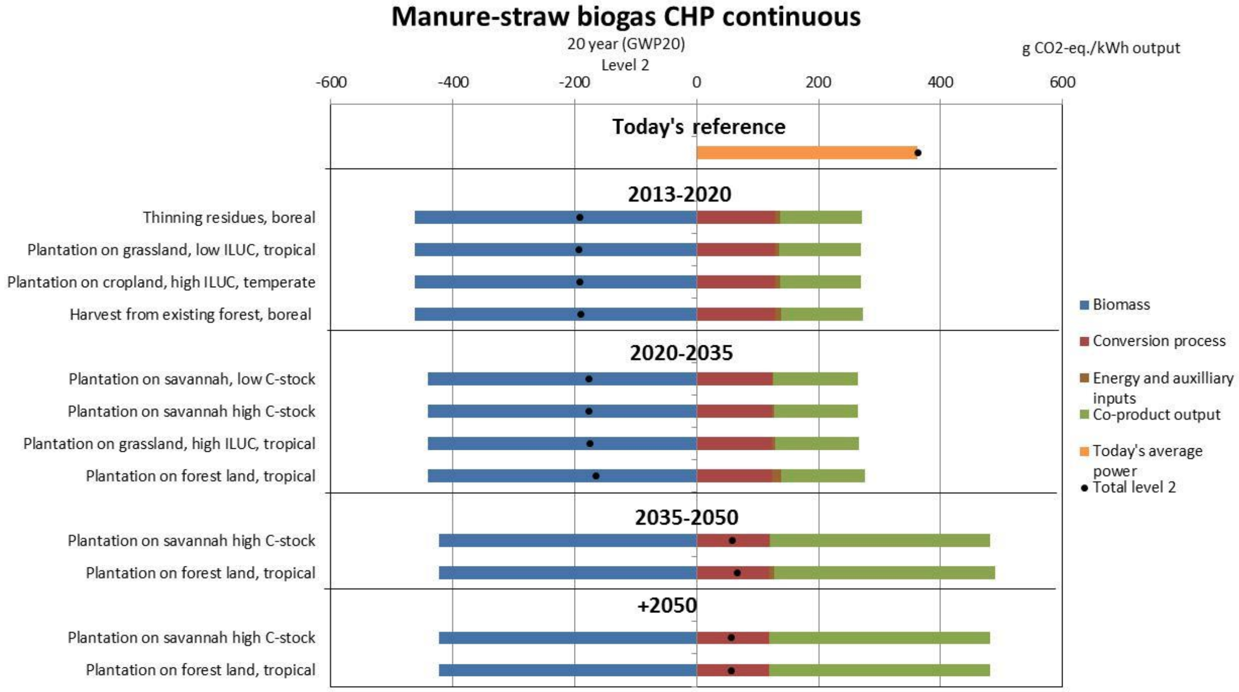
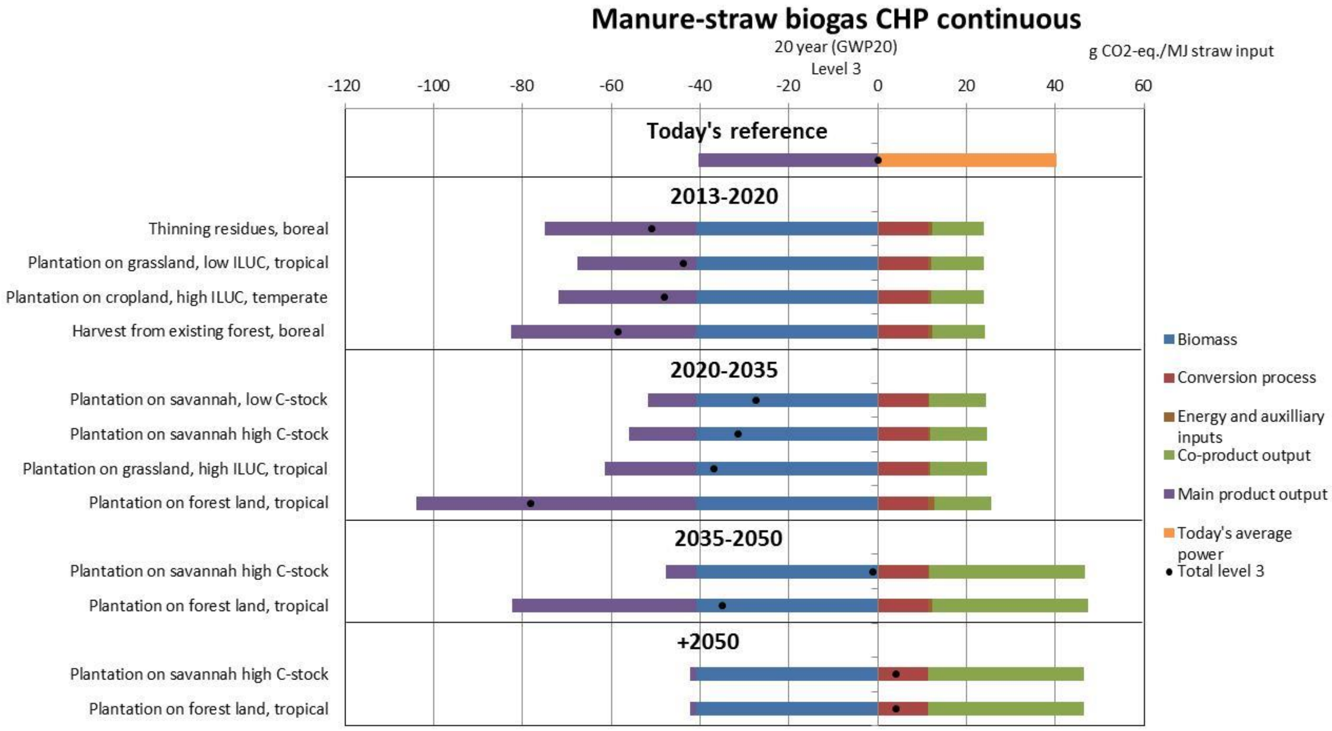

Manure-straw biogas CHP continuous
20 year (GWP20)
Level 2
g CO2-eq./kWh output
-600
-400
-200
0
200
400
600
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Today's average power
Total level 2

Figure 0-11


Manure-straw biogas CHP continuous
20 year (GWP20)
Level 3
g CO2-eq./MJ straw input
-120
-100
-80
-60
-40
-20
0
20
40
60
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product output
Today's average power
Total level 3

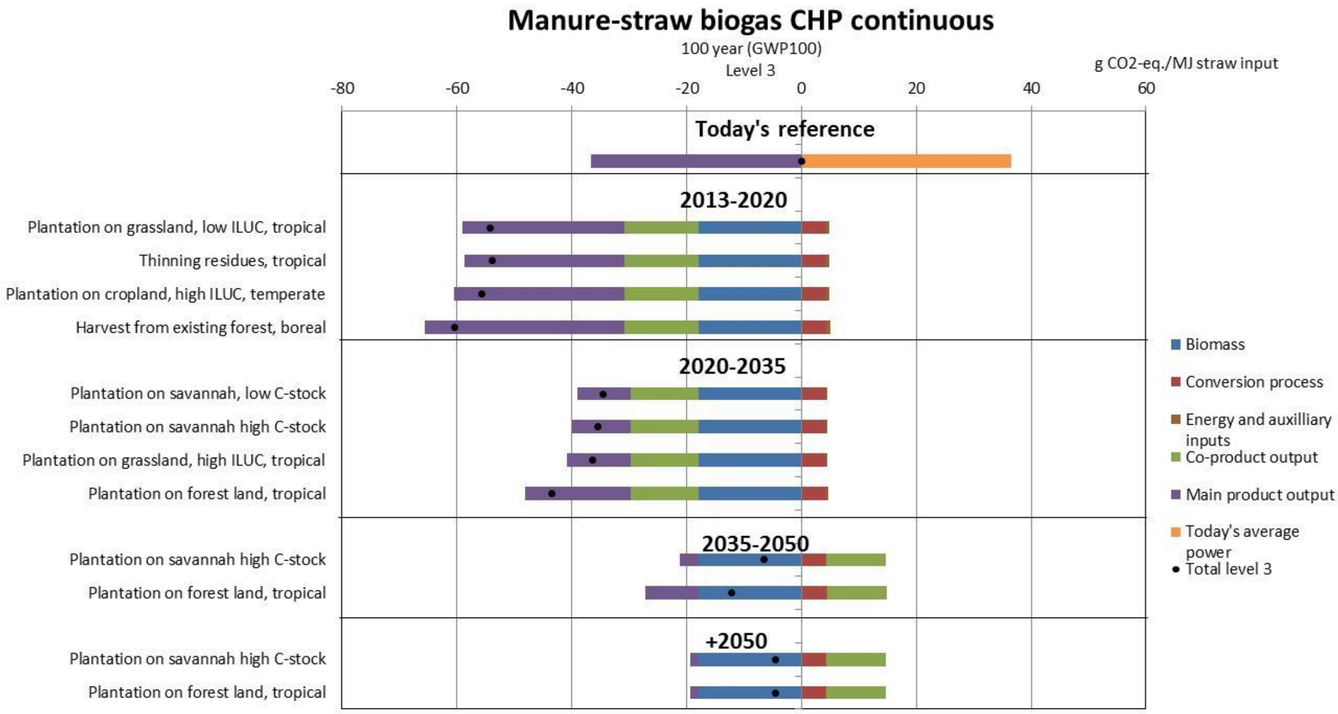
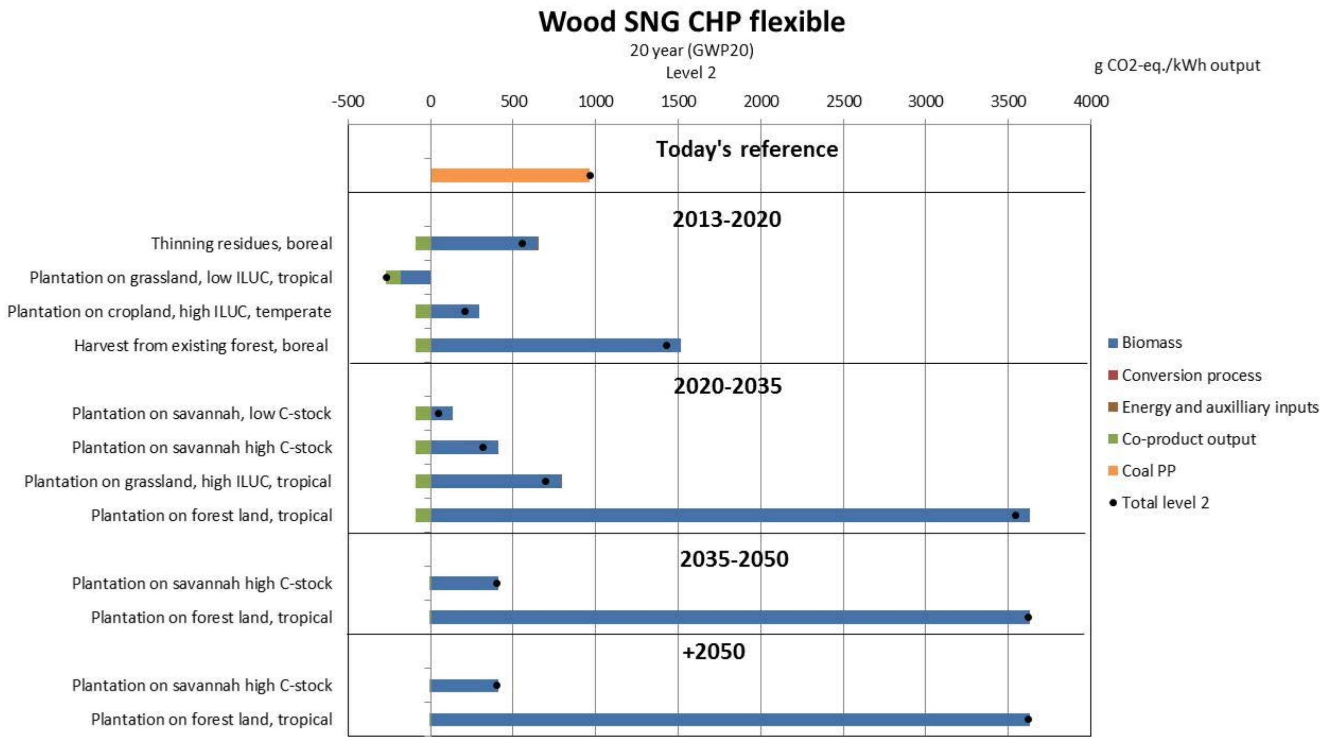

Manure-straw biogas CHP continuous
100 year (GWP100)
Level 3
g CO2-eq./MJ straw input
-80
-60
-40
-20
0
20
40
60
Today's reference
2013-2020
Plantation on grassland, low ILUC, tropical
Thinning residues, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product output
Today's average power
Total level 3

Figure 0-12


Wood SNG CHP flexible
20 year (GWP20)
Level 2
g CO2-eq./kWh output
-500
0
500
1000
1500
2000
2500
3000
3500
4000
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Coal PP
Total level 2

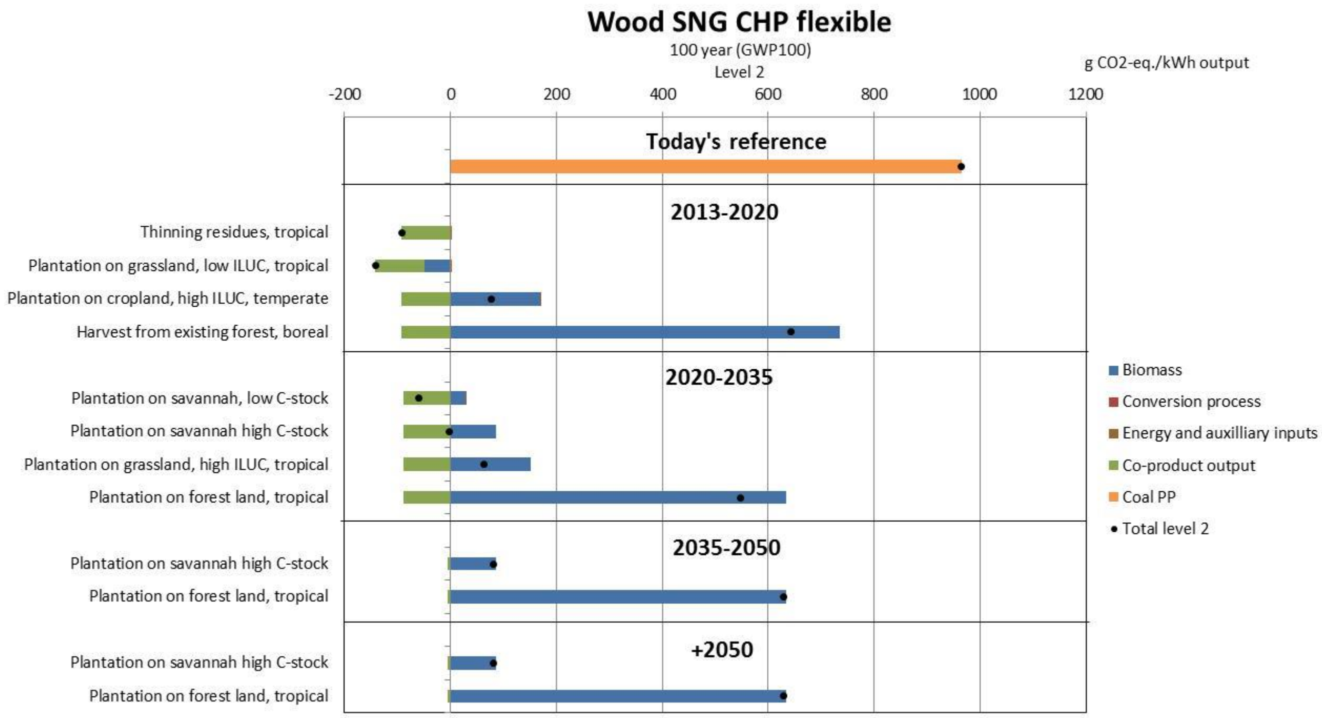

Wood SNG CHP flexible
100 year (GWP100)
Level 2
g CO2-eq./kWh output
-200
0
200
400
600
800
1000
1200
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Coal PP
Total level 2

Figure 0-13

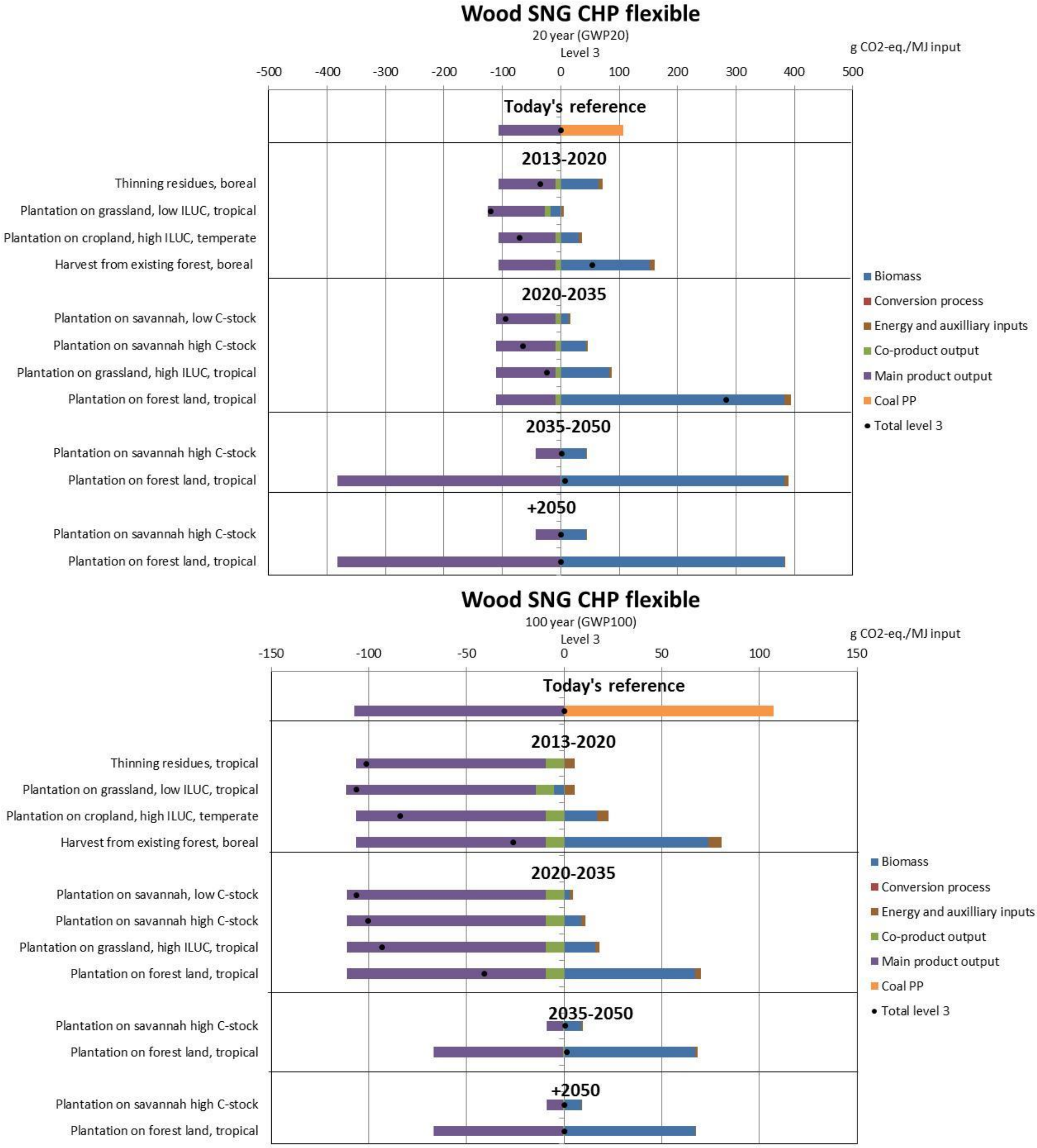

Wood SNG CHP flexible
20 year (GWP20)
Level 3
g CO2-eq./MJ input
-500 -400 -300 -200 -100 0 100 200 300 400 500
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product output
Coal PP
Total level 3
Wood SNG CHP flexible
100 year (GWP100)
Level 3
g CO2-eq./MJ input
-150 -100 -50 0 50 100 150
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product output
Coal PP
Total level 3

Figure 0-14

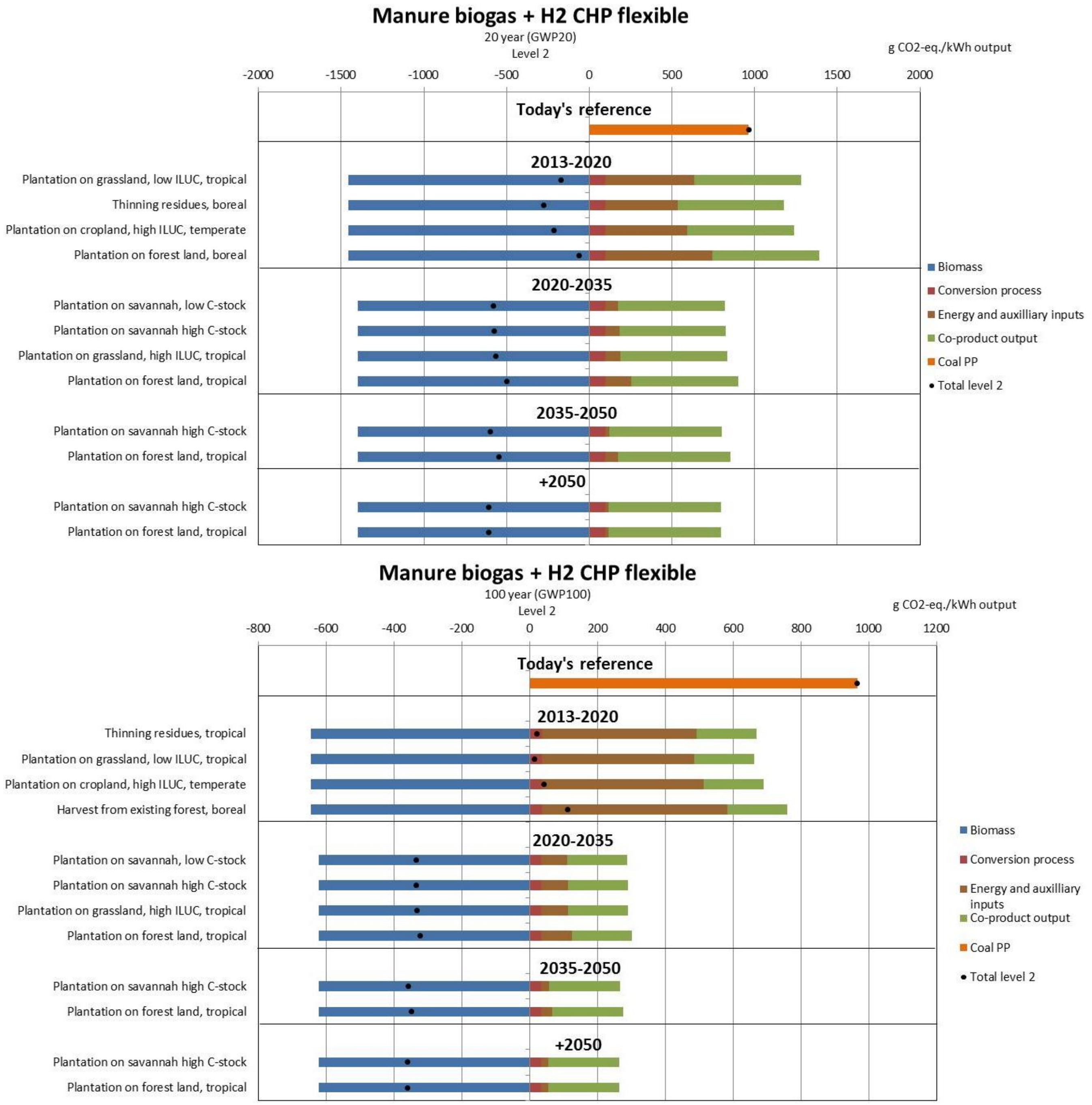
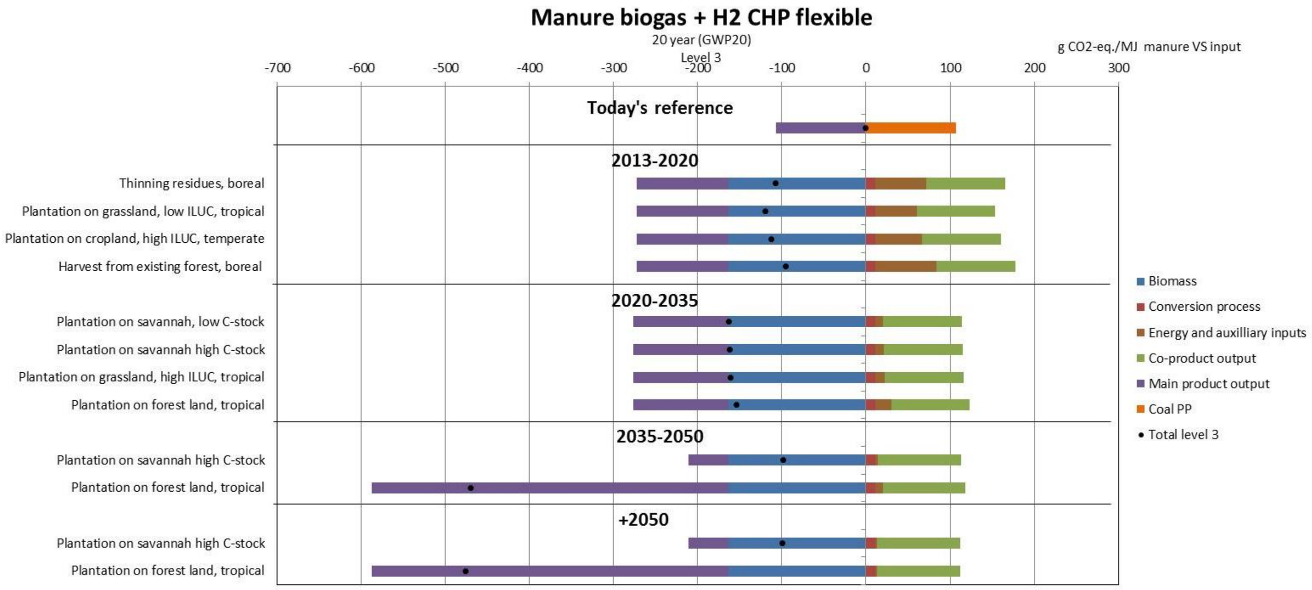

Manure biogas + H2 CHP flexible
20 year (GWP20)
Level 2
g CO2-eq./kWh output
-2000
-1500
-1000
-500
0
500
1000
1500
2000
Today's reference
2013-2020
Plantation on grassland, low ILUC, tropical
Thinning residues, boreal
Plantation on cropland, high ILUC, temperate
Plantation on forest land, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Coal PP
Total level 2
Manure biogas + H2 CHP flexible
100 year (GWP100)
Level 2
g CO2-eq./kWh output
-800
-600
-400
-200
0
200
400
600
800
1000
1200
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Coal PP
Total level 2

Figure 0-15


Manure biogas + H2 CHP flexible
20 year (GWP20)
Level 3
g CO2-eq./MJ manure VS input
-700
-600
-500
-400
-300
-200
-100
0
100
200
300
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product output
Coal PP
Total level 3

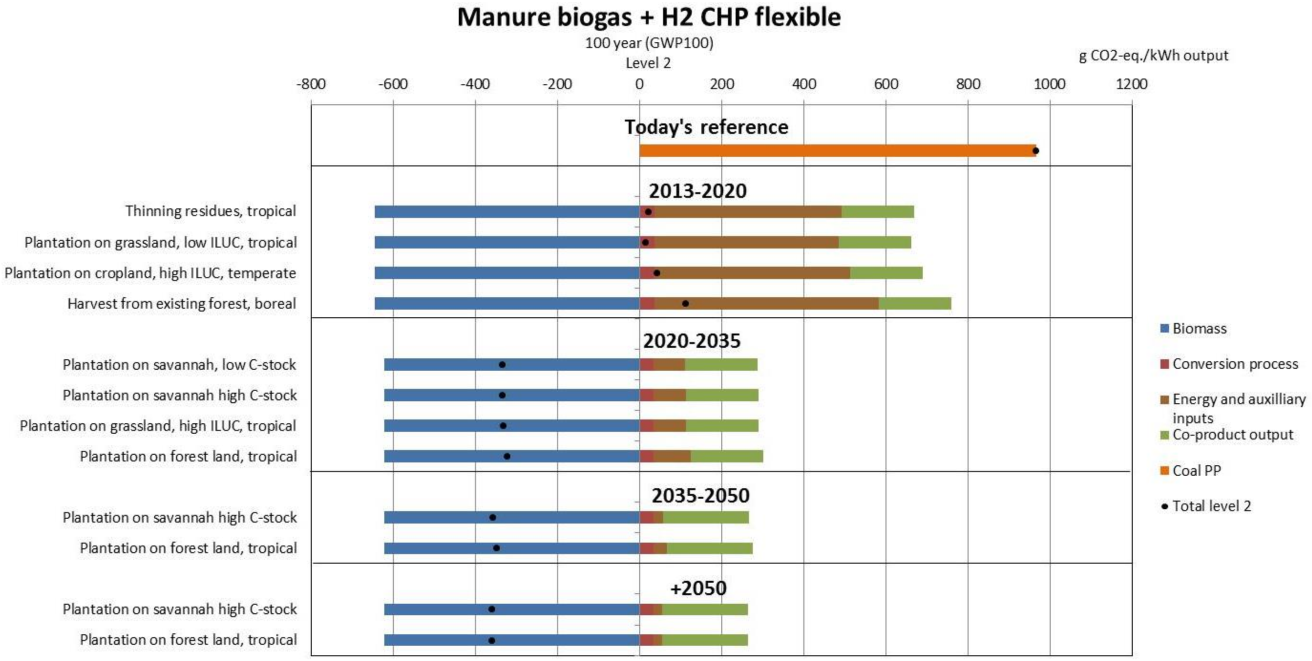
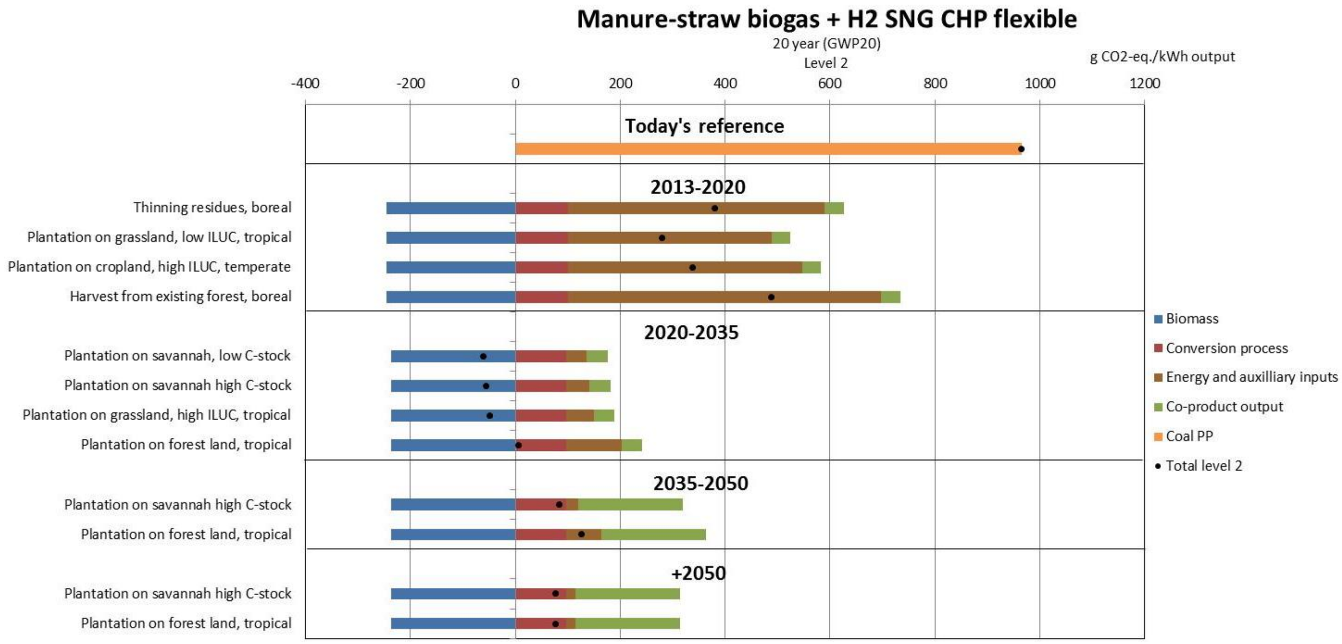

Manure biogas + H2 CHP flexible
100 year (GWP100)
Level 2
g CO2-eq./kWh output
-800
-600
-400
-200
0
200
400
600
800
1000
1200
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Coal PP
Total level 2

Figure 0-16


Manure-straw biogas + H2 SNG CHP flexible
20 year (GWP20)
Level 2
g CO2-eq./kWh output
-400
-200
0
200
400
600
800
1000
1200
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Coal PP
Total level 2

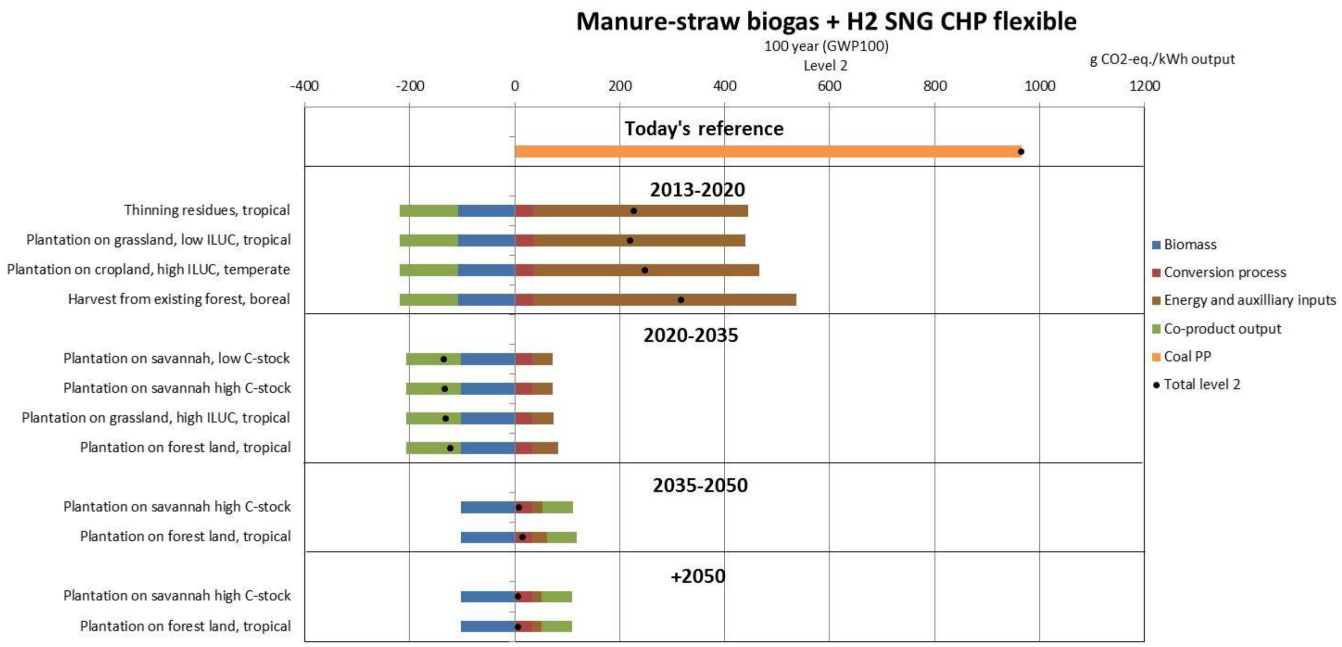

Manure-straw biogas + H2 SNG CHP flexible
100 year (GWP100)
Level 2
g CO2-eq./kWh output
-400
-200
0
200
400
600
800
1000
1200
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Coal PP
Total level 2

Figure 0-17

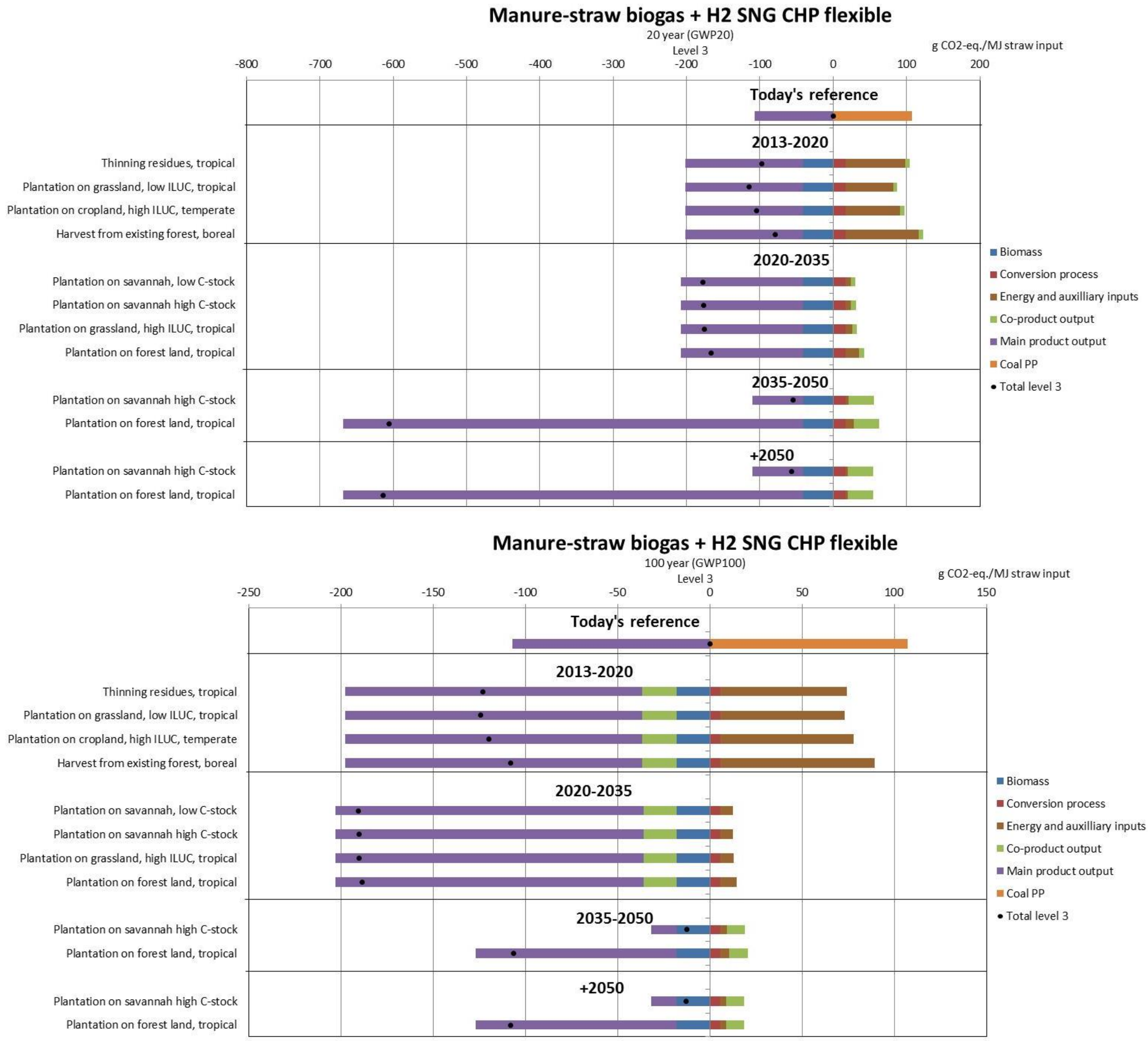
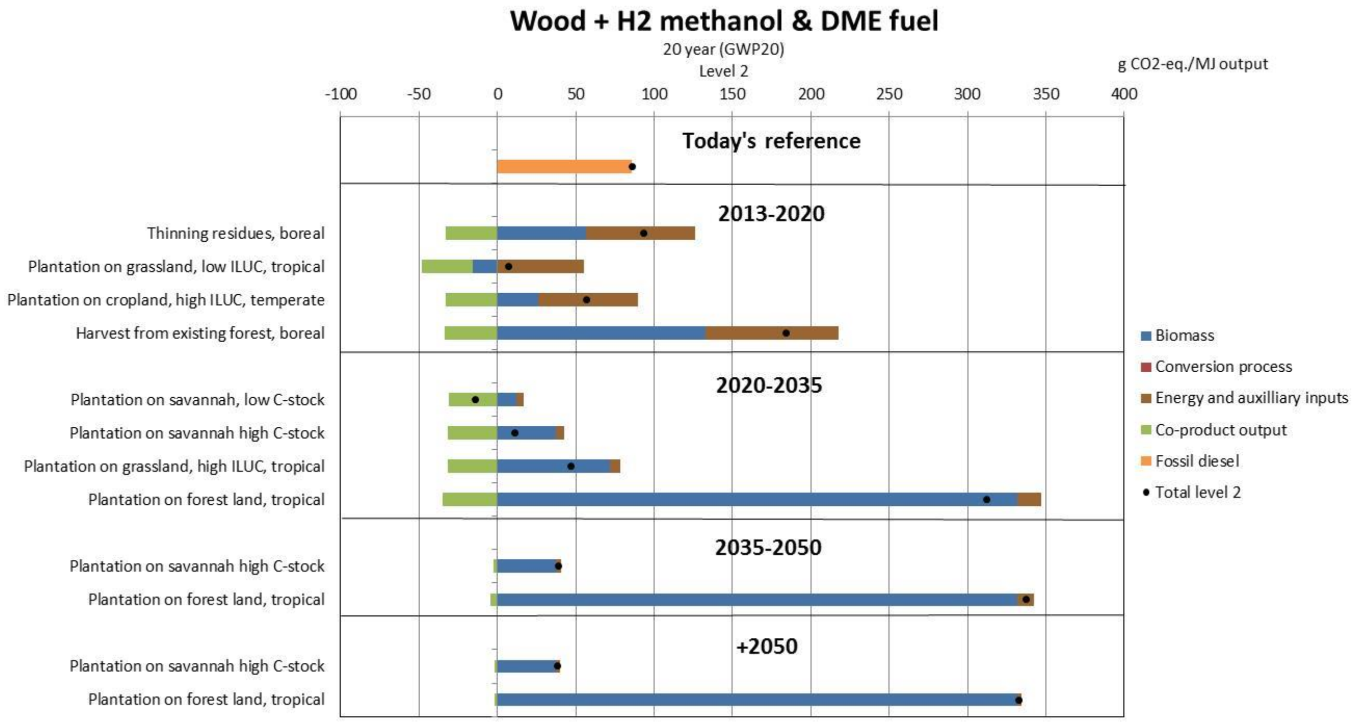

Manure-straw biogas + H2 SNG CHP flexible
20 year (GWP20)
Level 3
g CO2-eq./MJ straw input
-800
-700
-600
-500
-400
-300
-200
-100
0
100
200
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product output
Coal PP
Total level 3
Manure-straw biogas + H2 SNG CHP flexible
100 year (GWP100)
Level 3
g CO2-eq./MJ straw input
-250
-200
-150
-100
-50
0
50
100
150
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product output
Coal PP
Total level 3

Figure 0-18


Wood + H2 methanol & DME fuel
20 year (GWP20)
Level 2
g CO2-eq./MJ output
-100
-50
0
50
100
150
200
250
300
350
400
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Fossil diesel
Total level 2

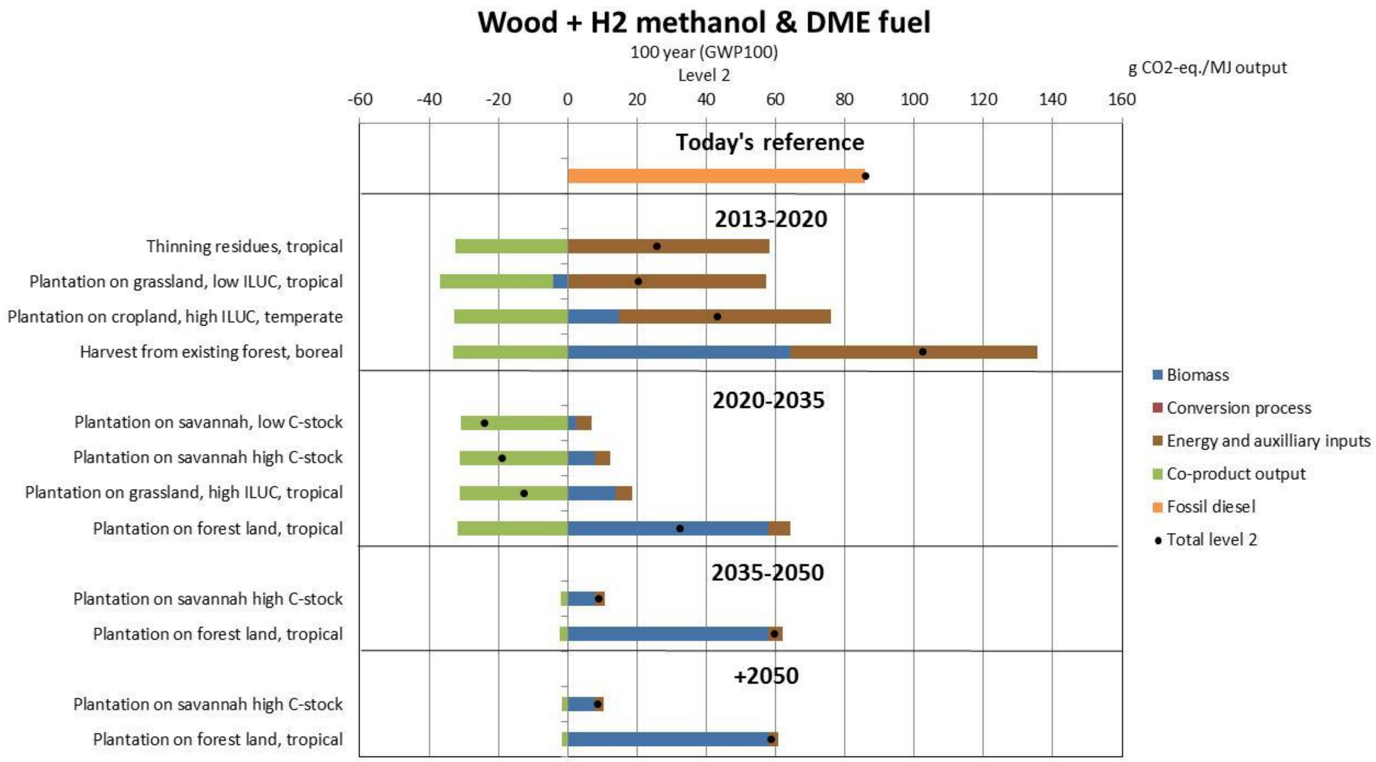

Wood + H2 methanol & DME fuel
100 year (GWP100)
Level 2
g CO2-eq./MJ output
-60
-40
-20
0
20
40
60
80
100
120
140
160
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Fossil diesel
Total level 2

Figure 0-19

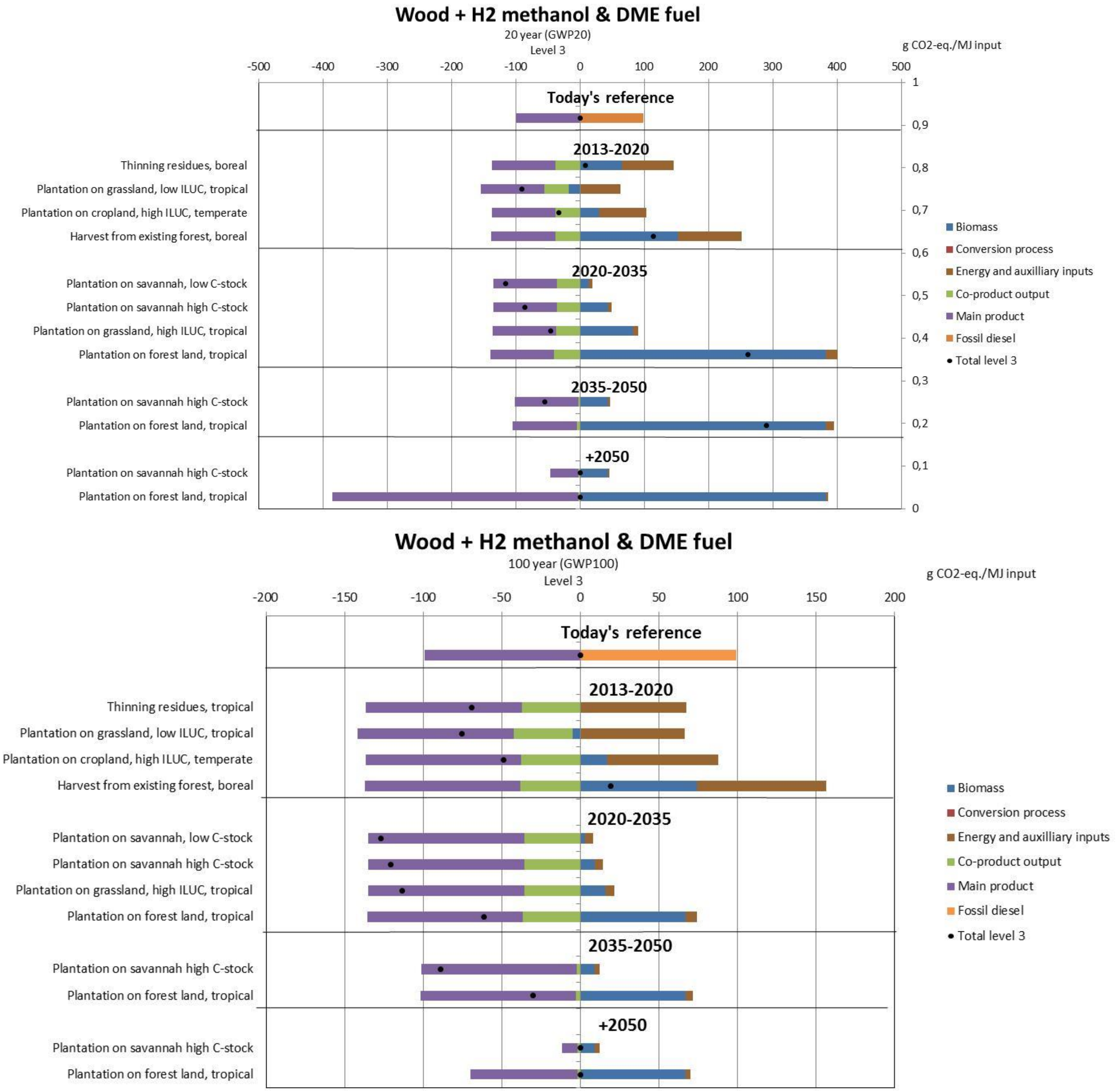

Wood + H2 methanol & DME fuel
20 year (GWP20)
Level 3
g CO2-eq./MJ input
-500 -400 -300 -200 -100 0 100 200 300 400 500
1 0,9 0,8 0,7 0,6 0,5 0,4 0,3 0,2 0,1 0
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Fossil diesel
Total level 3
Wood + H2 methanol & DME fuel
100 year (GWP100)
Level 3
g CO2-eq./MJ input
-200 -150 -100 -50 0 50 100 150 200
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Fossil diesel
Total level 3

Figure 0-20

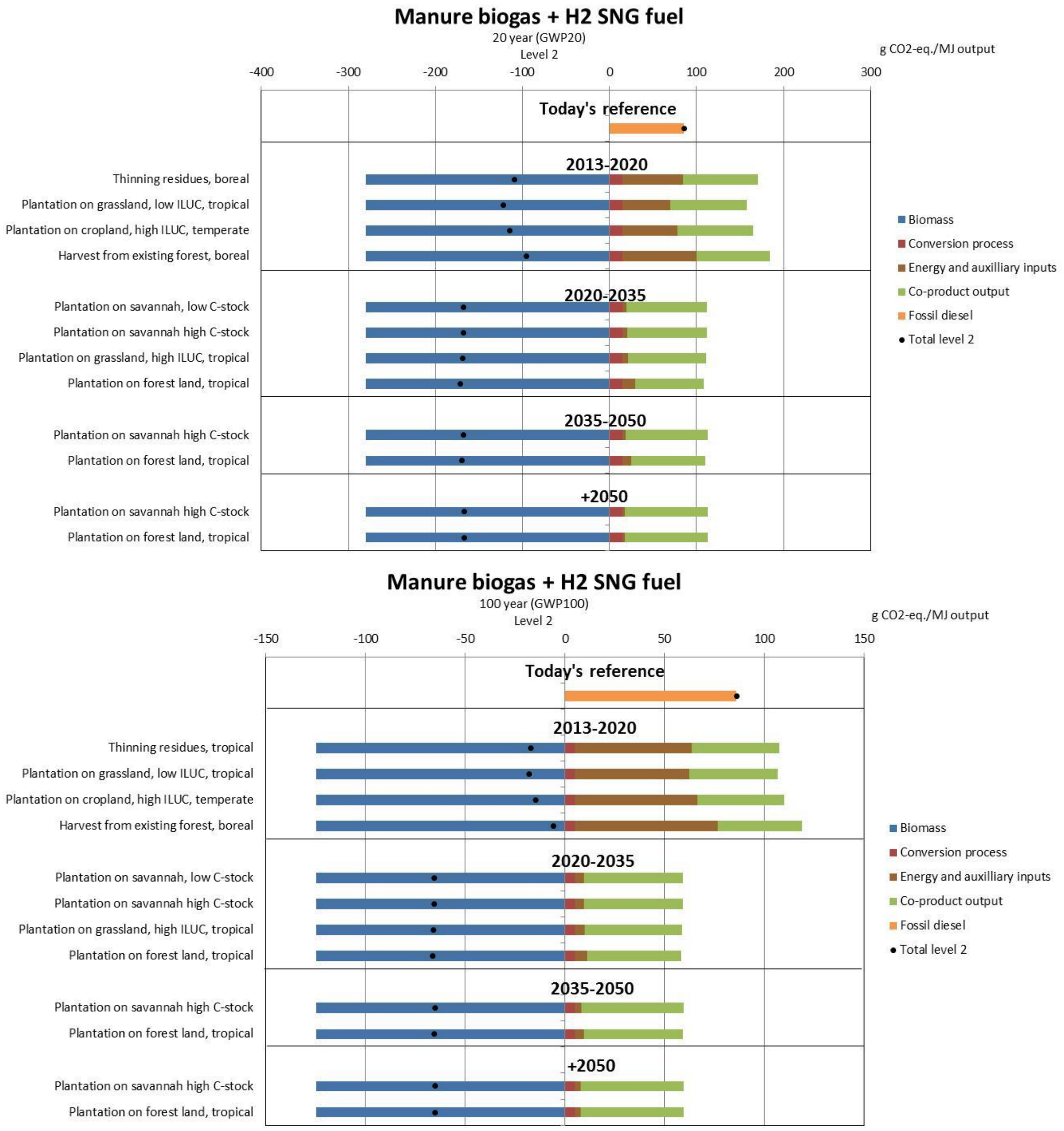
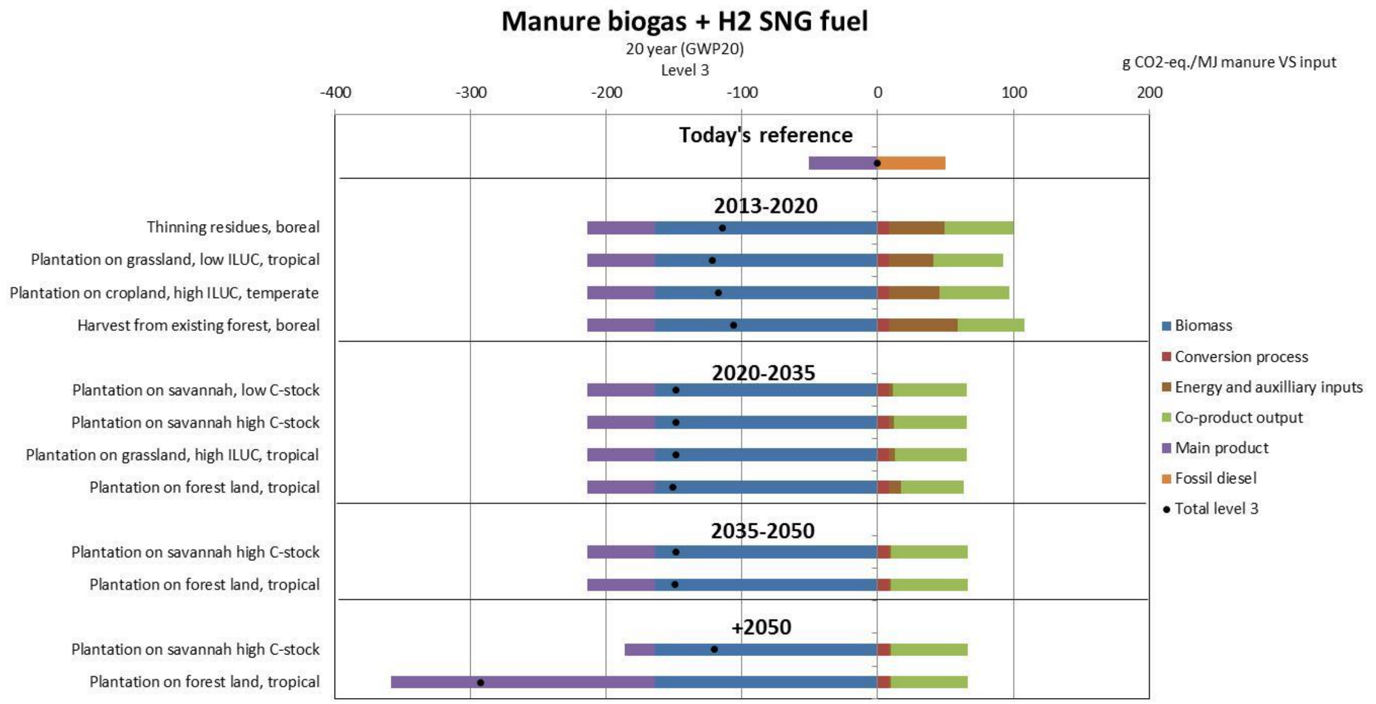

Manure biogas + H2 SNG fuel
20 year (GWP20)
Level 2
g CO2-eq./MJ output
-400
-300
-200
-100
0
100
200
300
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Fossil diesel
Total level 2
Manure biogas + H2 SNG fuel
100 year (GWP100)
Level 2
g CO2-eq./MJ output
-150
-100
-50
0
50
100
150
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Fossil diesel
Total level 2

Figure 0-21


Manure biogas + H2 SNG fuel
20 year (GWP20)
Level 3
g CO2-eq./MJ manure VS input
-400
-300
-200
-100
0
100
200
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Fossil diesel
Total level 3

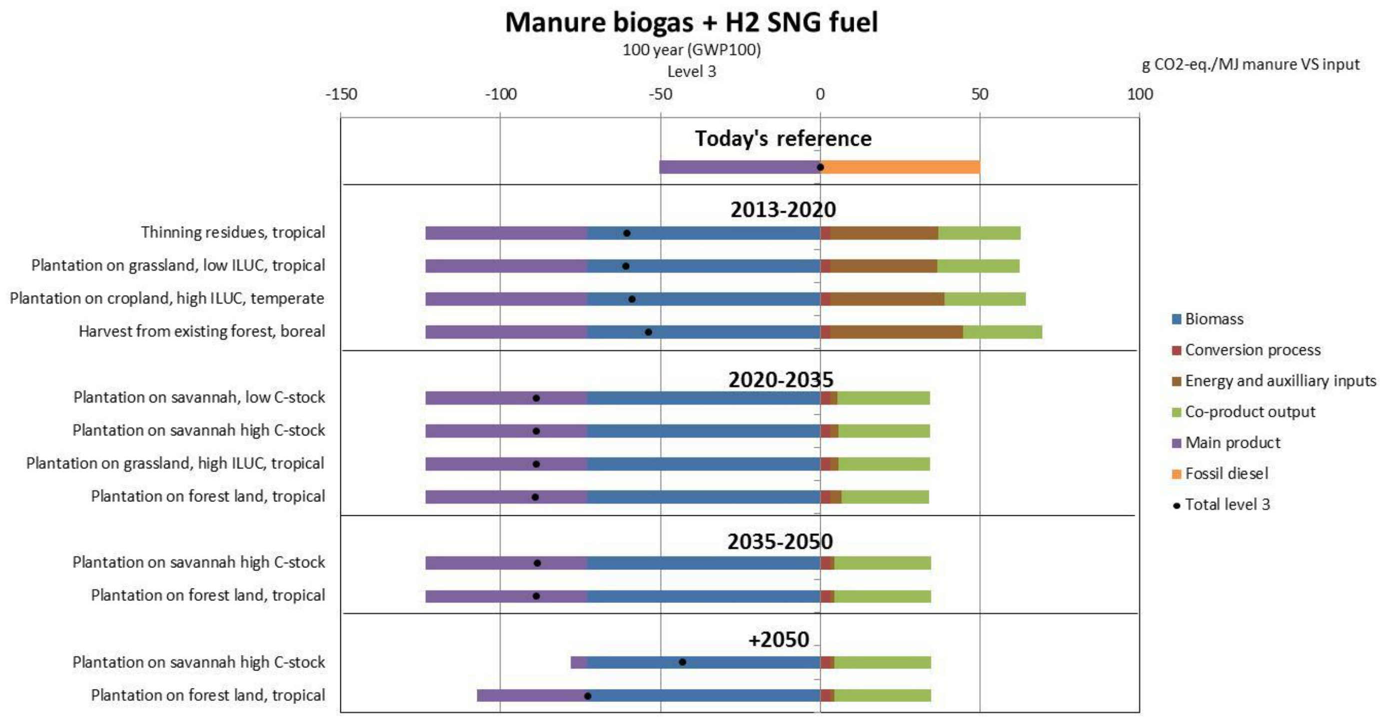
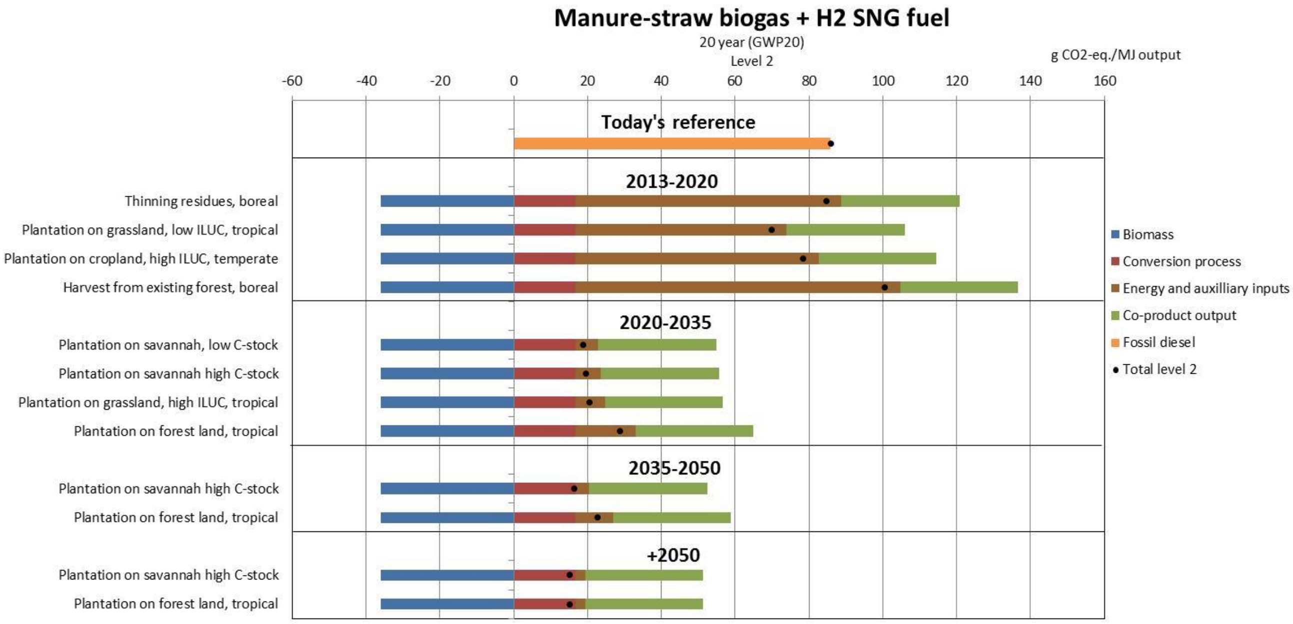

Manure biogas + H2 SNG fuel
100 year (GWP100)
Level 3
g CO2-eq./MJ manure VS input
-150
-100
-50
0
50
100
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Fossil diesel
Total level 3

Figure 0-22


Manure-straw biogas + H2 SNG fuel
20 year (GWP20)
Level 2
g CO2-eq./MJ output
-60
-40
-20
0
20
40
60
80
100
120
140
160
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Fossil diesel
Total level 2

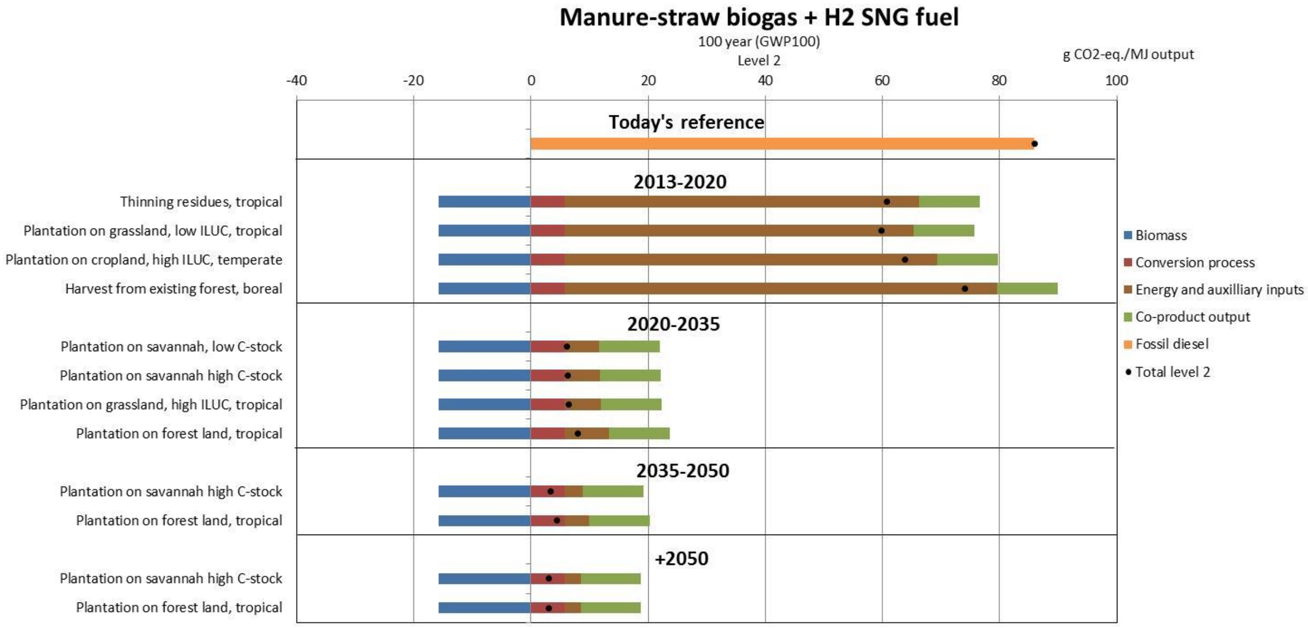
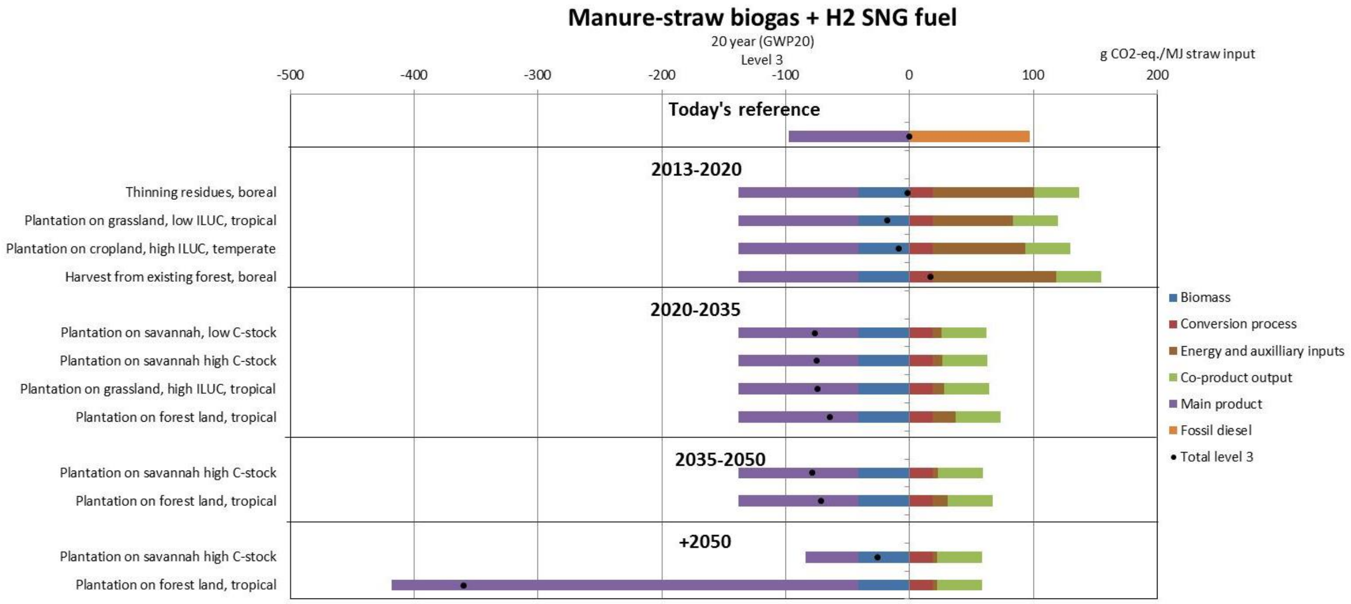

Manure-straw biogas + H2 SNG fuel
100 year (GWP100)
Level 2
g CO2-eq./MJ output
-40
-20
0
20
40
60
80
100
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Fossil diesel
Total level 2

Figure 0-23


Manure-straw biogas + H2 SNG fuel
20 year (GWP20)
Level 3
g CO2-eq./MJ straw input
-500
-400
-300
-200
-100
0
100
200
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Fossil diesel
Total level 3

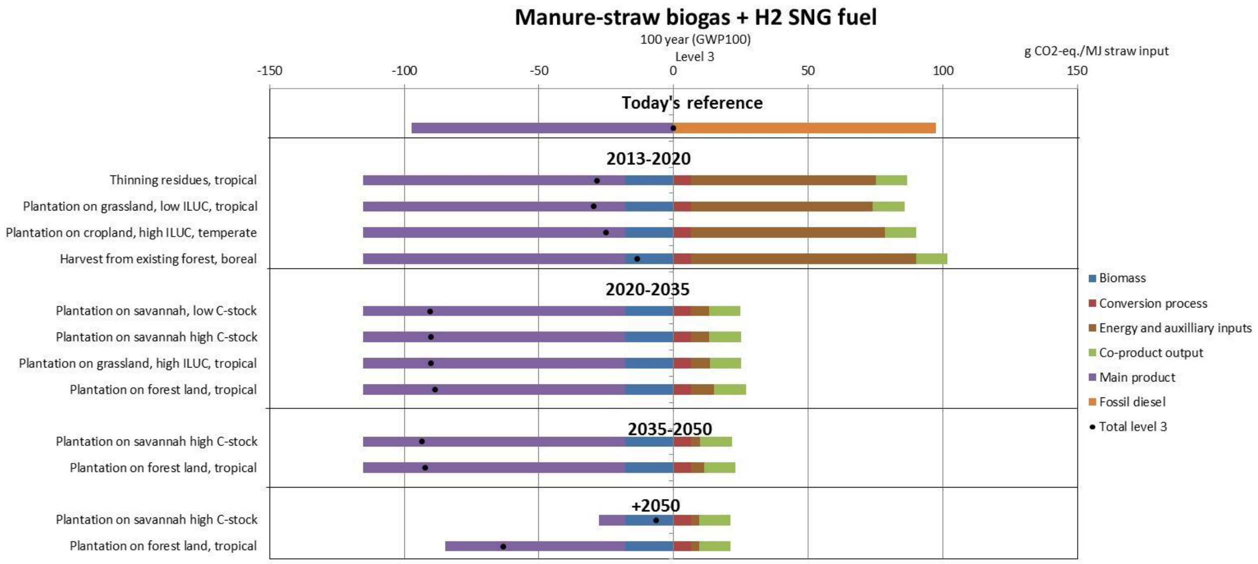
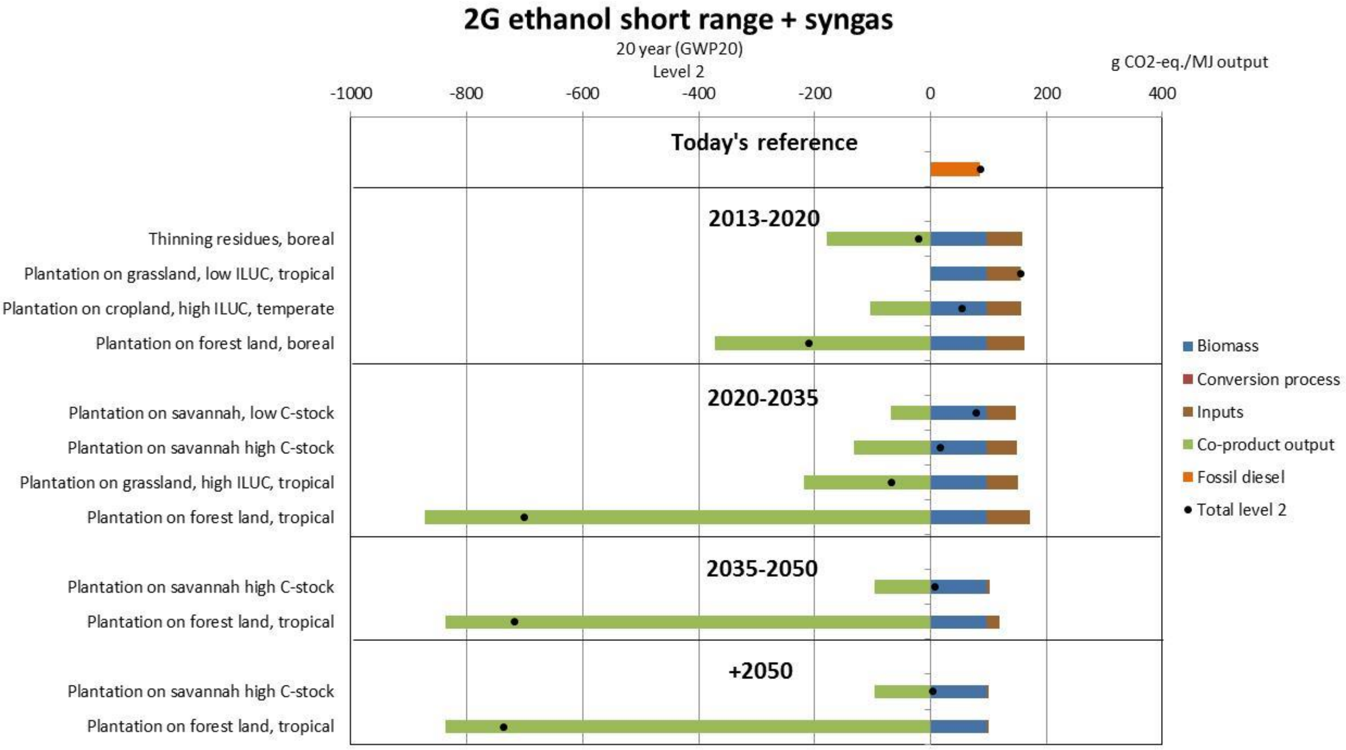

Manure-straw biogas + H2 SNG fuel
100 year (GWP100)
Level 3
g CO2-eq./MJ straw input
-150
-100
-50
0
50
100
150
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Fossil diesel
Total level 3

Figure 0-24


2G ethanol short range + syngas
20 year (GWP20)
Level 2
g CO2-eq./MJ output
-1000
-800
-600
-400
-200
0
200
400
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Plantation on forest land, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Inputs
Co-product output
Fossil diesel
Total level 2

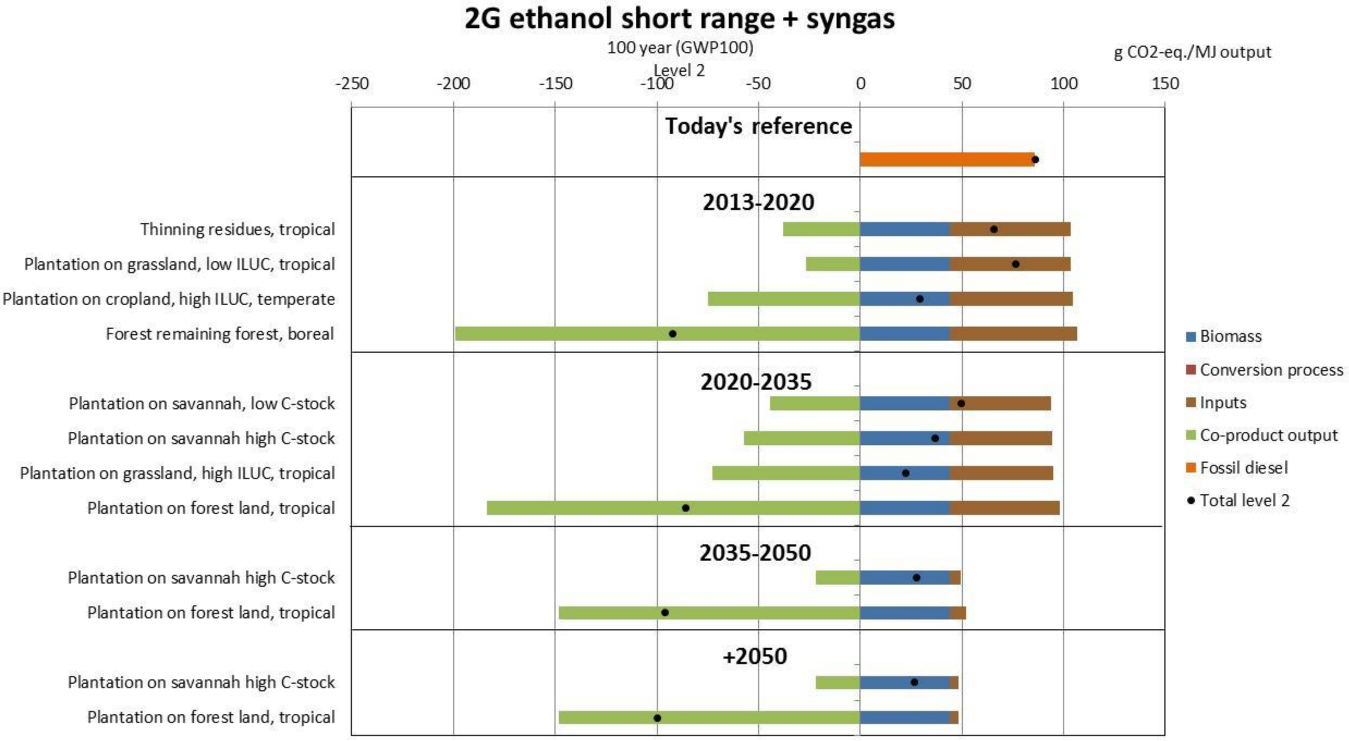
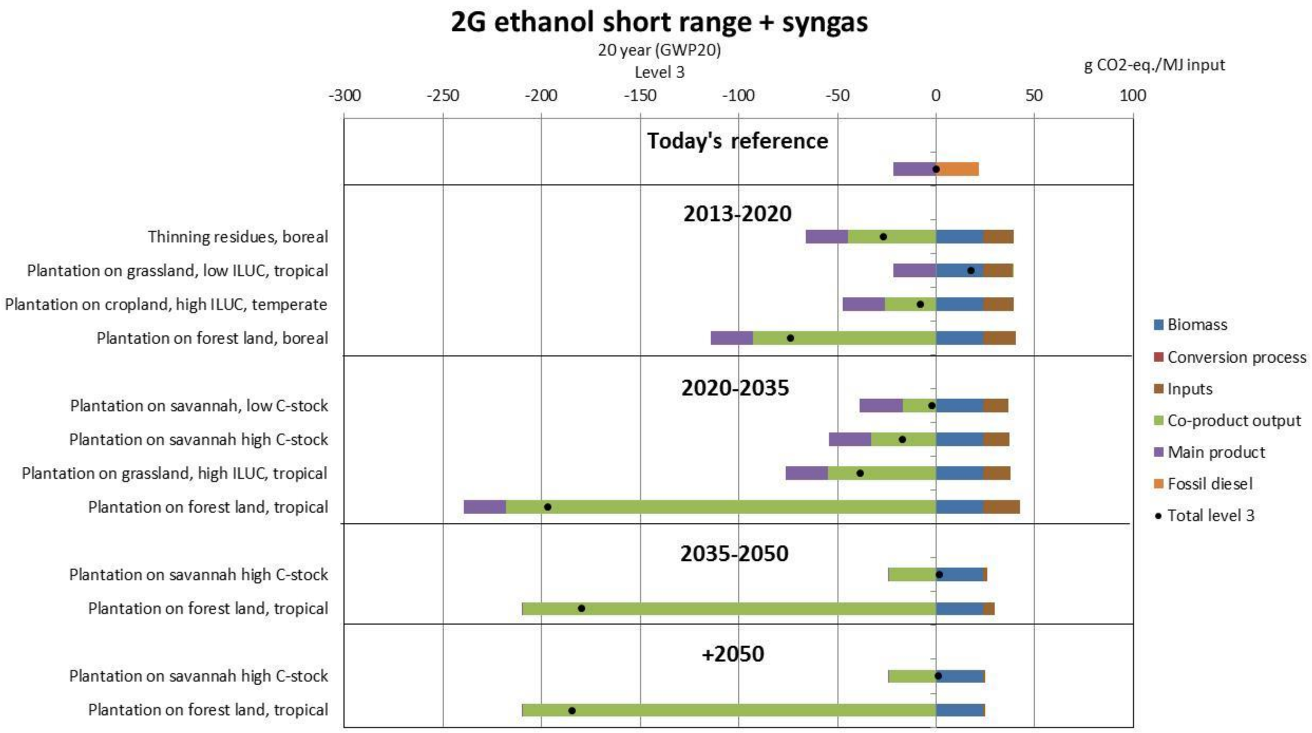

2G ethanol short range + syngas
100 year (GWP100)
Level 2
g CO2-eq./MJ output
-250
-200
-150
-100
-50
0
50
100
150
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Forest remaining forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Inputs
Co-product output
Fossil diesel
Total level 2

Figure 0-25


2G ethanol short range + syngas
20 year (GWP20)
Level 3
g CO2-eq./MJ input
-300
-250
-200
-150
-100
-50
0
50
100
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Plantation on forest land, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Inputs
Co-product output
Main product
Fossil diesel
Total level 3

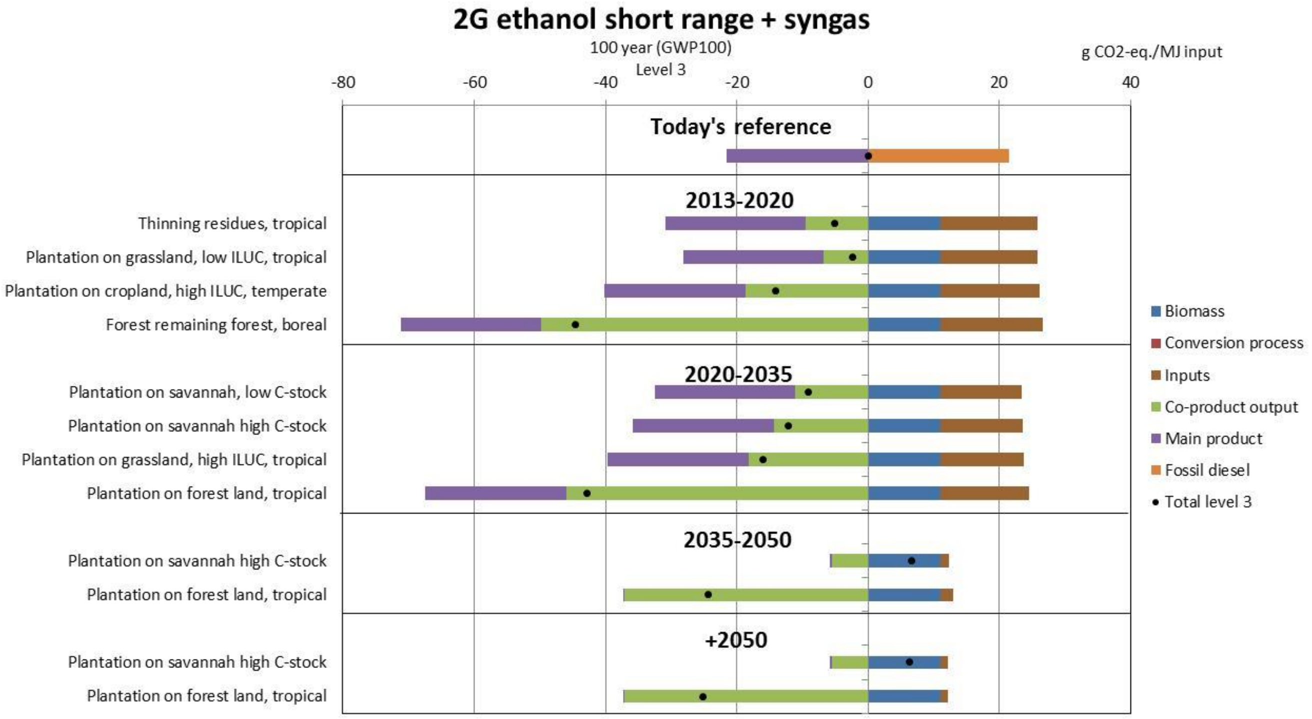

2G ethanol short range + syngas
100 year (GWP100)
Level 3
g CO2-eq./MJ input
-80
-60
-40
-20
0
20
40
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Forest remaining forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Inputs
Co-product output
Main product
Fossil diesel
Total level 3

Figure 0-26

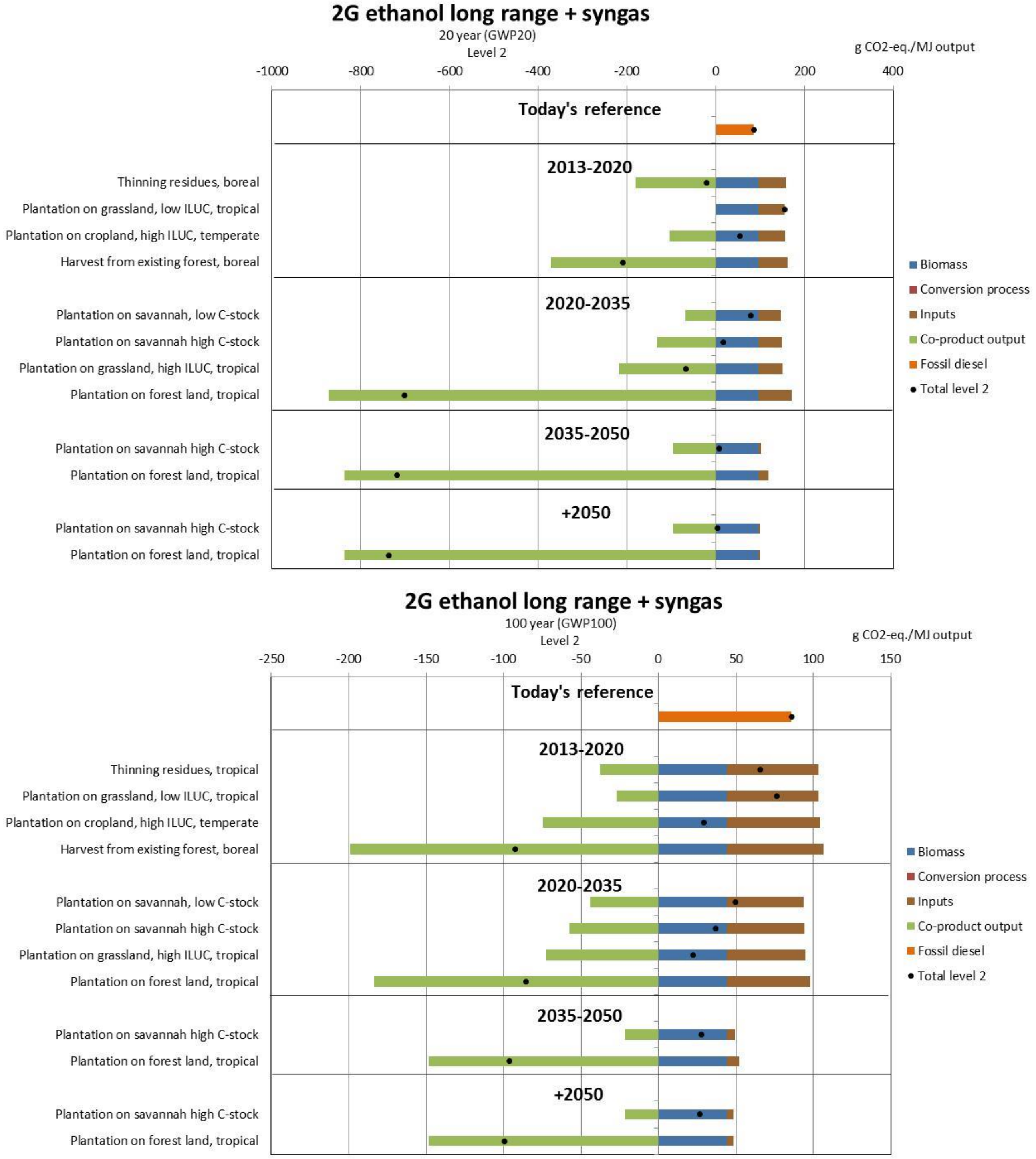
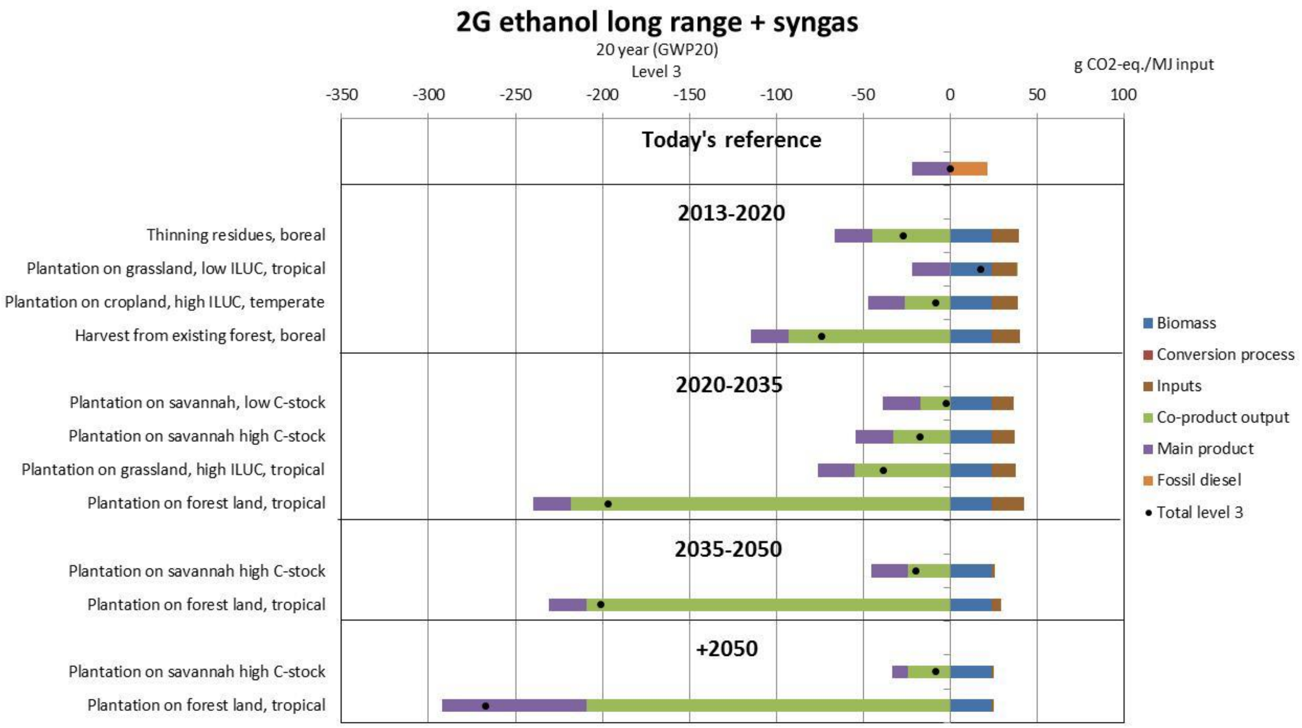

2G ethanol long range + syngas
20 year (GWP20)
Level 2
g CO2-eq./MJ output
-1000 -800 -600 -400 -200 0 200 400
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Inputs
Co-product output
Fossil diesel
Total level 2
2G ethanol long range + syngas
100 year (GWP100)
Level 2
g CO2-eq./MJ output
-250 -200 -150 -100 -50 0 50 100 150
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Inputs
Co-product output
Fossil diesel
Total level 2

Figure 0-27


2G ethanol long range + syngas
20 year (GWP20)
Level 3
g CO2-eq./MJ input
-350
-300
-250
-200
-150
-100
-50
0
50
100
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Inputs
Co-product output
Main product
Fossil diesel
Total level 3

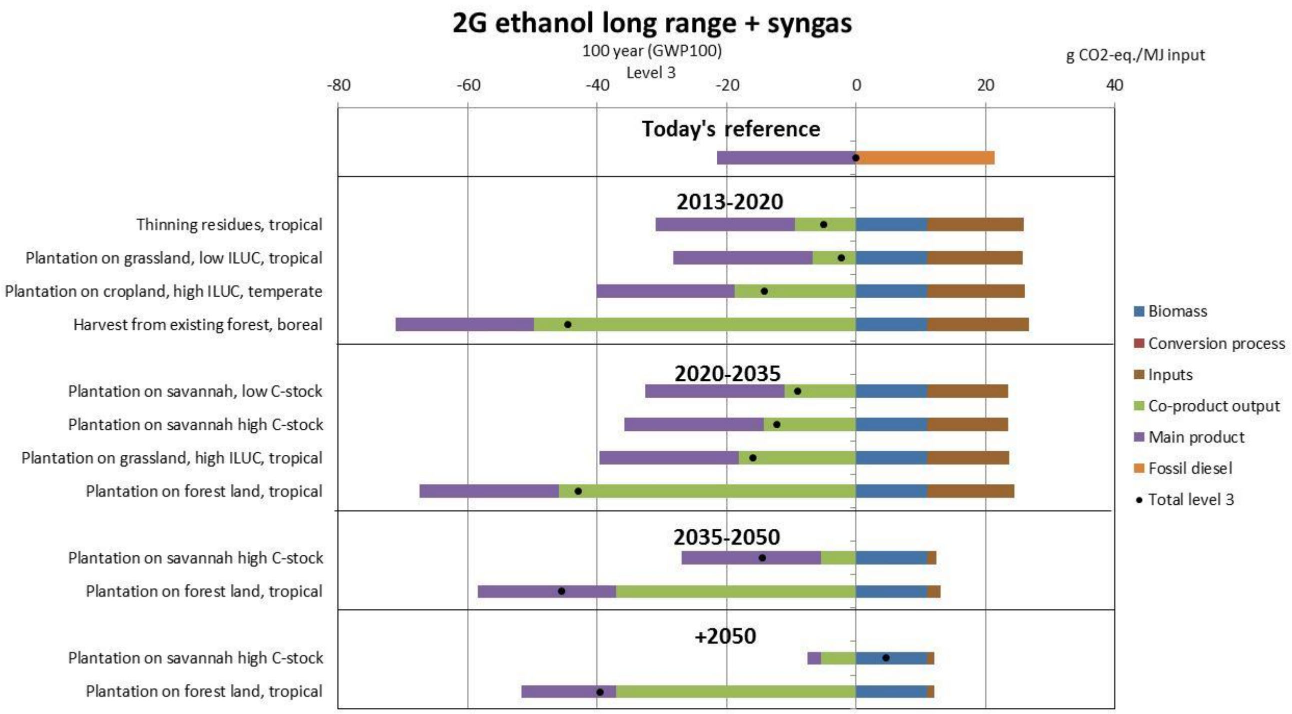
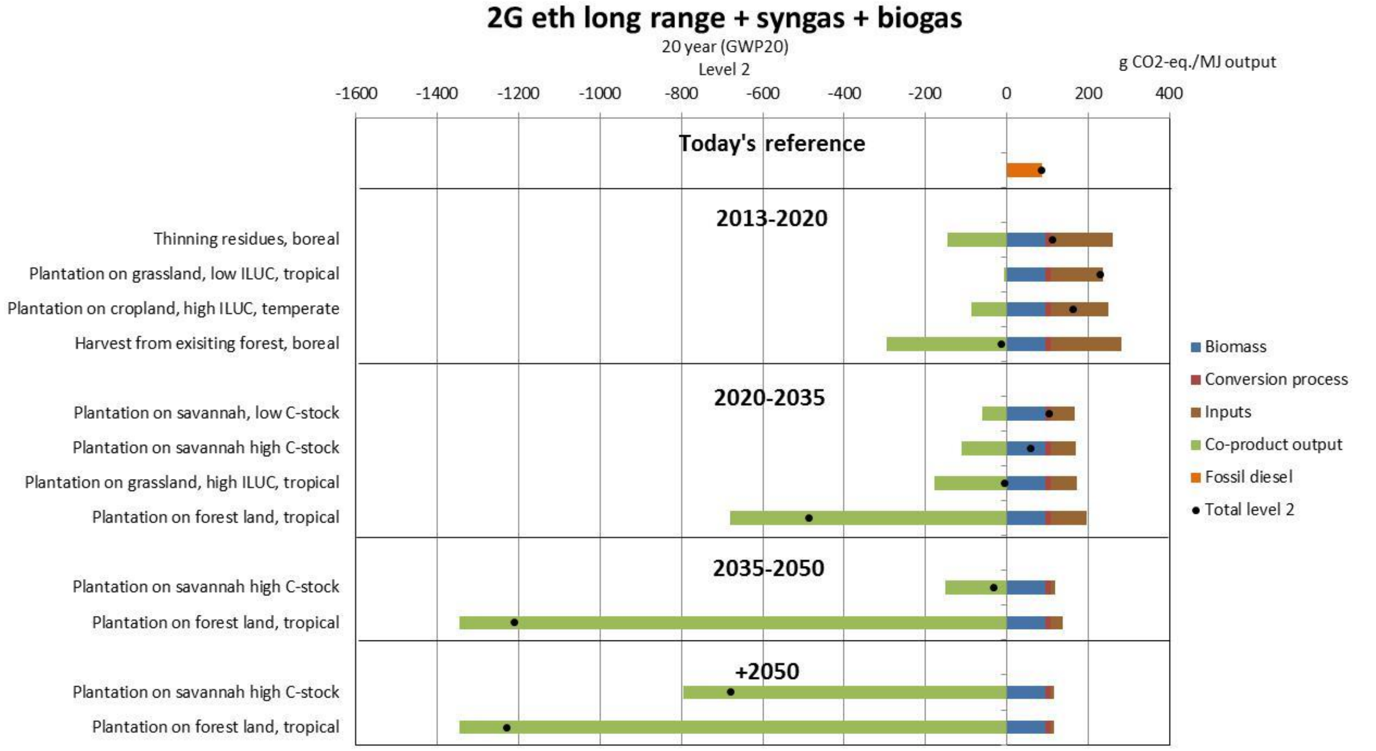

2G ethanol long range + syngas
100 year (GWP100)
Level 3
g CO2-eq./MJ input
-80
-60
-40
-20
0
20
40
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from existing forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Inputs
Co-product output
Main product
Fossil diesel
Total level 3

Figure 0-28


2G eth long range + syngas + biogas
20 year (GWP20)
Level 2
g CO2-eq./MJ output
-1600 -1400 -1200 -1000 -800 -600 -400 -200 0 200 400
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from exisiting forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Inputs
Co-product output
Fossil diesel
Total level 2

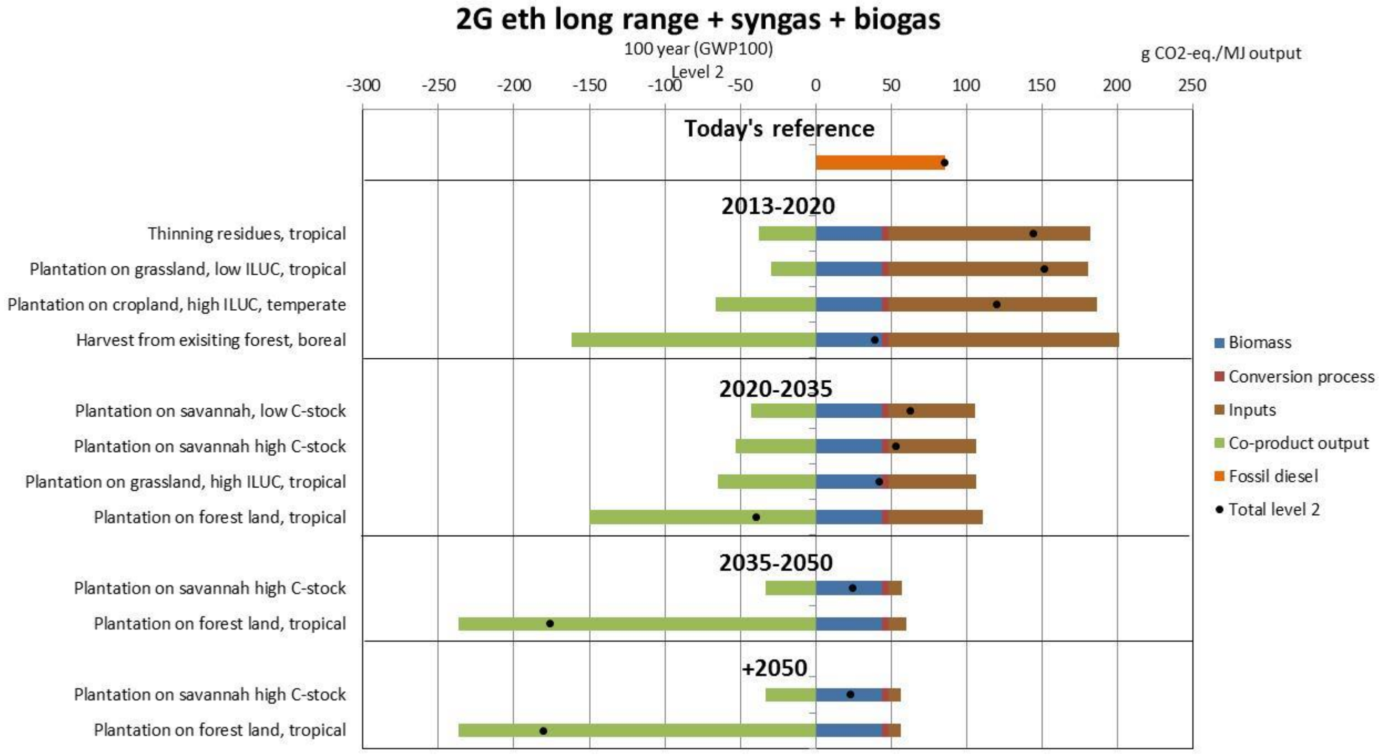
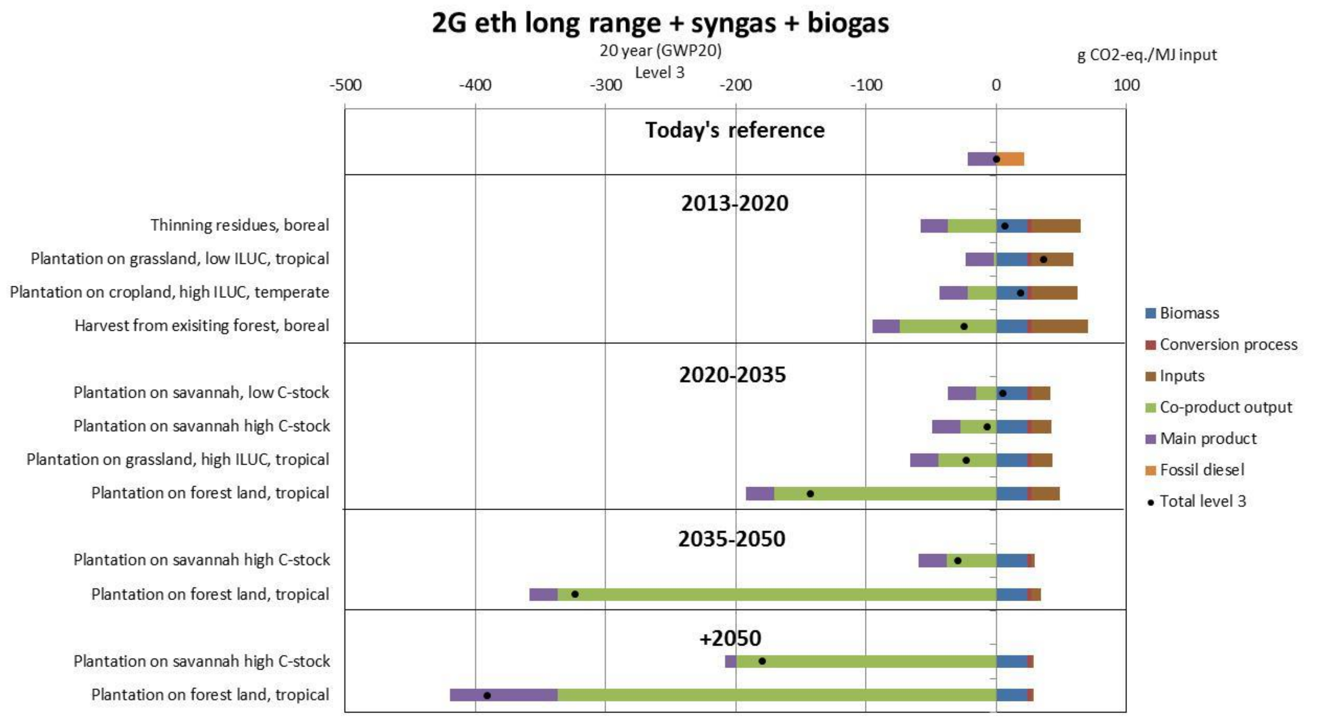

2G eth long range + syngas + biogas
100 year (GWP100)
Level 2
g CO2-eq./MJ output
-300 -250 -200 -150 -100 -50 0 50 100 150 200 250
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from exisiting forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Inputs
Co-product output
Fossil diesel
Total level 2

Figure 0-29


2G eth long range + syngas + biogas
20 year (GWP20)
Level 3
g CO2-eq./MJ input
-500
-400
-300
-200
-100
0
100
Today's reference
2013-2020
Thinning residues, boreal
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from exisiting forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Inputs
Co-product output
Main product
Fossil diesel
Total level 3

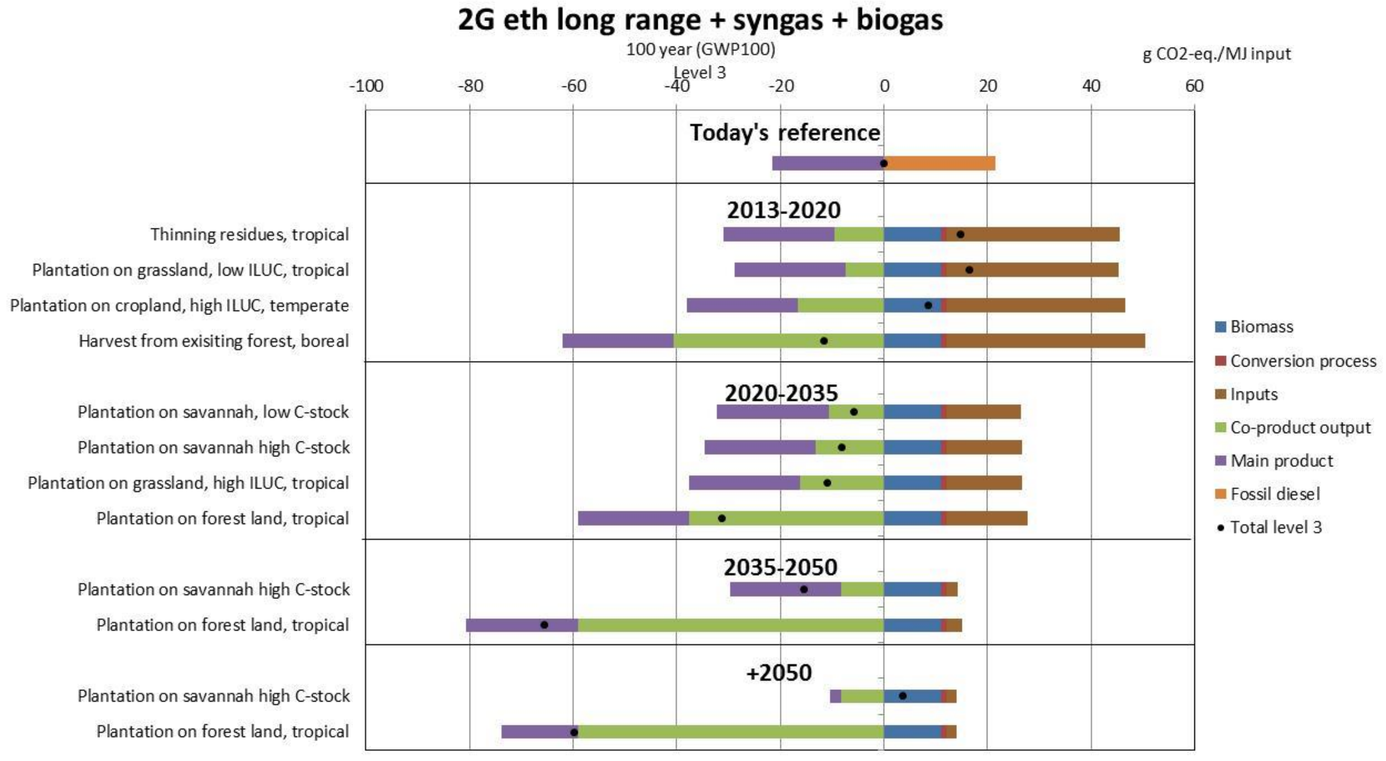

2G eth long range + syngas + biogas
100 year (GWP100)
Level 3
g CO2-eq./MJ input
-100
-80
-60
-40
-20
0
20
40
60
Today's reference
2013-2020
Thinning residues, tropical
Plantation on grassland, low ILUC, tropical
Plantation on cropland, high ILUC, temperate
Harvest from exisiting forest, boreal
2020-2035
Plantation on savannah, low C-stock
Plantation on savannah high C-stock
Plantation on grassland, high ILUC, tropical
Plantation on forest land, tropical
2035-2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
+2050
Plantation on savannah high C-stock
Plantation on forest land, tropical
Biomass
Conversion process
Inputs
Co-product output
Main product
Fossil diesel
Total level 3

Figure 0-30

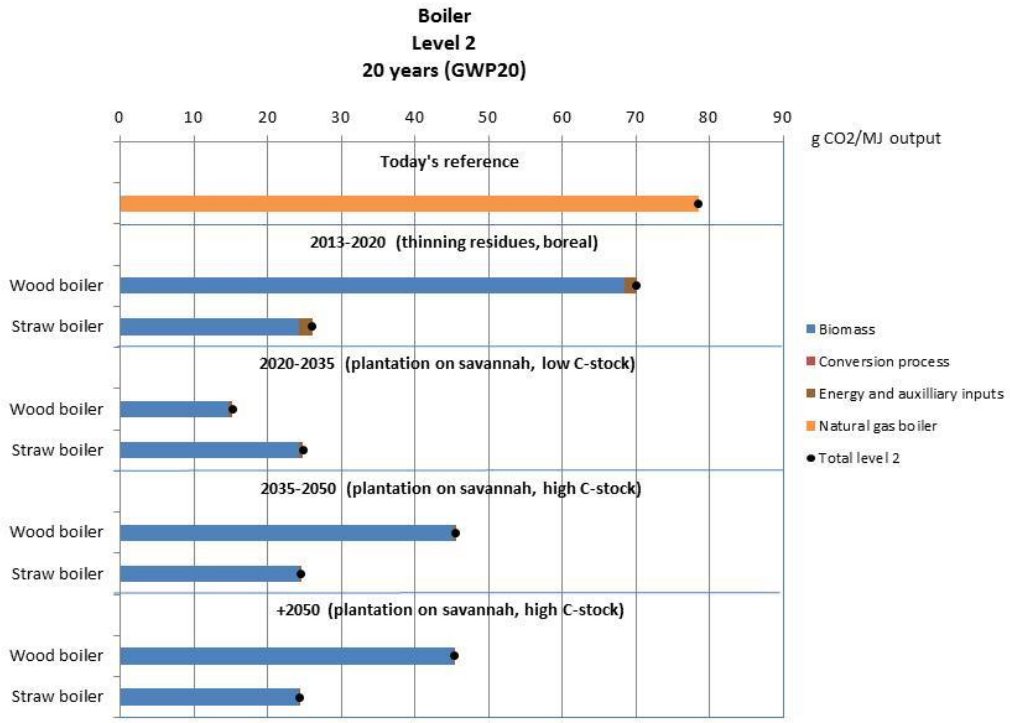


Figure 0-31

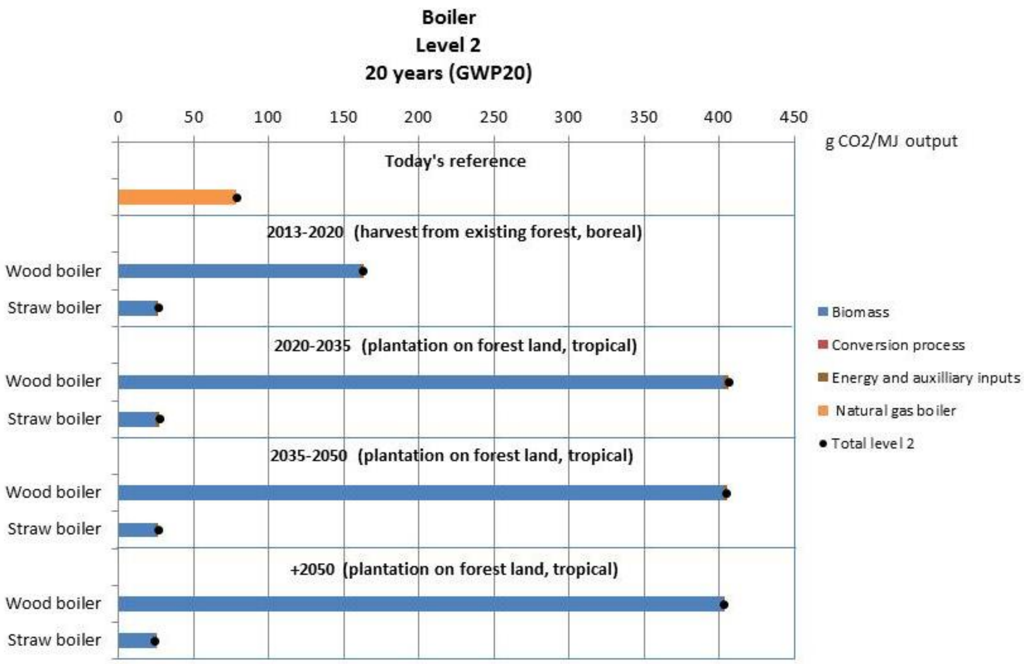


Figure 0-32

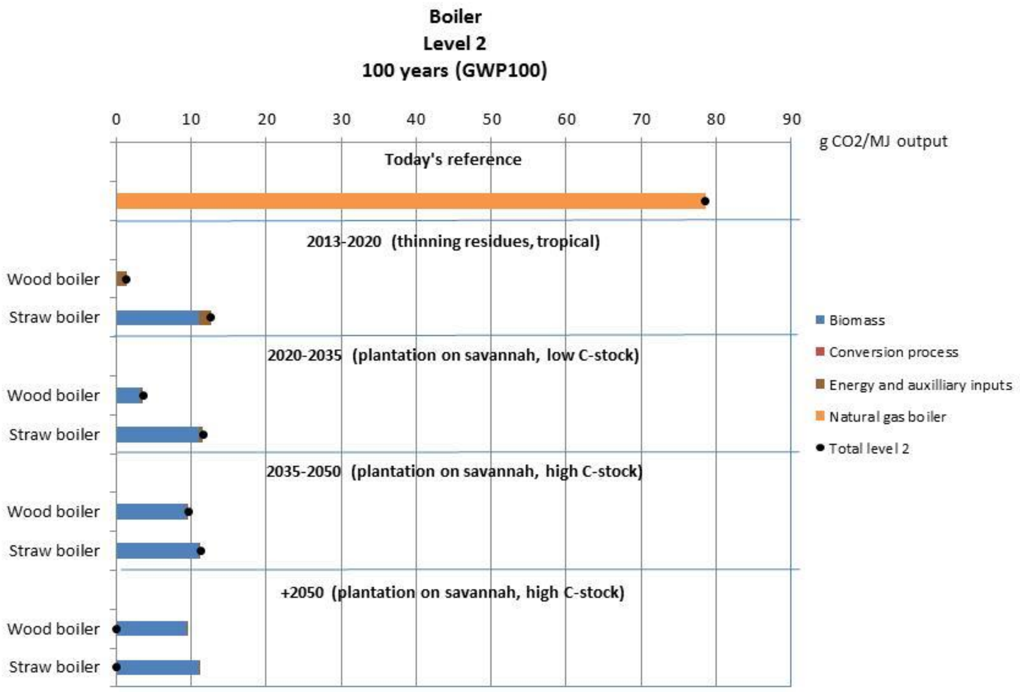


Figure 0-33

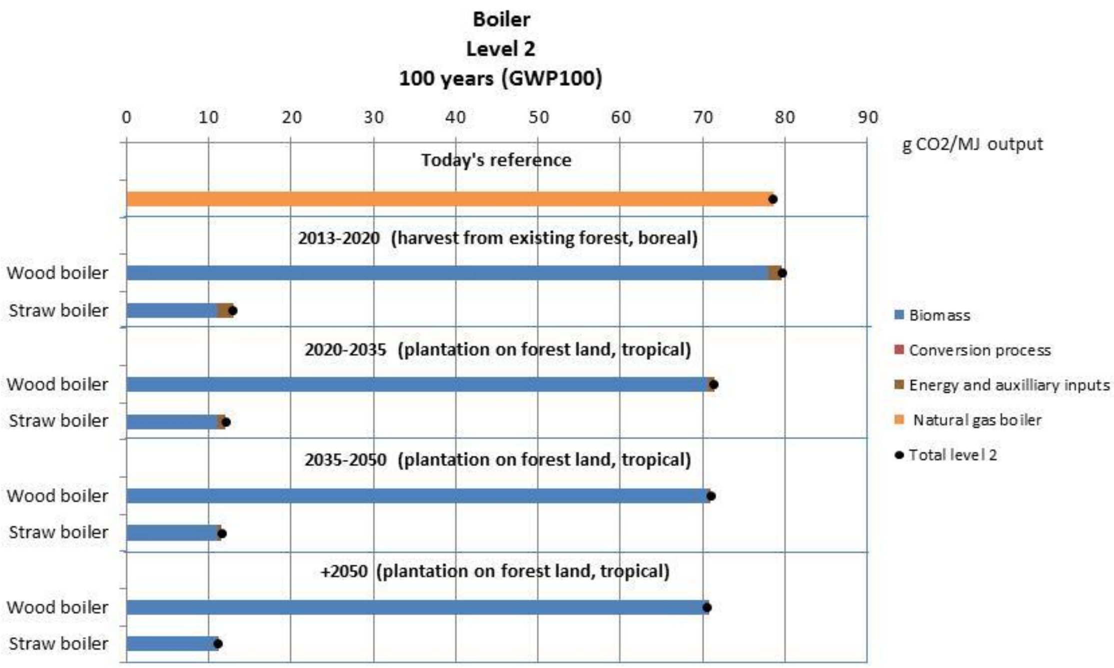


Figure 0-34

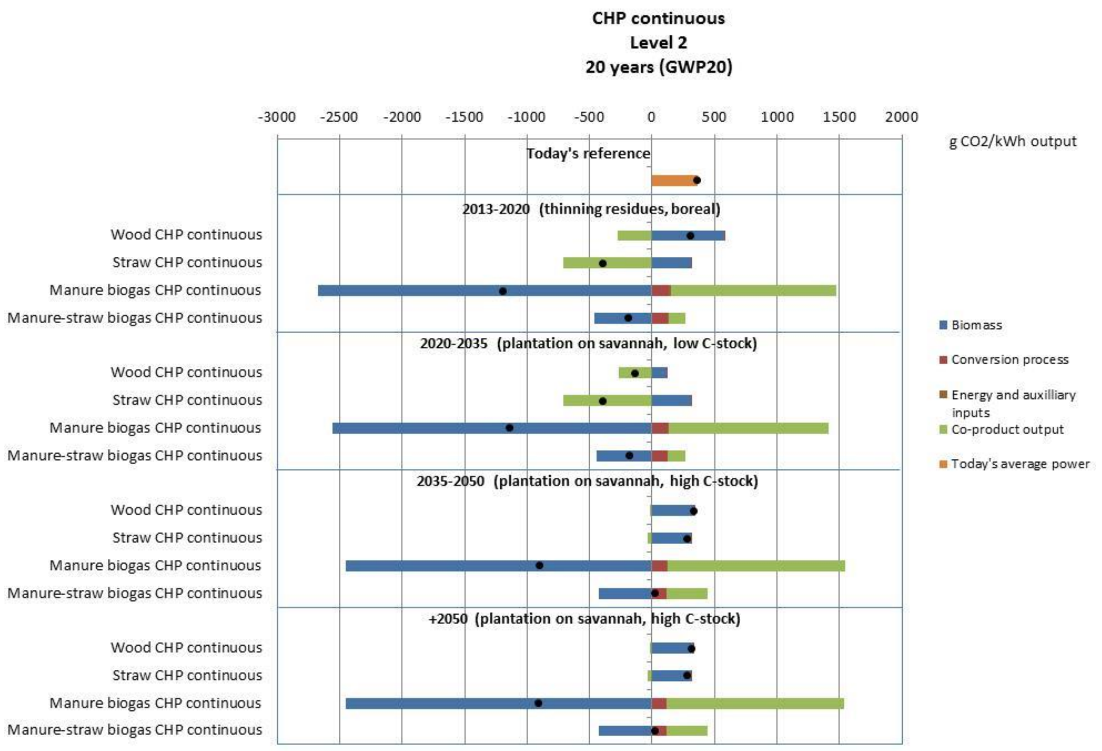


Figure 0-35

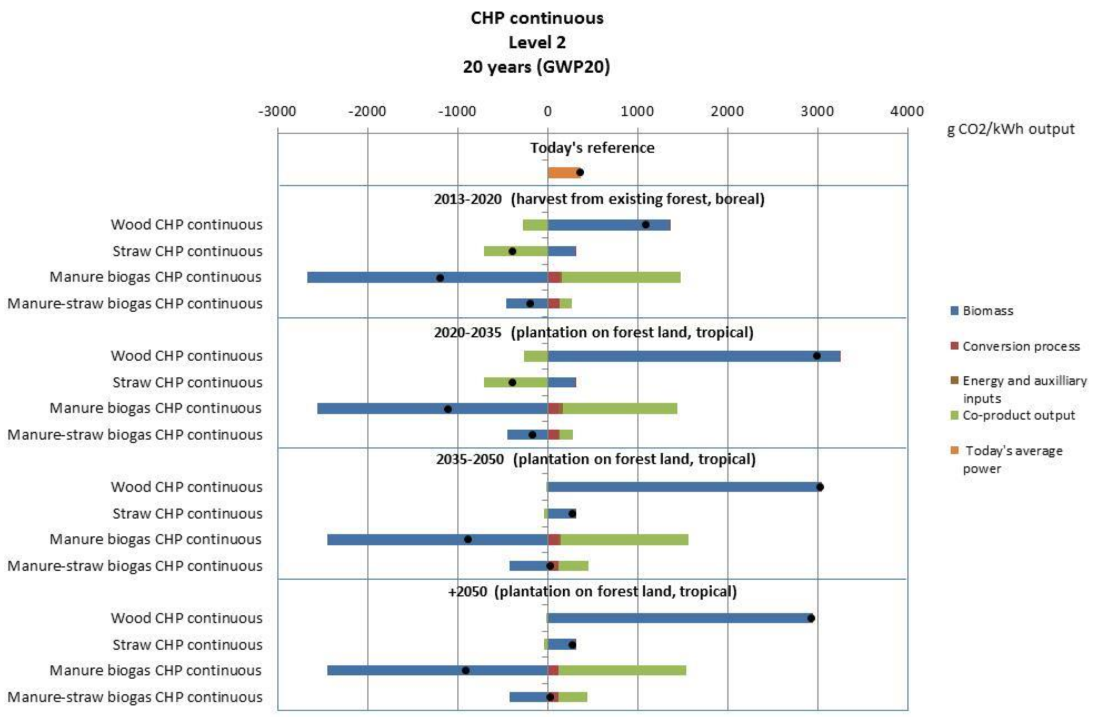


Figure 0-36

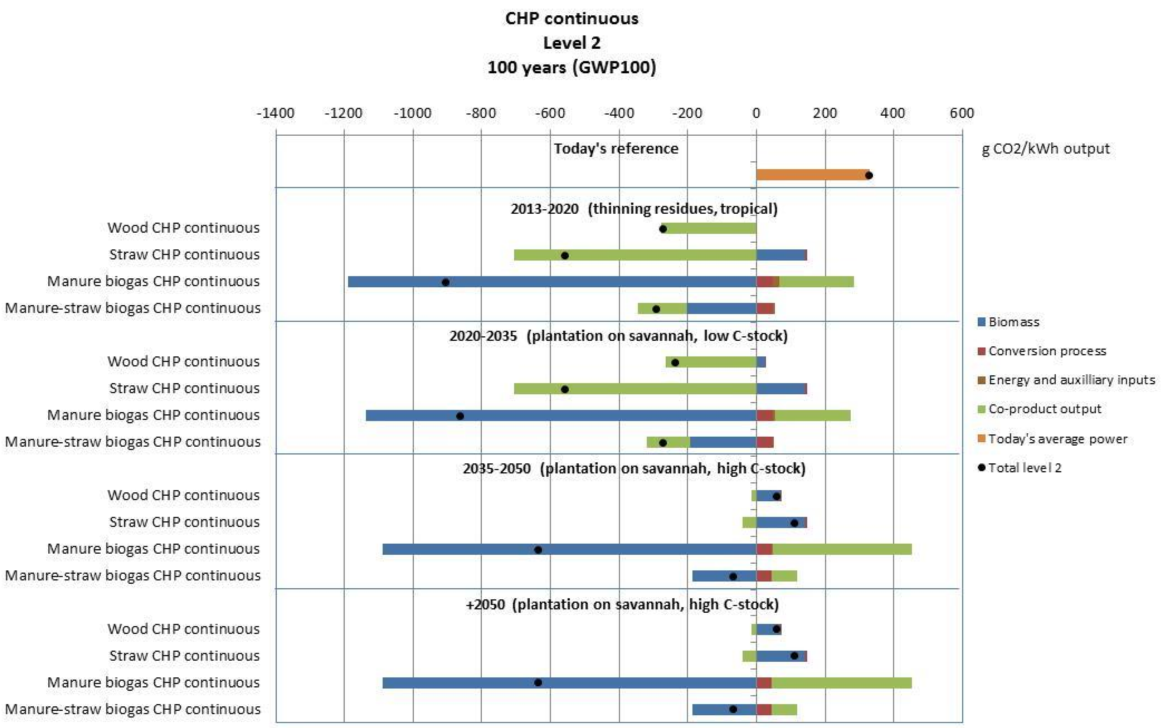


Figure 0-37

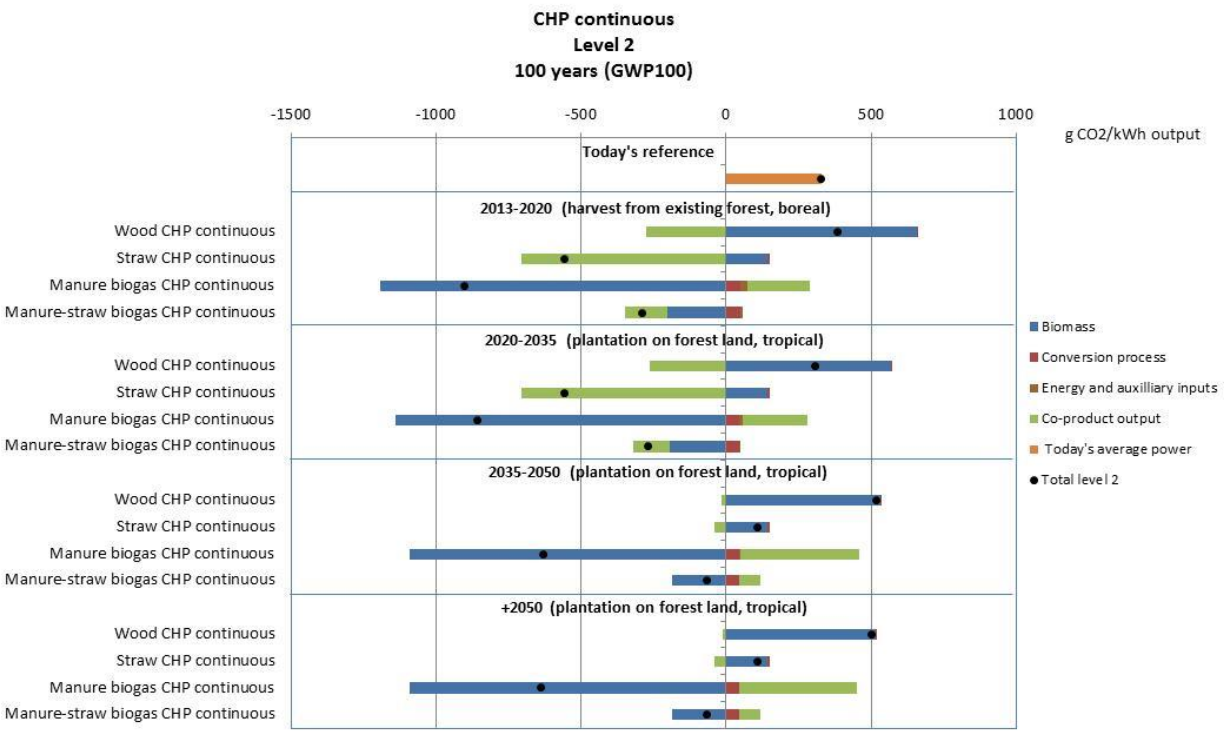


Figure 0-38

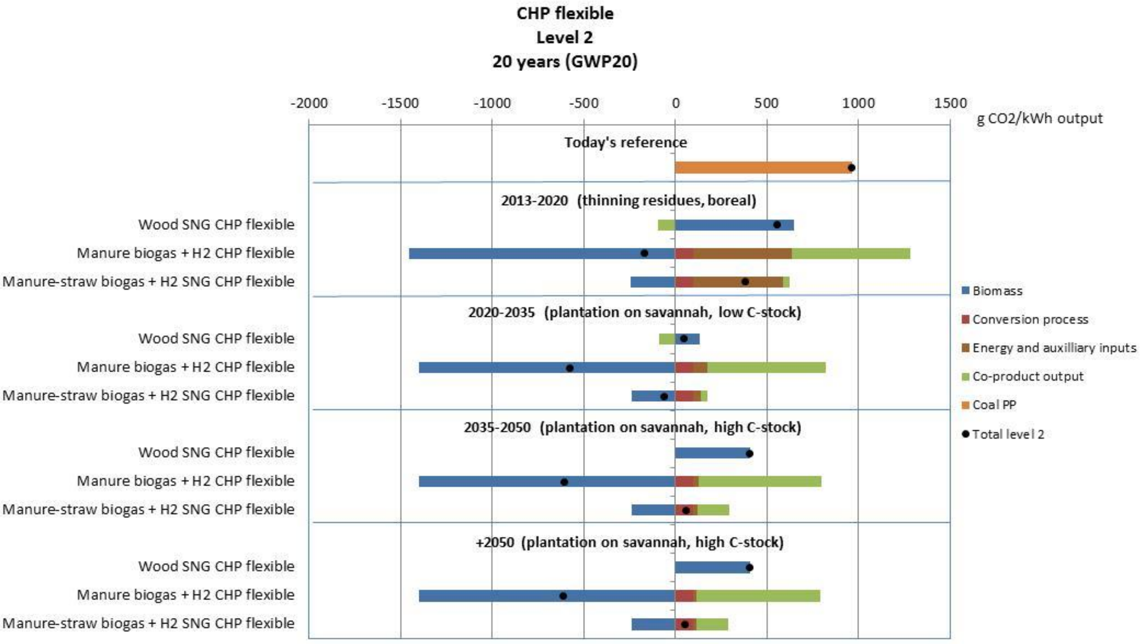


Figure 0-39

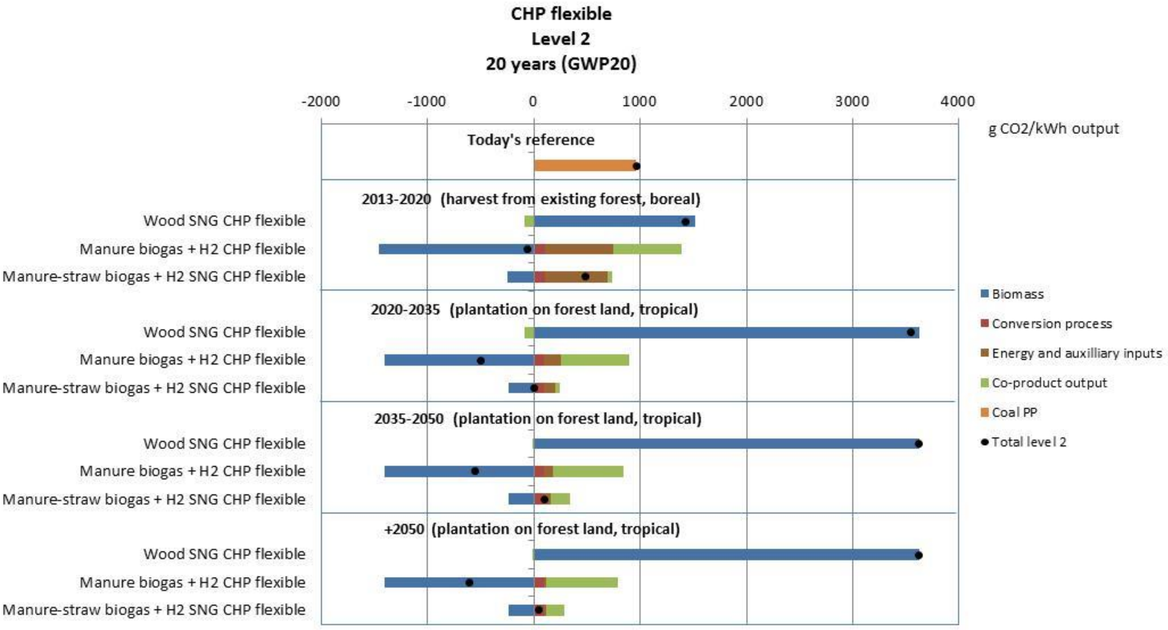


Figure 0-40

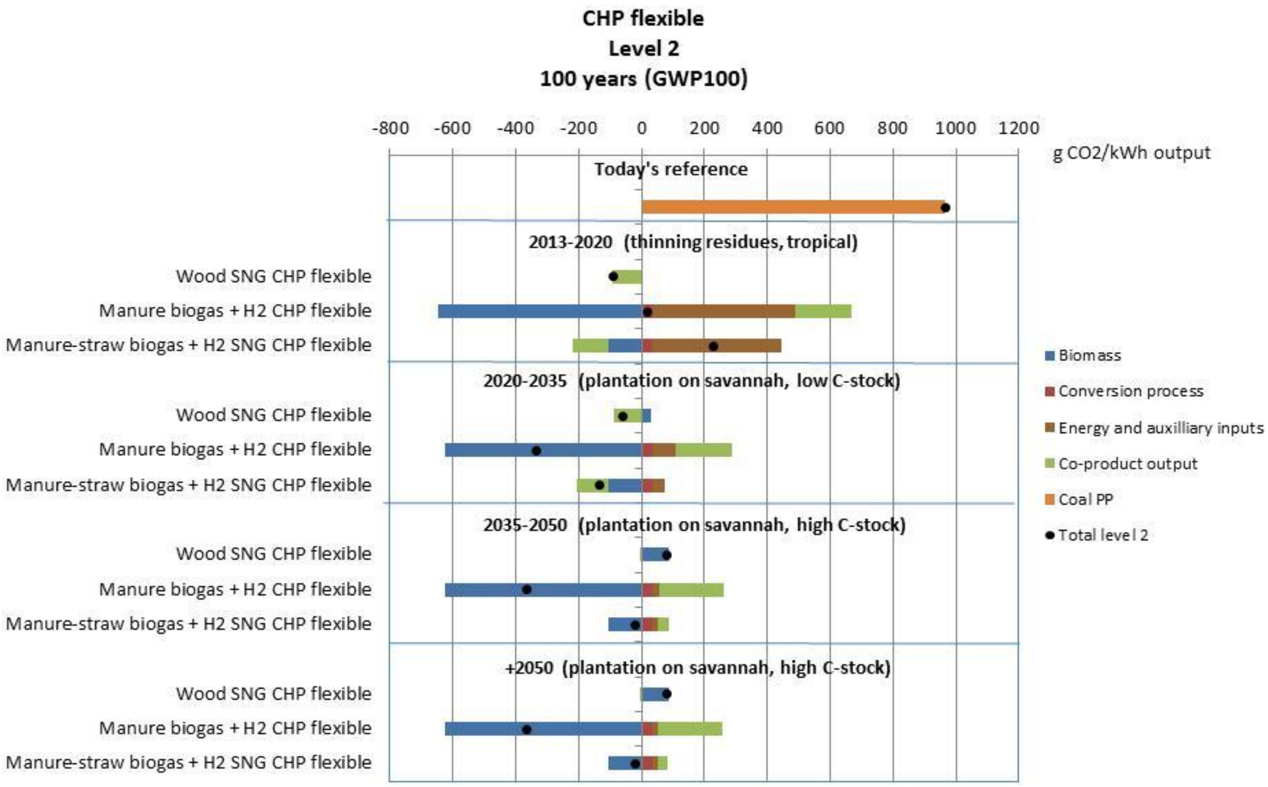


Figure 0-41

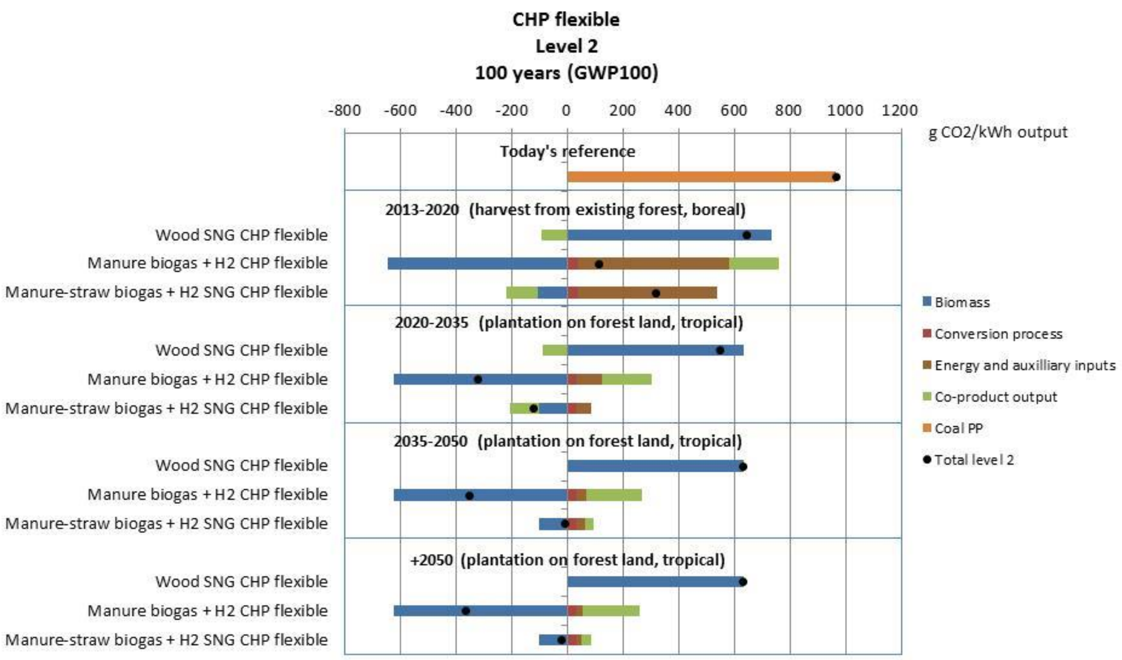


Figure 0-42

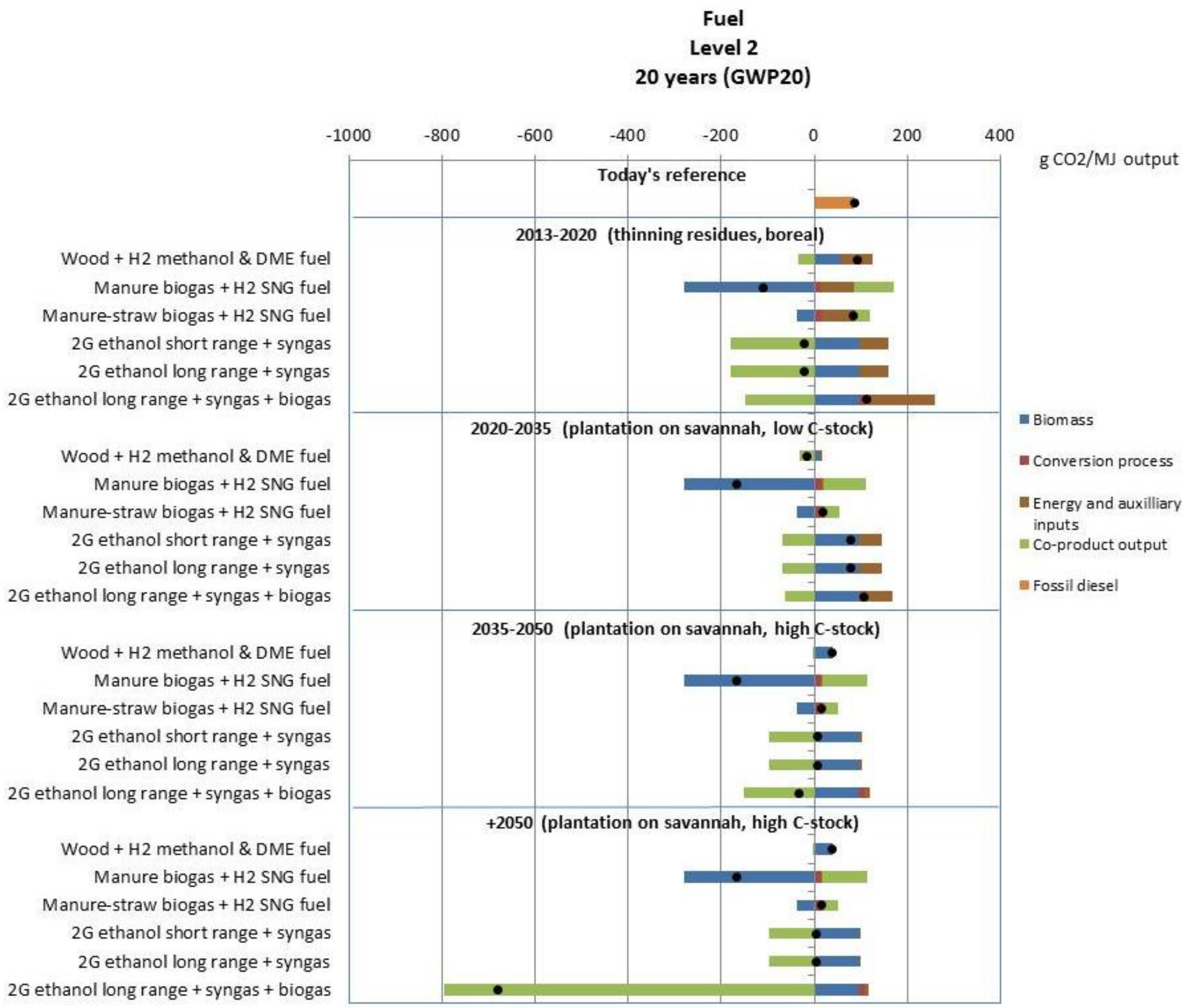

Fuel
Level 2
20 years (GWP20)
-1000
-800
-600
-400
-200
0
200
400
g CO2/MJ output
Today's reference
2013-2020 (thinning residues, boreal)
Wood + H2 methanol & DME fuel
Manure biogas + H2 SNG fuel
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
2020-2035 (plantation on savannah, low C-stock)
Wood + H2 methanol & DME fuel
Manure biogas + H2 SNG fuel
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
2035-2050 (plantation on savannah, high C-stock)
Wood + H2 methanol & DME fuel
Manure biogas + H2 SNG fuel
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
+2050 (plantation on savannah, high C-stock)
Wood + H2 methanol & DME fuel
Manure biogas + H2 SNG fuel
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Fossil diesel

Figure 0-43

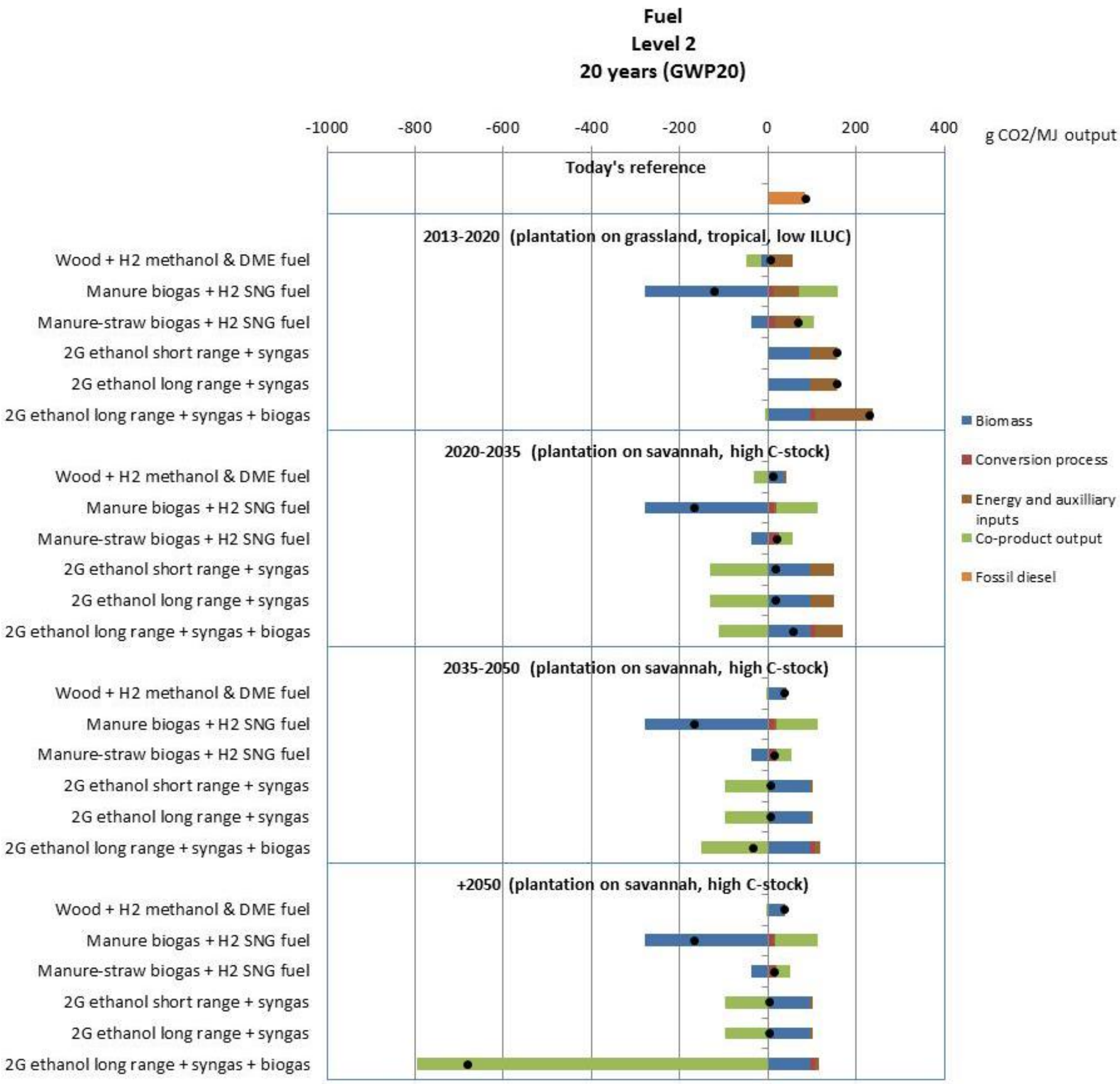

Fuel
Level 2
20 years (GWP20)
-1000
-800
-600
-400
-200
0
200
400
g CO2/MJ output
Today's reference
2013-2020 (plantation on grassland, tropical, low ILUC)
Wood + H2 methanol & DME fuel
Manure biogas + H2 SNG fuel
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
2020-2035 (plantation on savannah, high C-stock)
Wood + H2 methanol & DME fuel
Manure biogas + H2 SNG fuel
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
2035-2050 (plantation on savannah, high C-stock)
Wood + H2 methanol & DME fuel
Manure biogas + H2 SNG fuel
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
+2050 (plantation on savannah, high C-stock)
Wood + H2 methanol & DME fuel
Manure biogas + H2 SNG fuel
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Fossil diesel

Figure 0-44

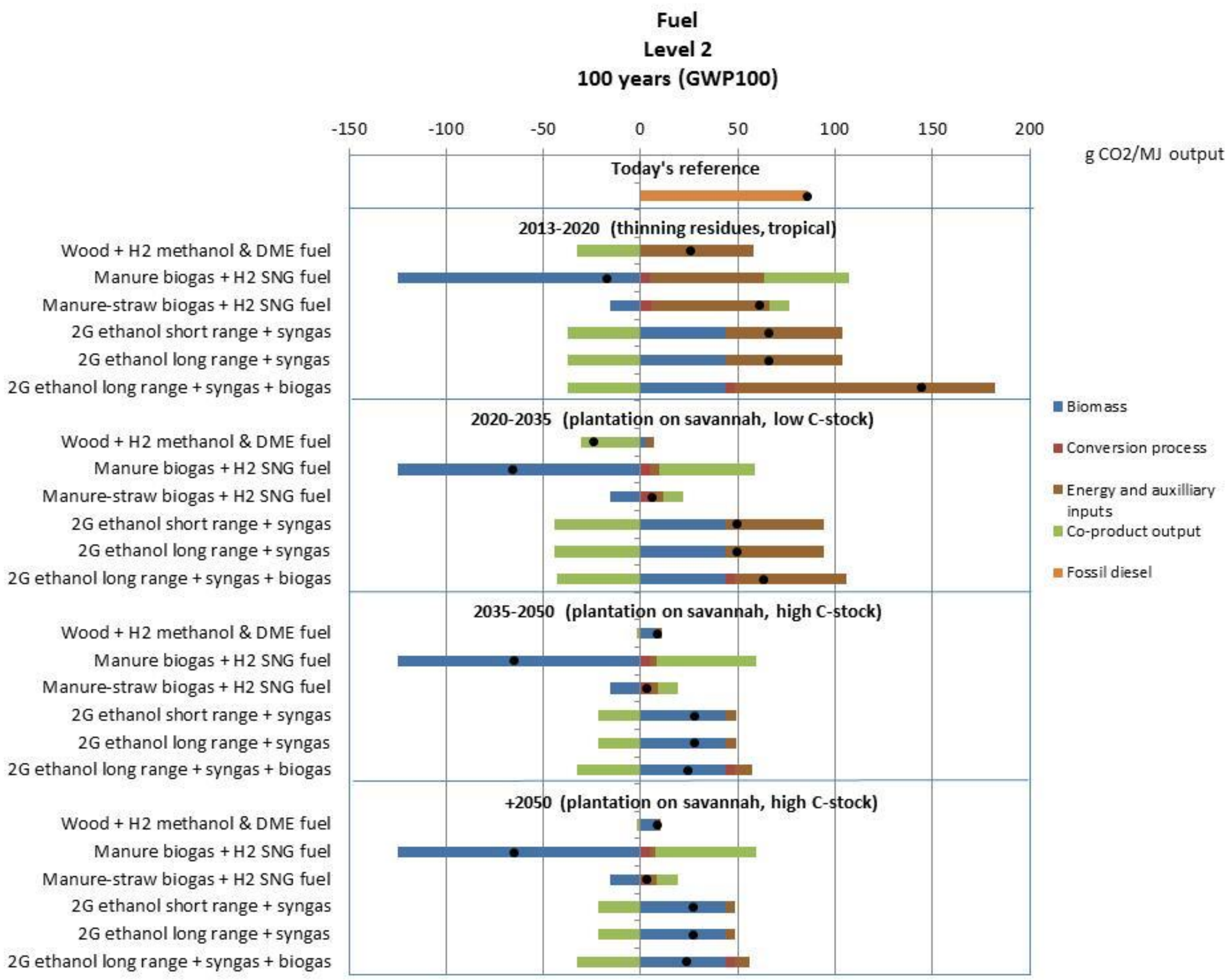

Fuel
Level 2
100 years (GWP100)
-150
-100
-50
0
50
100
150
200
g CO2/MJ output
Today's reference
2013-2020 (thinning residues, tropical)
Wood + H2 methanol & DME fuel
Manure biogas + H2 SNG fuel
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
2020-2035 (plantation on savannah, low C-stock)
Wood + H2 methanol & DME fuel
Manure biogas + H2 SNG fuel
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
2035-2050 (plantation on savannah, high C-stock)
Wood + H2 methanol & DME fuel
Manure biogas + H2 SNG fuel
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
+2050 (plantation on savannah, high C-stock)
Wood + H2 methanol & DME fuel
Manure biogas + H2 SNG fuel
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Fossil diesel

Figure 0-45

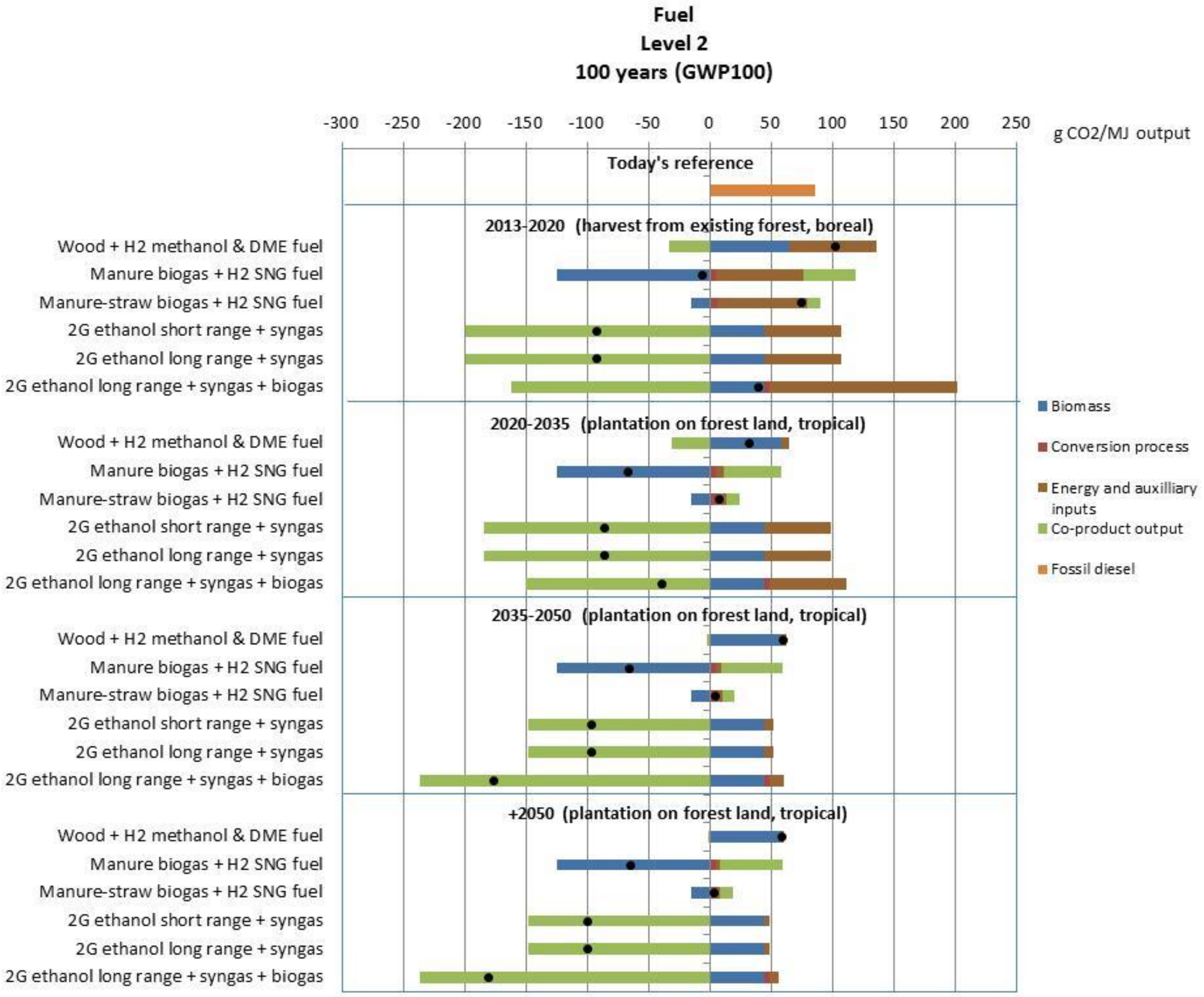

Fuel
Level 2
100 years (GWP100)
-300 -250 -200 -150 -100 -50 0 50 100 150 200 250
g CO2/MJ output
Today's reference
2013-2020 (harvest from existing forest, boreal)
Wood + H2 methanol & DME fuel
Manure biogas + H2 SNG fuel
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
2020-2035 (plantation on forest land, tropical)
2035-2050 (plantation on forest land, tropical)
+2050 (plantation on forest land, tropical)
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Fossil diesel

Figure 0-46

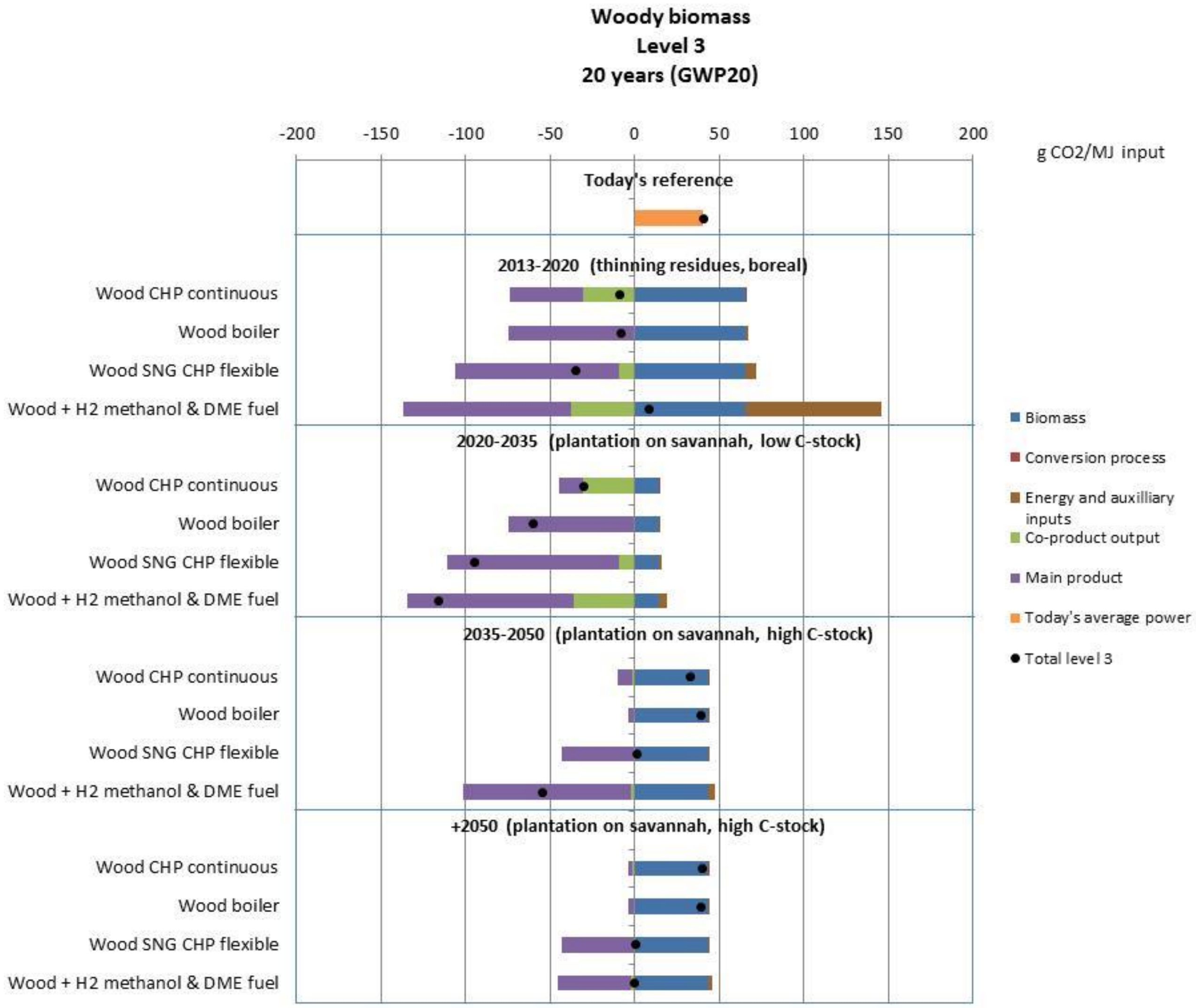

Woody biomass
Level 3
20 years (GWP20)
-200
-150
-100
-50
0
50
100
150
200
g CO2/MJ input
Today's reference
2013-2020 (thinning residues, boreal)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
2020-2035 (plantation on savannah, low C-stock)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
2035-2050 (plantation on savannah, high C-stock)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
+2050 (plantation on savannah, high C-stock)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Today's average power
Total level 3

Figure 0-47

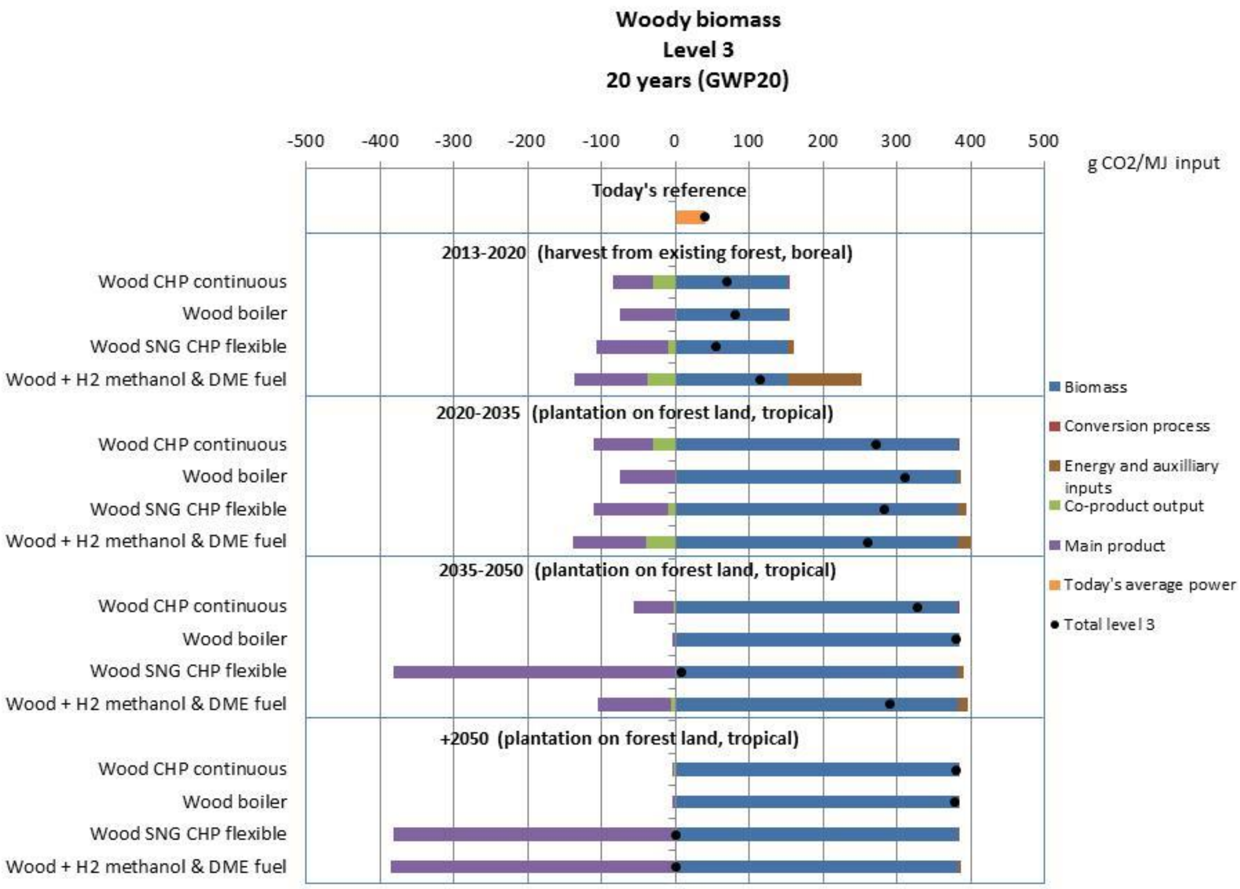

Woody biomass
Level 3
20 years (GWP20)
-500 -400 -300 -200 -100 0 100 200 300 400 500
g CO2/MJ input
Today's reference
2013-2020 (harvest from existing forest, boreal)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
2020-2035 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
2035-2050 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
+2050 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Today's average power
Total level 3

Figure 0-48

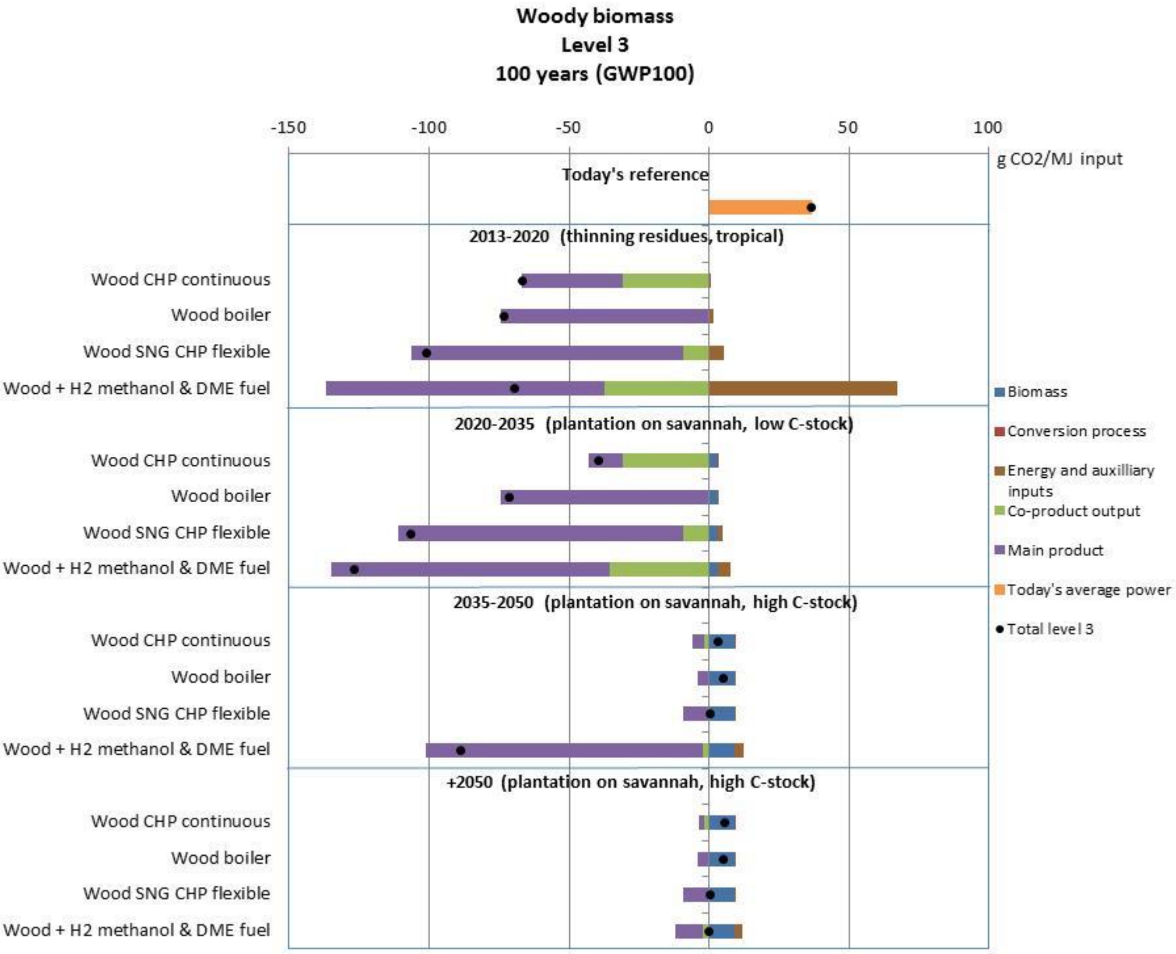

Woody biomass
Level 3
100 years (GWP100)
-150
-100
-50
0
50
100
g CO2/MJ input
Today's reference
2013-2020 (thinning residues, tropical)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
2020-2035 (plantation on savannah, low C-stock)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
2035-2050 (plantation on savannah, high C-stock)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
+2050 (plantation on savannah, high C-stock)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Today's average power
Total level 3

Figure 0-49

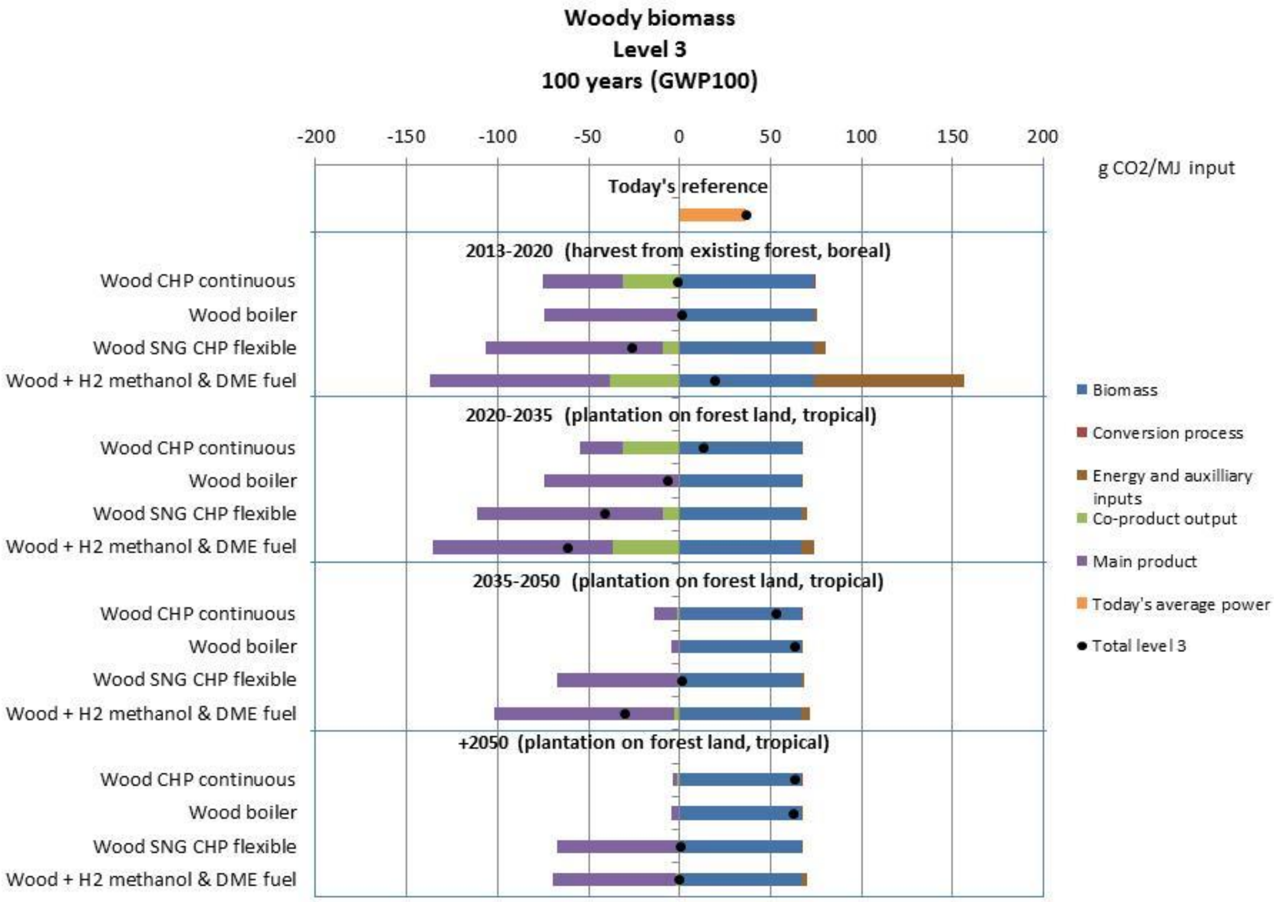

Woody biomass
Level 3
100 years (GWP100)
-200
-150
-100
-50
0
50
100
150
200
g CO2/MJ input
Today's reference
2013-2020 (harvest from existing forest, boreal)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
2020-2035 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
2035-2050 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
+2050 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood SNG CHP flexible
Wood + H2 methanol & DME fuel
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Today's average power
Total level 3

Figure 0-50

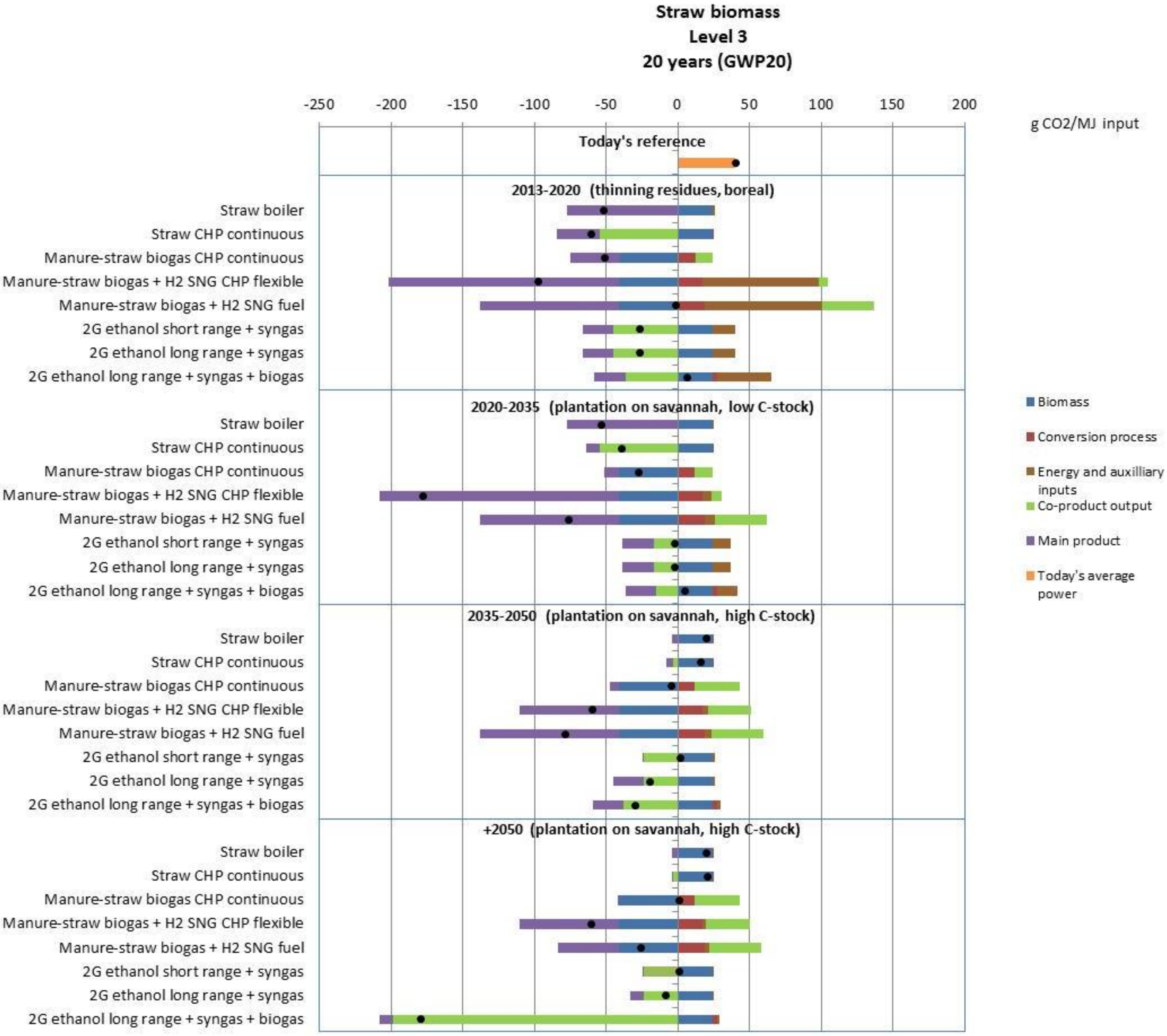

Straw biomass
Level 3
20 years (GWP20)
-250 -200 -150 -100 -50 0 50 100 150 200
g CO2/MJ input
Today's reference
2013-2020 (thinning residues, boreal)
Straw boiler
Straw CHP continuous
Manure-straw biogas CHP continuous
Manure-straw biogas + H2 SNG CHP flexible
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
2020-2035 (plantation on savannah, low C-stock)
2035-2050 (plantation on savannah, high C-stock)
+2050 (plantation on savannah, high C-stock)
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Today's average power

Figure 0-51

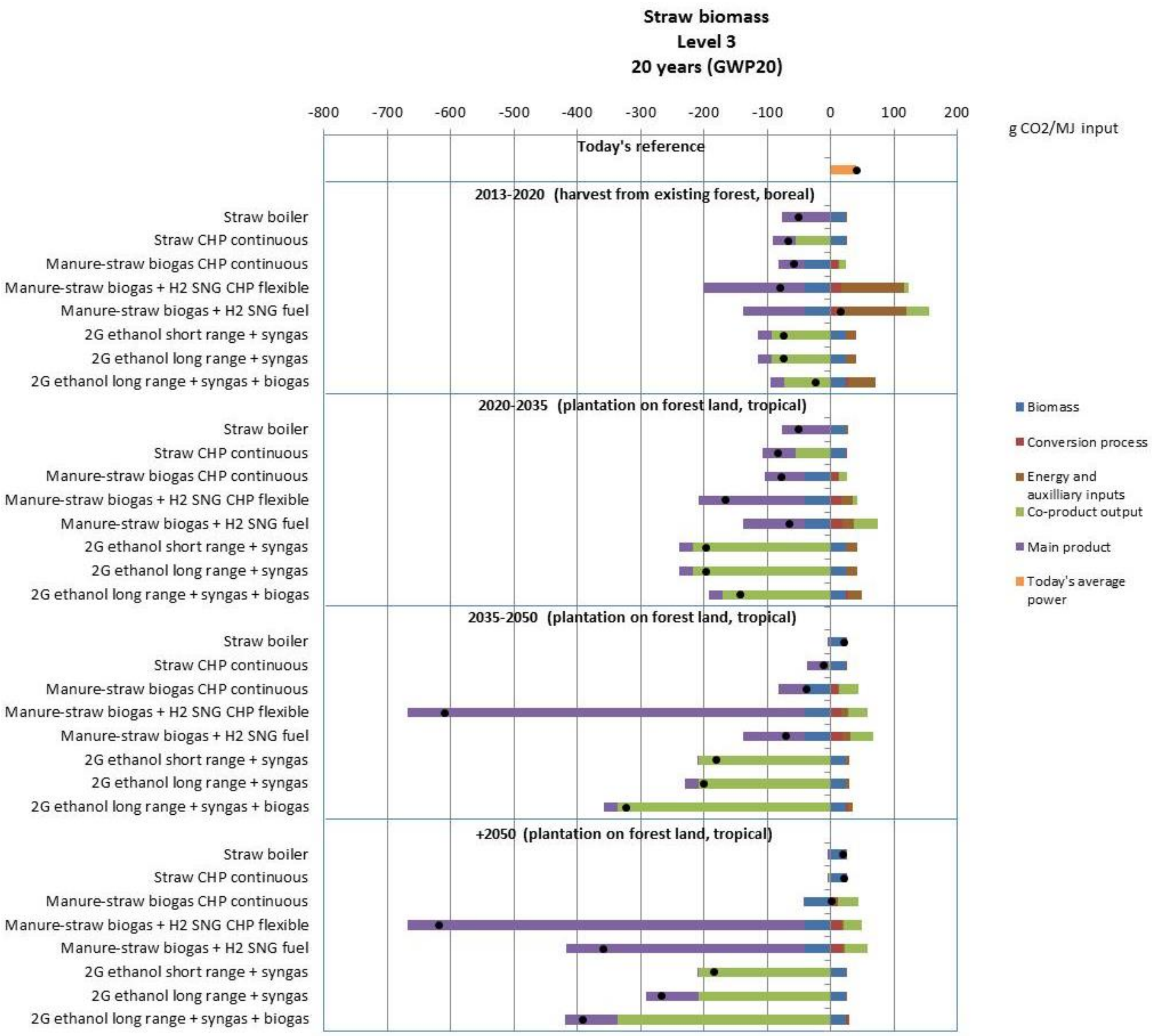

Straw biomass
Level 3
20 years (GWP20)
-800
-700
-600
-500
-400
-300
-200
-100
0
100
200
g CO2/MJ input
Today's reference
2013-2020 (harvest from existing forest, boreal)
Straw boiler
Straw CHP continuous
Manure-straw biogas CHP continuous
Manure-straw biogas + H2 SNG CHP flexible
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
2020-2035 (plantation on forest land, tropical)
Straw boiler
Straw CHP continuous
Manure-straw biogas CHP continuous
Manure-straw biogas + H2 SNG CHP flexible
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
2035-2050 (plantation on forest land, tropical)
Straw boiler
Straw CHP continuous
Manure-straw biogas CHP continuous
Manure-straw biogas + H2 SNG CHP flexible
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
+2050 (plantation on forest land, tropical)
Straw boiler
Straw CHP continuous
Manure-straw biogas CHP continuous
Manure-straw biogas + H2 SNG CHP flexible
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Today's average power

Figure 0-52

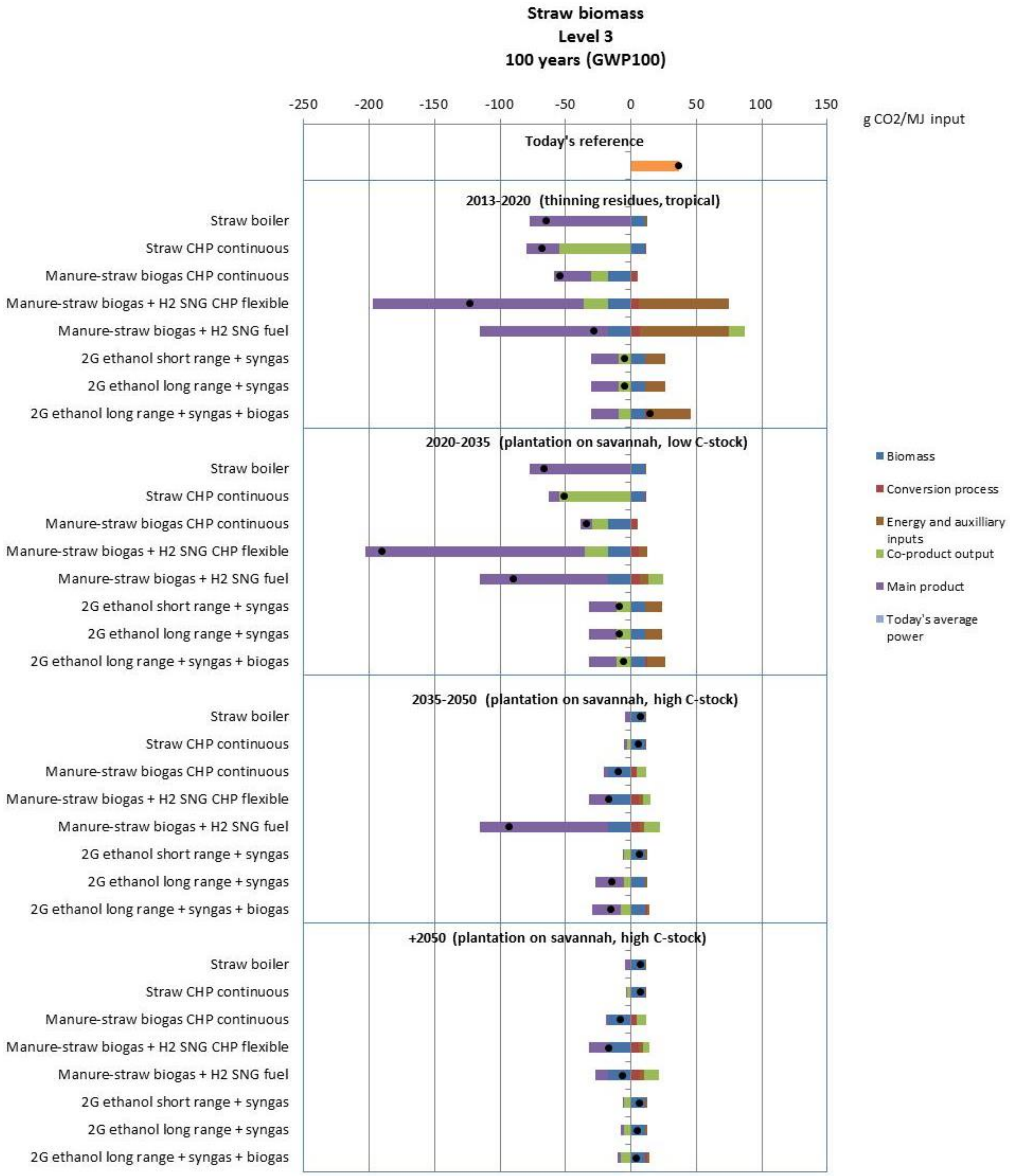

Straw biomass
Level 3
100 years (GWP100)
-250
-200
-150
-100
-50
0
50
100
150
g CO2/MJ input
Today's reference
2013-2020 (thinning residues, tropical)
Straw boiler
Straw CHP continuous
Manure-straw biogas CHP continuous
Manure-straw biogas + H2 SNG CHP flexible
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
2020-2035 (plantation on savannah, low C-stock)
Straw boiler
Straw CHP continuous
Manure-straw biogas CHP continuous
Manure-straw biogas + H2 SNG CHP flexible
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
2035-2050 (plantation on savannah, high C-stock)
Straw boiler
Straw CHP continuous
Manure-straw biogas CHP continuous
Manure-straw biogas + H2 SNG CHP flexible
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
+2050 (plantation on savannah, high C-stock)
Straw boiler
Straw CHP continuous
Manure-straw biogas CHP continuous
Manure-straw biogas + H2 SNG CHP flexible
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Today's average power

Figure 0-53

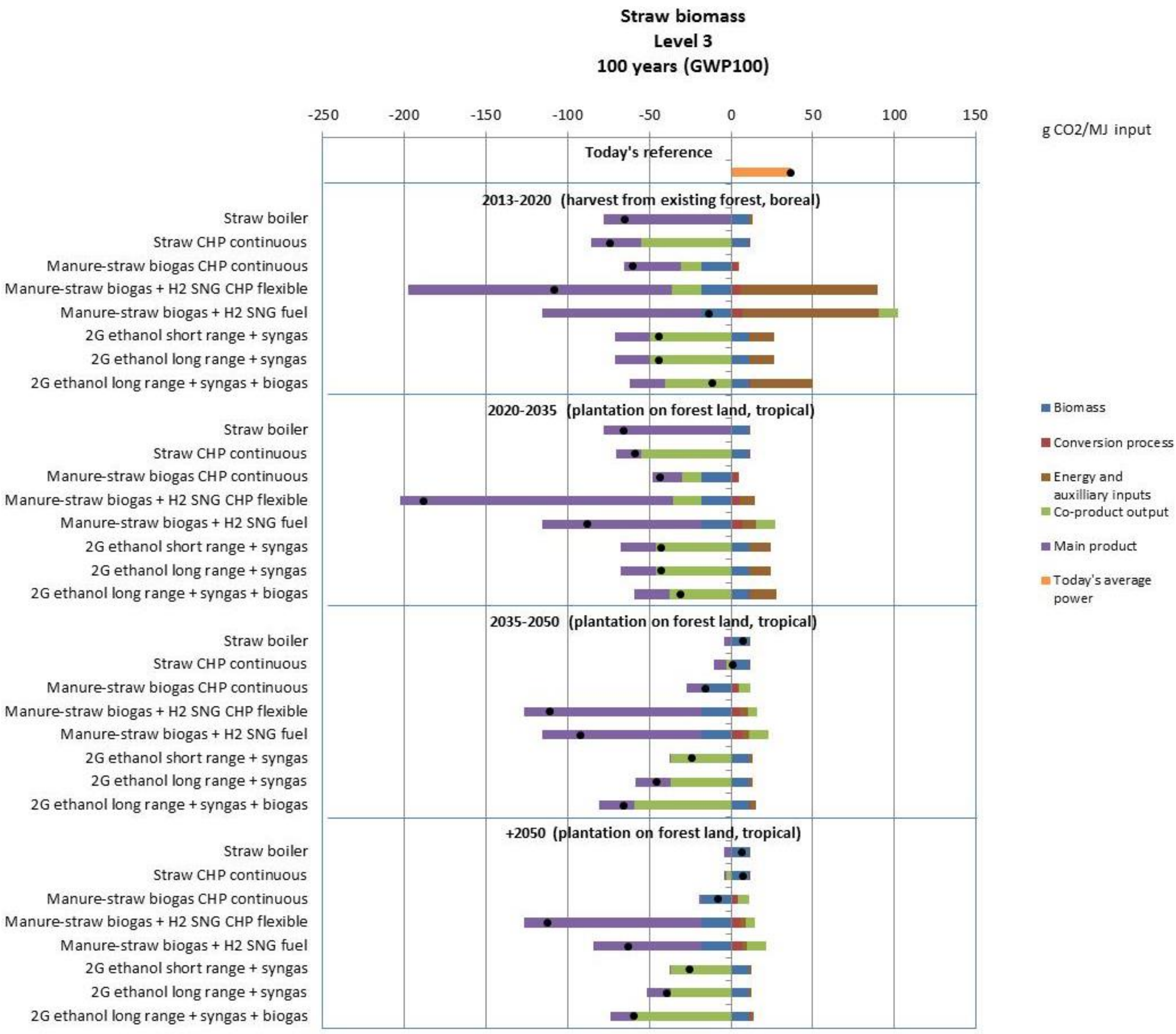

Straw biomass
Level 3
100 years (GWP100)
-250
-200
-150
-100
-50
0
50
100
150
g CO2/MJ input
Today's reference
2013-2020 (harvest from existing forest, boreal)
Straw boiler
Straw CHP continuous
Manure-straw biogas CHP continuous
Manure-straw biogas + H2 SNG CHP flexible
Manure-straw biogas + H2 SNG fuel
2G ethanol short range + syngas
2G ethanol long range + syngas
2G ethanol long range + syngas + biogas
2020-2035 (plantation on forest land, tropical)
2035-2050 (plantation on forest land, tropical)
+2050 (plantation on forest land, tropical)
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product
Today's average power

Figure 0-54

I.2 Subsection

Biomass types	**20 year time horizon Level 3**	**100 Year time horizon Level 3**
Woody biomass	55, 56, 57, 58	59, 60, 61, 62
Straw biomass	63, 64, 65, 66	67, 68, 69, 70

Conversion pathways, energy supply	**20 year time horizon Level 2**	**100 Year time horizon Level 2**
CHP continuous, power	71, 72, 73, 74	75, 76, 77, 78
CHP flexible, power	79, 80, 81, 82,	83, 84, 85, 86
Boiler, heat	87, 88, 89, 90	91, 92, 93, 94
Fermentation +, transport fuel	95, 96, 97, 98	99, 100, 101, 102

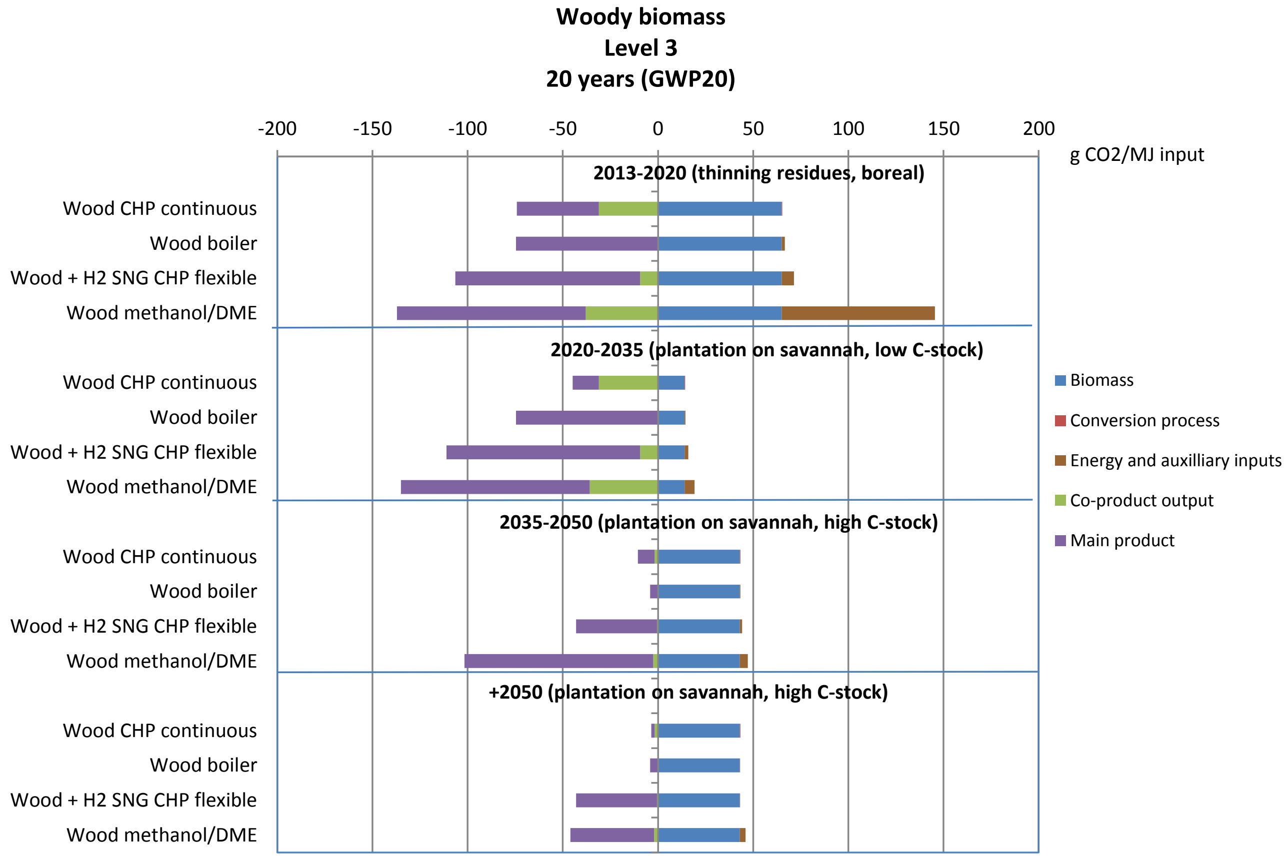

Woody biomass
Level 3
20 years (GWP20)
-200
-150
-100
-50
0
50
100
150
200
g CO2/MJ input
2013-2020 (thinning residues, boreal)
2020-2035 (plantation on savannah, low C-stock)
2035-2050 (plantation on savannah, high C-stock)
+2050 (plantation on savannah, high C-stock)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 55

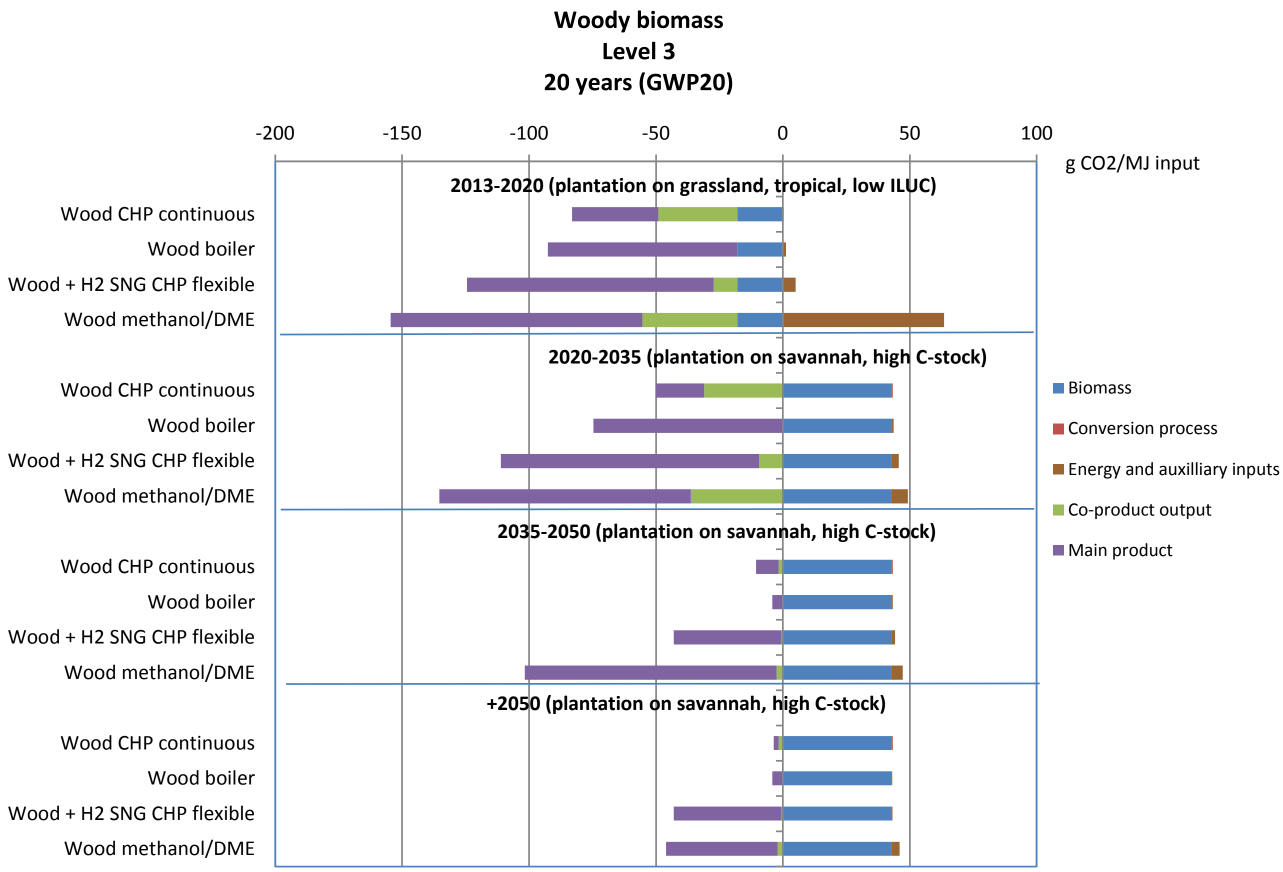

Woody biomass
Level 3
20 years (GWP20)
-200
-150
-100
-50
0
50
100
g CO2/MJ input
2013-2020 (plantation on grassland, tropical, low ILUC)
2020-2035 (plantation on savannah, high C-stock)
2035-2050 (plantation on savannah, high C-stock)
+2050 (plantation on savannah, high C-stock)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 56

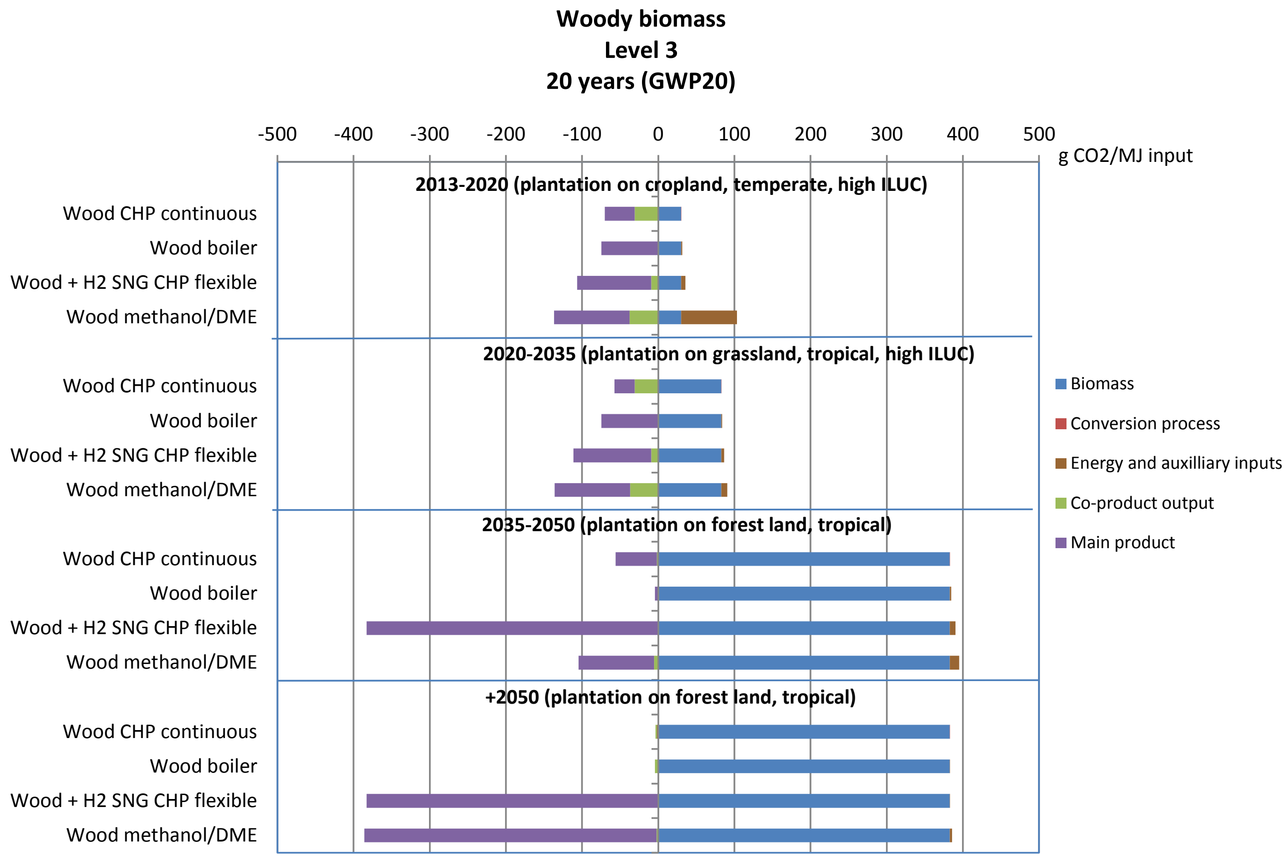

Woody biomass
Level 3
20 years (GWP20)
-500
-400
-300
-200
-100
0
100
200
300
400
500
g CO2/MJ input
2013-2020 (plantation on cropland, temperate, high ILUC)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
2020-2035 (plantation on grassland, tropical, high ILUC)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
2035-2050 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
+2050 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 0-557

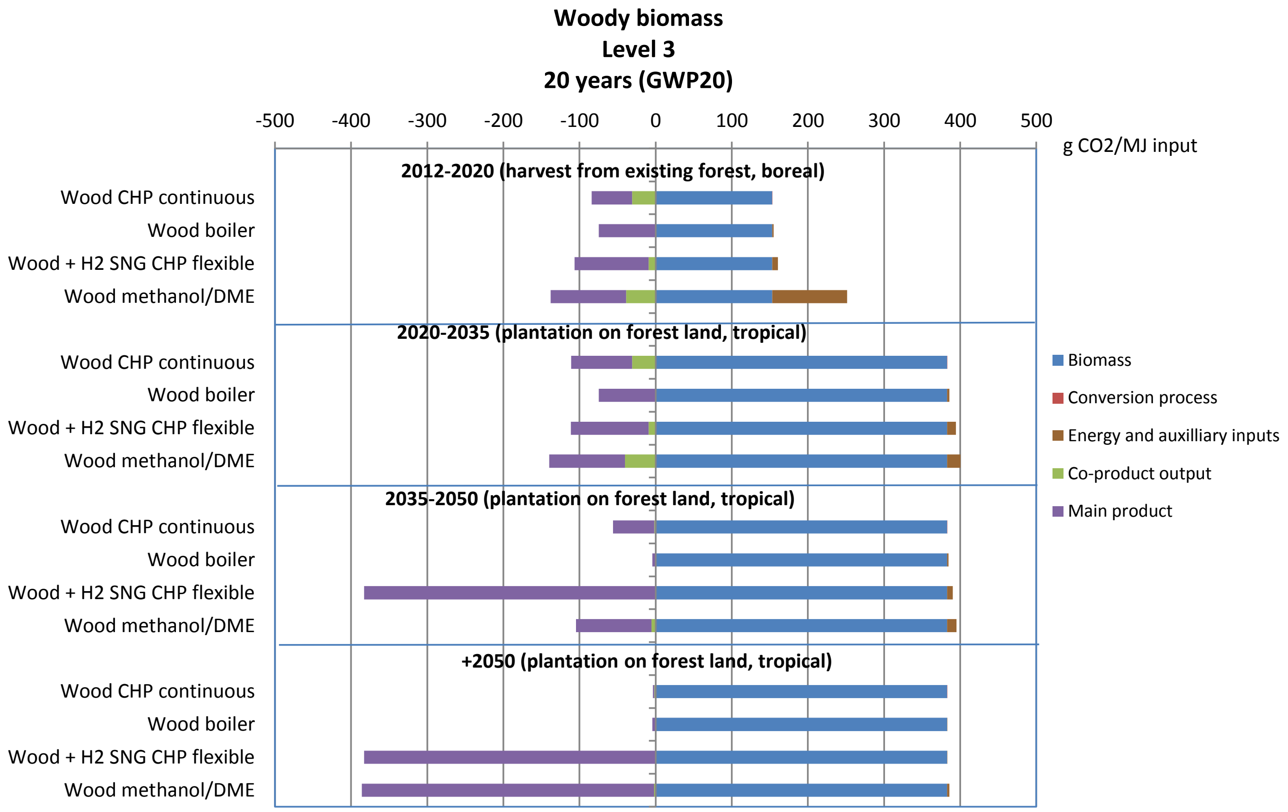

Woody biomass
Level 3
20 years (GWP20)
-500 -400 -300 -200 -100 0 100 200 300 400 500
g CO2/MJ input
2012-2020 (harvest from existing forest, boreal)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
2020-2035 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
2035-2050 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
+2050 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 0-568

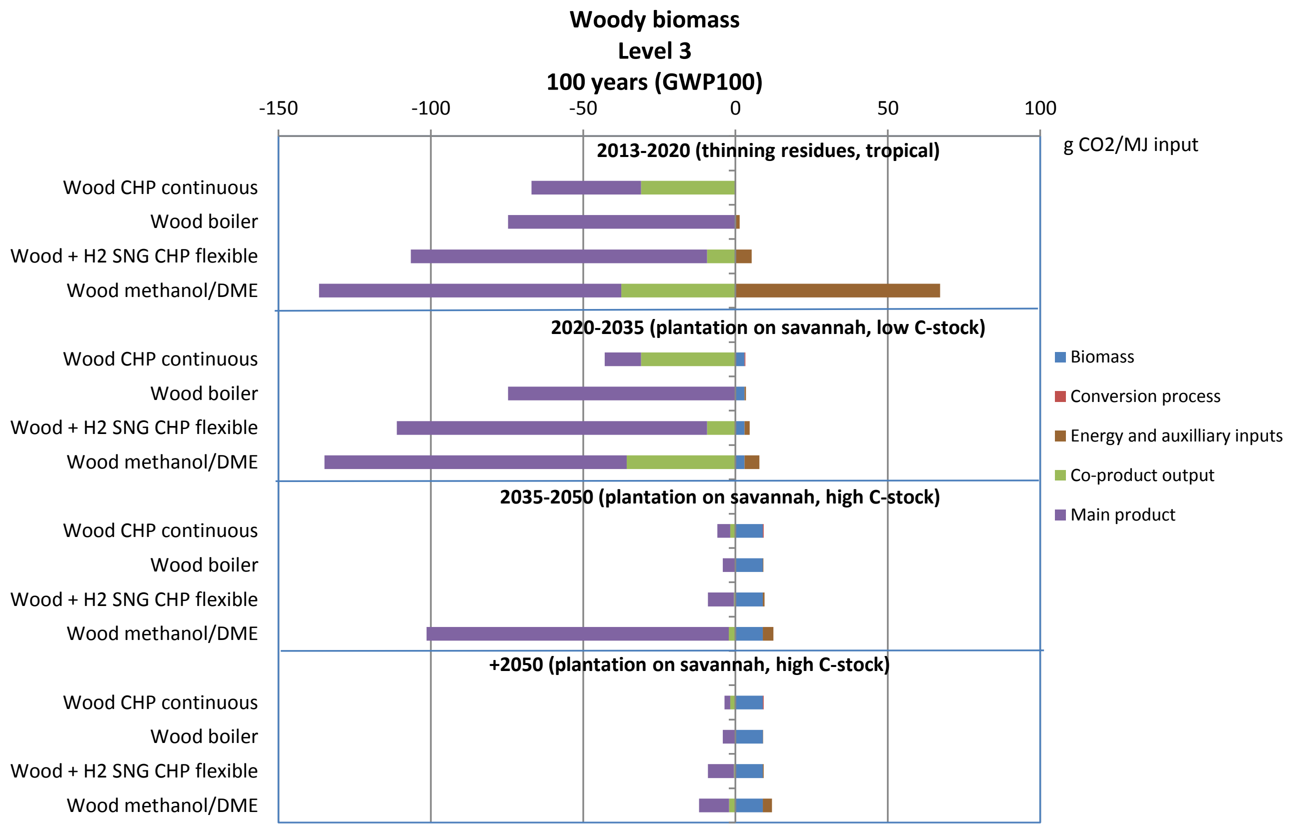

Woody biomass
Level 3
100 years (GWP100)
-150
-100
-50
0
50
100
g CO2/MJ input
2013-2020 (thinning residues, tropical)
2020-2035 (plantation on savannah, low C-stock)
2035-2050 (plantation on savannah, high C-stock)
+2050 (plantation on savannah, high C-stock)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 59

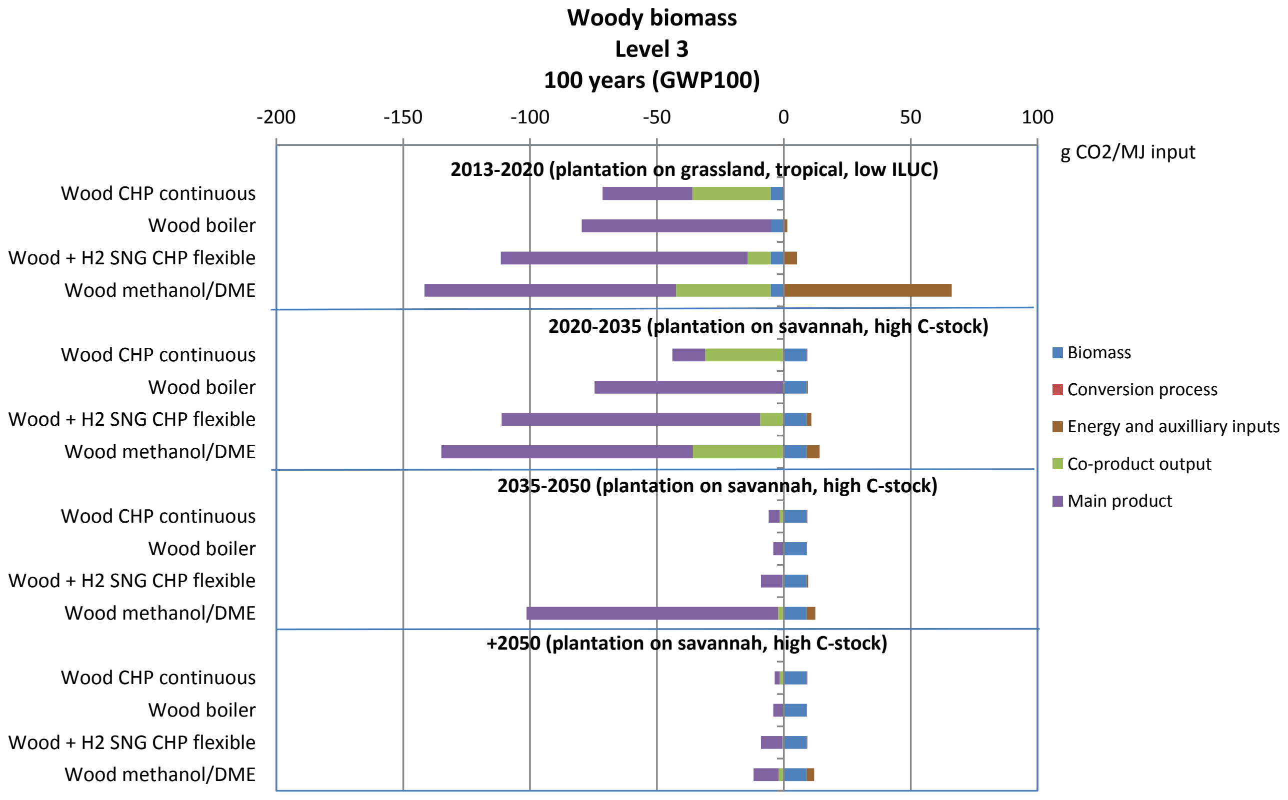

Woody biomass
Level 3
100 years (GWP100)
-200
-150
-100
-50
0
50
100
g CO2/MJ input
2013-2020 (plantation on grassland, tropical, low ILUC)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
2020-2035 (plantation on savannah, high C-stock)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
2035-2050 (plantation on savannah, high C-stock)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
+2050 (plantation on savannah, high C-stock)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 60

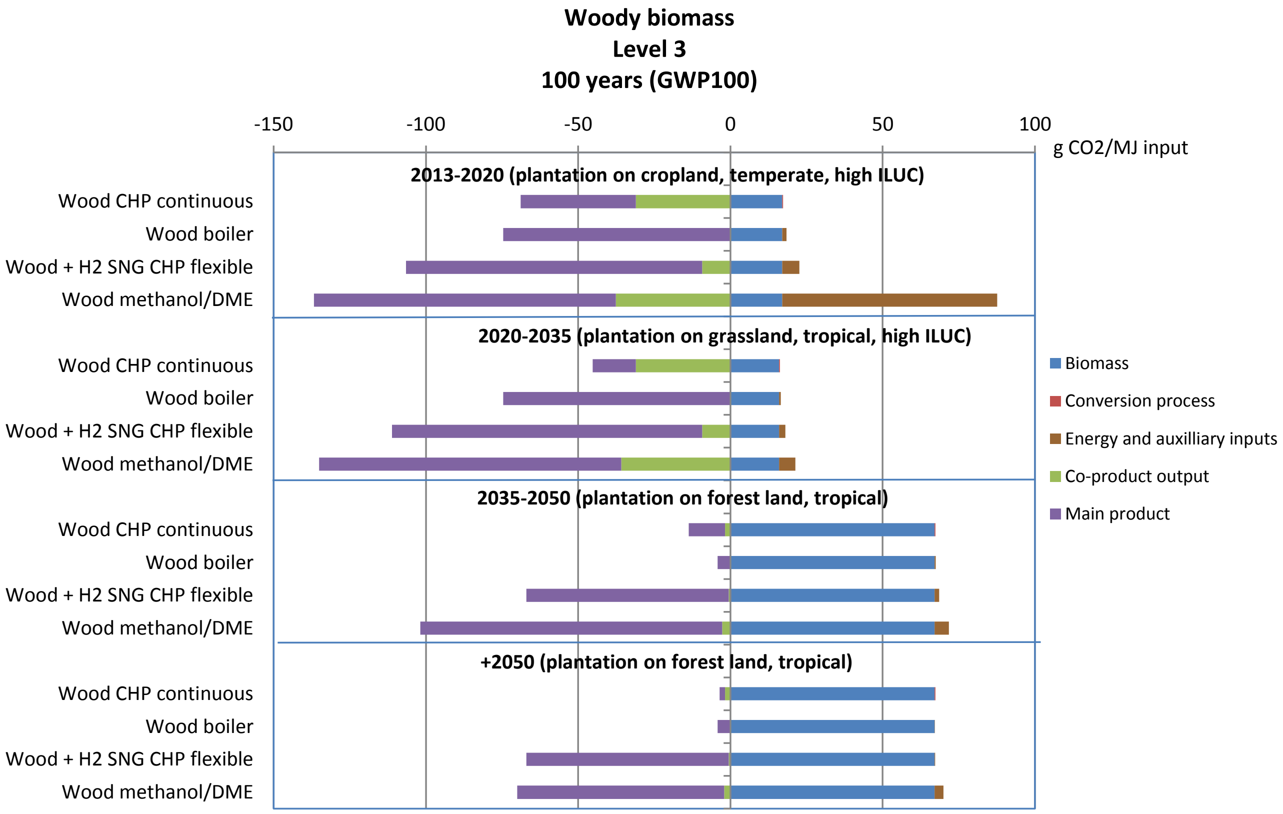

Woody biomass
Level 3
100 years (GWP100)
-150
-100
-50
0
50
100
g CO2/MJ input
2013-2020 (plantation on cropland, temperate, high ILUC)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
2020-2035 (plantation on grassland, tropical, high ILUC)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
2035-2050 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
+2050 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 61

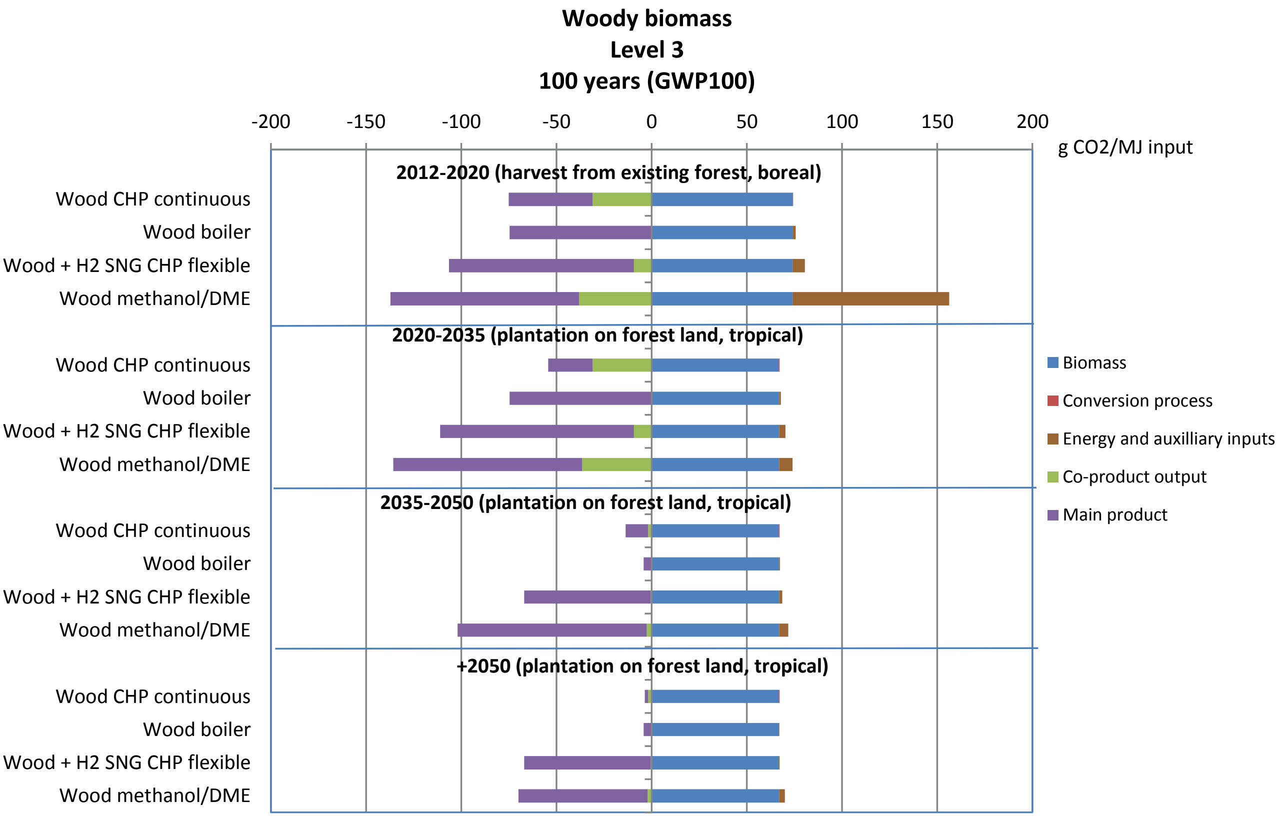

Woody biomass
Level 3
100 years (GWP100)
-200
-150
-100
-50
0
50
100
150
200
g CO2/MJ input
2012-2020 (harvest from existing forest, boreal)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
2020-2035 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
2035-2050 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
+2050 (plantation on forest land, tropical)
Wood CHP continuous
Wood boiler
Wood + H2 SNG CHP flexible
Wood methanol/DME
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 62

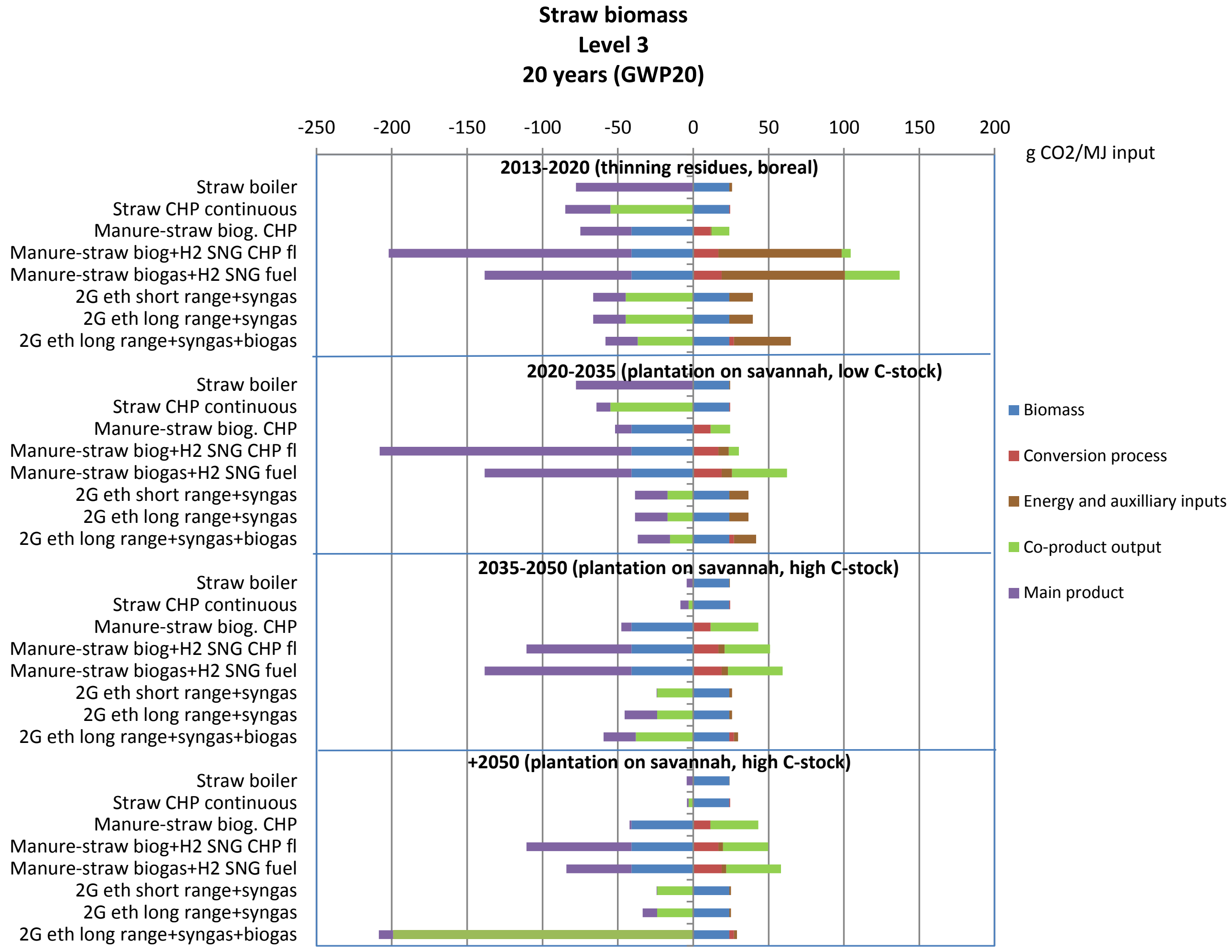

Straw biomass
Level 3
20 years (GWP20)
-250
-200
-150
-100
-50
0
50
100
150
200
g CO2/MJ input
2013-2020 (thinning residues, boreal)
2020-2035 (plantation on savannah, low C-stock)
2035-2050 (plantation on savannah, high C-stock)
+2050 (plantation on savannah, high C-stock)
Straw boiler
Straw CHP continuous
Manure-straw biog. CHP
Manure-straw biog+H2 SNG CHP fl
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 63

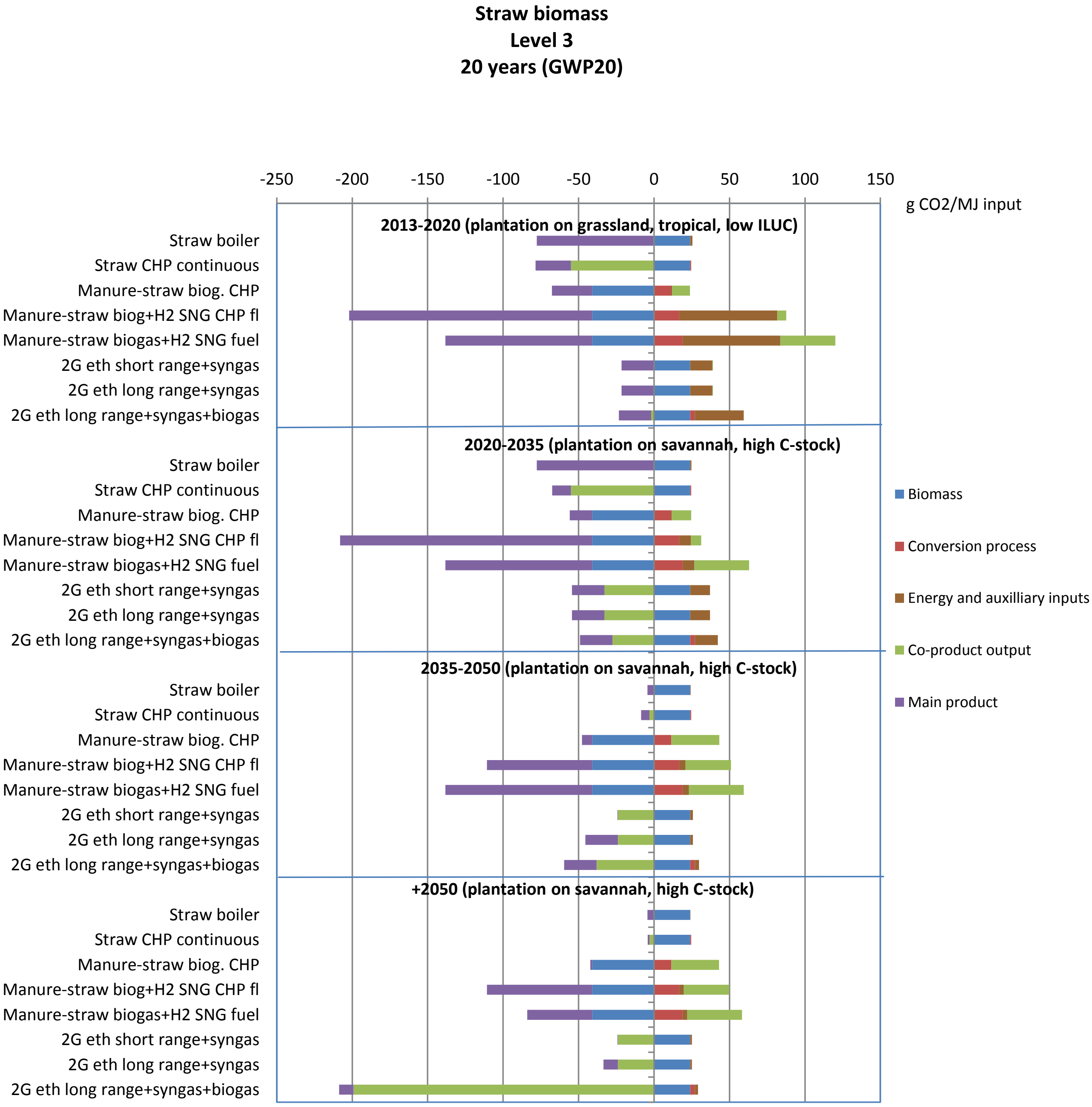

Straw biomass
Level 3
20 years (GWP20)
-250
-200
-150
-100
-50
0
50
100
150
g CO2/MJ input
2013-2020 (plantation on grassland, tropical, low ILUC)
Straw boiler
Straw CHP continuous
Manure-straw biog. CHP
Manure-straw biog+H2 SNG CHP fl
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
2020-2035 (plantation on savannah, high C-stock)
Straw boiler
Straw CHP continuous
Manure-straw biog. CHP
Manure-straw biog+H2 SNG CHP fl
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
2035-2050 (plantation on savannah, high C-stock)
Straw boiler
Straw CHP continuous
Manure-straw biog. CHP
Manure-straw biog+H2 SNG CHP fl
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
+2050 (plantation on savannah, high C-stock)
Straw boiler
Straw CHP continuous
Manure-straw biog. CHP
Manure-straw biog+H2 SNG CHP fl
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 64

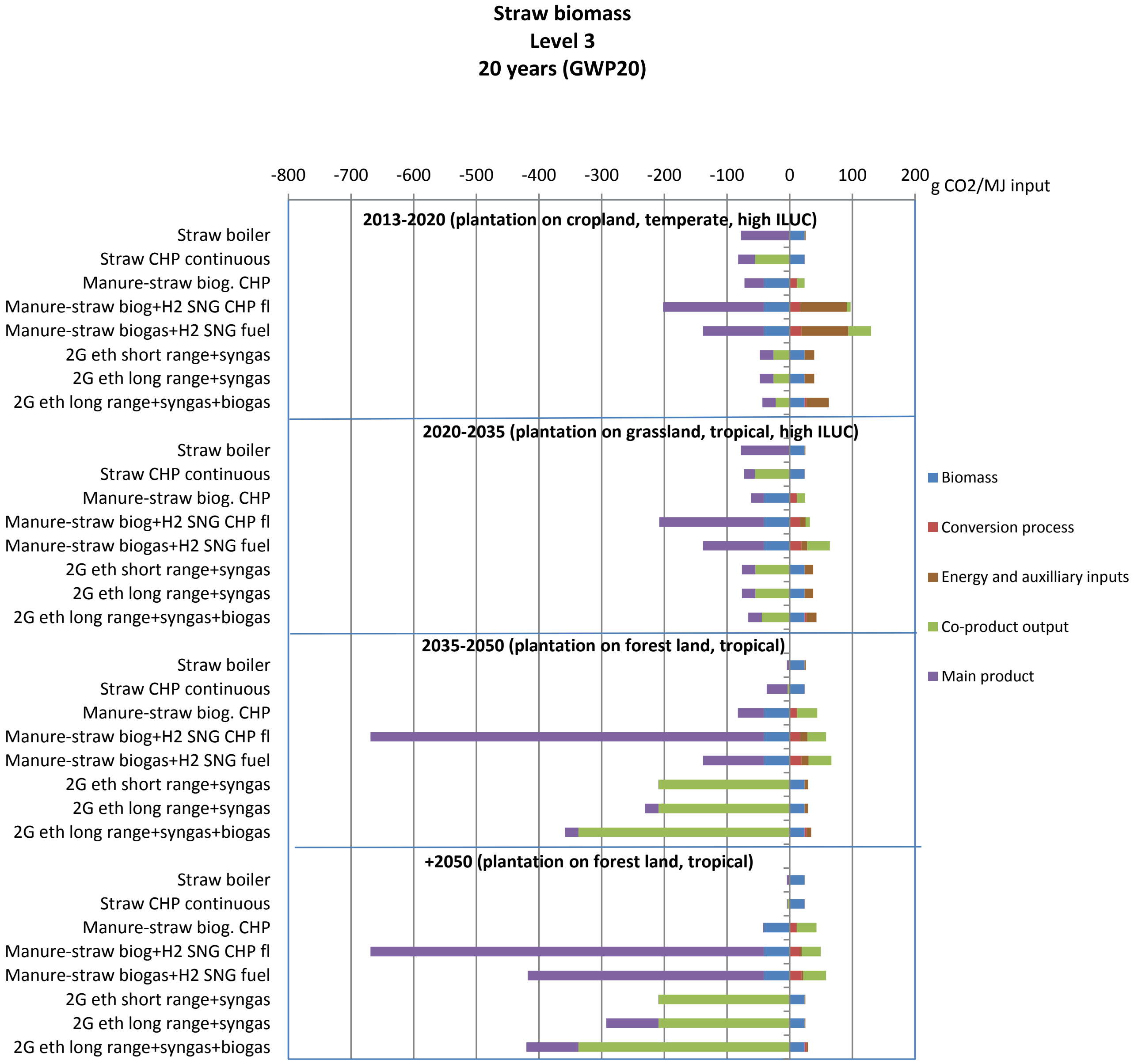

Straw biomass
Level 3
20 years (GWP20)
-800
-700
-600
-500
-400
-300
-200
-100
0
100
200
g CO2/MJ input
2013-2020 (plantation on cropland, temperate, high ILUC)
2020-2035 (plantation on grassland, tropical, high ILUC)
2035-2050 (plantation on forest land, tropical)
+2050 (plantation on forest land, tropical)
Straw boiler
Straw CHP continuous
Manure-straw biog. CHP
Manure-straw biog+H2 SNG CHP fl
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 65

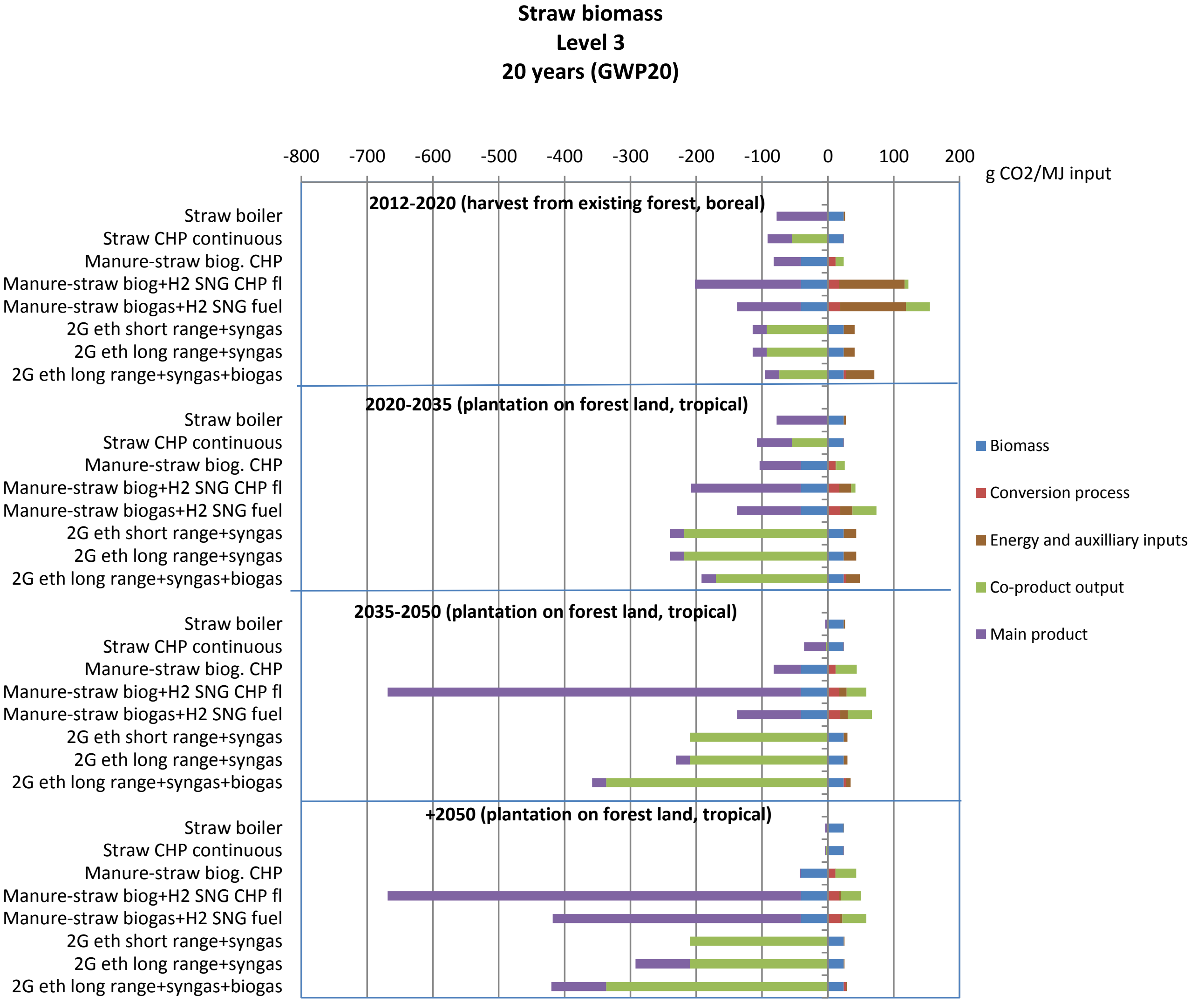

Straw biomass
Level 3
20 years (GWP20)
-800 -700 -600 -500 -400 -300 -200 -100 0 100 200
g CO2/MJ input
2012-2020 (harvest from existing forest, boreal)
2020-2035 (plantation on forest land, tropical)
2035-2050 (plantation on forest land, tropical)
+2050 (plantation on forest land, tropical)
Straw boiler
Straw CHP continuous
Manure-straw biog. CHP
Manure-straw biog+H2 SNG CHP fl
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 66

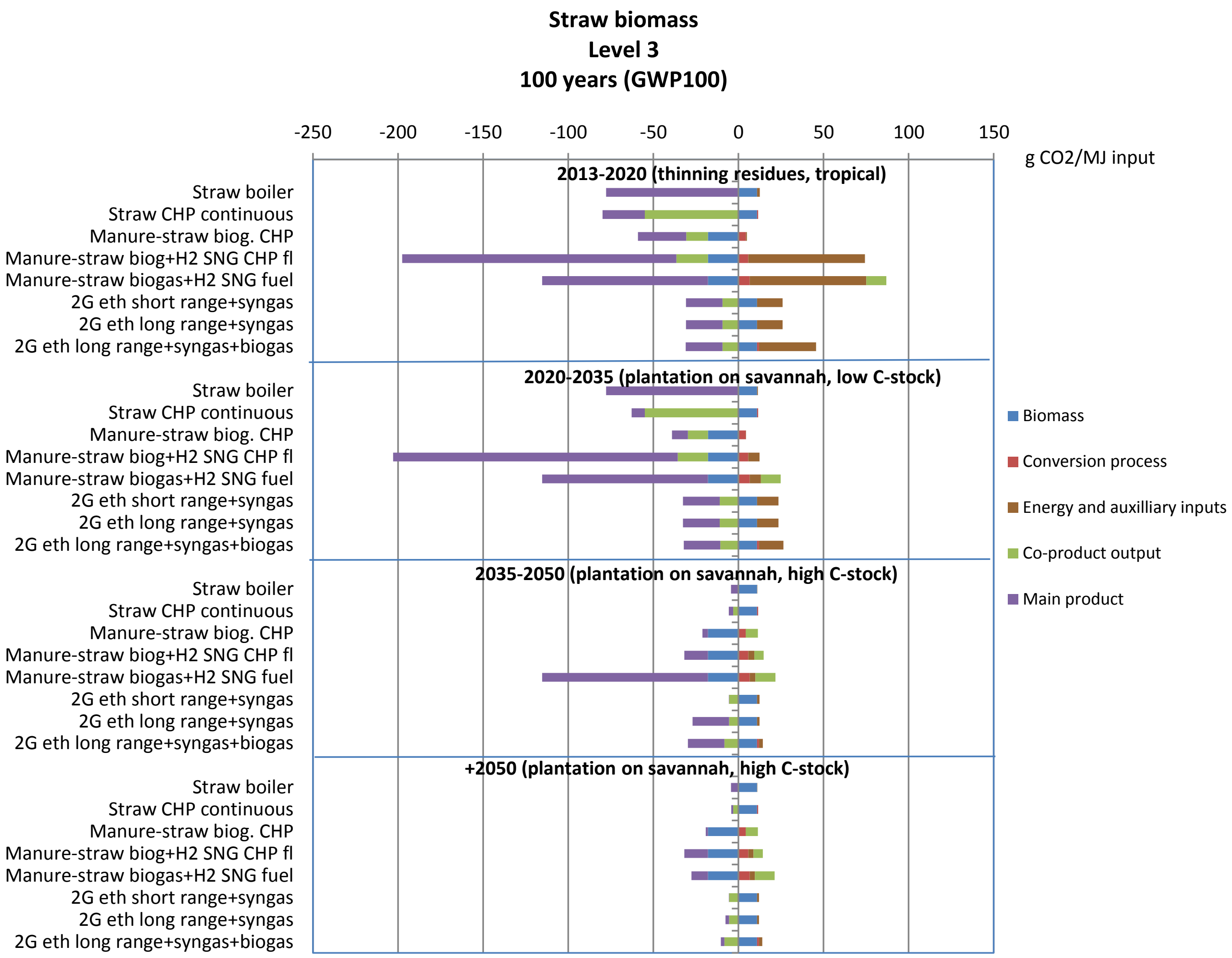

Straw biomass
Level 3
100 years (GWP100)
-250
-200
-150
-100
-50
0
50
100
150
g CO2/MJ input
2013-2020 (thinning residues, tropical)
2020-2035 (plantation on savannah, low C-stock)
2035-2050 (plantation on savannah, high C-stock)
+2050 (plantation on savannah, high C-stock)
Straw boiler
Straw CHP continuous
Manure-straw biog. CHP
Manure-straw biog+H2 SNG CHP fl
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 67

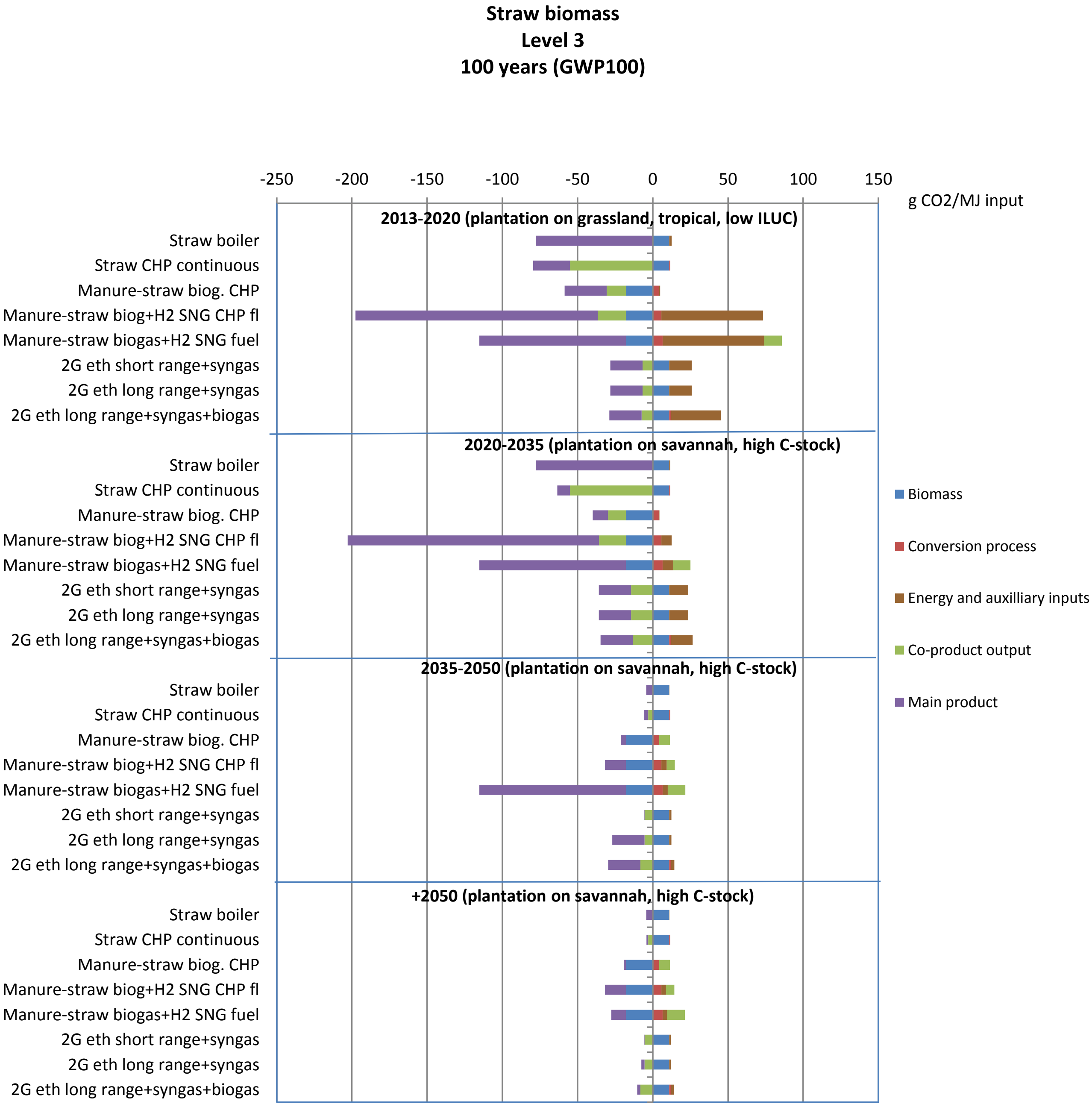

Straw biomass
Level 3
100 years (GWP100)
-250
-200
-150
-100
-50
0
50
100
150
g CO2/MJ input
2013-2020 (plantation on grassland, tropical, low ILUC)
2020-2035 (plantation on savannah, high C-stock)
2035-2050 (plantation on savannah, high C-stock)
+2050 (plantation on savannah, high C-stock)
Straw boiler
Straw CHP continuous
Manure-straw biog. CHP
Manure-straw biog+H2 SNG CHP fl
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 68

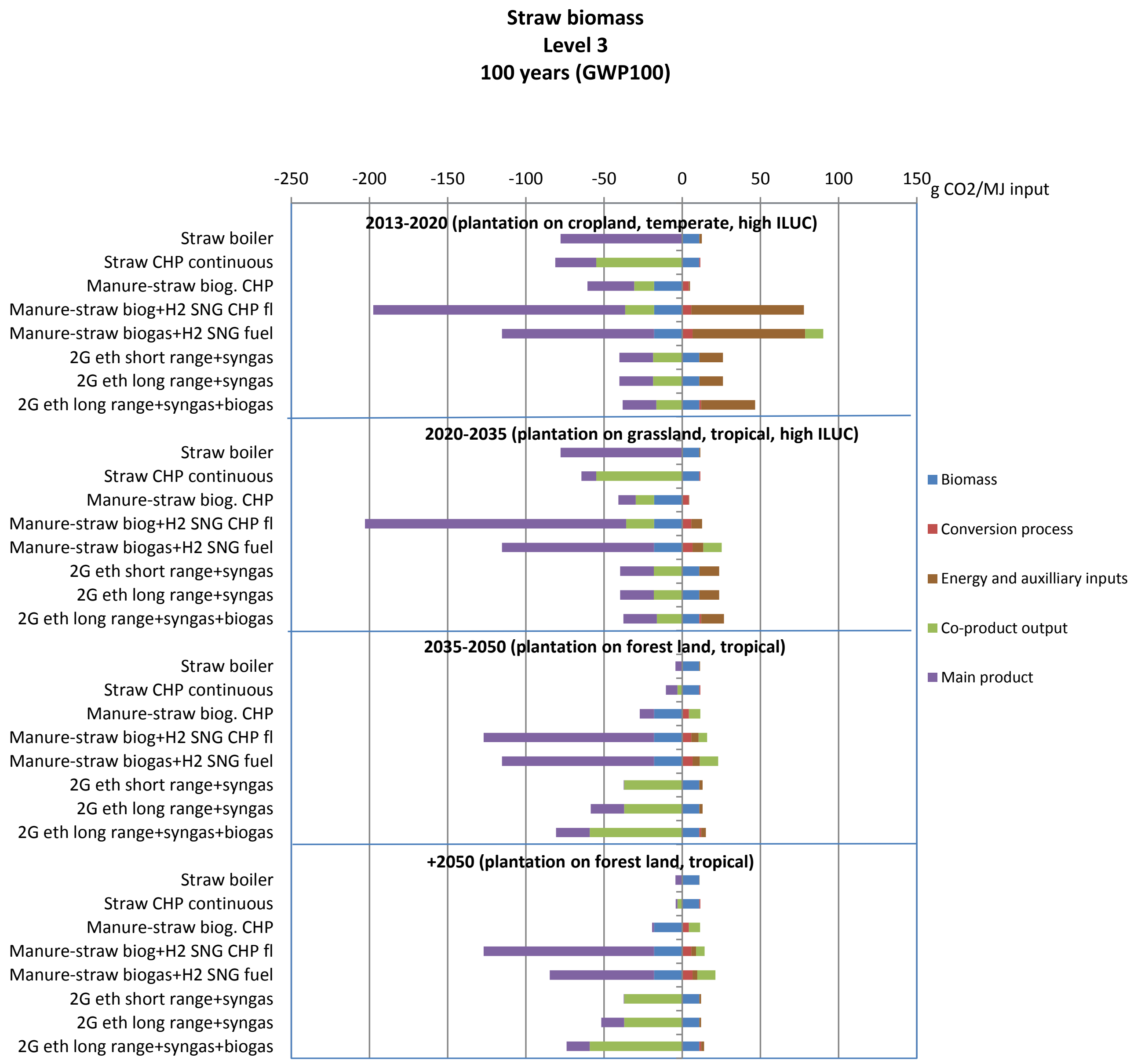

Straw biomass
Level 3
100 years (GWP100)
-250
-200
-150
-100
-50
0
50
100
150
g CO2/MJ input
2013-2020 (plantation on cropland, temperate, high ILUC)
2020-2035 (plantation on grassland, tropical, high ILUC)
2035-2050 (plantation on forest land, tropical)
+2050 (plantation on forest land, tropical)
Straw boiler
Straw CHP continuous
Manure-straw biog. CHP
Manure-straw biog+H2 SNG CHP fl
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 69

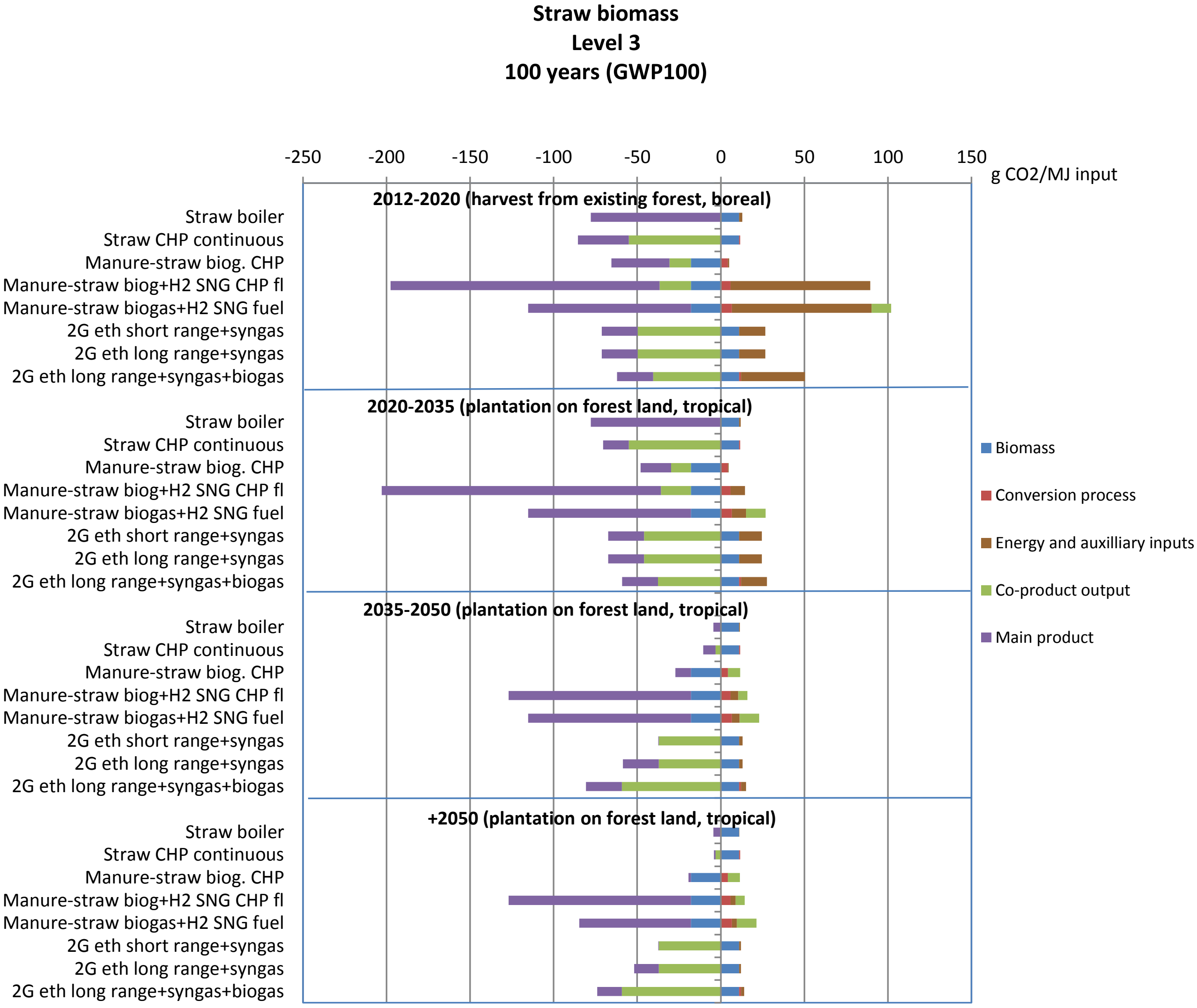

Straw biomass
Level 3
100 years (GWP100)
-250
-200
-150
-100
-50
0
50
100
150
g CO2/MJ input
2012-2020 (harvest from existing forest, boreal)
2020-2035 (plantation on forest land, tropical)
2035-2050 (plantation on forest land, tropical)
+2050 (plantation on forest land, tropical)
Straw boiler
Straw CHP continuous
Manure-straw biog. CHP
Manure-straw biog+H2 SNG CHP fl
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output
Main product

Figure 70

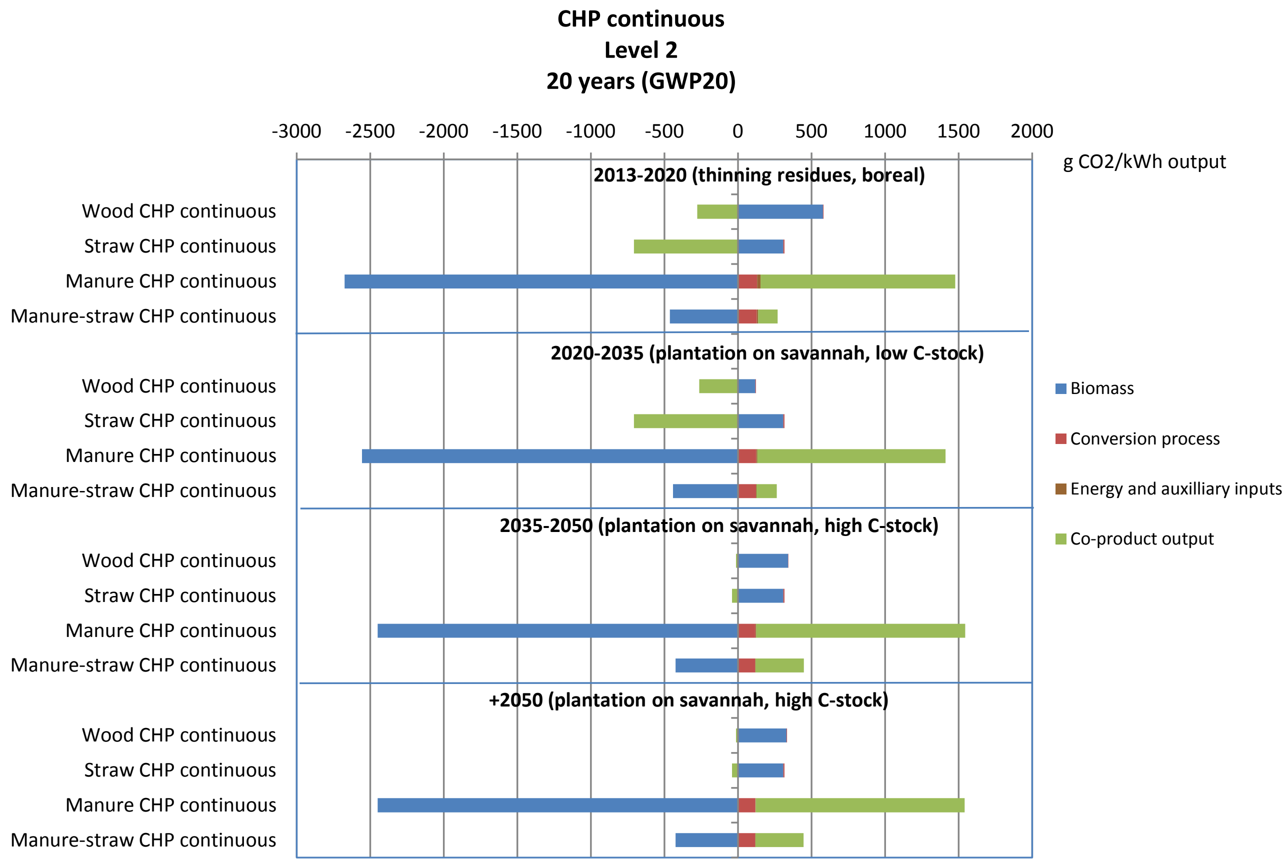

CHP continuous
Level 2
20 years (GWP20)
-3000
-2500
-2000
-1500
-1000
-500
0
500
1000
1500
2000
g CO2/kWh output
2013-2020 (thinning residues, boreal)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
2020-2035 (plantation on savannah, low C-stock)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
2035-2050 (plantation on savannah, high C-stock)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
+2050 (plantation on savannah, high C-stock)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output

Figure 71

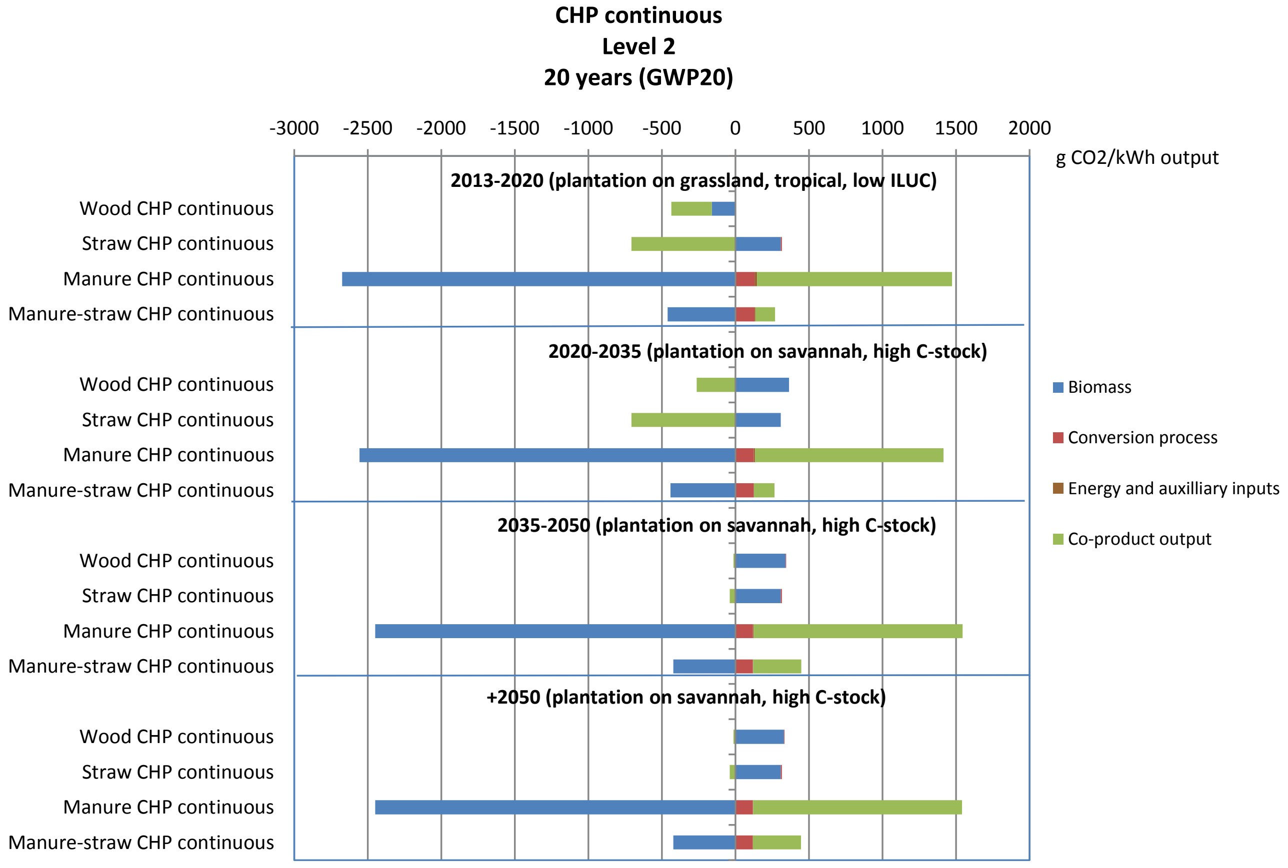

CHP continuous
Level 2
20 years (GWP20)
-3000
-2500
-2000
-1500
-1000
-500
0
500
1000
1500
2000
g CO2/kWh output
2013-2020 (plantation on grassland, tropical, low ILUC)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
2020-2035 (plantation on savannah, high C-stock)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
2035-2050 (plantation on savannah, high C-stock)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
+2050 (plantation on savannah, high C-stock)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output

Figure 72

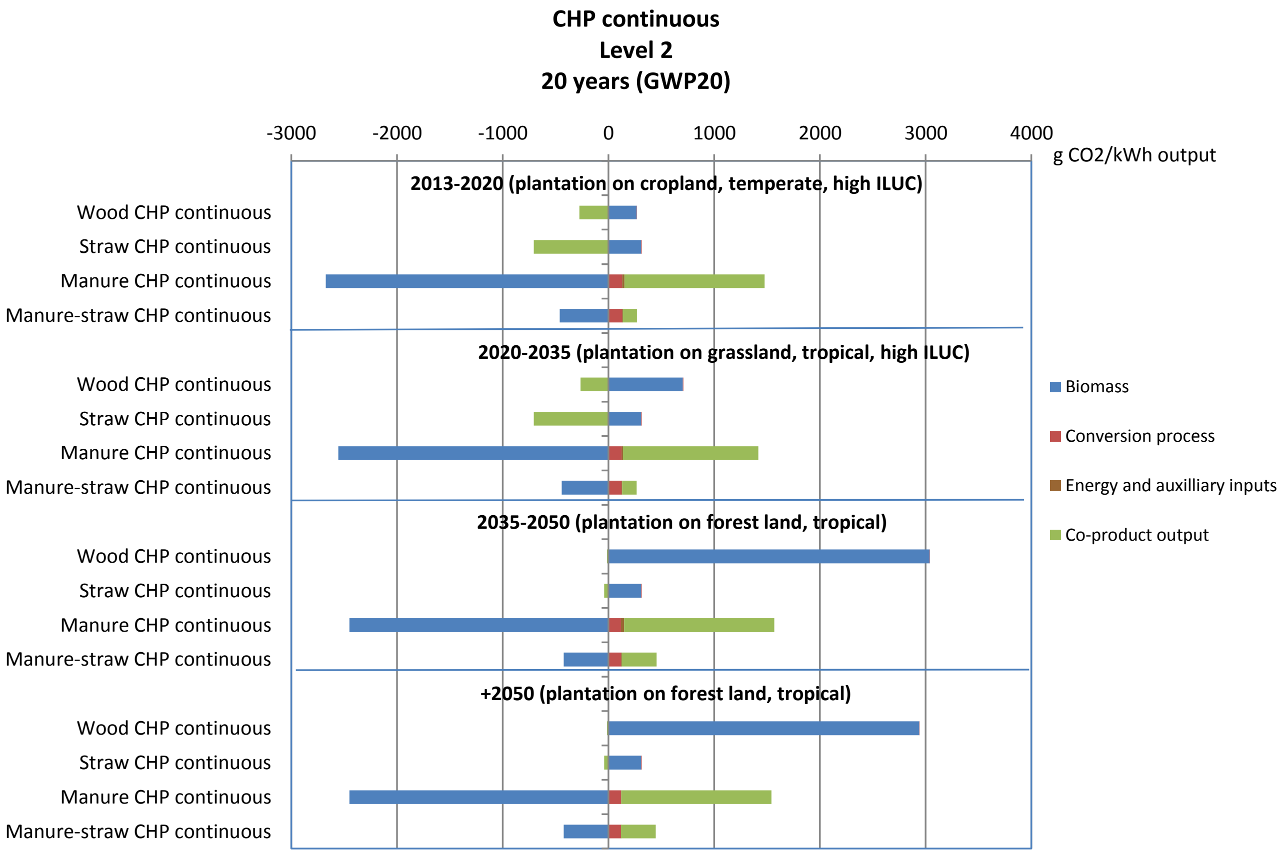

CHP continuous
Level 2
20 years (GWP20)
-3000
-2000
-1000
0
1000
2000
3000
4000
g CO2/kWh output
2013-2020 (plantation on cropland, temperate, high ILUC)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
2020-2035 (plantation on grassland, tropical, high ILUC)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
2035-2050 (plantation on forest land, tropical)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
+2050 (plantation on forest land, tropical)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output

Figure 73

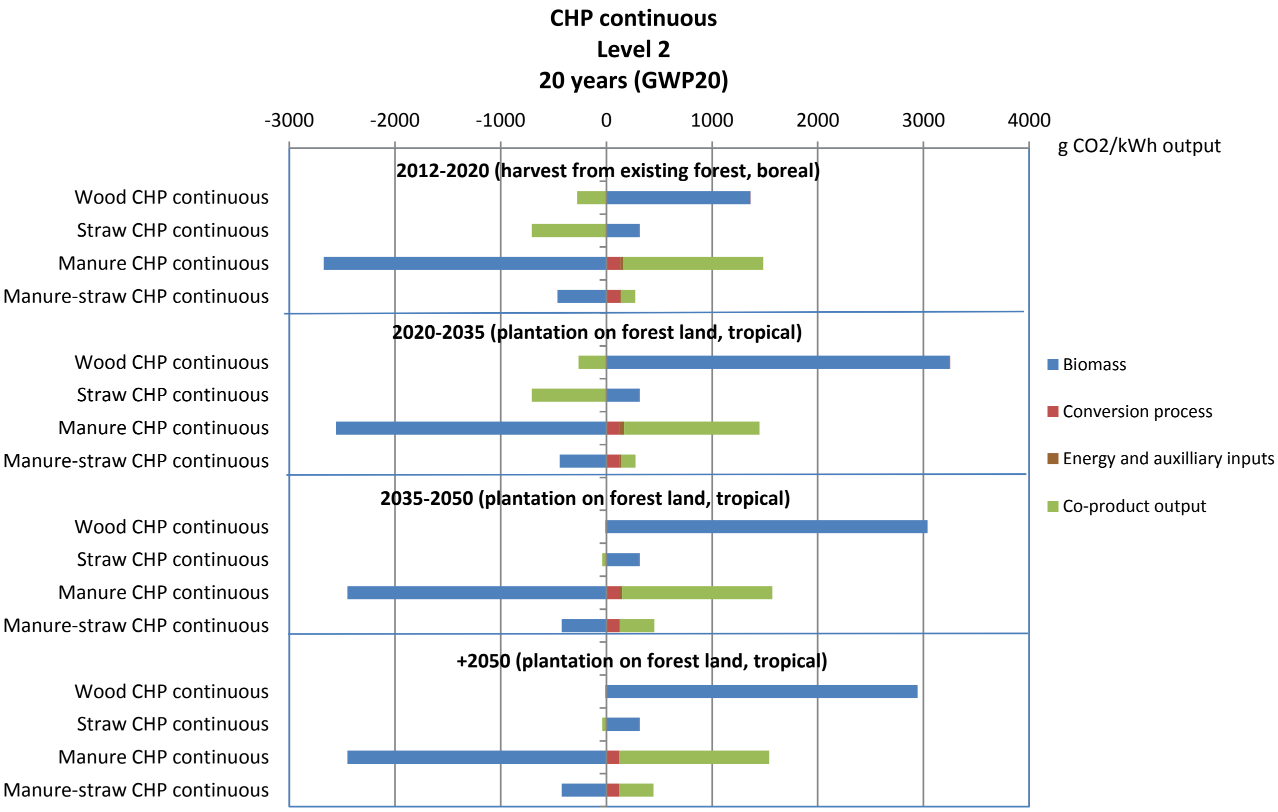

CHP continuous
Level 2
20 years (GWP20)
-3000
-2000
-1000
0
1000
2000
3000
4000
g CO2/kWh output
2012-2020 (harvest from existing forest, boreal)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
2020-2035 (plantation on forest land, tropical)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
2035-2050 (plantation on forest land, tropical)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
+2050 (plantation on forest land, tropical)
Wood CHP continuous
Straw CHP continuous
Manure CHP continuous
Manure-straw CHP continuous
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output

Figure 74

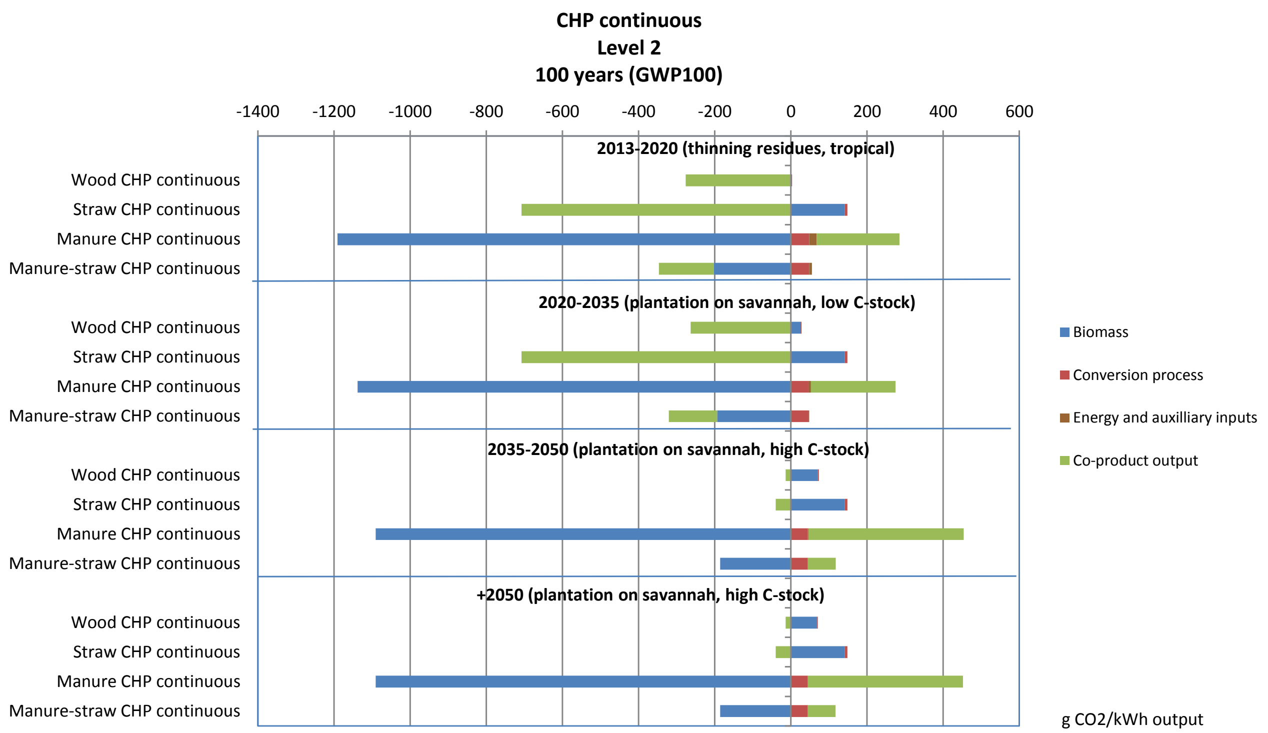


Figure 75

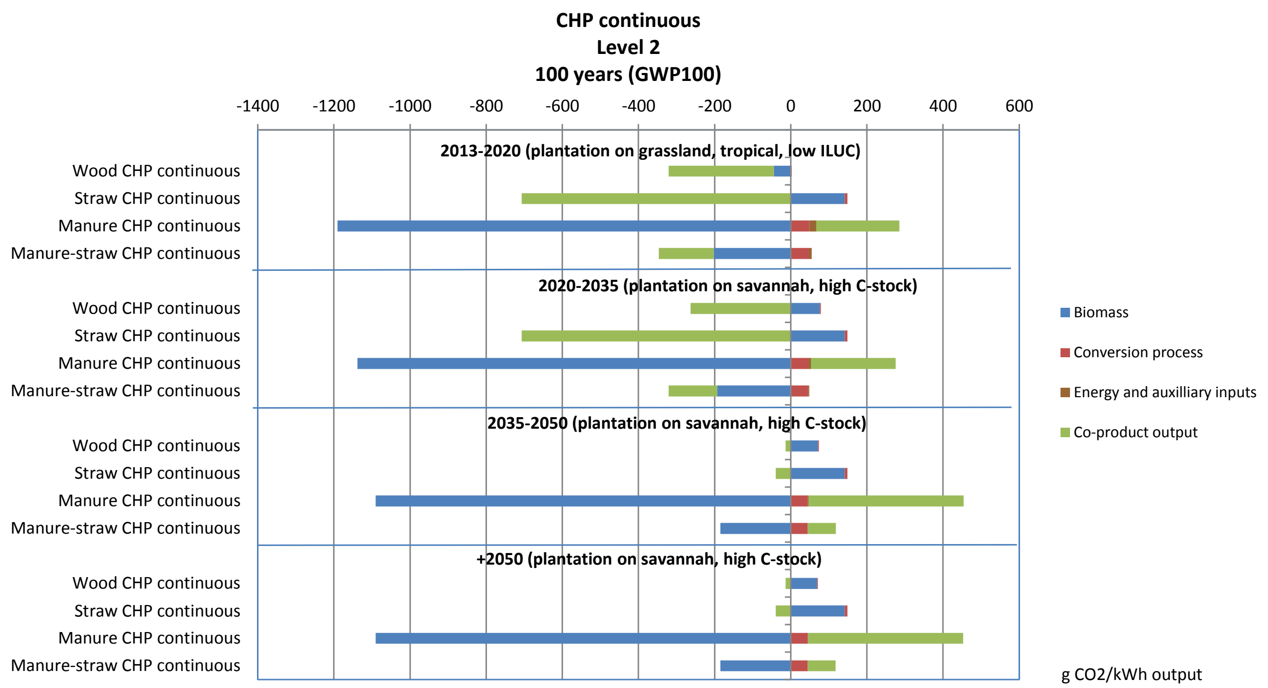


Figure 76

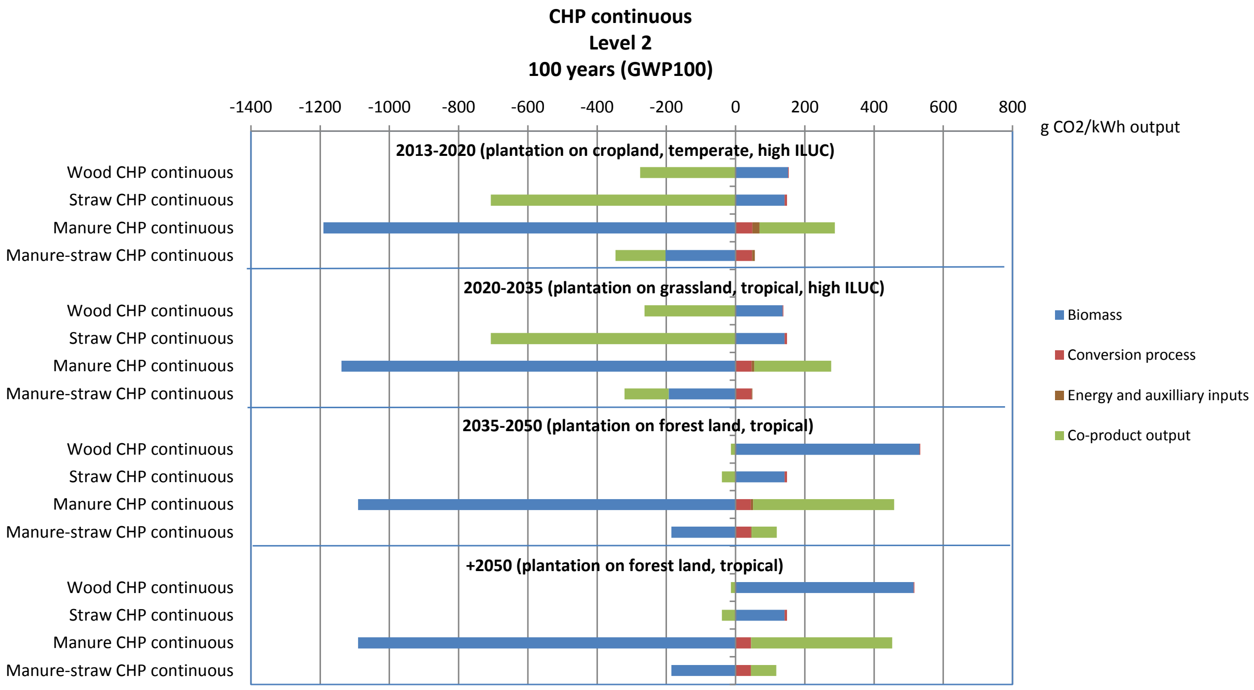


Figure 77

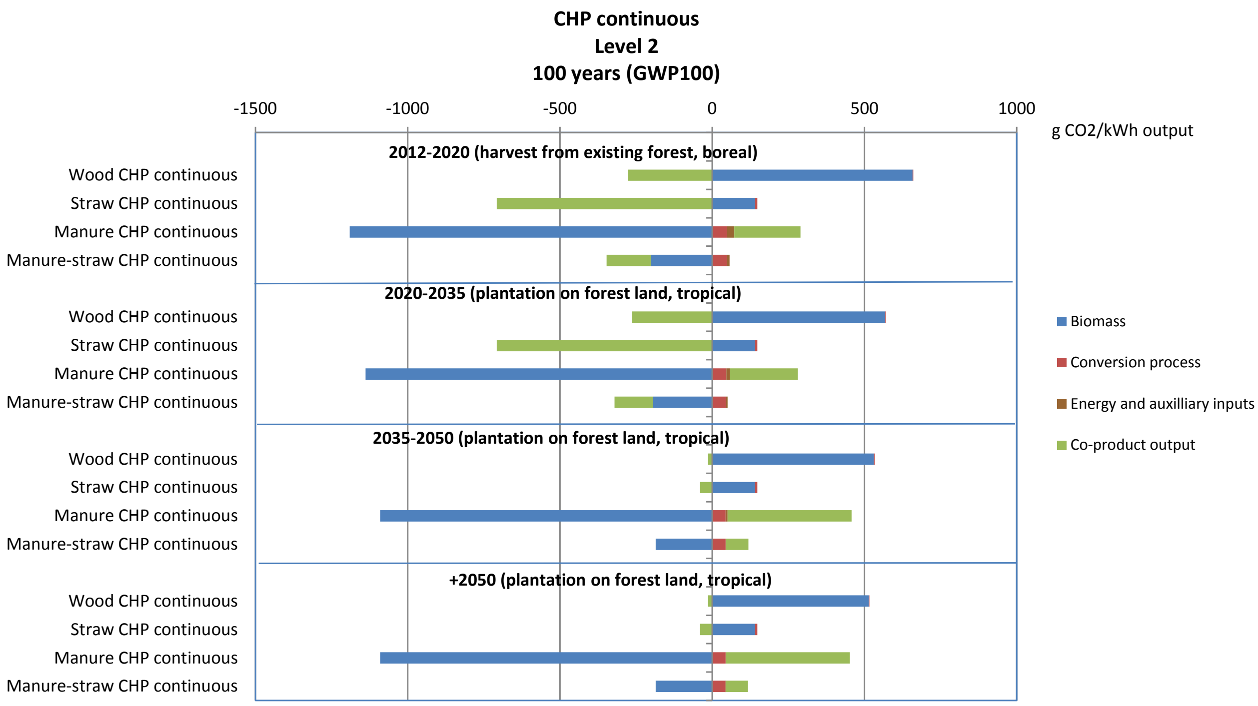


Figure 78

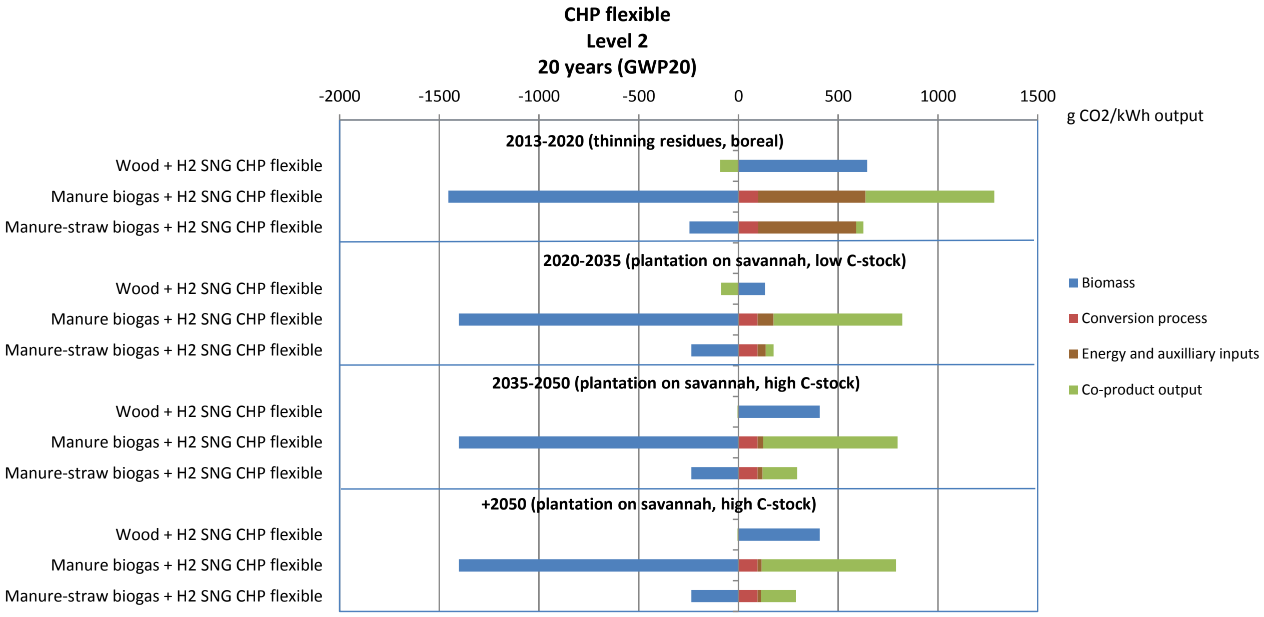


Figure 79

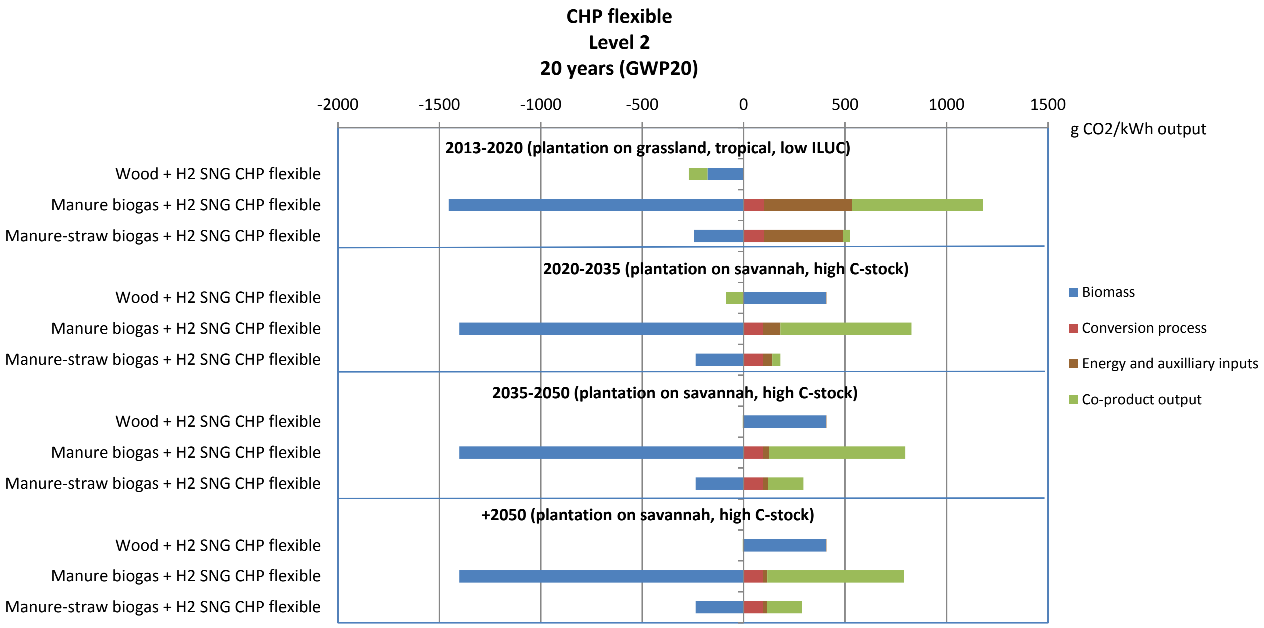


Figure 80

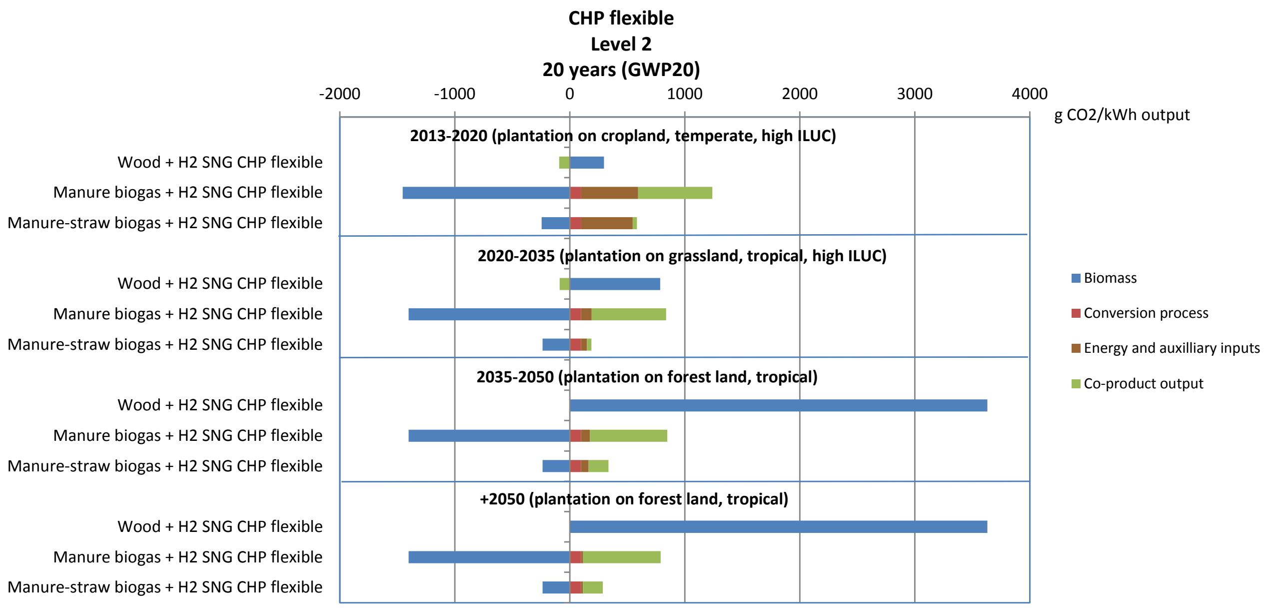


Figure 81

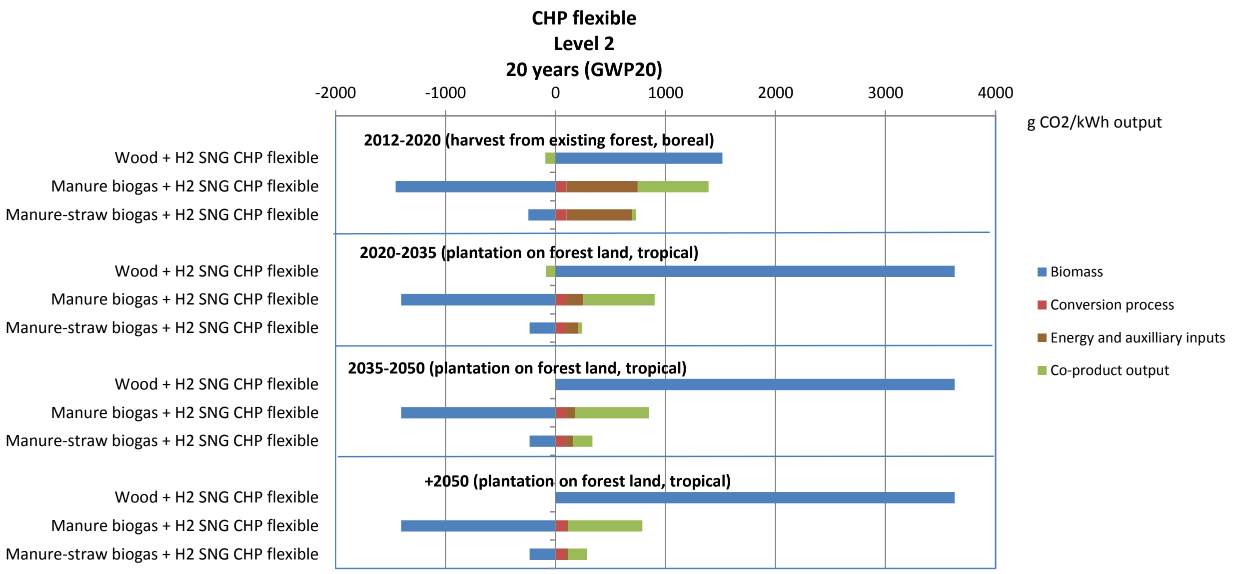


Figure 82

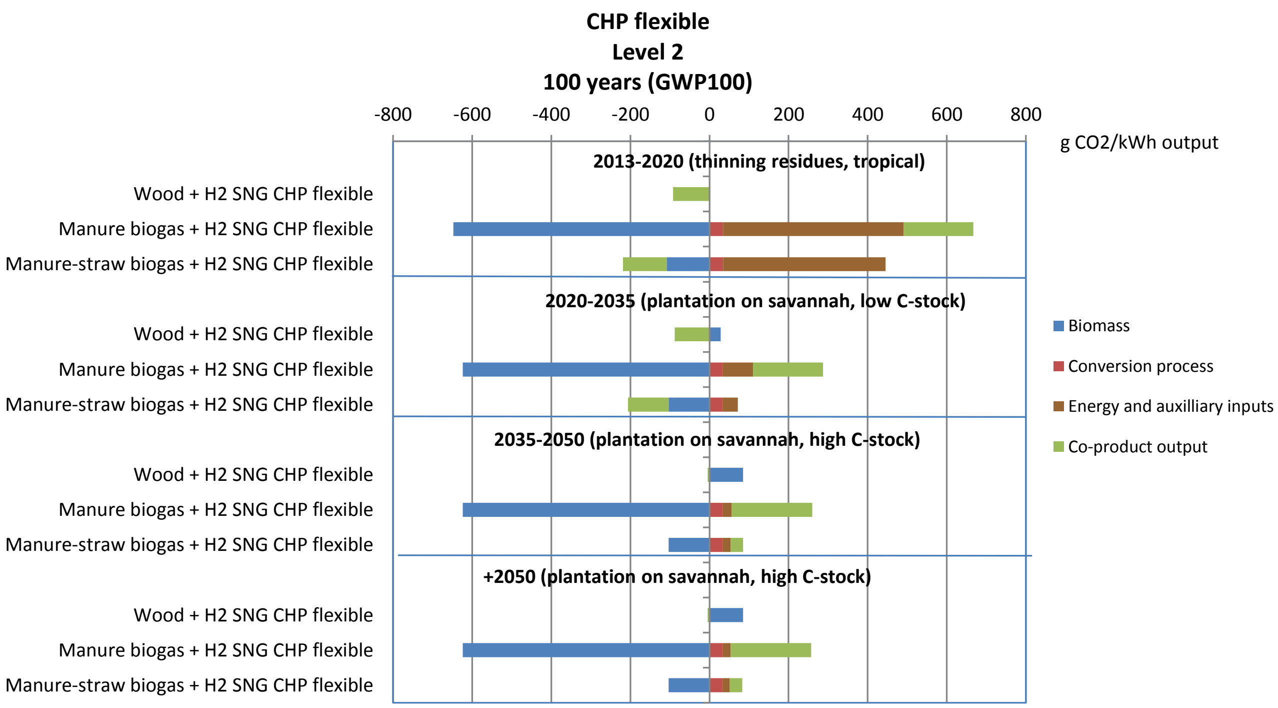


Figure 83

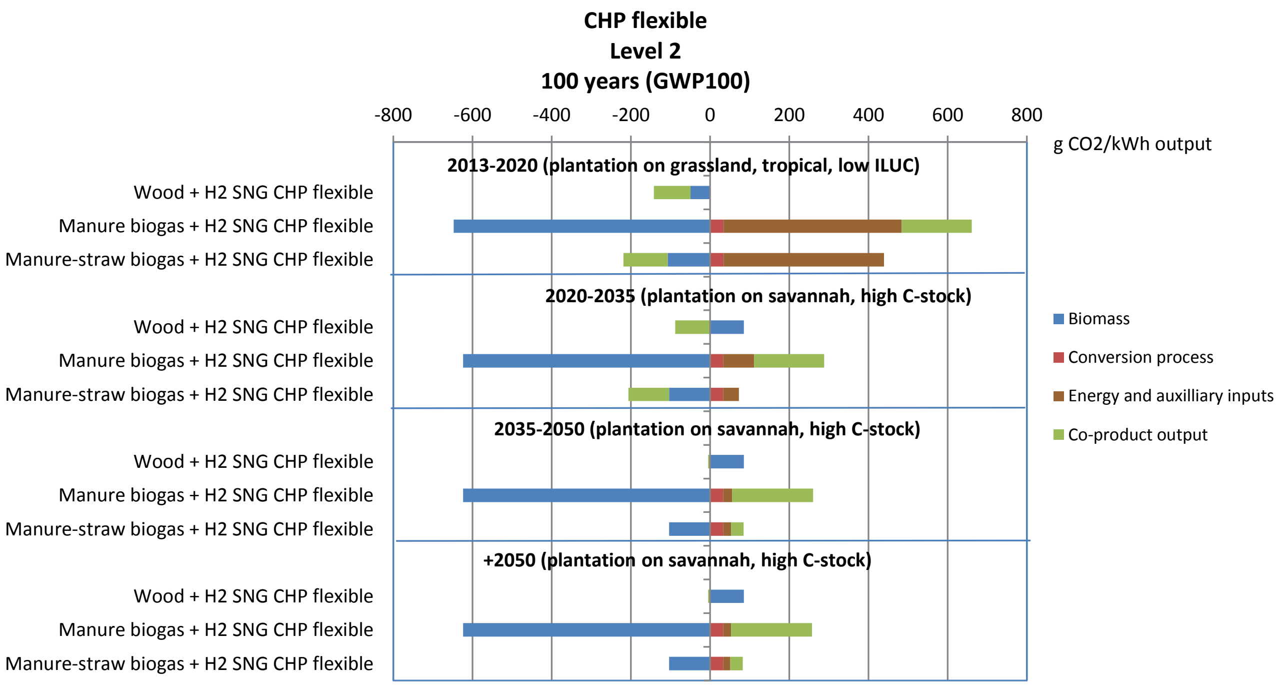


Figure 84

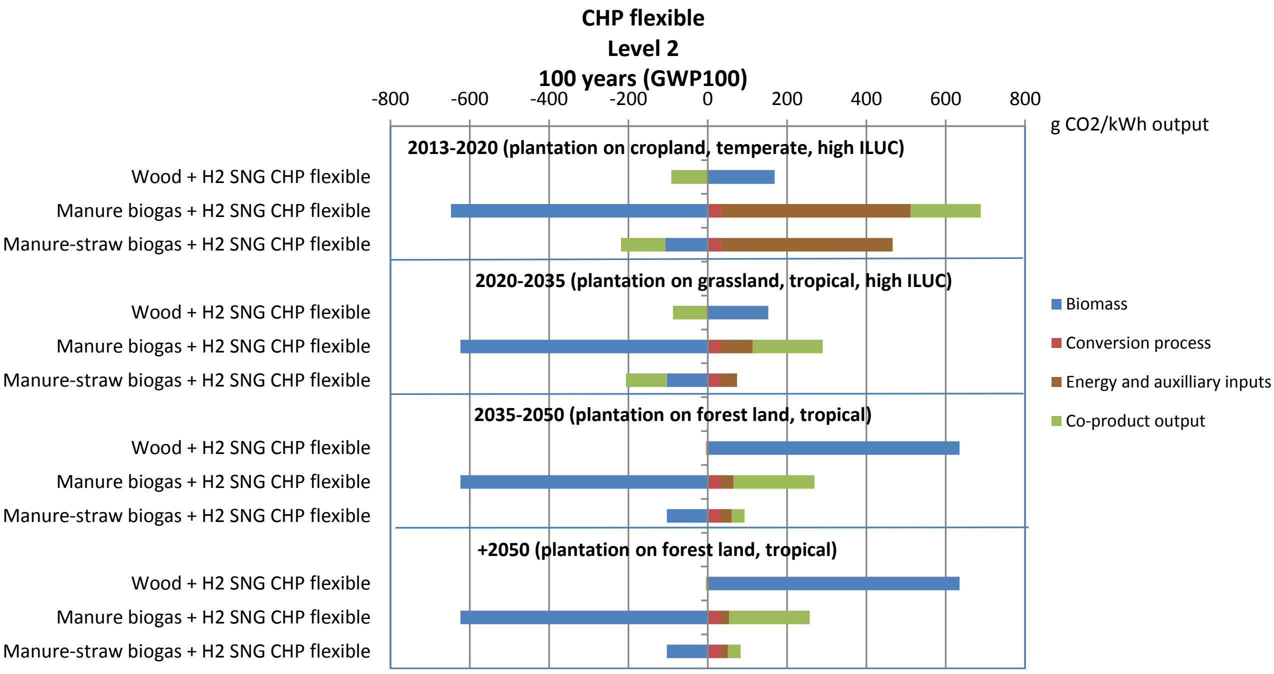


Figure 85

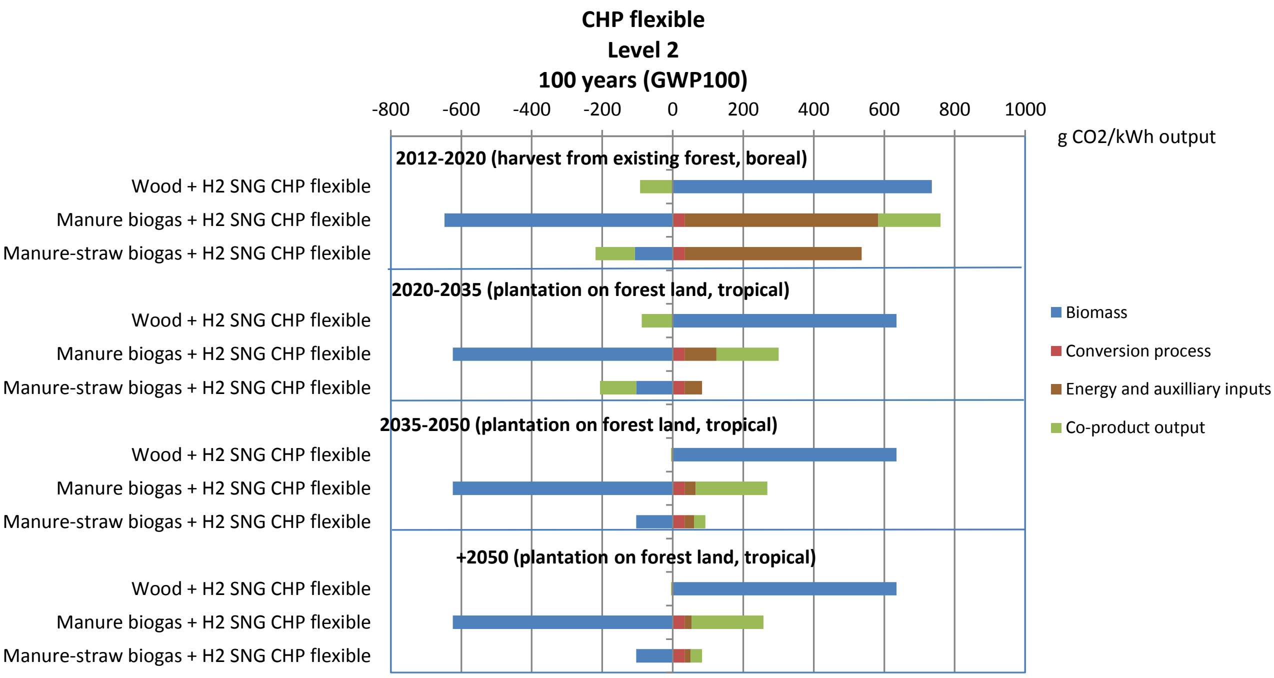


Figure 86

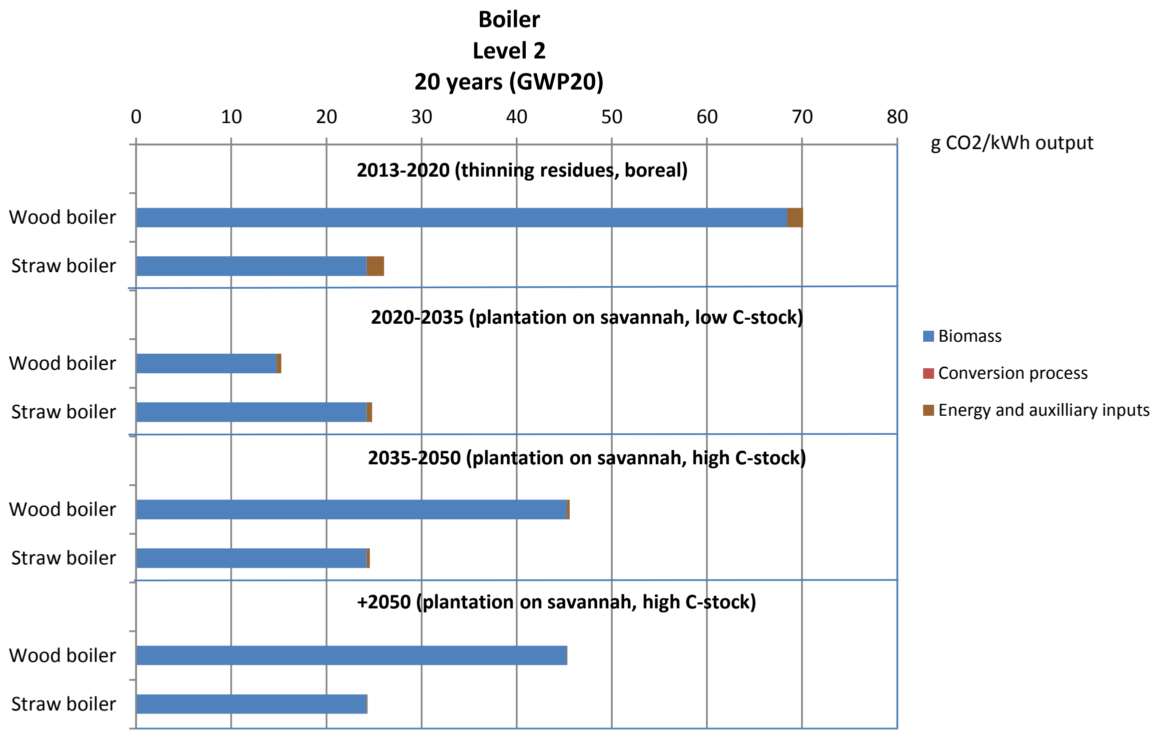


Figure 87

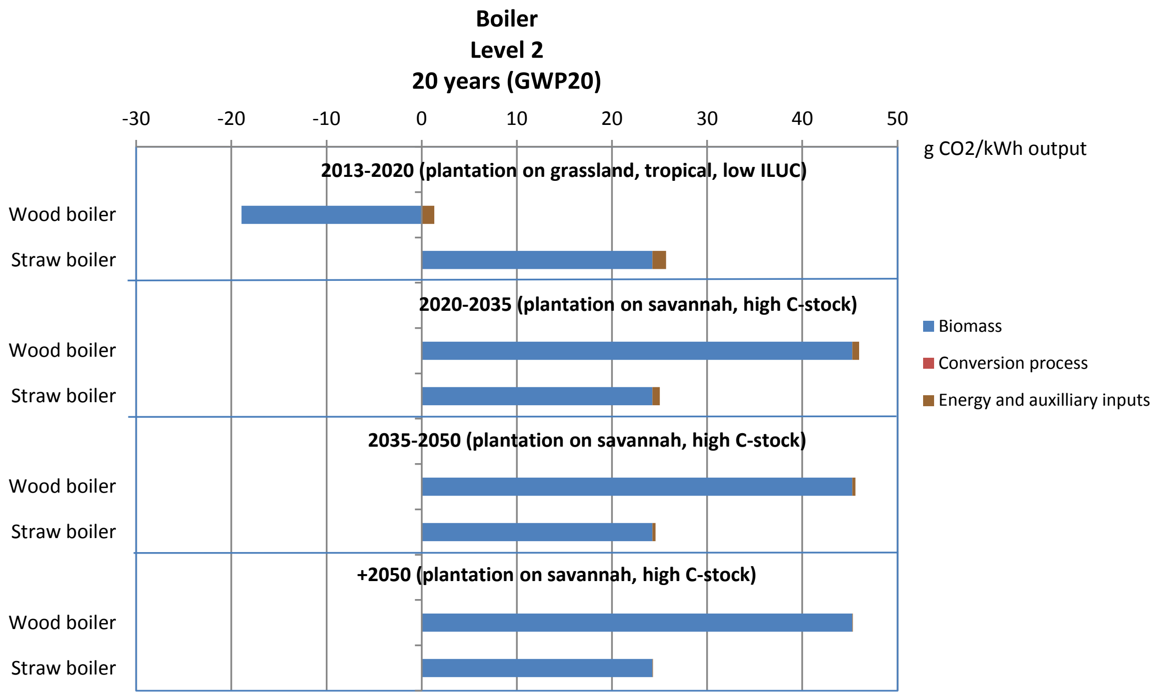


Figure 88

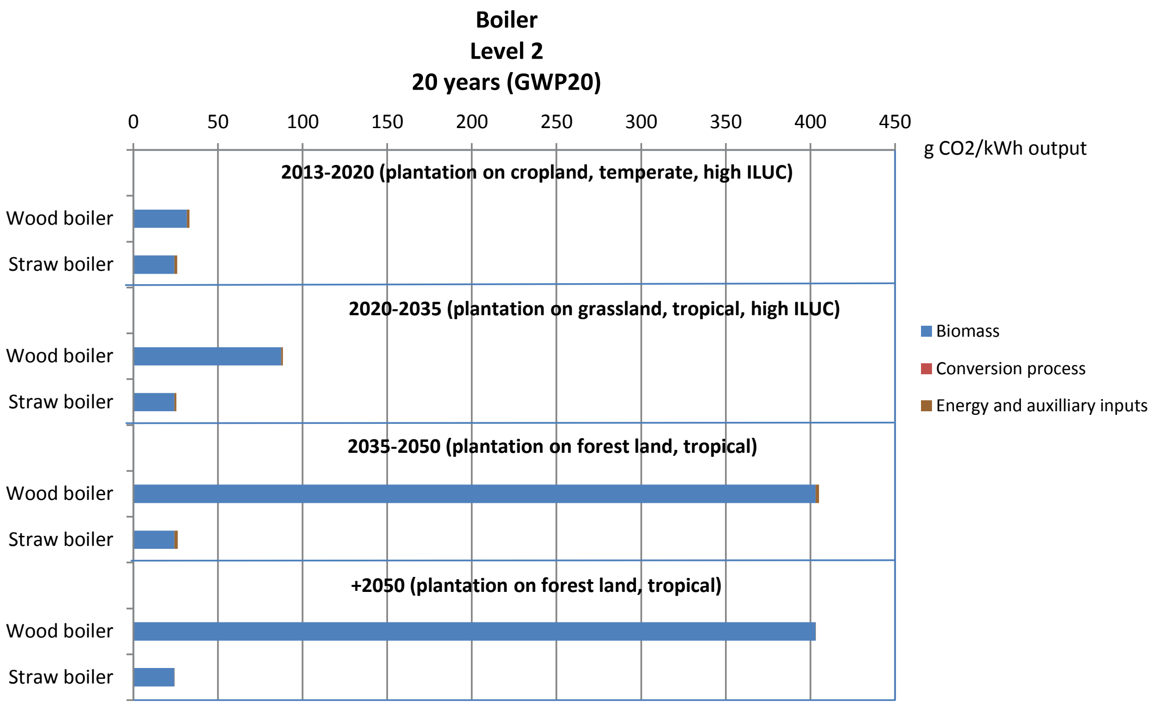


Figure 89

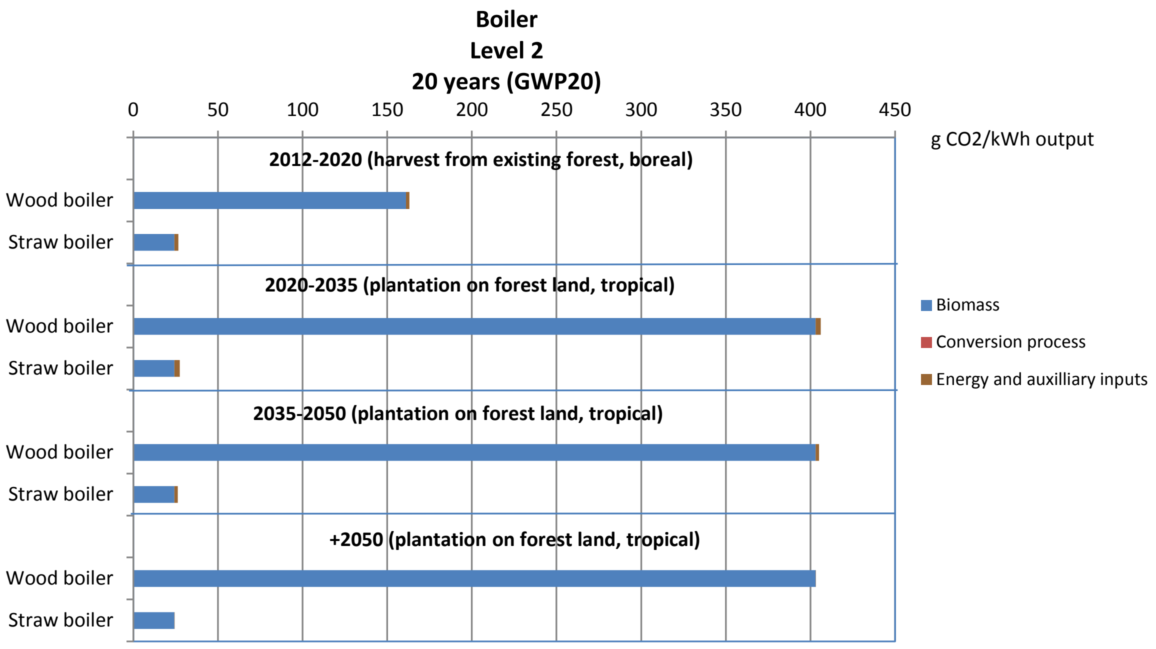


Figure 90

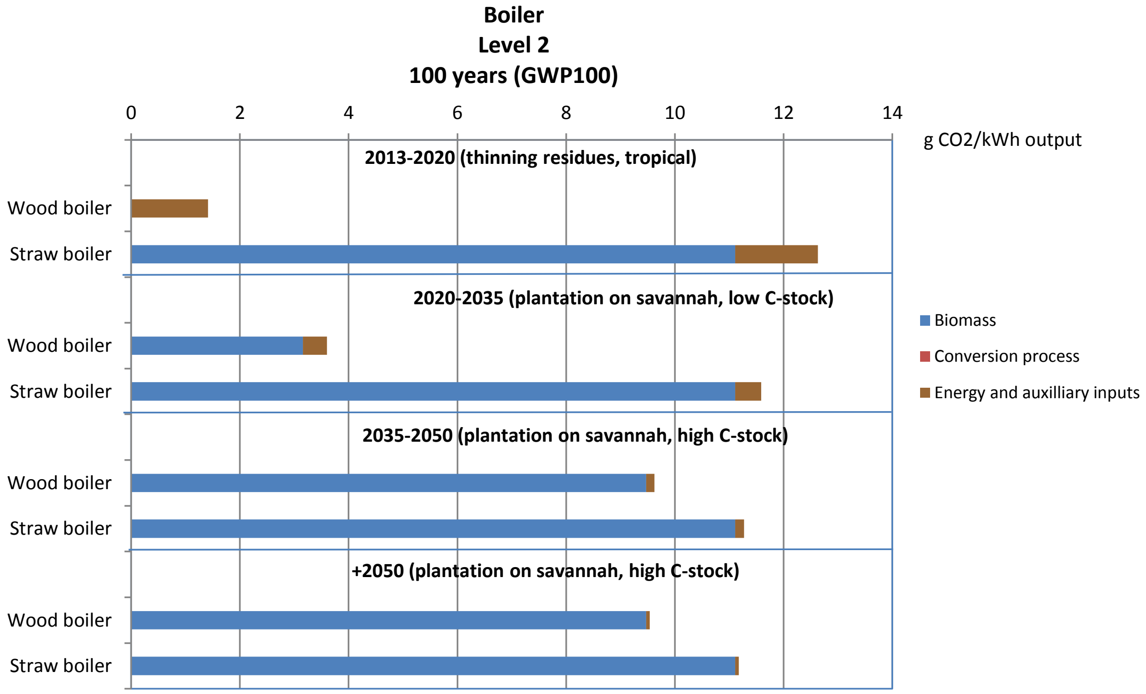


Figure 91

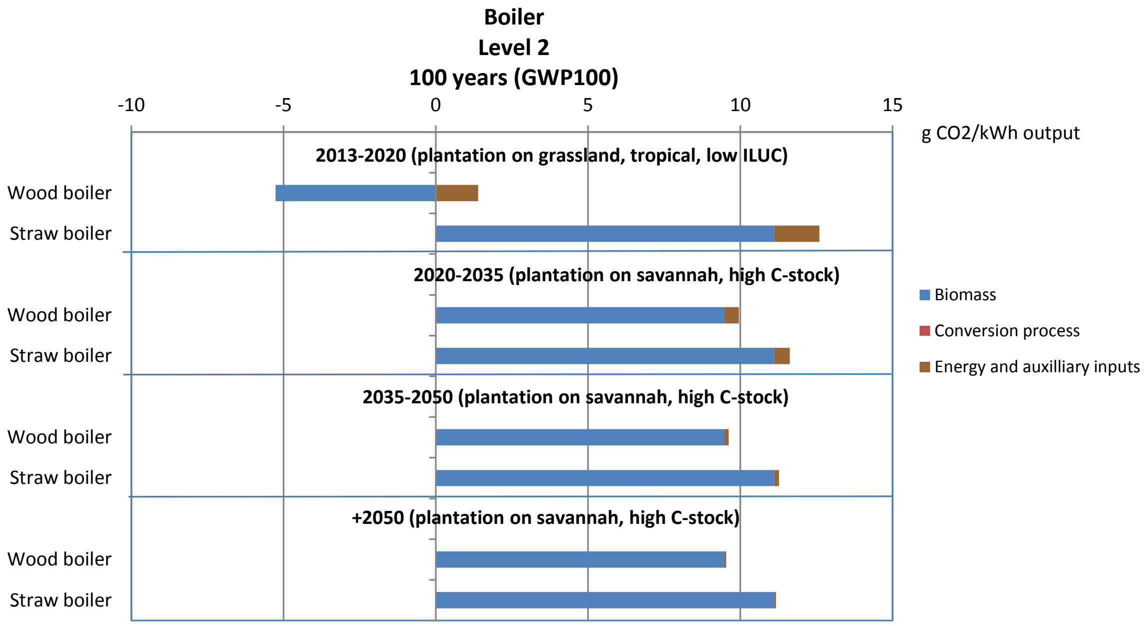


Figure 92

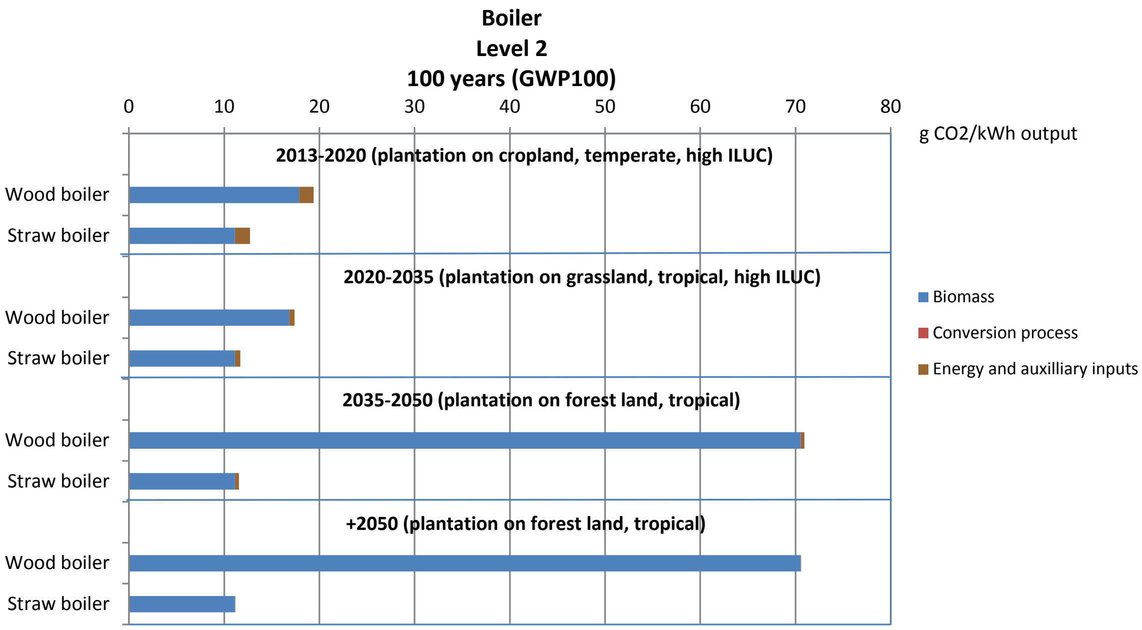


Figure 93

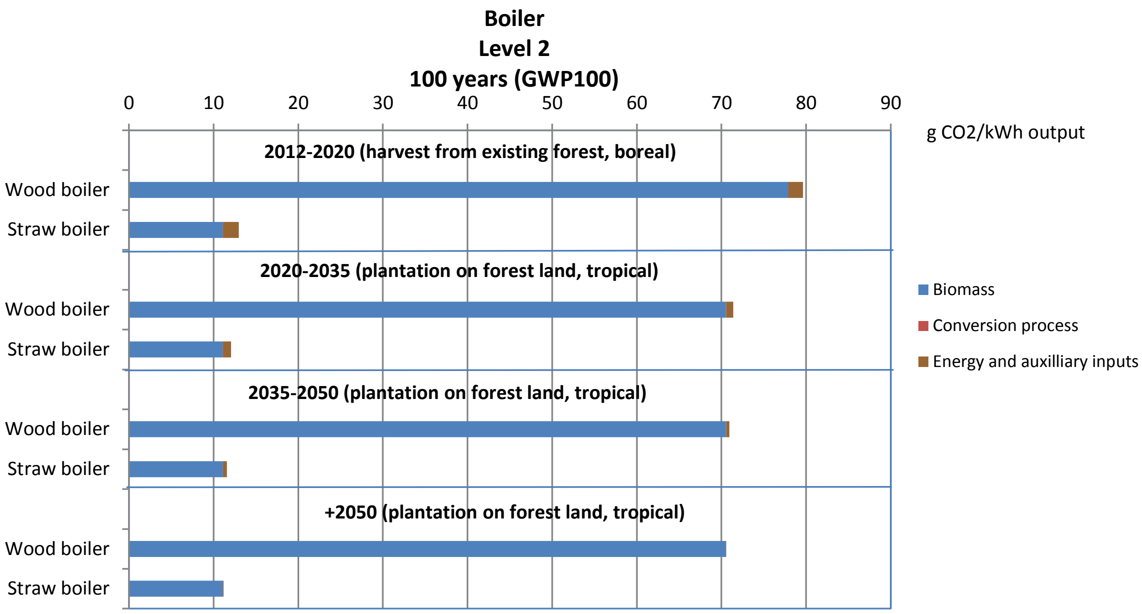


Figure 94

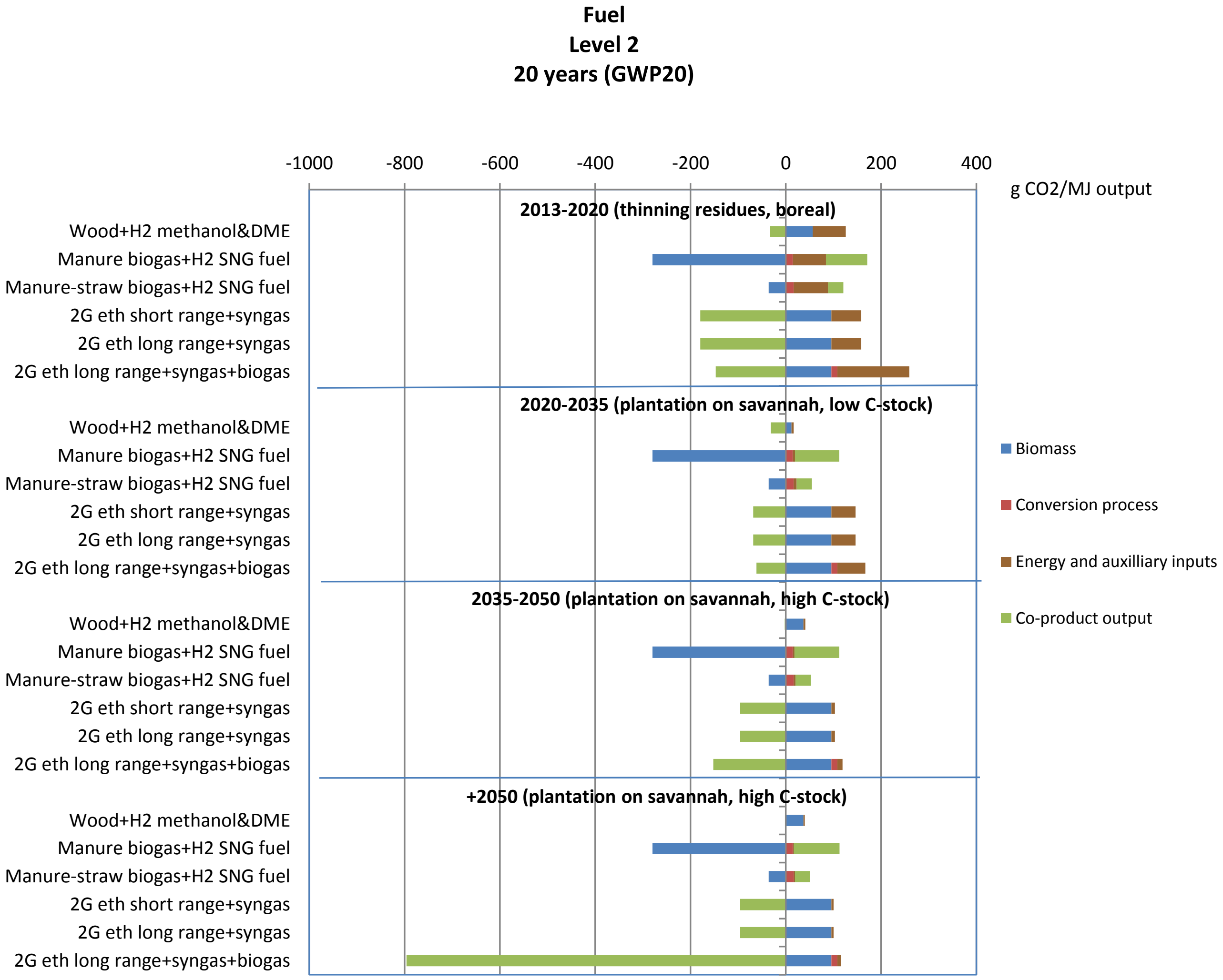

Fuel
Level 2
20 years (GWP20)
-1000
-800
-600
-400
-200
0
200
400
g CO2/MJ output
2013-2020 (thinning residues, boreal)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
2020-2035 (plantation on savannah, low C-stock)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
2035-2050 (plantation on savannah, high C-stock)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
+2050 (plantation on savannah, high C-stock)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output

Figure 95

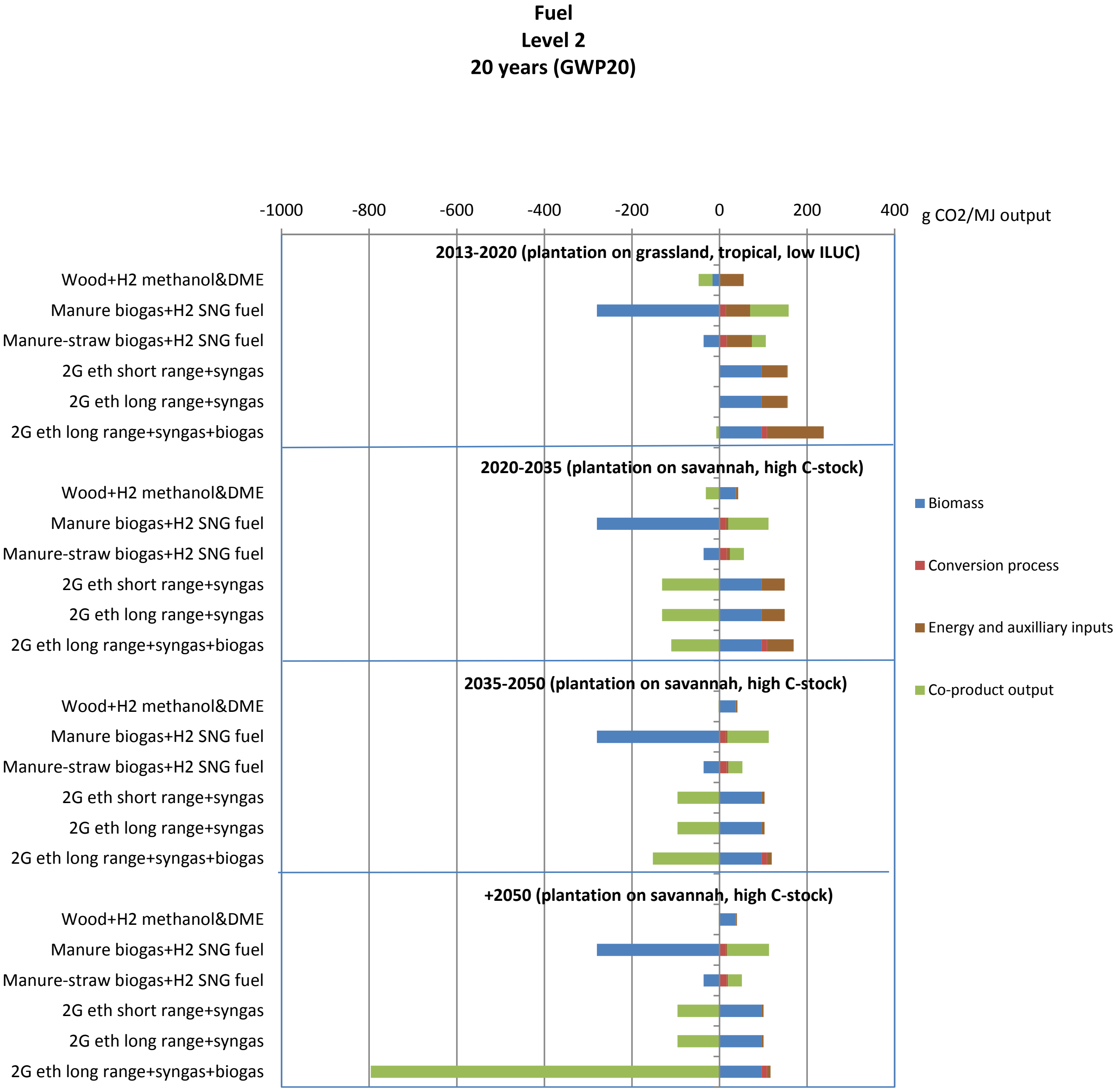

Fuel
Level 2
20 years (GWP20)
-1000
-800
-600
-400
-200
0
200
400
g CO2/MJ output
2013-2020 (plantation on grassland, tropical, low ILUC)
2020-2035 (plantation on savannah, high C-stock)
2035-2050 (plantation on savannah, high C-stock)
+2050 (plantation on savannah, high C-stock)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output

Figure 96

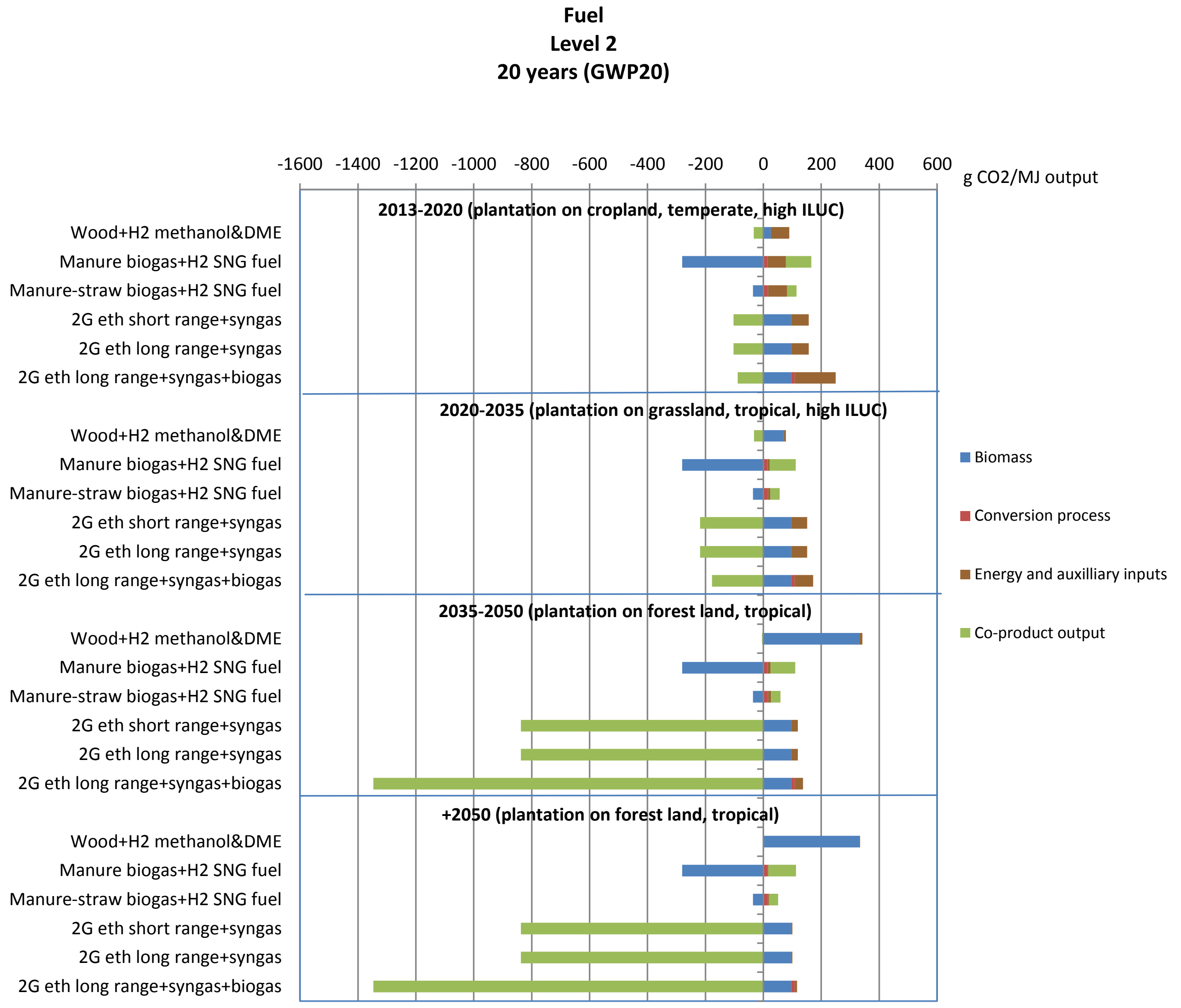

Fuel
Level 2
20 years (GWP20)
-1600
-1400
-1200
-1000
-800
-600
-400
-200
0
200
400
600
g CO2/MJ output
2013-2020 (plantation on cropland, temperate, high ILUC)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
2020-2035 (plantation on grassland, tropical, high ILUC)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
2035-2050 (plantation on forest land, tropical)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
+2050 (plantation on forest land, tropical)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output

Figure 97

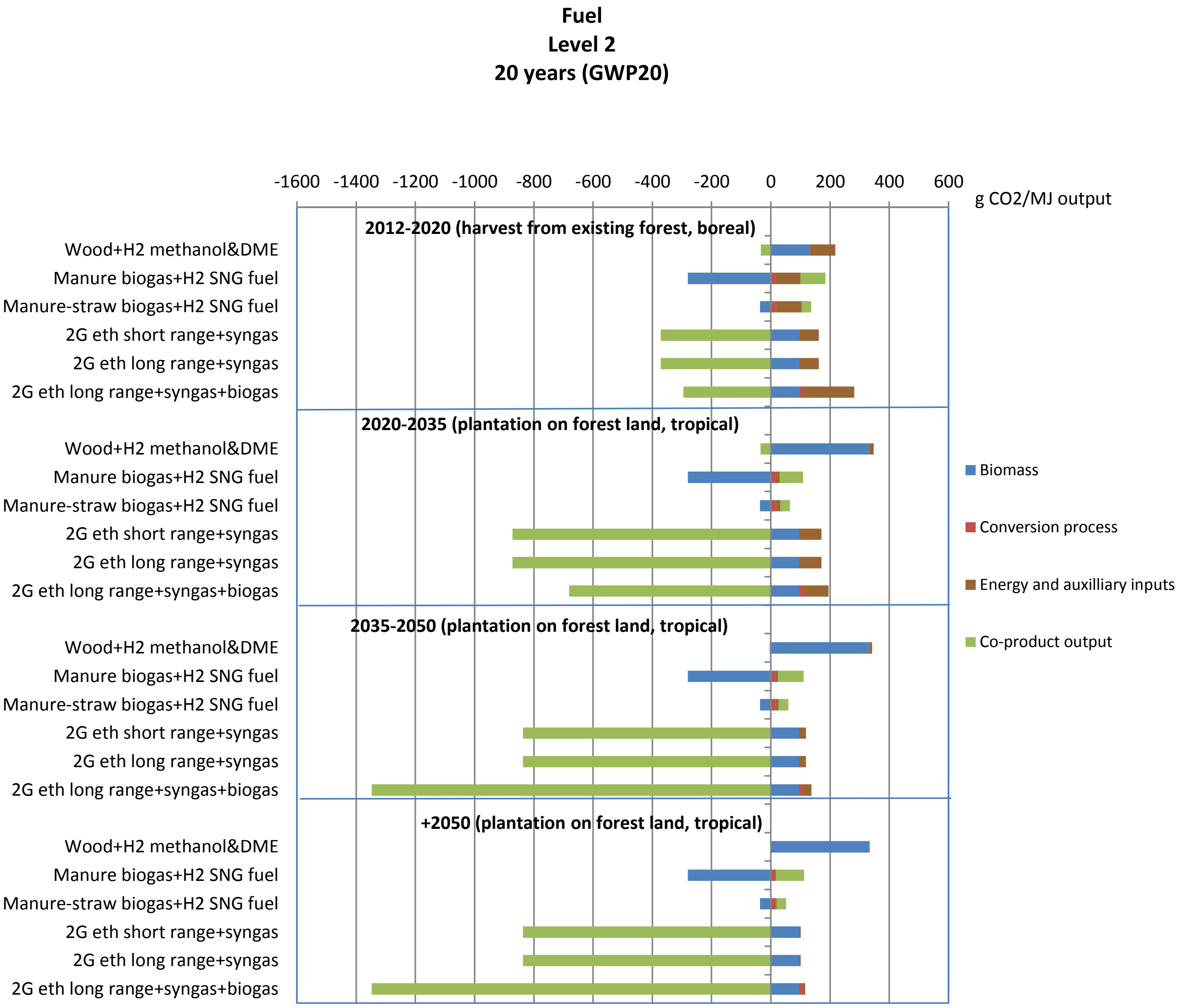

Fuel
Level 2
20 years (GWP20)
-1600 -1400 -1200 -1000 -800 -600 -400 -200 0 200 400 600
g CO2/MJ output
2012-2020 (harvest from existing forest, boreal)
2020-2035 (plantation on forest land, tropical)
2035-2050 (plantation on forest land, tropical)
+2050 (plantation on forest land, tropical)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output

Figure 98

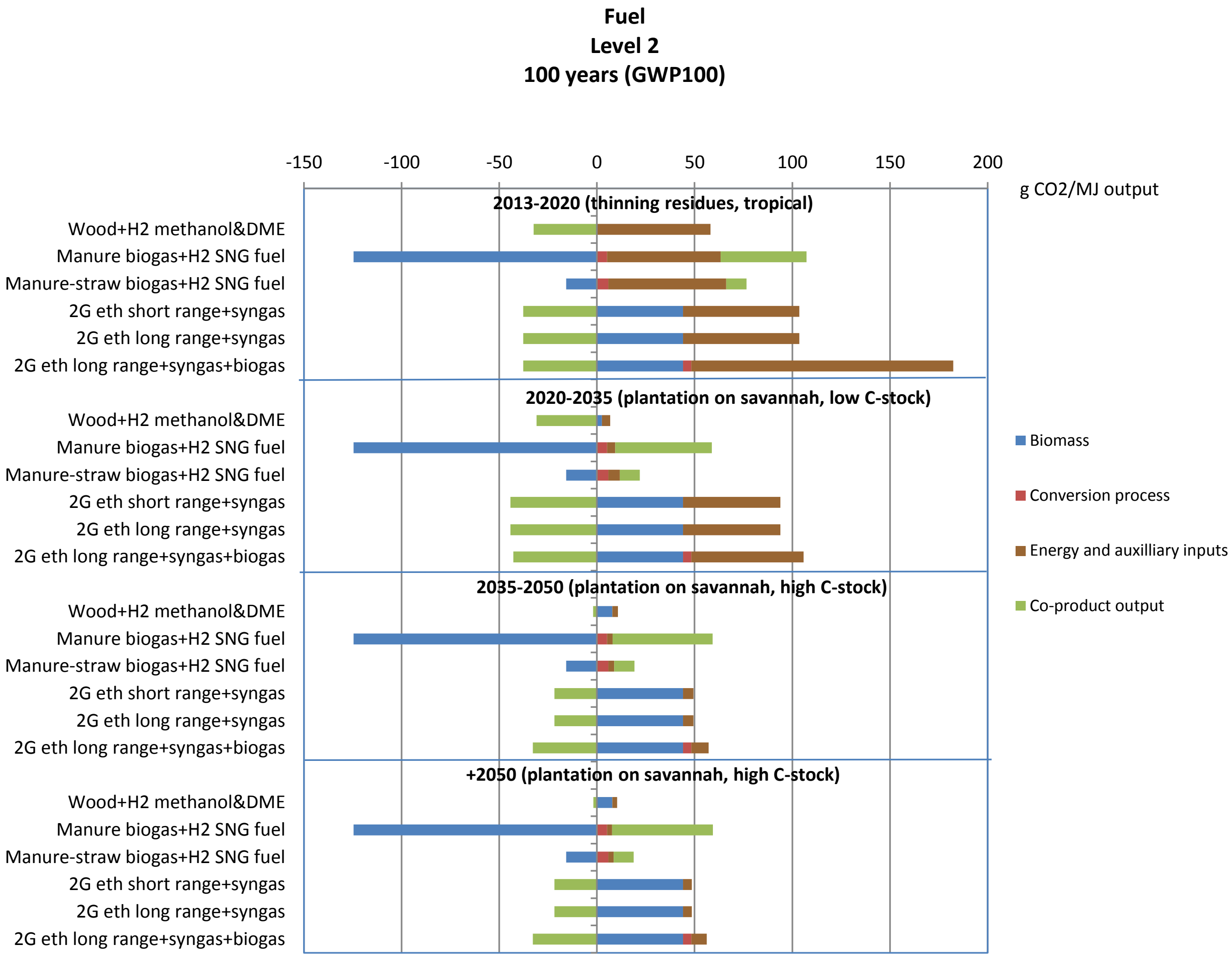

Fuel
Level 2
100 years (GWP100)
-150
-100
-50
0
50
100
150
200
g CO2/MJ output
2013-2020 (thinning residues, tropical)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
2020-2035 (plantation on savannah, low C-stock)
2035-2050 (plantation on savannah, high C-stock)
+2050 (plantation on savannah, high C-stock)
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output

Figure 99

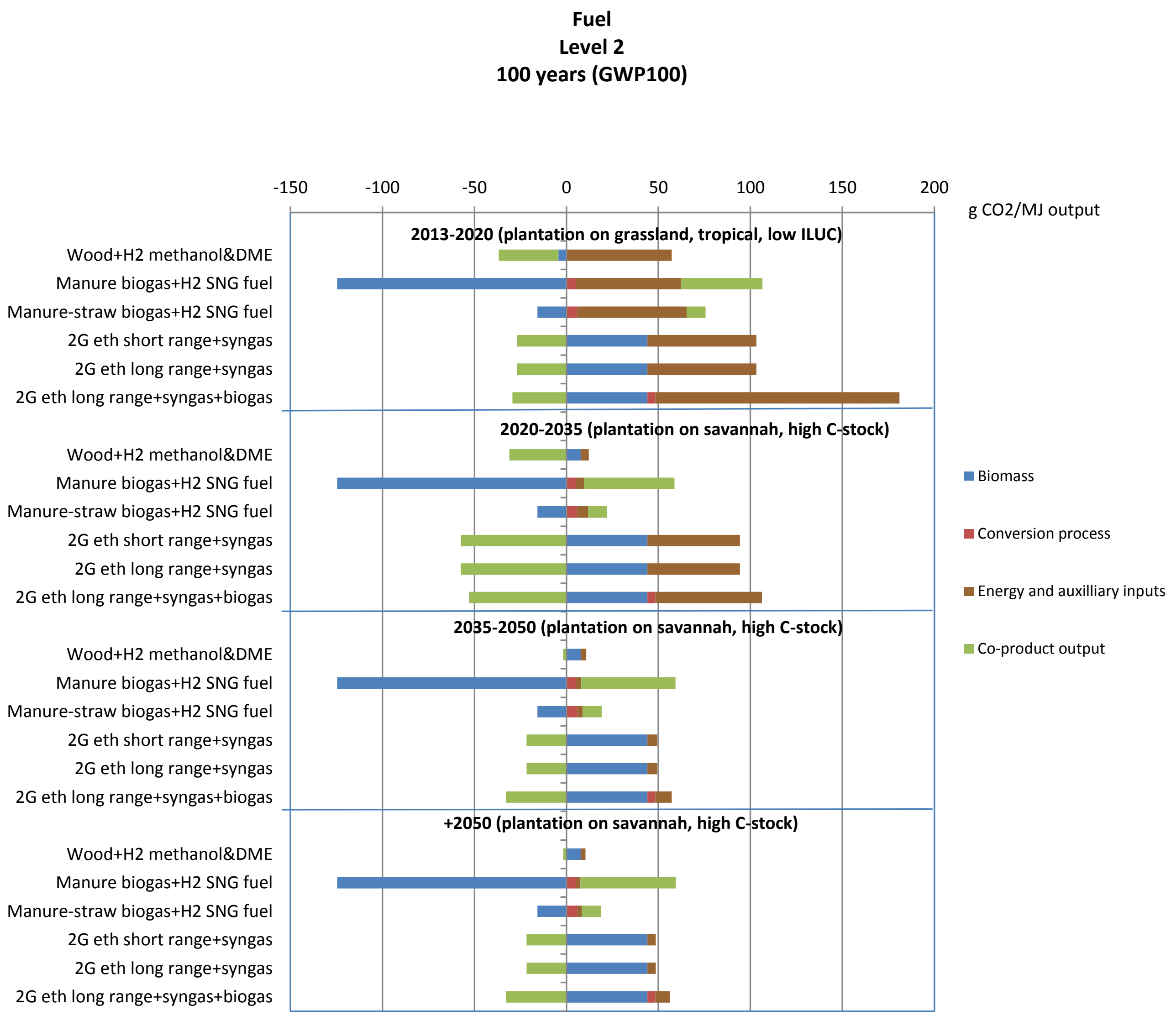

Fuel
Level 2
100 years (GWP100)
-150
-100
-50
0
50
100
150
200
g CO2/MJ output
2013-2020 (plantation on grassland, tropical, low ILUC)
2020-2035 (plantation on savannah, high C-stock)
2035-2050 (plantation on savannah, high C-stock)
+2050 (plantation on savannah, high C-stock)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output

Figure 100

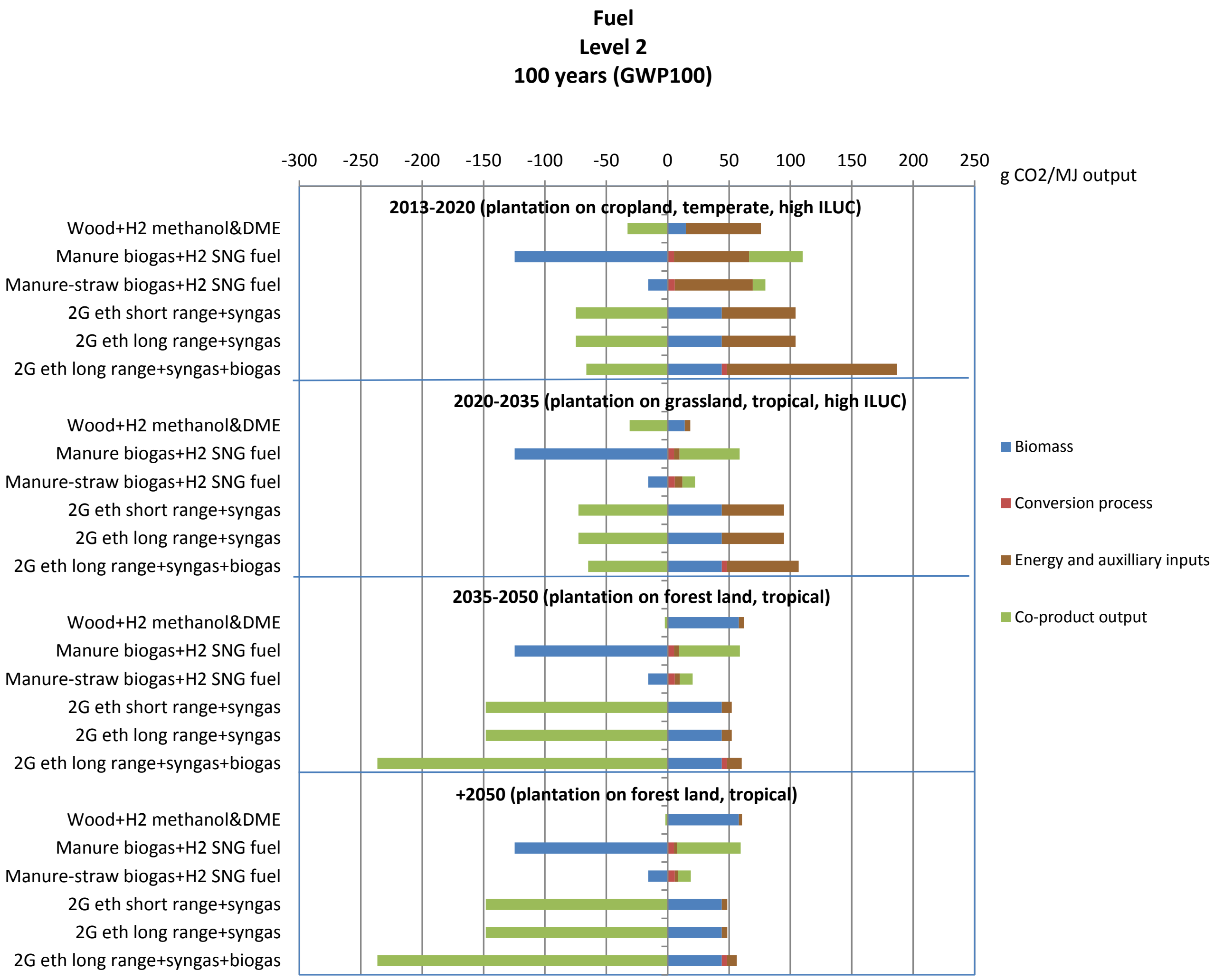

Fuel
Level 2
100 years (GWP100)
-300
-250
-200
-150
-100
-50
0
50
100
150
200
250
g CO2/MJ output
2013-2020 (plantation on cropland, temperate, high ILUC)
2020-2035 (plantation on grassland, tropical, high ILUC)
2035-2050 (plantation on forest land, tropical)
+2050 (plantation on forest land, tropical)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output

Figure 101

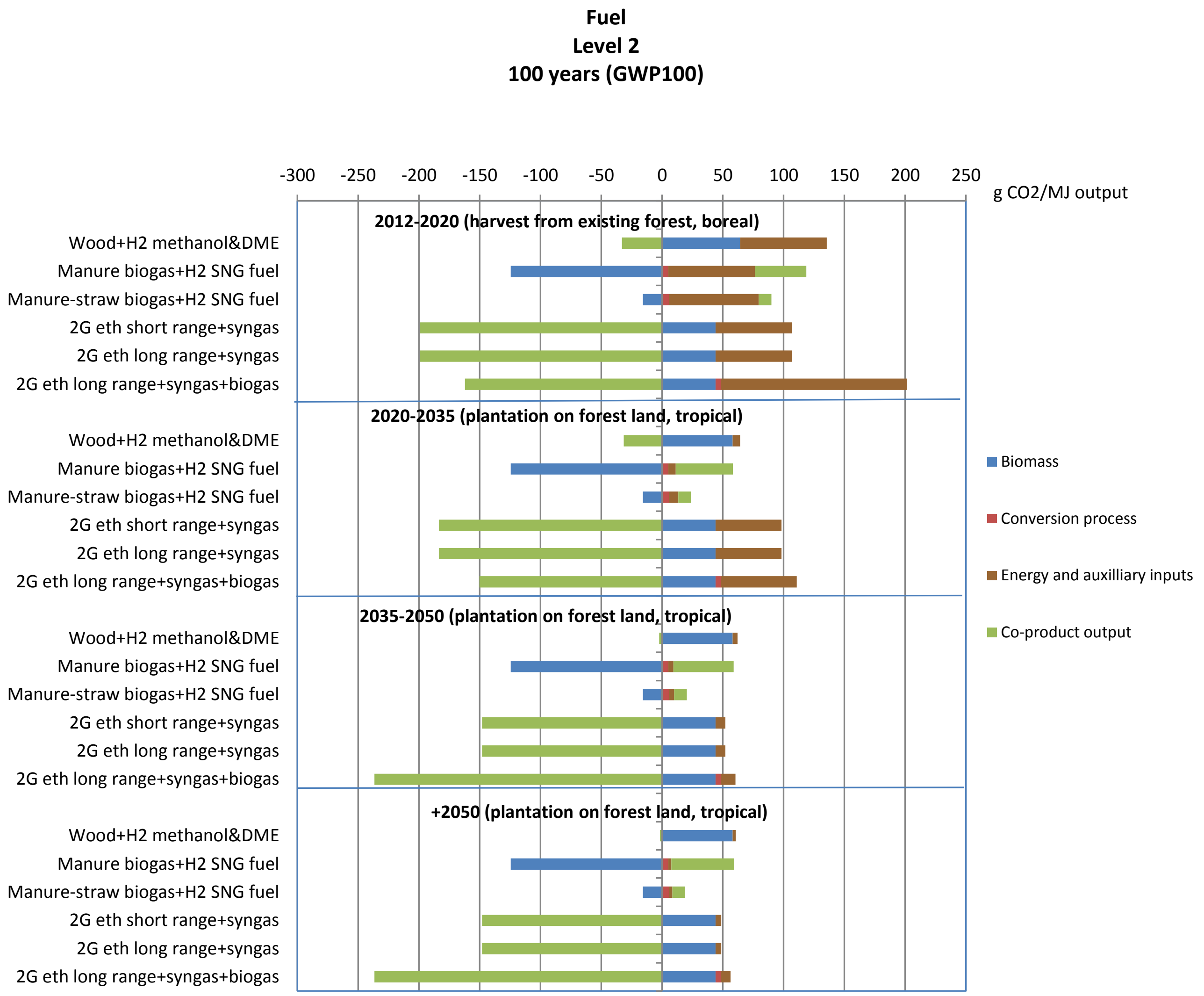
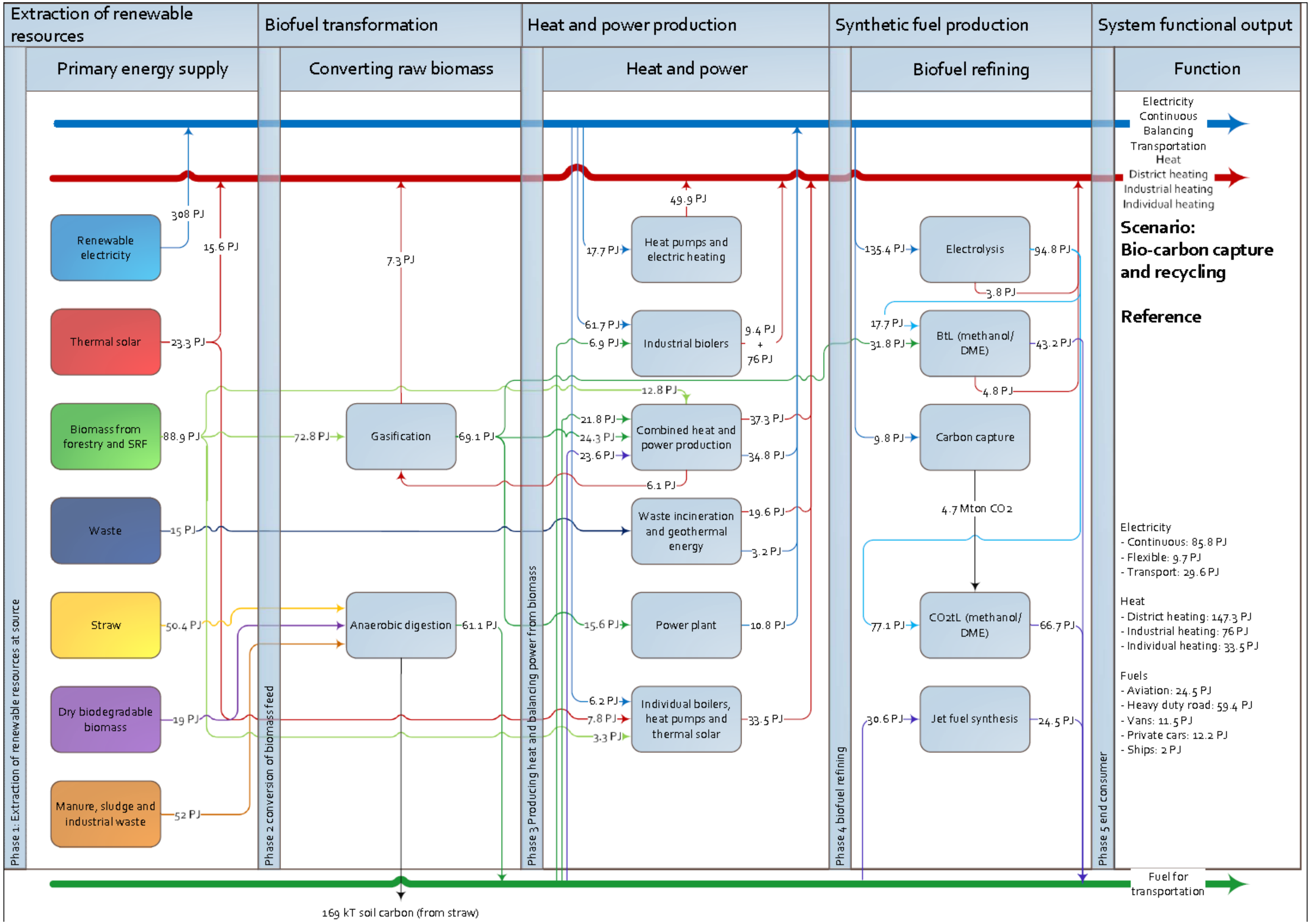
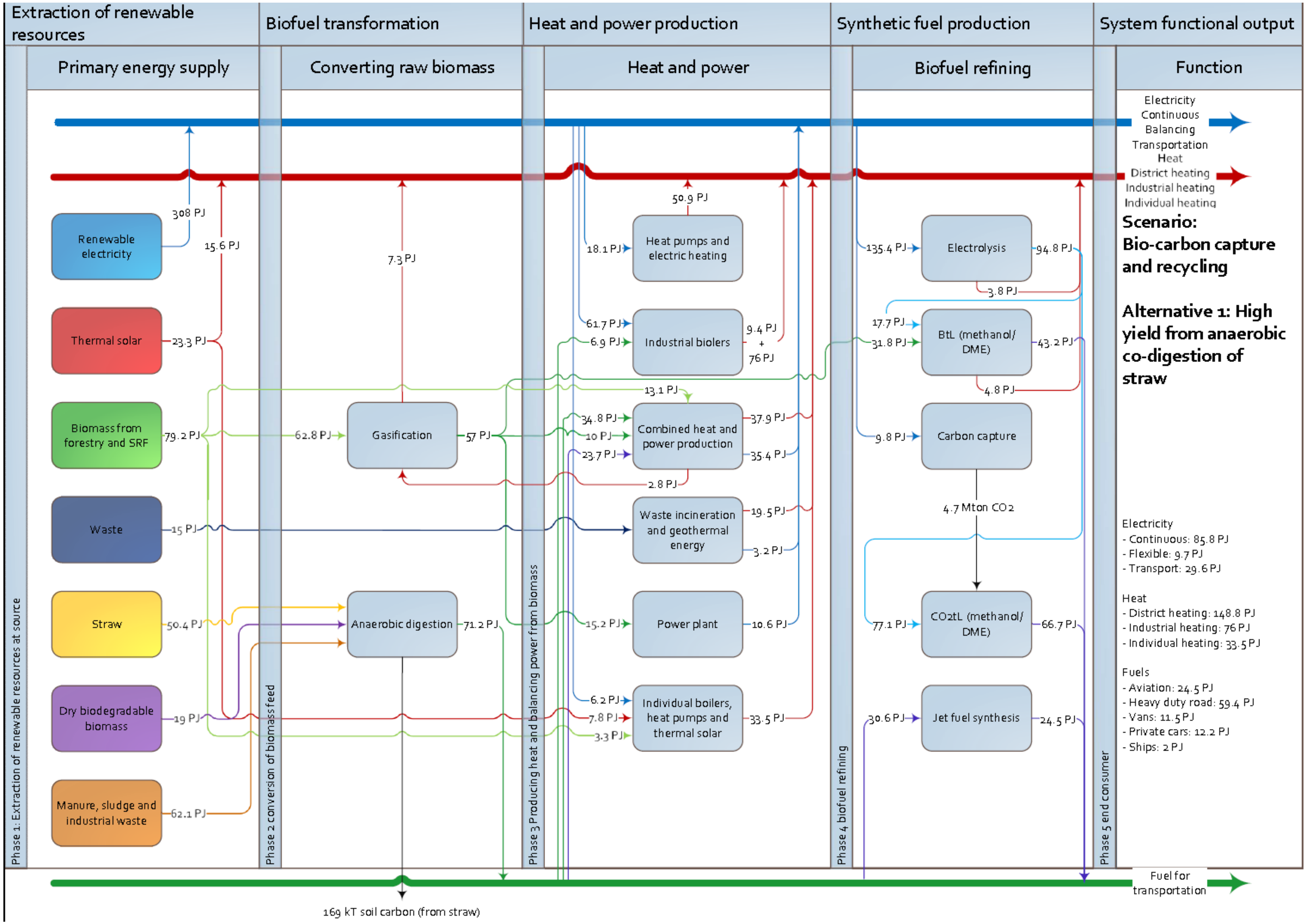
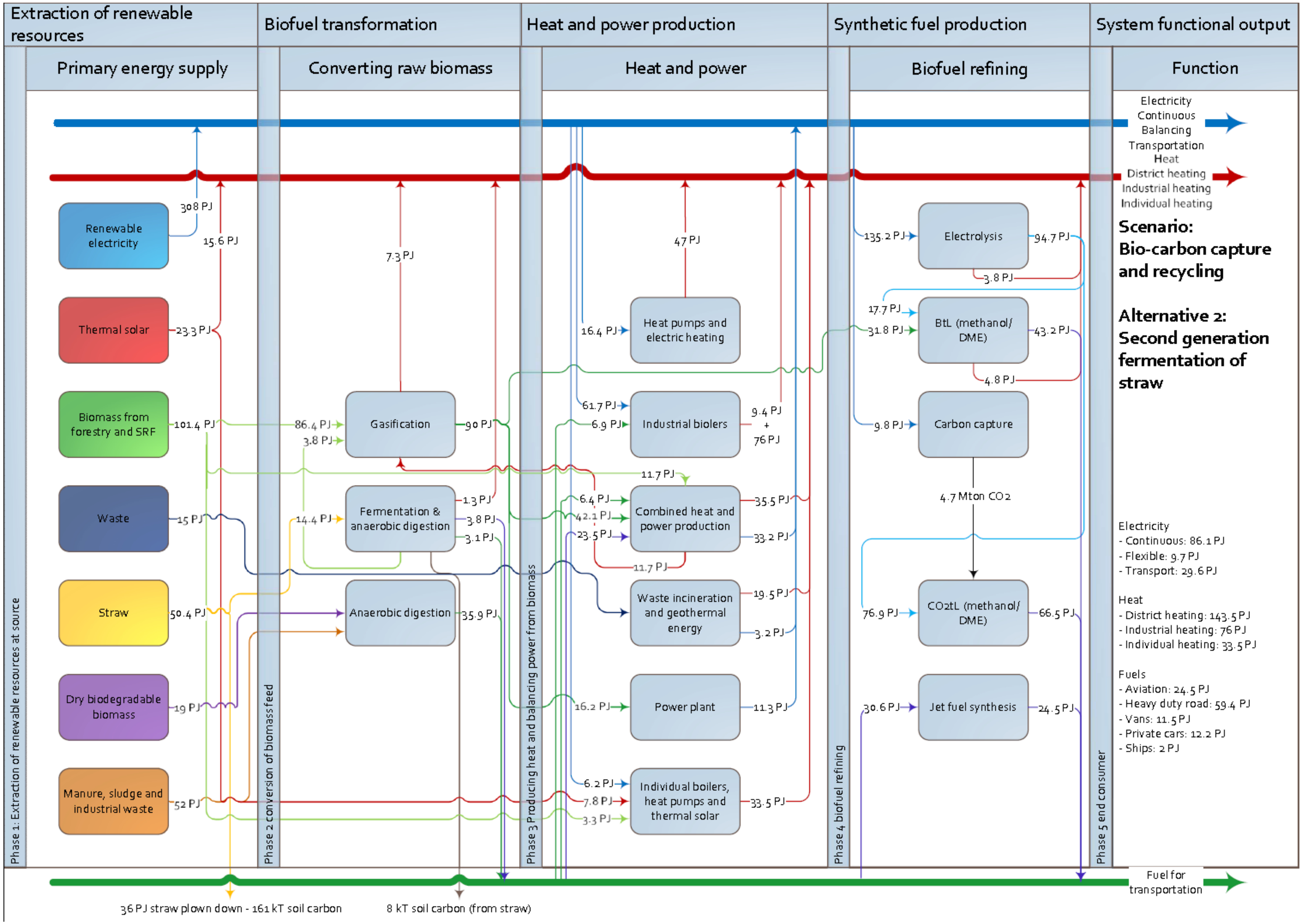

Fuel
Level 2
100 years (GWP100)
-300
-250
-200
-150
-100
-50
0
50
100
150
200
250
g CO2/MJ output
2012-2020 (harvest from existing forest, boreal)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
2020-2035 (plantation on forest land, tropical)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
2035-2050 (plantation on forest land, tropical)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
+2050 (plantation on forest land, tropical)
Wood+H2 methanol&DME
Manure biogas+H2 SNG fuel
Manure-straw biogas+H2 SNG fuel
2G eth short range+syngas
2G eth long range+syngas
2G eth long range+syngas+biogas
Biomass
Conversion process
Energy and auxilliary inputs
Co-product output

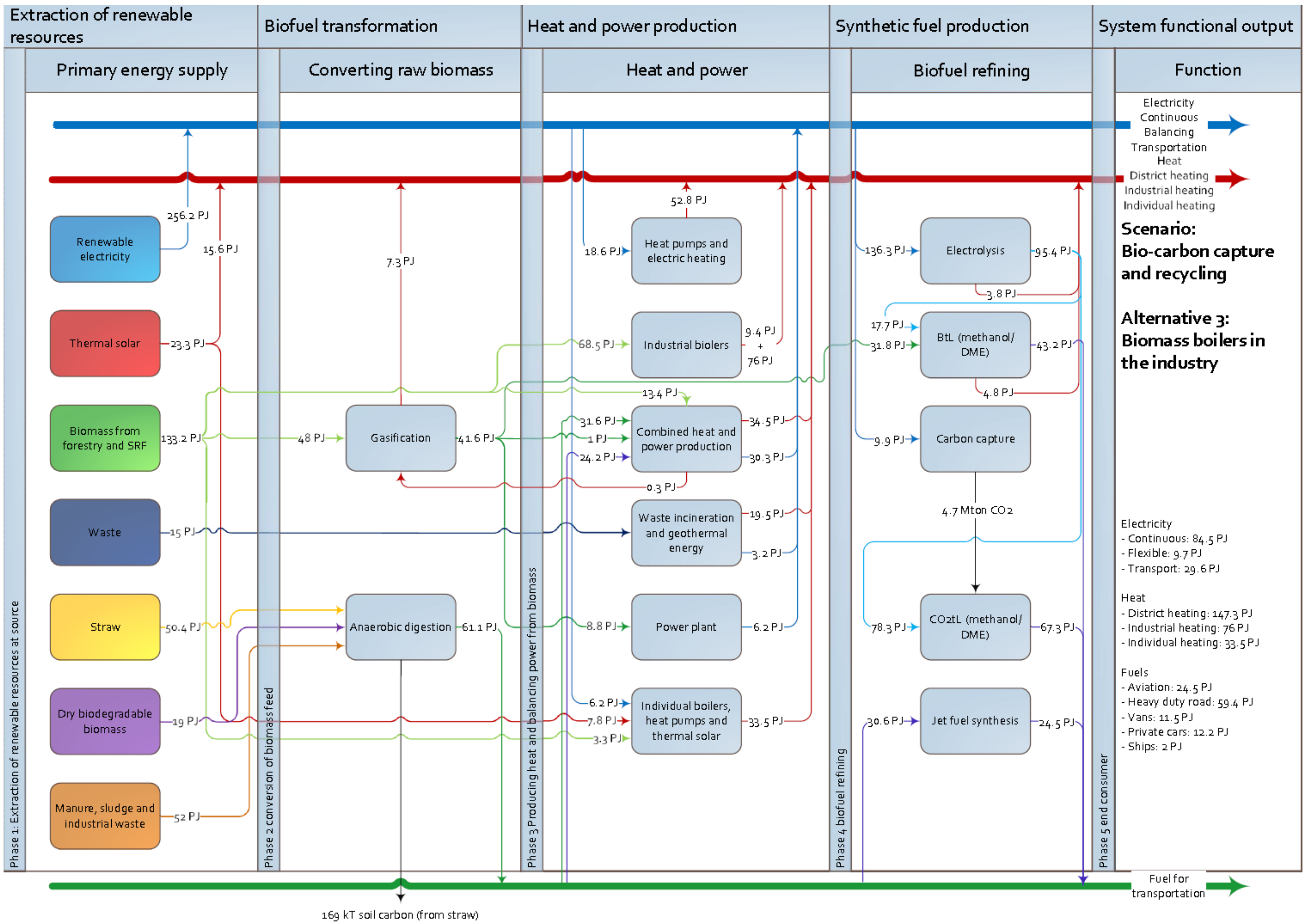
Figure 102

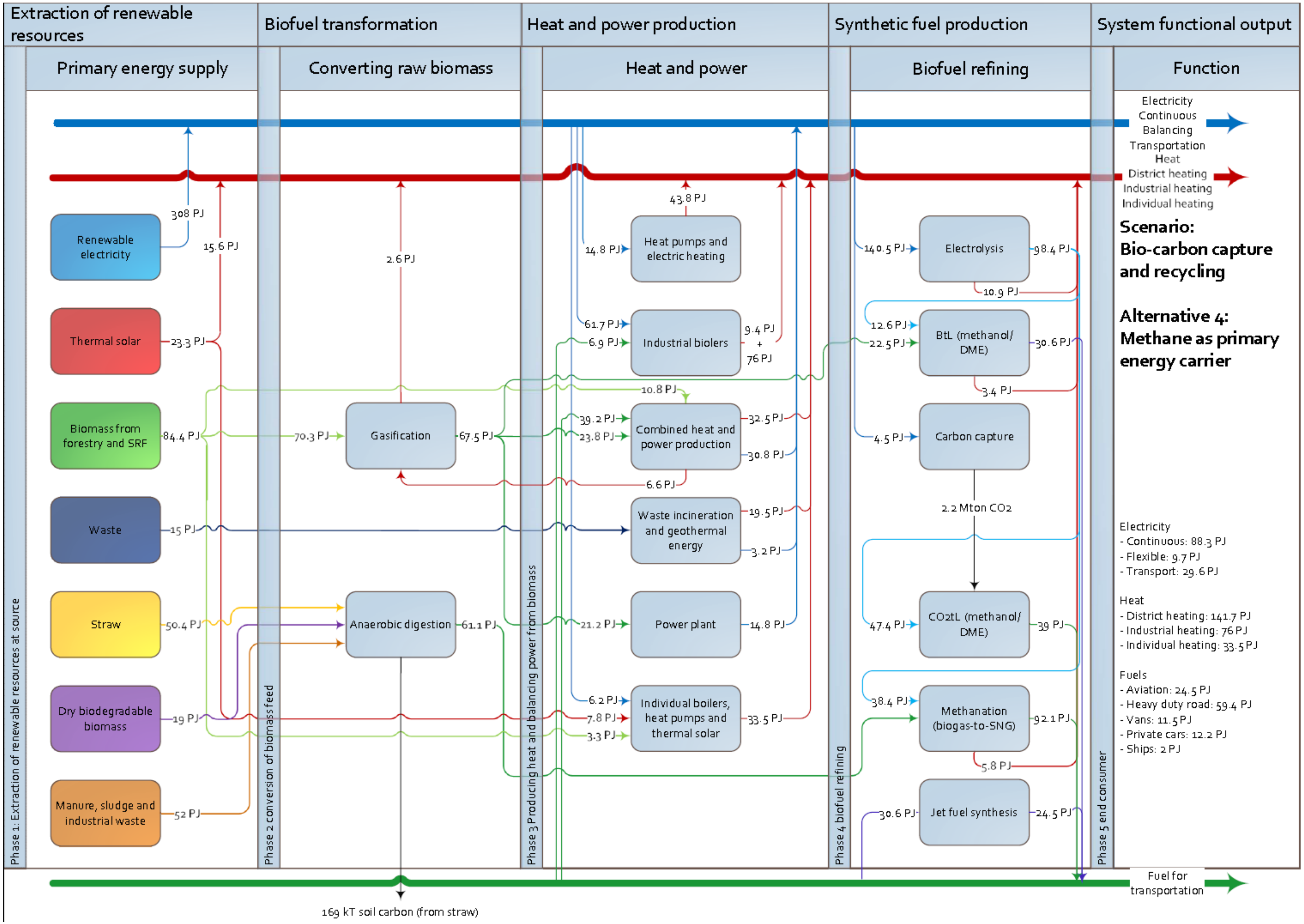
Appendix J Energy system scenarios

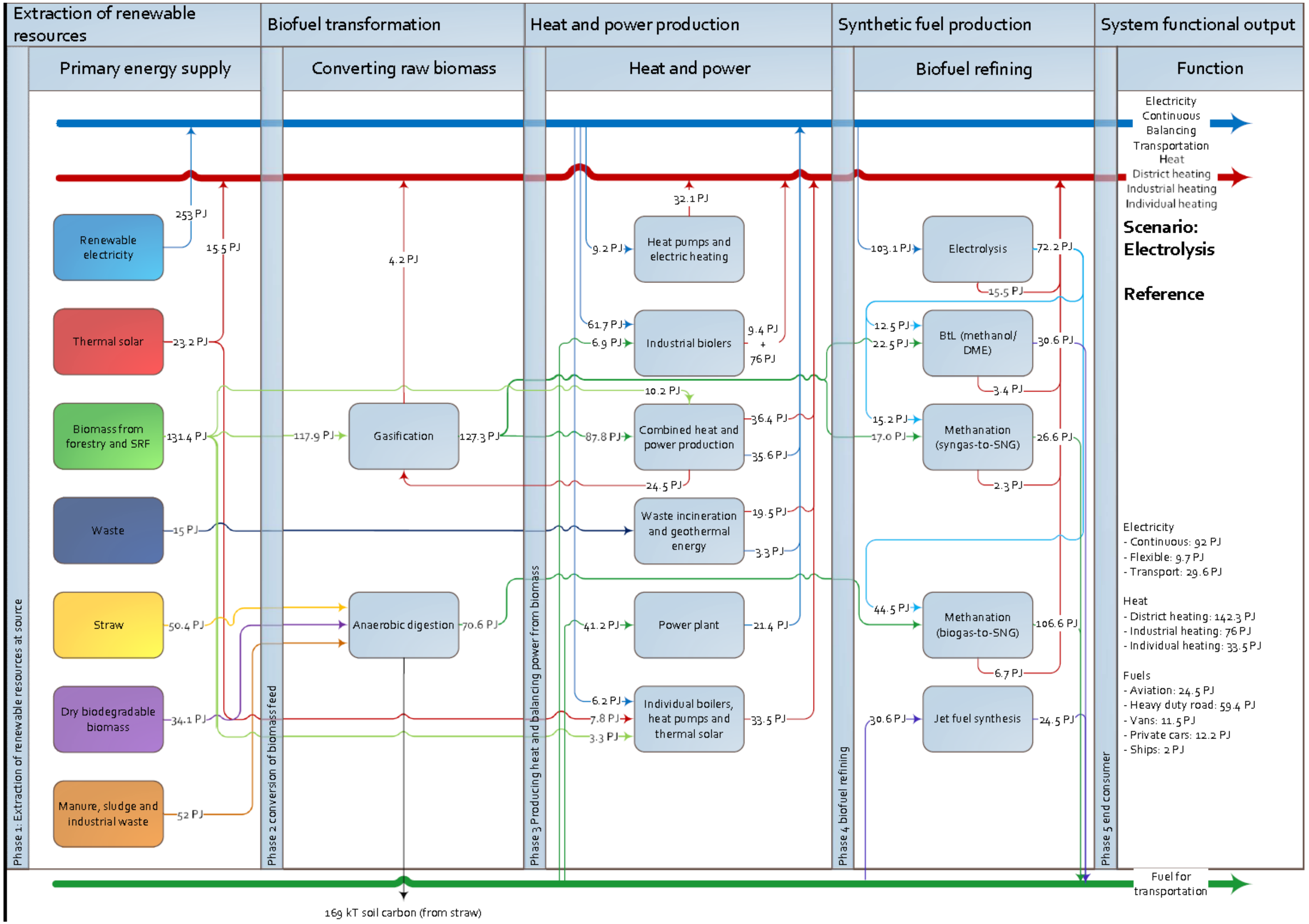

Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario:
Bio-carbon capture and recycling
Reference
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
Gasification
Anaerobic digestion
Heat pumps and electric heating
Industrial biolers
Combined heat and power production
Waste incineration and geothermal energy
Power plant
Individual boilers, heat pumps and thermal solar
Electrolysis
BtL (methanol/ DME)
Carbon capture
CO2tL (methanol/ DME)
Jet fuel synthesis
308 PJ
15.6 PJ
23.3 PJ
88.9 PJ
72.8 PJ
69.1 PJ
7.3 PJ
15 PJ
50.4 PJ
19 PJ
52 PJ
61.1 PJ
49.9 PJ
17.7 PJ
61.7 PJ
6.9 PJ
9.4 PJ
+
76 PJ
12.8 PJ
21.8 PJ
24.3 PJ
23.6 PJ
37.3 PJ
34.8 PJ
6.1 PJ
19.6 PJ
3.2 PJ
15.6 PJ
10.8 PJ
6.2 PJ
7.8 PJ
3.3 PJ
33.5 PJ
135.4 PJ
94.8 PJ
3.8 PJ
17.7 PJ
31.8 PJ
43.2 PJ
4.8 PJ
9.8 PJ
4.7 Mton CO2
77.1 PJ
66.7 PJ
30.6 PJ
24.5 PJ
Electricity
- Continuous: 85.8 PJ
- Flexible: 9.7 PJ
- Transport: 29.6 PJ
Heat
- District heating: 147.3 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 59.4 PJ
- Vans: 11.5 PJ
- Private cars: 12.2 PJ
- Ships: 2 PJ
Fuel for transportation
169 kT soil carbon (from straw)
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer

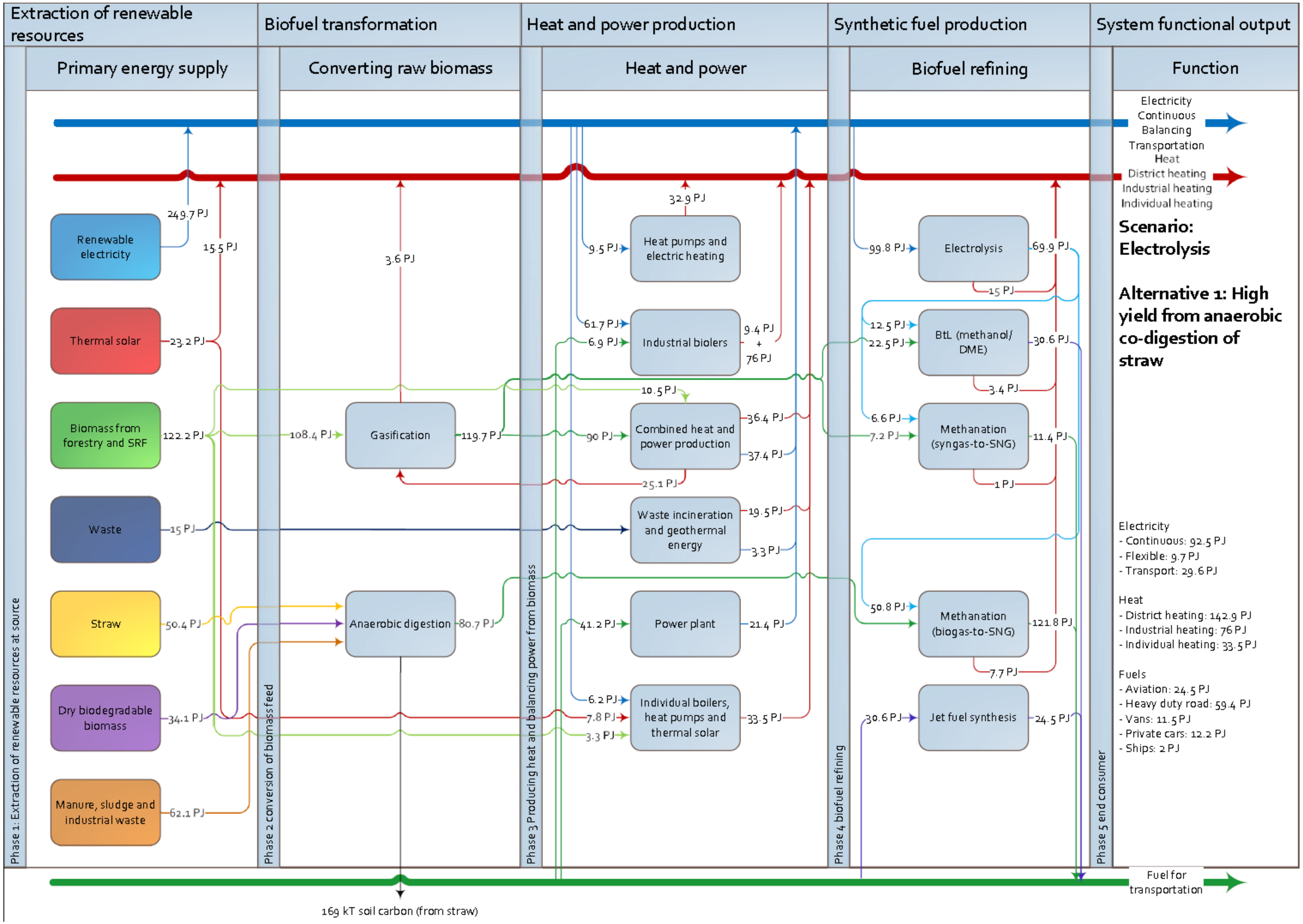

Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario:
Bio-carbon capture and recycling
Alternative 1: High yield from anaerobic co-digestion of straw
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
Gasification
Anaerobic digestion
Heat pumps and electric heating
Industrial biolers
Combined heat and power production
Waste incineration and geothermal energy
Power plant
Individual boilers, heat pumps and thermal solar
Electrolysis
BtL (methanol/ DME)
Carbon capture
CO2tL (methanol/ DME)
Jet fuel synthesis
308 PJ
15.6 PJ
23.3 PJ
79.2 PJ
15 PJ
50.4 PJ
19 PJ
62.1 PJ
7.3 PJ
62.8 PJ
57 PJ
71.2 PJ
50.9 PJ
18.1 PJ
61.7 PJ
6.9 PJ
9.4 PJ
+
76 PJ
13.1 PJ
34.8 PJ
10 PJ
23.7 PJ
37.9 PJ
35.4 PJ
2.8 PJ
19.5 PJ
3.2 PJ
15.2 PJ
10.6 PJ
6.2 PJ
7.8 PJ
3.3 PJ
33.5 PJ
135.4 PJ
94.8 PJ
3.8 PJ
17.7 PJ
31.8 PJ
43.2 PJ
4.8 PJ
9.8 PJ
4.7 Mton CO2
77.1 PJ
66.7 PJ
30.6 PJ
24.5 PJ
Electricity
- Continuous: 85.8 PJ
- Flexible: 9.7 PJ
- Transport: 29.6 PJ
Heat
- District heating: 148.8 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 59.4 PJ
- Vans: 11.5 PJ
- Private cars: 12.2 PJ
- Ships: 2 PJ
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer
Fuel for transportation
169 kT soil carbon (from straw)

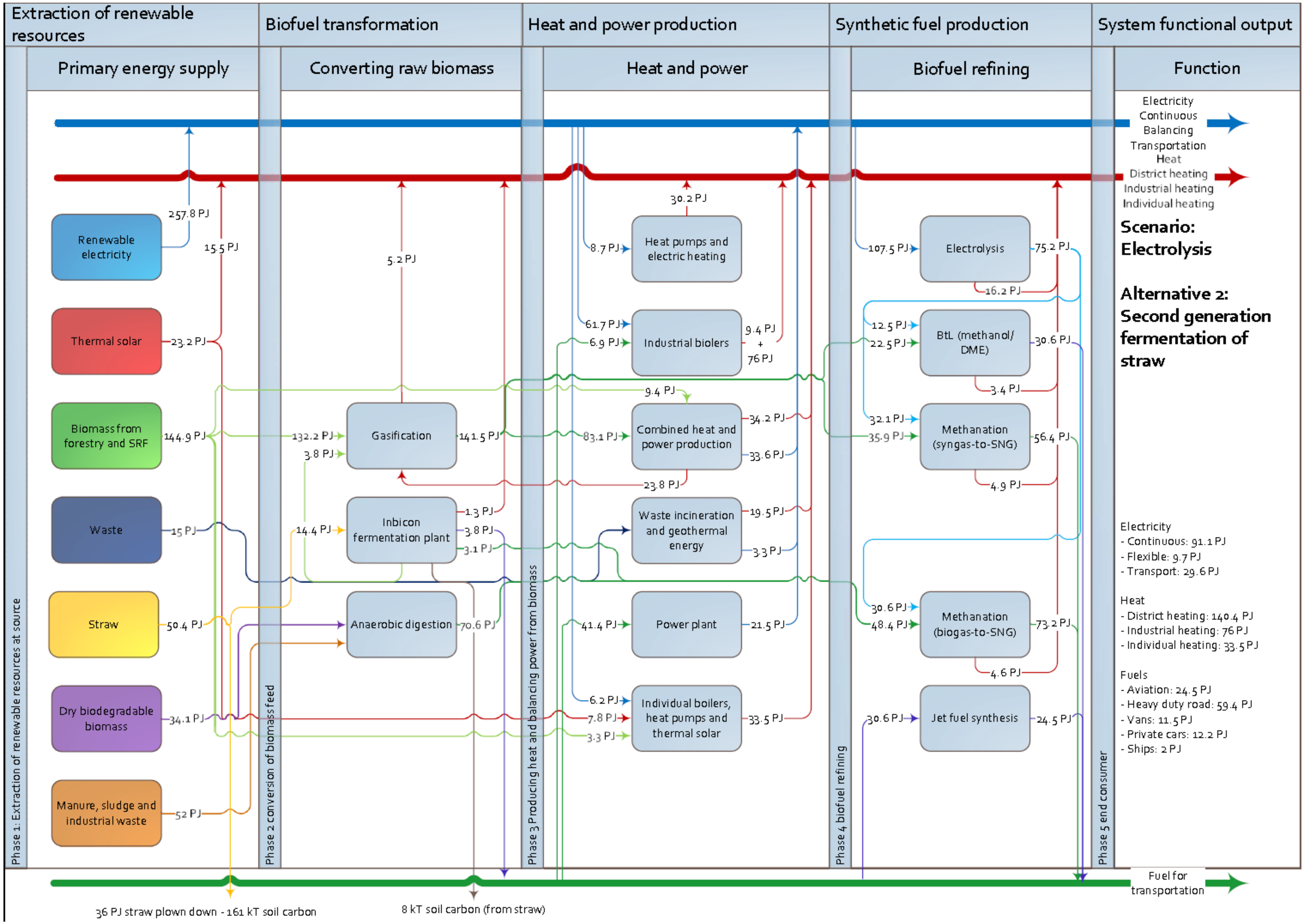

Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario:
Bio-carbon capture and recycling
Alternative 2:
Second generation fermentation of straw
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
308 PJ
15.6 PJ
23.3 PJ
101.4 PJ
15 PJ
50.4 PJ
19 PJ
52 PJ
7.3 PJ
86.4 PJ
3.8 PJ
Gasification
90 PJ
14.4 PJ
Fermentation & anaerobic digestion
1.3 PJ
3.8 PJ
3.1 PJ
Anaerobic digestion
35.9 PJ
47 PJ
16.4 PJ
Heat pumps and electric heating
61.7 PJ
6.9 PJ
Industrial biolers
9.4 PJ
+
76 PJ
11.7 PJ
6.4 PJ
42.1 PJ
23.5 PJ
Combined heat and power production
35.5 PJ
33.2 PJ
11.7 PJ
Waste incineration and geothermal energy
19.5 PJ
3.2 PJ
16.2 PJ
Power plant
11.3 PJ
6.2 PJ
7.8 PJ
3.3 PJ
Individual boilers, heat pumps and thermal solar
33.5 PJ
135.2 PJ
Electrolysis
94.7 PJ
3.8 PJ
17.7 PJ
31.8 PJ
BtL (methanol/ DME)
43.2 PJ
4.8 PJ
9.8 PJ
Carbon capture
4.7 Mton CO2
76.9 PJ
CO2tL (methanol/ DME)
66.5 PJ
30.6 PJ
Jet fuel synthesis
24.5 PJ
Electricity
- Continuous: 86.1 PJ
- Flexible: 9.7 PJ
- Transport: 29.6 PJ
Heat
- District heating: 143.5 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 59.4 PJ
- Vans: 11.5 PJ
- Private cars: 12.2 PJ
- Ships: 2 PJ
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer
Fuel for transportation
36 PJ straw plown down - 161 kT soil carbon
8 kT soil carbon (from straw)

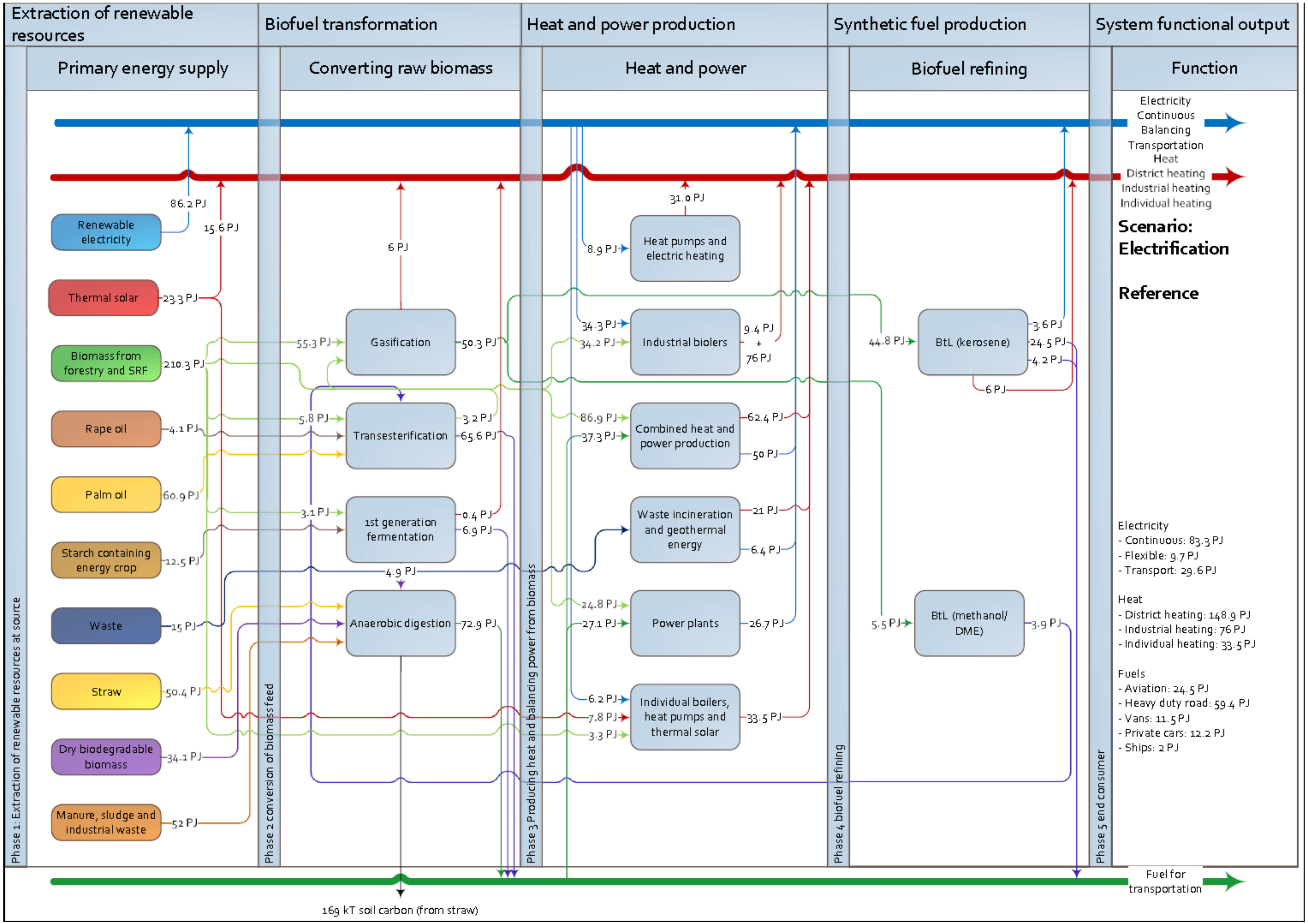

Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario:
Bio-carbon capture and recycling
Alternative 3:
Biomass boilers in the industry
Renewable electricity
256.2 PJ
15.6 PJ
Thermal solar
23.3 PJ
Biomass from forestry and SRF
133.2 PJ
48 PJ
Gasification
41.6 PJ
7.3 PJ
Waste
15 PJ
Straw
50.4 PJ
Dry biodegradable biomass
19 PJ
Manure, sludge and industrial waste
52 PJ
Anaerobic digestion
61.1 PJ
52.8 PJ
Heat pumps and electric heating
18.6 PJ
Industrial biolers
68.5 PJ
9.4 PJ
+
76 PJ
13.4 PJ
Combined heat and power production
31.6 PJ
1 PJ
24.2 PJ
34.5 PJ
30.3 PJ
0.3 PJ
Waste incineration and geothermal energy
19.5 PJ
3.2 PJ
Power plant
8.8 PJ
6.2 PJ
Individual boilers, heat pumps and thermal solar
6.2 PJ
7.8 PJ
3.3 PJ
33.5 PJ
Electrolysis
136.3 PJ
95.4 PJ
3.8 PJ
BtL (methanol/ DME)
17.7 PJ
31.8 PJ
43.2 PJ
4.8 PJ
Carbon capture
9.9 PJ
4.7 Mton CO2
CO2tL (methanol/ DME)
78.3 PJ
67.3 PJ
Jet fuel synthesis
30.6 PJ
24.5 PJ
Electricity
- Continuous: 84.5 PJ
- Flexible: 9.7 PJ
- Transport: 29.6 PJ
Heat
- District heating: 147.3 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 59.4 PJ
- Vans: 11.5 PJ
- Private cars: 12.2 PJ
- Ships: 2 PJ
Fuel for transportation
169 kT soil carbon (from straw)
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer

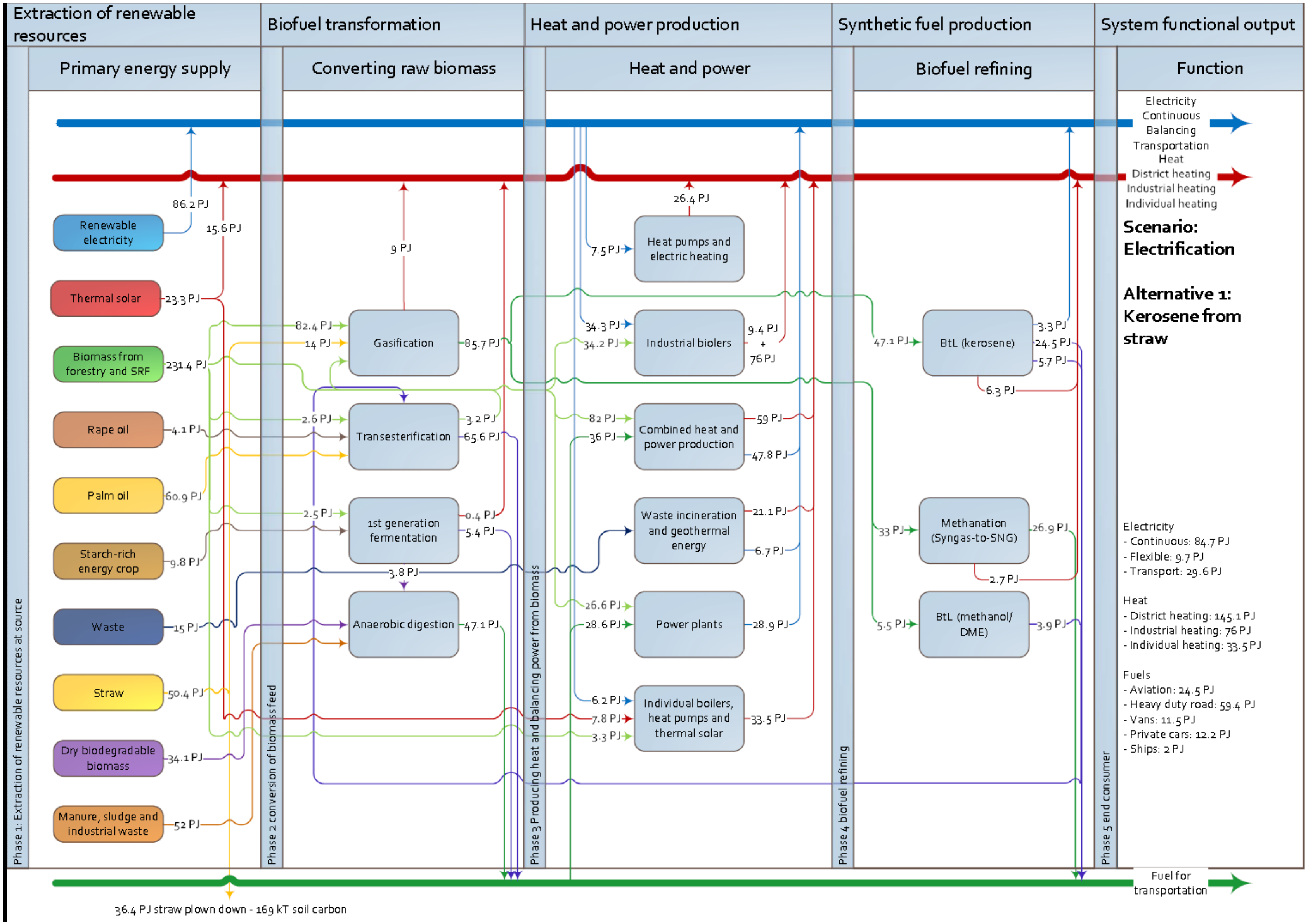

Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario:
Bio-carbon capture and recycling
Alternative 4:
Methane as primary energy carrier
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
Gasification
Anaerobic digestion
Heat pumps and electric heating
Industrial biolers
Combined heat and power production
Waste incineration and geothermal energy
Power plant
Individual boilers, heat pumps and thermal solar
Electrolysis
BtL (methanol/ DME)
Carbon capture
CO2tL (methanol/ DME)
Methanation (biogas-to-SNG)
Jet fuel synthesis
2.2 Mton CO2
308 PJ
15.6 PJ
23.3 PJ
84.4 PJ
15 PJ
50.4 PJ
19 PJ
52 PJ
2.6 PJ
70.3 PJ
67.5 PJ
61.1 PJ
43.8 PJ
14.8 PJ
61.7 PJ
6.9 PJ
9.4 PJ
+
76 PJ
10.8 PJ
39.2 PJ
23.8 PJ
32.5 PJ
30.8 PJ
6.6 PJ
19.5 PJ
3.2 PJ
21.2 PJ
14.8 PJ
6.2 PJ
7.8 PJ
3.3 PJ
33.5 PJ
140.5 PJ
98.4 PJ
10.9 PJ
12.6 PJ
22.5 PJ
30.6 PJ
3.4 PJ
4.5 PJ
47.4 PJ
39 PJ
38.4 PJ
92.1 PJ
5.8 PJ
30.6 PJ
24.5 PJ
Electricity
- Continuous: 88.3 PJ
- Flexible: 9.7 PJ
- Transport: 29.6 PJ
Heat
- District heating: 141.7 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 59.4 PJ
- Vans: 11.5 PJ
- Private cars: 12.2 PJ
- Ships: 2 PJ
Fuel for transportation
169 kT soil carbon (from straw)
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer

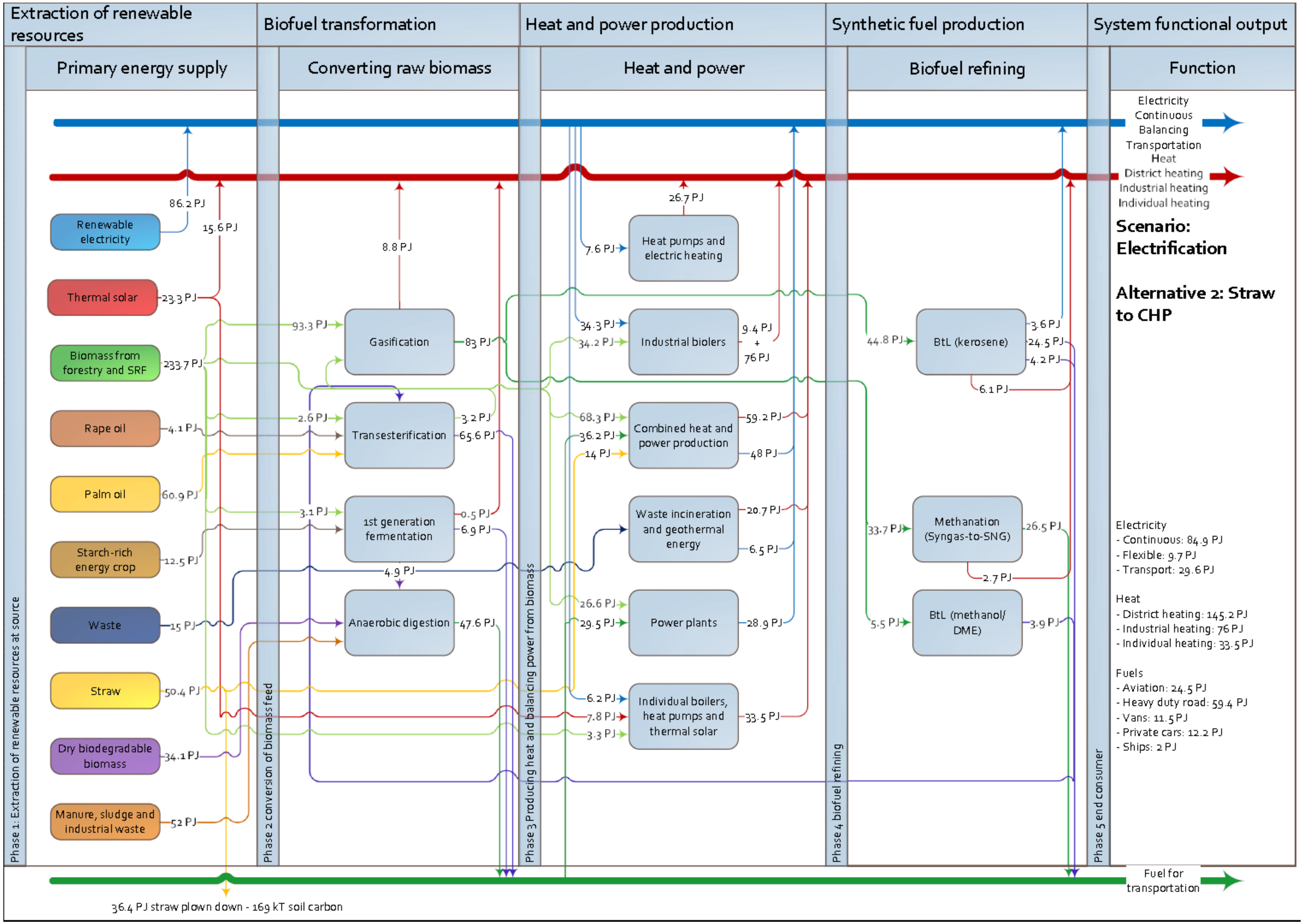

Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario: Electrolysis
Reference
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
Gasification
Anaerobic digestion
Heat pumps and electric heating
Industrial biolers
Combined heat and power production
Waste incineration and geothermal energy
Power plant
Individual boilers, heat pumps and thermal solar
Electrolysis
BtL (methanol/ DME)
Methanation (syngas-to-SNG)
Methanation (biogas-to-SNG)
Jet fuel synthesis
253 PJ
15.5 PJ
23.2 PJ
131.4 PJ
15 PJ
50.4 PJ
34.1 PJ
52 PJ
4.2 PJ
117.9 PJ
127.3 PJ
70.6 PJ
32.1 PJ
9.2 PJ
61.7 PJ
6.9 PJ
9.4 PJ + 76 PJ
10.2 PJ
87.8 PJ
36.4 PJ
35.6 PJ
24.5 PJ
19.5 PJ
3.3 PJ
41.2 PJ
21.4 PJ
6.2 PJ
7.8 PJ
3.3 PJ
33.5 PJ
103.1 PJ
72.2 PJ
15.5 PJ
12.5 PJ
22.5 PJ
30.6 PJ
3.4 PJ
15.2 PJ
17.0 PJ
26.6 PJ
2.3 PJ
44.5 PJ
106.6 PJ
6.7 PJ
30.6 PJ
24.5 PJ
Electricity
- Continuous: 92 PJ
- Flexible: 9.7 PJ
- Transport: 29.6 PJ
Heat
- District heating: 142.3 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 59.4 PJ
- Vans: 11.5 PJ
- Private cars: 12.2 PJ
- Ships: 2 PJ
Fuel for transportation
169 kT soil carbon (from straw)
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer

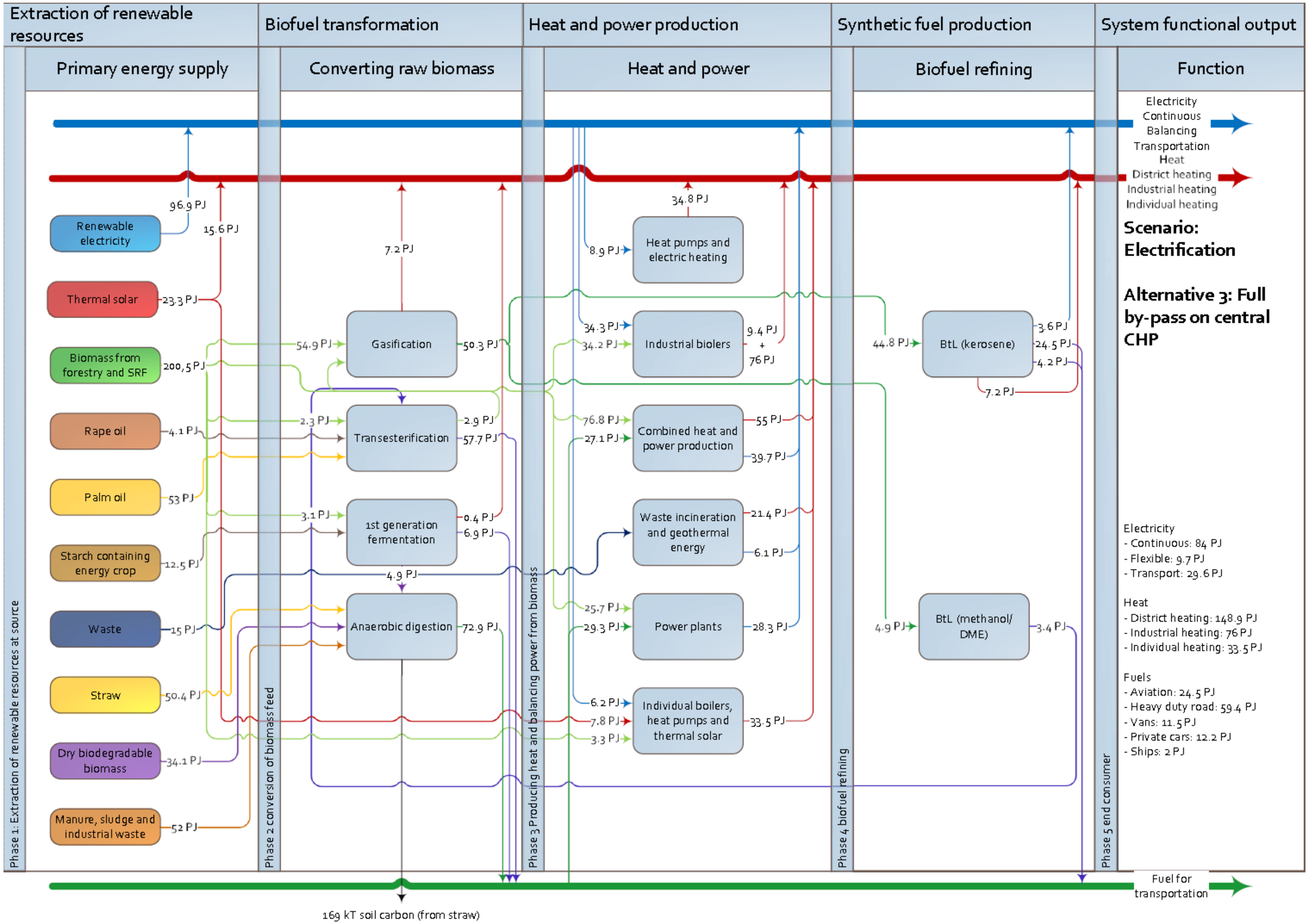

Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario: Electrolysis
Alternative 1: High yield from anaerobic co-digestion of straw
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
249.7 PJ
15.5 PJ
23.2 PJ
122.2 PJ
15 PJ
50.4 PJ
34.1 PJ
62.1 PJ
3.6 PJ
108.4 PJ
Gasification
119.7 PJ
Anaerobic digestion
80.7 PJ
32.9 PJ
9.5 PJ
Heat pumps and electric heating
61.7 PJ
6.9 PJ
Industrial biolers
9.4 PJ
+
76 PJ
10.5 PJ
90 PJ
Combined heat and power production
36.4 PJ
37.4 PJ
25.1 PJ
Waste incineration and geothermal energy
19.5 PJ
3.3 PJ
41.2 PJ
Power plant
21.4 PJ
6.2 PJ
7.8 PJ
3.3 PJ
Individual boilers, heat pumps and thermal solar
33.5 PJ
99.8 PJ
Electrolysis
69.9 PJ
15 PJ
12.5 PJ
22.5 PJ
BtL (methanol/ DME)
30.6 PJ
3.4 PJ
6.6 PJ
7.2 PJ
Methanation (syngas-to-SNG)
11.4 PJ
1 PJ
50.8 PJ
Methanation (biogas-to-SNG)
121.8 PJ
7.7 PJ
30.6 PJ
Jet fuel synthesis
24.5 PJ
Electricity
- Continuous: 92.5 PJ
- Flexible: 9.7 PJ
- Transport: 29.6 PJ
Heat
- District heating: 142.9 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 59.4 PJ
- Vans: 11.5 PJ
- Private cars: 12.2 PJ
- Ships: 2 PJ
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer
Fuel for transportation
169 kT soil carbon (from straw)

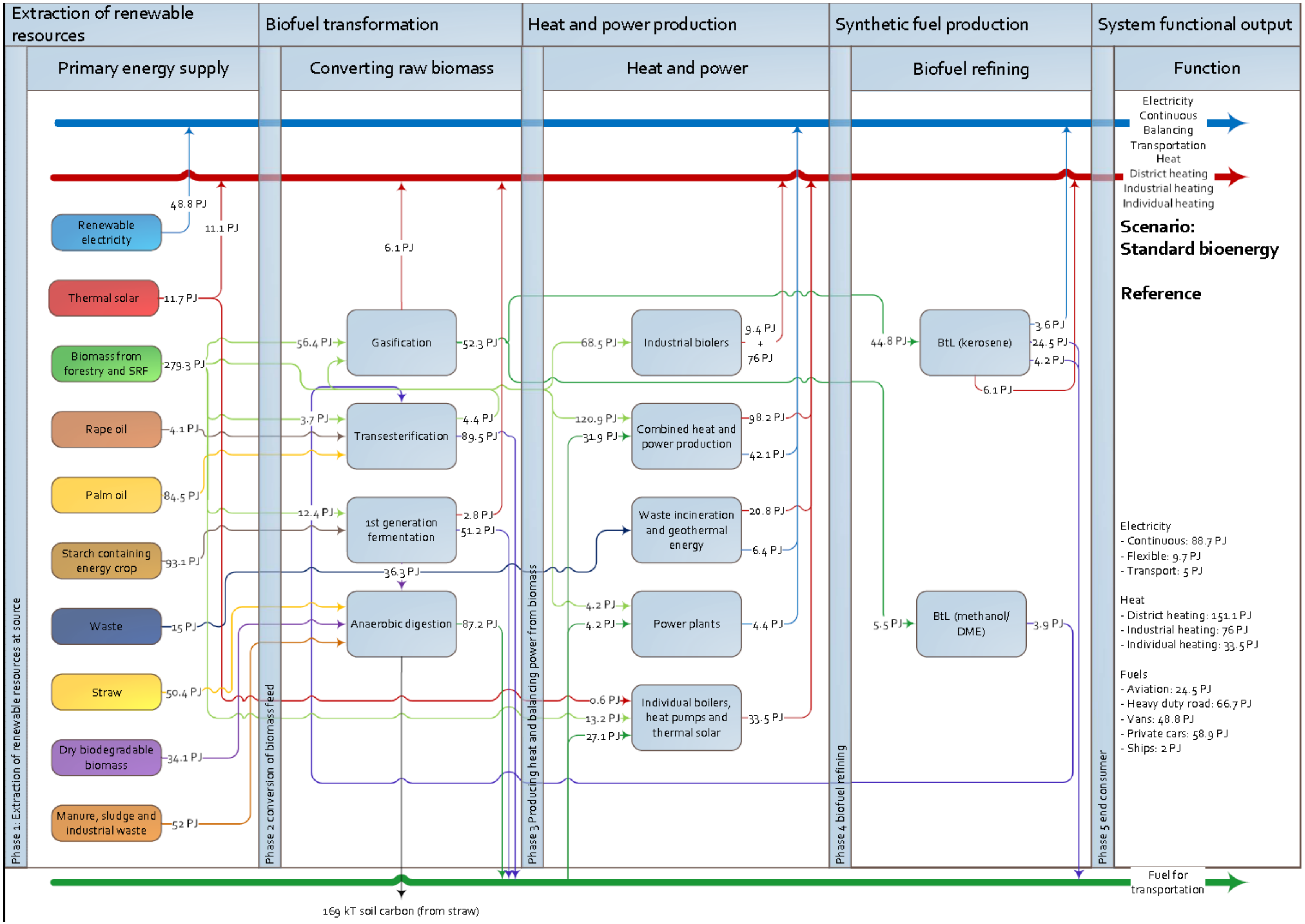

Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario:
Electrolysis
Alternative 2:
Second generation fermentation of straw
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
Gasification
Inbicon fermentation plant
Anaerobic digestion
Heat pumps and electric heating
Industrial biolers
Combined heat and power production
Waste incineration and geothermal energy
Power plant
Individual boilers, heat pumps and thermal solar
Electrolysis
BtL (methanol/ DME)
Methanation (syngas-to-SNG)
Methanation (biogas-to-SNG)
Jet fuel synthesis
257.8 PJ
15.5 PJ
23.2 PJ
144.9 PJ
15 PJ
50.4 PJ
34.1 PJ
52 PJ
5.2 PJ
132.2 PJ
3.8 PJ
141.5 PJ
14.4 PJ
1.3 PJ
3.8 PJ
3.1 PJ
70.6 PJ
30.2 PJ
8.7 PJ
61.7 PJ
6.9 PJ
9.4 PJ
+
76 PJ
9.4 PJ
83.1 PJ
34.2 PJ
33.6 PJ
23.8 PJ
19.5 PJ
3.3 PJ
41.4 PJ
21.5 PJ
6.2 PJ
7.8 PJ
3.3 PJ
33.5 PJ
107.5 PJ
75.2 PJ
16.2 PJ
12.5 PJ
22.5 PJ
30.6 PJ
3.4 PJ
32.1 PJ
35.9 PJ
56.4 PJ
4.9 PJ
30.6 PJ
48.4 PJ
73.2 PJ
4.6 PJ
30.6 PJ
24.5 PJ
Electricity
- Continuous: 91.1 PJ
- Flexible: 9.7 PJ
- Transport: 29.6 PJ
Heat
- District heating: 140.4 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 59.4 PJ
- Vans: 11.5 PJ
- Private cars: 12.2 PJ
- Ships: 2 PJ
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer
Fuel for transportation
36 PJ straw plown down - 161 kT soil carbon
8 kT soil carbon (from straw)

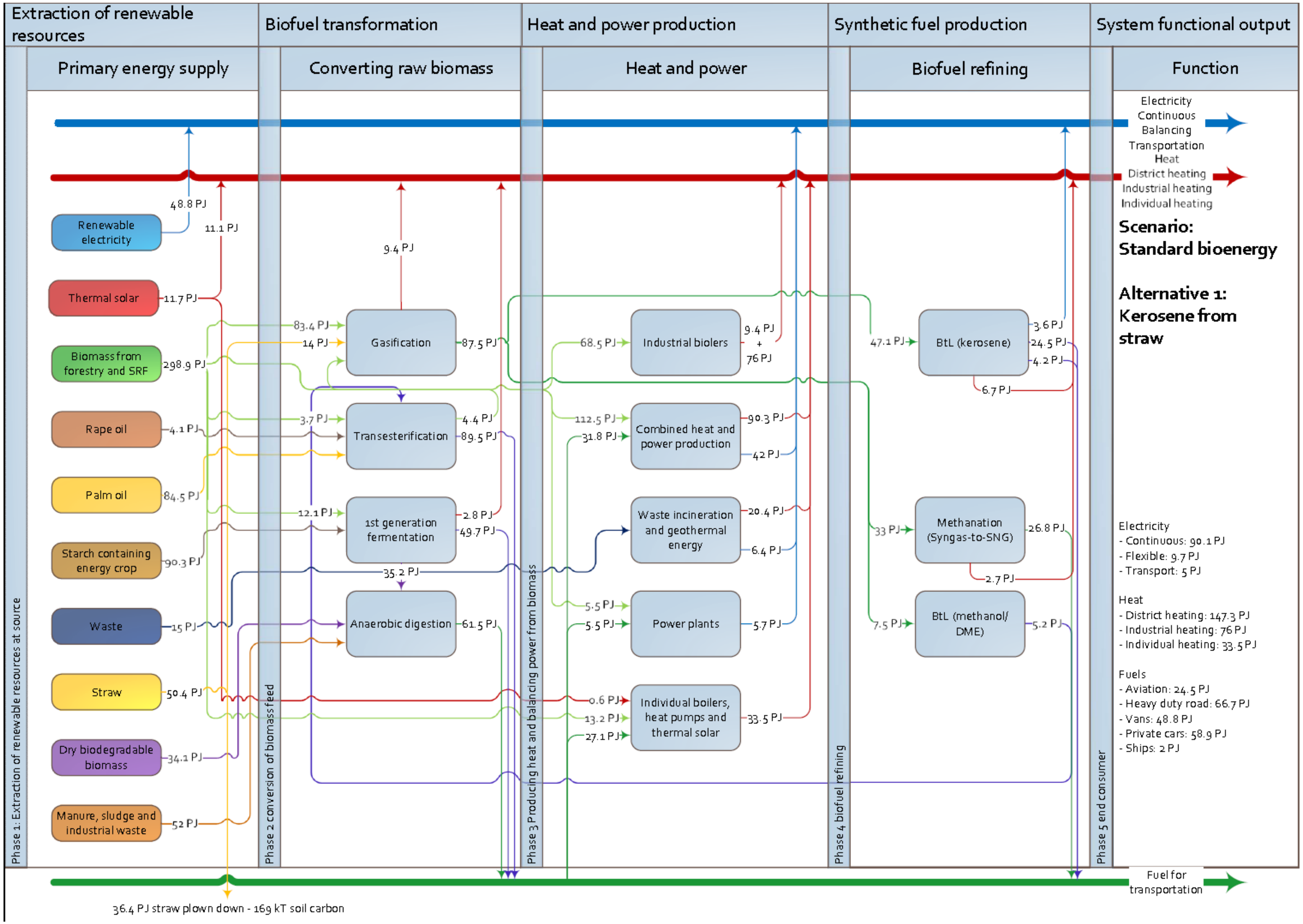

Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario: Electrification
Reference
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Rape oil
Palm oil
Starch containing energy crop
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
86.2 PJ
15.6 PJ
23.3 PJ
210.3 PJ
4.1 PJ
60.9 PJ
12.5 PJ
15 PJ
50.4 PJ
34.1 PJ
52 PJ
6 PJ
55.3 PJ
Gasification
50.3 PJ
5.8 PJ
Transesterification
3.2 PJ
65.6 PJ
3.1 PJ
1st generation fermentation
0.4 PJ
6.9 PJ
4.9 PJ
Anaerobic digestion
72.9 PJ
31.0 PJ
8.9 PJ
Heat pumps and electric heating
34.3 PJ
34.2 PJ
Industrial biolers
9.4 PJ
+
76 PJ
86.9 PJ
37.3 PJ
Combined heat and power production
62.4 PJ
50 PJ
Waste incineration and geothermal energy
21 PJ
6.4 PJ
24.8 PJ
27.1 PJ
Power plants
26.7 PJ
6.2 PJ
7.8 PJ
3.3 PJ
Individual boilers, heat pumps and thermal solar
33.5 PJ
44.8 PJ
BtL (kerosene)
3.6 PJ
24.5 PJ
4.2 PJ
6 PJ
5.5 PJ
BtL (methanol/ DME)
3.9 PJ
Electricity
- Continuous: 83.3 PJ
- Flexible: 9.7 PJ
- Transport: 29.6 PJ
Heat
- District heating: 148.9 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 59.4 PJ
- Vans: 11.5 PJ
- Private cars: 12.2 PJ
- Ships: 2 PJ
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer
Fuel for transportation
169 kT soil carbon (from straw)

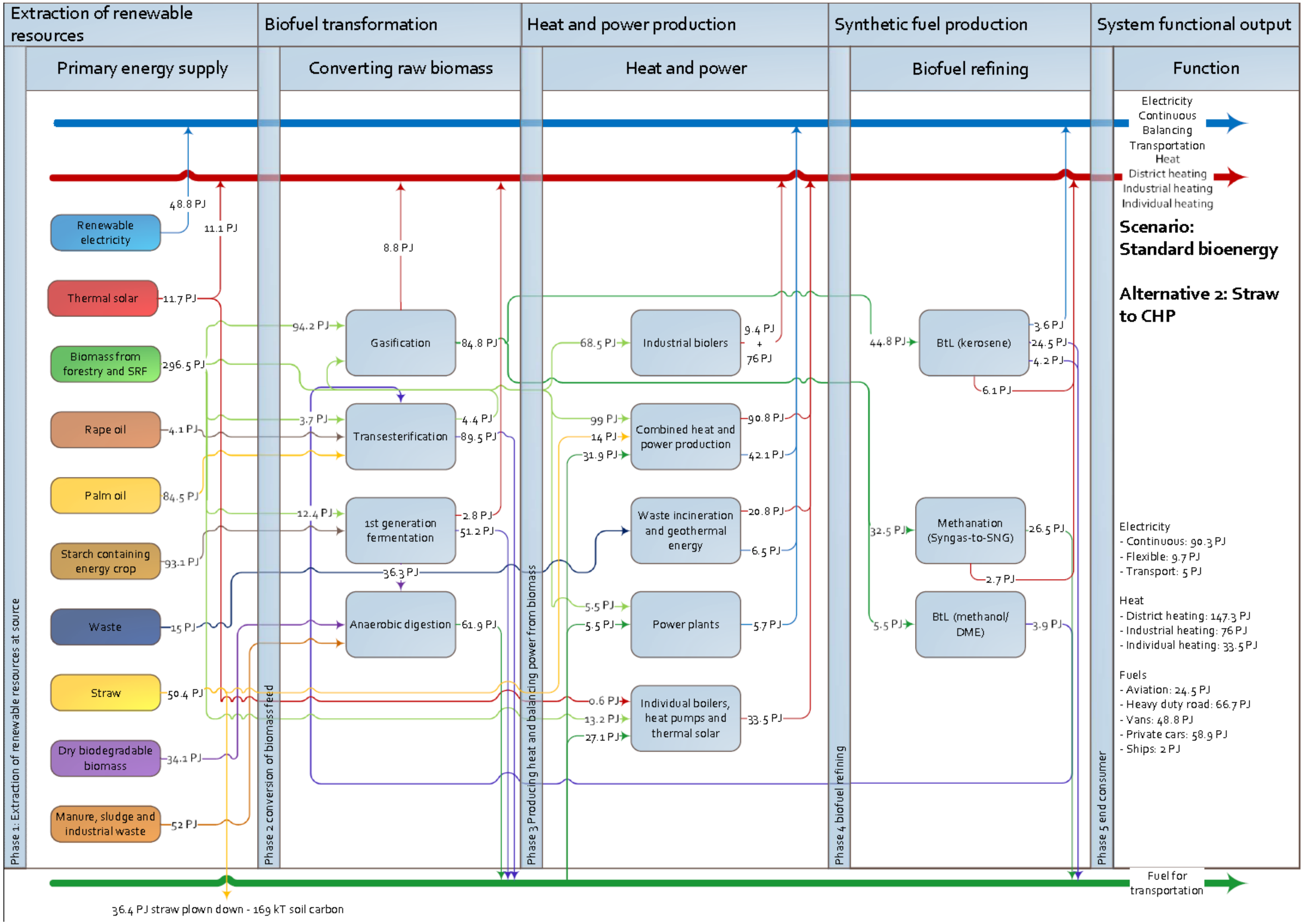

Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario: Electrification
Alternative 1: Kerosene from straw
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Rape oil
Palm oil
Starch-rich energy crop
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
86.2 PJ
15.6 PJ
23.3 PJ
231.4 PJ
4.1 PJ
60.9 PJ
9.8 PJ
15 PJ
50.4 PJ
34.1 PJ
52 PJ
Gasification
Transesterification
1st generation fermentation
Anaerobic digestion
9 PJ
82.4 PJ
14 PJ
85.7 PJ
2.6 PJ
3.2 PJ
65.6 PJ
2.5 PJ
0.4 PJ
5.4 PJ
3.8 PJ
47.1 PJ
Heat pumps and electric heating
Industrial biolers
Combined heat and power production
Waste incineration and geothermal energy
Power plants
Individual boilers, heat pumps and thermal solar
26.4 PJ
7.5 PJ
34.3 PJ
34.2 PJ
9.4 PJ + 76 PJ
82 PJ
36 PJ
59 PJ
47.8 PJ
21.1 PJ
6.7 PJ
26.6 PJ
28.6 PJ
28.9 PJ
6.2 PJ
7.8 PJ
3.3 PJ
33.5 PJ
BtL (kerosene)
Methanation (Syngas-to-SNG)
BtL (methanol/ DME)
47.1 PJ
3.3 PJ
24.5 PJ
5.7 PJ
6.3 PJ
33 PJ
26.9 PJ
2.7 PJ
5.5 PJ
3.9 PJ
Electricity
- Continuous: 84.7 PJ
- Flexible: 9.7 PJ
- Transport: 29.6 PJ
Heat
- District heating: 145.1 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 59.4 PJ
- Vans: 11.5 PJ
- Private cars: 12.2 PJ
- Ships: 2 PJ
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer
Fuel for transportation
36.4 PJ straw plown down - 169 kT soil carbon


Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario: Electrification
Alternative 2: Straw to CHP
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Rape oil
Palm oil
Starch-rich energy crop
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
Gasification
Transesterification
1st generation fermentation
Anaerobic digestion
Heat pumps and electric heating
Industrial biolers
Combined heat and power production
Waste incineration and geothermal energy
Power plants
Individual boilers, heat pumps and thermal solar
BtL (kerosene)
Methanation (Syngas-to-SNG)
BtL (methanol/ DME)
86.2 PJ
15.6 PJ
23.3 PJ
233.7 PJ
4.1 PJ
60.9 PJ
12.5 PJ
15 PJ
50.4 PJ
34.1 PJ
52 PJ
8.8 PJ
93.3 PJ
83 PJ
2.6 PJ
3.2 PJ
65.6 PJ
3.1 PJ
0.5 PJ
6.9 PJ
4.9 PJ
47.6 PJ
26.7 PJ
7.6 PJ
34.3 PJ
34.2 PJ
9.4 PJ
+
76 PJ
68.3 PJ
36.2 PJ
14 PJ
59.2 PJ
48 PJ
20.7 PJ
6.5 PJ
26.6 PJ
29.5 PJ
28.9 PJ
6.2 PJ
7.8 PJ
3.3 PJ
33.5 PJ
44.8 PJ
3.6 PJ
24.5 PJ
4.2 PJ
6.1 PJ
33.7 PJ
26.5 PJ
2.7 PJ
5.5 PJ
3.9 PJ
Electricity
- Continuous: 84.9 PJ
- Flexible: 9.7 PJ
- Transport: 29.6 PJ
Heat
- District heating: 145.2 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 59.4 PJ
- Vans: 11.5 PJ
- Private cars: 12.2 PJ
- Ships: 2 PJ
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer
Fuel for transportation
36.4 PJ straw plown down - 169 kT soil carbon


Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario: Electrification
Alternative 3: Full by-pass on central CHP
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Rape oil
Palm oil
Starch containing energy crop
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
96.9 PJ
15.6 PJ
23.3 PJ
200,5 PJ
4.1 PJ
53 PJ
12.5 PJ
15 PJ
50.4 PJ
34.1 PJ
52 PJ
Gasification
Transesterification
1st generation fermentation
Anaerobic digestion
7.2 PJ
54.9 PJ
50.3 PJ
2.3 PJ
2.9 PJ
57.7 PJ
3.1 PJ
0.4 PJ
6.9 PJ
4.9 PJ
72.9 PJ
Heat pumps and electric heating
Industrial biolers
Combined heat and power production
Waste incineration and geothermal energy
Power plants
Individual boilers, heat pumps and thermal solar
34.8 PJ
8.9 PJ
34.3 PJ
34.2 PJ
9.4 PJ
+
76 PJ
76.8 PJ
27.1 PJ
55 PJ
39.7 PJ
21.4 PJ
6.1 PJ
25.7 PJ
29.3 PJ
28.3 PJ
6.2 PJ
7.8 PJ
3.3 PJ
33.5 PJ
BtL (kerosene)
BtL (methanol/ DME)
44.8 PJ
3.6 PJ
24.5 PJ
4.2 PJ
7.2 PJ
4.9 PJ
3.4 PJ
Electricity
- Continuous: 84 PJ
- Flexible: 9.7 PJ
- Transport: 29.6 PJ
Heat
- District heating: 148.9 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 59.4 PJ
- Vans: 11.5 PJ
- Private cars: 12.2 PJ
- Ships: 2 PJ
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer
Fuel for transportation
169 kT soil carbon (from straw)


Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario:
Standard bioenergy
Reference
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Rape oil
Palm oil
Starch containing energy crop
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
48.8 PJ
11.1 PJ
11.7 PJ
279.3 PJ
4.1 PJ
84.5 PJ
93.1 PJ
15 PJ
50.4 PJ
34.1 PJ
52 PJ
Gasification
Transesterification
1st generation fermentation
Anaerobic digestion
6.1 PJ
56.4 PJ
52.3 PJ
3.7 PJ
4.4 PJ
89.5 PJ
12.4 PJ
2.8 PJ
51.2 PJ
36.3 PJ
87.2 PJ
Industrial biolers
Combined heat and power production
Waste incineration and geothermal energy
Power plants
Individual boilers, heat pumps and thermal solar
68.5 PJ
9.4 PJ
+
76 PJ
120.9 PJ
31.9 PJ
98.2 PJ
42.1 PJ
20.8 PJ
6.4 PJ
4.2 PJ
4.2 PJ
4.4 PJ
0.6 PJ
13.2 PJ
27.1 PJ
33.5 PJ
BtL (kerosene)
BtL (methanol/ DME)
44.8 PJ
3.6 PJ
24.5 PJ
4.2 PJ
6.1 PJ
5.5 PJ
3.9 PJ
Electricity
- Continuous: 88.7 PJ
- Flexible: 9.7 PJ
- Transport: 5 PJ
Heat
- District heating: 151.1 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 66.7 PJ
- Vans: 48.8 PJ
- Private cars: 58.9 PJ
- Ships: 2 PJ
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer
Fuel for transportation
169 kT soil carbon (from straw)


Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario:
Standard bioenergy
Alternative 1:
Kerosene from straw
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Rape oil
Palm oil
Starch containing energy crop
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
48.8 PJ
11.1 PJ
11.7 PJ
298.9 PJ
4.1 PJ
84.5 PJ
90.3 PJ
15 PJ
50.4 PJ
34.1 PJ
52 PJ
9.4 PJ
83.4 PJ
14 PJ
Gasification
87.5 PJ
3.7 PJ
Transesterification
4.4 PJ
89.5 PJ
12.1 PJ
1st generation fermentation
2.8 PJ
49.7 PJ
35.2 PJ
Anaerobic digestion
61.5 PJ
68.5 PJ
Industrial biolers
9.4 PJ
+
76 PJ
112.5 PJ
31.8 PJ
Combined heat and power production
90.3 PJ
42 PJ
Waste incineration and geothermal energy
20.4 PJ
6.4 PJ
5.5 PJ
5.5 PJ
Power plants
5.7 PJ
0.6 PJ
13.2 PJ
27.1 PJ
Individual boilers, heat pumps and thermal solar
33.5 PJ
47.1 PJ
BtL (kerosene)
3.6 PJ
24.5 PJ
4.2 PJ
6.7 PJ
33 PJ
Methanation (Syngas-to-SNG)
26.8 PJ
2.7 PJ
7.5 PJ
BtL (methanol/ DME)
5.2 PJ
Electricity
- Continuous: 90.1 PJ
- Flexible: 9.7 PJ
- Transport: 5 PJ
Heat
- District heating: 147.3 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 66.7 PJ
- Vans: 48.8 PJ
- Private cars: 58.9 PJ
- Ships: 2 PJ
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer
Fuel for transportation
36.4 PJ straw plown down - 169 kT soil carbon


Extraction of renewable resources
Biofuel transformation
Heat and power production
Synthetic fuel production
System functional output
Primary energy supply
Converting raw biomass
Heat and power
Biofuel refining
Function
Electricity
Continuous
Balancing
Transportation
Heat
District heating
Industrial heating
Individual heating
Scenario:
Standard bioenergy
Alternative 2: Straw to CHP
Renewable electricity
Thermal solar
Biomass from forestry and SRF
Rape oil
Palm oil
Starch containing energy crop
Waste
Straw
Dry biodegradable biomass
Manure, sludge and industrial waste
48.8 PJ
11.1 PJ
11.7 PJ
296.5 PJ
4.1 PJ
84.5 PJ
93.1 PJ
15 PJ
50.4 PJ
34.1 PJ
52 PJ
8.8 PJ
94.2 PJ
Gasification
84.8 PJ
3.7 PJ
Transesterification
4.4 PJ
89.5 PJ
12.4 PJ
1st generation fermentation
2.8 PJ
51.2 PJ
36.3 PJ
Anaerobic digestion
61.9 PJ
68.5 PJ
Industrial biolers
9.4 PJ
+
76 PJ
99 PJ
14 PJ
31.9 PJ
Combined heat and power production
90.8 PJ
42.1 PJ
Waste incineration and geothermal energy
20.8 PJ
6.5 PJ
5.5 PJ
5.5 PJ
Power plants
5.7 PJ
0.6 PJ
13.2 PJ
27.1 PJ
Individual boilers, heat pumps and thermal solar
33.5 PJ
44.8 PJ
BtL (kerosene)
3.6 PJ
24.5 PJ
4.2 PJ
6.1 PJ
32.5 PJ
Methanation (Syngas-to-SNG)
26.5 PJ
2.7 PJ
5.5 PJ
BtL (methanol/ DME)
3.9 PJ
Electricity
- Continuous: 90.3 PJ
- Flexible: 9.7 PJ
- Transport: 5 PJ
Heat
- District heating: 147.3 PJ
- Industrial heating: 76 PJ
- Individual heating: 33.5 PJ
Fuels
- Aviation: 24.5 PJ
- Heavy duty road: 66.7 PJ
- Vans: 48.8 PJ
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- Ships: 2 PJ
Phase 1: Extraction of renewable resources at source
Phase 2 conversion of biomass feed
Phase 3 Producing heat and balancing power from biomass
Phase 4 biofuel refining
Phase 5 end consumer
Fuel for transportation
36.4 PJ straw plown down - 169 kT soil carbon

Appendix K Marginal input streams and output streams

		Period	Type	Bio part of electricity	Bio type		Unit	GWP100	GWP20	CO_2 100 years	CO2 20 years	CH4	N2O
INPUT electricity	Flexible	13-20	Average	Wood CHP continuous	Plantation on savannah	Low	g CO2-e/kWh	323	334	287	298	1,35	0
					Plantation on savannah	High	g CO2-e/kWh	329	362	293	326	1,35	0
					Plantation on grassland, low	Temperate	g CO2-e/kWh	314	244	278	208	1,35	0
					Plantation on grassland, low	Tropical	g CO2-e/kWh	315	302	279	267	1,35	0
					Plantation on grassland, high	Temperate	g CO2-e/kWh	328	311	292	275	1,35	0
					Plantation on grassland, high	Tropical	g CO2-e/kWh	336	401	300	366	1,35	0
					Plantation on cropland, low	Temperate	g CO2-e/kWh	318	253	282	218	1,35	0
					Plantation on cropland, low	Tropical	g CO2-e/kWh	317	311	281	275	1,35	0
					Plantation on cropland, high	Temperate	g CO2-e/kWh	337	349	301	314	1,35	0
					Plantation on cropland, high	Tropical	g CO2-e/kWh	330	371	294	335	1,35	0
					Harvest from existing forest	Boreal	g CO2-e/kWh	392	470	357	434	1,35	0
					Harvest from existing forest	Temperate	g CO2-e/kWh	426	538	390	502	1,35	0
					Harvest from existing forest	Tropical	g CO2-e/kWh	360	441	324	405	1,35	0
					Residues from thinnings	Boreal	g CO2-e/kWh	320	384	284	348	1,35	0
					Residues from thinnings	Temperate	g CO2-e/kWh	320	320	284	284	1,35	0
					Residues from thinnings	Tropical	g CO2-e/kWh	320	320	284	284	1,35	0
					Plantation on forest land	Boreal	g CO2-e/kWh	422	838	386	802	1,35	0
					Plantation on forest land	Temperate	g CO2-e/kWh	510	1081	474	1045	1,35	0
					Plantation on forest land	Tropical	g CO2-e/kWh	386	695	350	659	1,35	0
					Straw	-	g CO2-e/kWh	350	350	314	314	1,35	0
					Manure	-	g CO2-e/kWh	350	350	314	314	1,35	0
		20-35	Wind				g CO2-e/kWh	14,2	14,2	13,3	13,3	0,04	0
		35-50	Wind				g CO2-e/kWh	14,2	14,2	13,3	13,3	0,04	0
		50+	Wind				g CO2-e/kWh	14,2	14,2	13,3	13,3	0,04	0

		Period	Type	Bio part of electricity	Bio type		Unit	GWP100	GWP20	CO_2 100 years	CO2 20 years	CH4	N2O
INPUT electricity	Continuous	13-20	Average	Wood CHP continuous	Plantation on savannah	Low	g CO2-e/kWh	323	334	287	298	1,35	0
					Plantation on savannah	High	g CO2-e/kWh	329	362	293	326	1,35	0
					Plantation on grassland, low	Temperate	g CO2-e/kWh	314	244	278	208	1,35	0
					Plantation on grassland, low	Tropical	g CO2-e/kWh	315	302	279	267	1,35	0
					Plantation on grassland, high	Temperate	g CO2-e/kWh	328	311	292	275	1,35	0
					Plantation on grassland, high	Tropical	g CO2-e/kWh	336	401	300	366	1,35	0
					Plantation on cropland, low	Temperate	g CO2-e/kWh	318	253	282	218	1,35	0
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					Plantation on cropland, high	Tropical	g CO2-e/kWh	330	371	294	335	1,35	0
					Harvest from existing forest	Boreal	g CO2-e/kWh	392	470	357	434	1,35	0
					Harvest from existing forest	Temperate	g CO2-e/kWh	426	538	390	502	1,35	0
					Harvest from existing forest	Tropical	g CO2-e/kWh	360	441	324	405	1,35	0
					Residues from thinnings	Boreal	g CO2-e/kWh	320	384	284	348	1,35	0
					Residues from thinnings	Temperate	g CO2-e/kWh	320	320	284	284	1,35	0
					Residues from thinnings	Tropical	g CO2-e/kWh	320	320	284	284	1,35	0
					Plantation on forest land	Boreal	g CO2-e/kWh	422	838	386	802	1,35	0
					Plantation on forest land	Temperate	g CO2-e/kWh	510	1081	474	1045	1,35	0
					Plantation on forest land	Tropical	g CO2-e/kWh	386	695	350	659	1,35	0
		20-35	Average	Wood CHP continuous	Plantation on savannah	Low	g CO2-e/kWh	101	118	88	105	0,54	0
					Plantation on savannah	High	g CO2-e/kWh	110	162	97	149	0,54	0
					Plantation on grassland, low	Temperate	g CO2-e/kWh	87	-22	74	-35	0,54	0
					Plantation on grassland, low	Tropical	g CO2-e/kWh	89	69	76	56	0,54	0
					Plantation on grassland, high	Temperate	g CO2-e/kWh	108	83	95	70	0,54	0
					Plantation on grassland, high	Tropical	g CO2-e/kWh	120	223	108	210	0,54	0
					Plantation on cropland, low	Temperate	g CO2-e/kWh	93	-7	80	-20	0,54	0
					Plantation on cropland, low	Tropical	g CO2-e/kWh	92	83	79	70	0,54	0
					Plantation on cropland, high	Temperate	g CO2-e/kWh	122	142	109	129	0,54	0
					Plantation on cropland, high	Tropical	g CO2-e/kWh	111	175	99	163	0,54	0
					Harvest from existing forest	Boreal	g CO2-e/kWh	209	329	196	316	0,54	0
					Harvest from existing forest	Temperate	g CO2-e/kWh	261	434	248	421	0,54	0
					Harvest from existing forest	Tropical	g CO2-e/kWh	159	283	146	271	0,54	0
					Residues from thinnings	Boreal	g CO2-e/kWh	96	195	83	182	0,54	0
					Residues from thinnings	Temperate	g CO2-e/kWh	96	96	83	83	0,54	0
					Residues from thinnings	Tropical	g CO2-e/kWh	96	96	83	83	0,54	0
					Plantation on forest land	Boreal	g CO2-e/kWh	254	901	242	889	0,54	0
					Plantation on forest land	Temperate	g CO2-e/kWh	391	1279	379	1266	0,54	0
					Plantation on forest land	Tropical	g CO2-e/kWh	198	679	185	666	0,54	0
		35-50	75 wind 25 bio	Wood CHP continuous	Plantation on savannah	Low	g CO2-e/kWh	27	39	27	39	0,07	0
					Plantation on savannah	High	g CO2-e/kWh	34	70	34	70	0,07	0
					Plantation on grassland, low	Temperate	g CO2-e/kWh	18	-58	18	-58	0,07	0
					Plantation on grassland, low	Tropical	g CO2-e/kWh	19	5,35	19	5,13	0,07	0
					Plantation on grassland, high	Temperate	g CO2-e/kWh	33	15	33	15	0,07	0
					Plantation on grassland, high	Tropical	g CO2-e/kWh	41	112	41	112	0,07	0
					Plantation on cropland, low	Temperate	g CO2-e/kWh	22	-47,5	22	-47,7	0,07	0
					Plantation on cropland, low	Tropical	g CO2-e/kWh	21	15	21	15	0,07	0
					Plantation on cropland, high	Temperate	g CO2-e/kWh	42	56	42	56	0,07	0
					Plantation on cropland, high	Tropical	g CO2-e/kWh	35	79	35	79	0,07	0
					Harvest from existing forest	Boreal	g CO2-e/kWh	102	186	102	186	0,07	0
					Harvest from existing forest	Temperate	g CO2-e/kWh	138	259	138	259	0,07	0
					Harvest from existing forest	Tropical	g CO2-e/kWh	68	154	67	154	0,07	0
					Residues from thinnings	Boreal	g CO2-e/kWh	24	93	24	93	0,07	0
					Residues from thinnings	Temperate	g CO2-e/kWh	24	24	24	24	0,07	0
					Residues from thinnings	Tropical	g CO2-e/kWh	24	24	24	24	0,07	0
					Plantation on forest land	Boreal	g CO2-e/kWh	134	583	134	583	0,07	0
					Plantation on forest land	Temperate	g CO2-e/kWh	229	845	229	845	0,07	0
					Plantation on forest land	Tropical	g CO2-e/kWh	95	429	95	429	0,07	0
		50+	Wind				g CO2-e/kWh	14,2	14,2	13,3	13,3	0,04	0

		Period	Type	Bio part of electricity	Bio type		Unit	GWP100	GWP20	CO_2 100 years	CO2 20 years	CH4	N2O
OUTPUT electricity	Continuous	13-20	Average	Wood CHP continuous	Plantation on savannah	Low	g CO2-e/kWh	323	334	287	298	1,35	0
					Plantation on savannah	High	g CO2-e/kWh	329	362	293	326	1,35	0
					Plantation on grassland, low	Temperate	g CO2-e/kWh	314	244	278	208	1,35	0
					Plantation on grassland, low	Tropical	g CO2-e/kWh	315	302	279	267	1,35	0
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					Plantation on cropland, low	Temperate	g CO2-e/kWh	318	253	282	218	1,35	0
					Plantation on cropland, low	Tropical	g CO2-e/kWh	317	311	281	275	1,35	0
					Plantation on cropland, high	Temperate	g CO2-e/kWh	337	349	301	314	1,35	0
					Plantation on cropland, high	Tropical	g CO2-e/kWh	330	371	294	335	1,35	0
					Harvest from existing forest	Boreal	g CO2-e/kWh	392	470	357	434	1,35	0
					Harvest from existing forest	Temperate	g CO2-e/kWh	426	538	390	502	1,35	0
					Harvest from existing forest	Tropical	g CO2-e/kWh	360	441	324	405	1,35	0
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					Residues from thinnings	Tropical	g CO2-e/kWh	320	320	284	284	1,35	0
					Plantation on forest land	Boreal	g CO2-e/kWh	422	838	386	802	1,35	0
					Plantation on forest land	Temperate	g CO2-e/kWh	510	1081	474	1045	1,35	0
					Plantation on forest land	Tropical	g CO2-e/kWh	386	695	350	659	1,35	0
		20-35	75 wind 25 bio	Wood CHP continuous	Plantation on savannah	Low	g CO2-e/kWh	101	118	88	105	0,54	0
					Plantation on savannah	High	g CO2-e/kWh	110	162	97	149	0,54	0
					Plantation on grassland, low	Temperate	g CO2-e/kWh	87	-22	74	-35	0,54	0
					Plantation on grassland, low	Tropical	g CO2-e/kWh	89	69	76	56	0,54	0
					Plantation on grassland, high	Temperate	g CO2-e/kWh	108	83	95	70	0,54	0
					Plantation on grassland, high	Tropical	g CO2-e/kWh	120	223	108	210	0,54	0
					Plantation on cropland, low	Temperate	g CO2-e/kWh	93	-7	80	-20	0,54	0
					Plantation on cropland, low	Tropical	g CO2-e/kWh	92	83	79	70	0,54	0
					Plantation on cropland, high	Temperate	g CO2-e/kWh	122	142	109	129	0,54	0
					Plantation on cropland, high	Tropical	g CO2-e/kWh	111	175	99	163	0,54	0
					Harvest from existing forest	Boreal	g CO2-e/kWh	209	329	196	316	0,54	0
					Harvest from existing forest	Temperate	g CO2-e/kWh	261	434	248	421	0,54	0
					Harvest from existing forest	Tropical	g CO2-e/kWh	159	283	146	271	0,54	0
					Residues from thinnings	Boreal	g CO2-e/kWh	96	195	83	182	0,54	0
					Residues from thinnings	Temperate	g CO2-e/kWh	96	96	83	83	0,54	0
					Residues from thinnings	Tropical	g CO2-e/kWh	96	96	83	83	0,54	0
					Plantation on forest land	Boreal	g CO2-e/kWh	254	901	242	889	0,54	0
					Plantation on forest land	Temperate	g CO2-e/kWh	391	1279	379	1266	0,54	0
					Plantation on forest land	Tropical	g CO2-e/kWh	198	679	185	666	0,54	0
		35-50	75 wind 25 bio	Wood CHP continuous	Plantation on savannah	Low	g CO2-e/kWh	27	39	27	39	0,07	0
					Plantation on savannah	High	g CO2-e/kWh	34	70	34	70	0,07	0
					Plantation on grassland, low	Temperate	g CO2-e/kWh	18	-58	18	-58	0,07	0
					Plantation on grassland, low	Tropical	g CO2-e/kWh	19	5	19	5	0,07	0
					Plantation on grassland, high	Temperate	g CO2-e/kWh	33	15	33	15	0,07	0
					Plantation on grassland, high	Tropical	g CO2-e/kWh	41	112	41	112	0,07	0
					Plantation on cropland, low	Temperate	g CO2-e/kWh	22	-47	22	-48	0,07	0
					Plantation on cropland, low	Tropical	g CO2-e/kWh	21	15	21	15	0,07	0
					Plantation on cropland, high	Temperate	g CO2-e/kWh	42	56	42	56	0,07	0
					Plantation on cropland, high	Tropical	g CO2-e/kWh	35	79	35	79	0,07	0
					Harvest from existing forest	Boreal	g CO2-e/kWh	102	186	102	186	0,07	0
					Harvest from existing forest	Temperate	g CO2-e/kWh	138	259	138	259	0,07	0
					Harvest from existing forest	Tropical	g CO2-e/kWh	68	154	67	154	0,07	0
					Residues from thinnings	Boreal	g CO2-e/kWh	24	93	24	93	0,07	0
					Residues from thinnings	Temperate	g CO2-e/kWh	24	24	24	24	0,07	0
					Residues from thinnings	Tropical	g CO2-e/kWh	24	24	24	24	0,07	0
					Plantation on forest land	Boreal	g CO2-e/kWh	134	583	134	583	0,07	0
					Plantation on forest land	Temperate	g CO2-e/kWh	229	845	229	845	0,07	0
					Plantation on forest land	Tropical	g CO2-e/kWh	95	429	95	429	0,07	0
		50+	Wind				g CO2-e/kWh	14,2	14,2	13,3	13,3	0,04	0

		Period	Type	Bio part of electricity	Bio type		Unit	GWP100	GWP20	CO_2 100 years	CO2 20 years	CH4	N2O
OUTPUT electricity	Flexible	13-20	Coal PP				g CO2-e/kWh	965	965	854	854	4,02	0
		20-35	Coal PP				g CO2-e/kWh	965	965	854	854	4,02	0
		35-50	Bio syngas PP	Wood SNG CHP flexible	Plantation on savannah	Low	g CO2-e/kWh	23,5	128	23,5	128	0	0
					Plantation on savannah	High	g CO2-e/kWh	80,4	403	80,4	403	0	0
					Plantation on grassland, low	Temperate	g CO2-e/kWh	-61,8	-744	-61,8	-744	0	0
					Plantation on grassland, low	Tropical	g CO2-e/kWh	-52,3	-175	-52,3	-175	0	0
					Plantation on grassland, high	Temperate	g CO2-e/kWh	70,9	-90	70,9	-90,2	0	0
					Plantation on grassland, high	Tropical	g CO2-e/kWh	147	782	147	782	0	0
					Plantation on cropland, low	Temperate	g CO2-e/kWh	-23,9	-649	-24	-649	0	0
					Plantation on cropland, low	Tropical	g CO2-e/kWh	-33,3	-90	-33	-90	0	0
					Plantation on cropland, high	Temperate	g CO2-e/kWh	156	279	156	279	0	0
					Plantation on cropland, high	Tropical	g CO2-e/kWh	90	488	90	488	0	0
					Harvest from existing forest	Boreal	g CO2-e/kWh	696	1445	696	1445	0	0
					Harvest from existing forest	Temperate	g CO2-e/kWh	1018	2099	1018	2099	0	0
					Harvest from existing forest	Tropical	g CO2-e/kWh	384	1161	384	1161	0	0
					Residues from thinnings	Boreal	g CO2-e/kWh	-4,73	611	-4,73	611	0	0
					Residues from thinnings	Temperate	g CO2-e/kWh	-4,92	-4,81	-4,92	-4,81	0	0
					Residues from thinnings	Tropical	g CO2-e/kWh	-4,92	-4,92	-4,92	-4,92	0	0
					Plantation on forest land	Boreal	g CO2-e/kWh	981	5008	981	5008	0	0
					Plantation on forest land	Temperate	g CO2-e/kWh	1833	7358	1833	7358	0	0
					Plantation on forest land	Tropical	g CO2-e/kWh	630	3624	630	3624	0	0
		50+	Bio syngas PP	Wood SNG CHP flexible	Plantation on savannah	Low	g CO2-e/kWh	23,5	128	23,5	128	0	0
					Plantation on savannah	High	g CO2-e/kWh	80,4	403	80,4	403	0	0
					Plantation on grassland, low	Temperate	g CO2-e/kWh	-61,8	-744	-61,8	-744	0	0
					Plantation on grassland, low	Tropical	g CO2-e/kWh	-52,3	-175	-52,3	-175	0	0
					Plantation on grassland, high	Temperate	g CO2-e/kWh	70,9	-90,2	70,9	-90,2	0	0
					Plantation on grassland, high	Tropical	g CO2-e/kWh	147	782	147	782	0	0
					Plantation on cropland, low	Temperate	g CO2-e/kWh	-23,9	-649	-23,9	-649	0	0
					Plantation on cropland, low	Tropical	g CO2-e/kWh	-33,3	-90,2	-33,3	-90,2	0	0
					Plantation on cropland, high	Temperate	g CO2-e/kWh	156	279	156	279	0	0
					Plantation on cropland, high	Tropical	g CO2-e/kWh	90	488	89,8	488	0	0
					Harvest from existing forest	Boreal	g CO2-e/kWh	696	1445	696	1445	0	0
					Harvest from existing forest	Temperate	g CO2-e/kWh	1018	2099	1018	2099	0	0
					Harvest from existing forest	Tropical	g CO2-e/kWh	384	1161	384	1161	0	0
					Residues from thinnings	Boreal	g CO2-e/kWh	-4,73	611	-4,73	611	0	0
					Residues from thinnings	Temperate	g CO2-e/kWh	-4,92	-4,81	-4,92	-4,81	0	0
					Residues from thinnings	Tropical	g CO2-e/kWh	-4,92	-4,92	-4,92	-4,92	0	0
					Plantation on forest land	Boreal	g CO2-e/kWh	981	5008	981	5008	0	0
					Plantation on forest land	Temperate	g CO2-e/kWh	1833	7358	1833	7358	0	0
					Plantation on forest land	Tropical	g CO2-e/kWh	630	3624	630	3624	0	0

		Period	Type	Bio part of electricity	Bio type		Unit	GWP100	GWP20	CO_2 100 years	CO2 20 years	CH4	N2O
Heat	Small DH	13-20	Natural gas boile				g CO2-e/MJ	78,6	78,6	70,4	70,4	0,32	0
		20-35					g CO2-e/MJ	78,6	78,6	70,4	70,4	0,32	0
		35-50	Electric boiler - wind power				g CO2-e/MJ	4,38	4,38	4,12	4,12	0,01	0
		50+					g CO2-e/MJ	4,38	4,38	4,12	4,12	0,01	0
	Large DH	13-20	Natural gas boile				g CO2-e/MJ	78,6	78,6	70,4	70,4	0,32	0
		20-35					g CO2-e/MJ	78,6	78,6	70,4	70,4	0,32	0
		35-50	Electric boiler - wind power				g CO2-e/MJ	1,13	1,13	1,06	1,06	0,003	0
		50+					g CO2-e/MJ	1,13	1,13	1,06	1,06	0,003	0
Transport fuels	Long range road	13-20	Fossil diesel				g CO2-e/MJ	85,9	85,9	84,2	84,2	0,04	0
		20-35	Fossil diesel				g CO2-e/MJ	85,9	85,9	84,2	84,2	0,04	0
		35-50	Fossil diesel				g CO2-e/MJ	85,9	85,9	84,2	84,2	0,04	0
		50+	Bio DME	Wood + H2 methanol & DME fuel	Plantation on savannah	Low	g CO2-e/MJ	3,39	12,9	3,39	12,9	0	0
					Plantation on savannah	High	g CO2-e/MJ	8,59	38,0	8,59	38,0	0	0
					Plantation on grassland, low	Temperate	g CO2-e/MJ	-4,40	-66,8	-4,40	-66,8	0	0
					Plantation on grassland, low	Tropical	g CO2-e/MJ	-3,54	-14,8	-3,54	-14,8	0	0
					Plantation on grassland, high	Temperate	g CO2-e/MJ	7,73	-7,00	7,73	-7,0	0	0
					Plantation on grassland, high	Tropical	g CO2-e/MJ	14,7	72,7	14,7	72,7	0	0
					Plantation on cropland, low	Temperate	g CO2-e/MJ	-0,94	-58,1	-0,94	-58,1	0	0
					Plantation on cropland, low	Tropical	g CO2-e/MJ	-1,80	-7,00	-1,80	-7,00	0	0
					Plantation on cropland, high	Temperate	g CO2-e/MJ	15,5	26,8	15,5	26,8	0	0
					Plantation on cropland, high	Tropical	g CO2-e/MJ	9,46	45,8	9,46	45,8	0	0
					Harvest from existing forest	Boreal	g CO2-e/MJ	64,9	133	64,9	133	0	0
					Harvest from existing forest	Temperate	g CO2-e/MJ	94,4	193	94,4	193	0	0
					Harvest from existing forest	Tropical	g CO2-e/MJ	36,3	107	36,3	107	0	0
					Residues from thinnings	Boreal	g CO2-e/MJ	0,81	57,1	0,81	57,1	0	0
					Residues from thinnings	Temperate	g CO2-e/MJ	0,80	0,80	0,80	0,80	0	0
					Residues from thinnings	Tropical	g CO2-e/MJ	0,80	0,80	0,80	0,80	0	0
					Plantation on forest land	Boreal	g CO2-e/MJ	90,9	459	90,9	459	0	0
					Plantation on forest land	Temperate	g CO2-e/MJ	169	674	169	674	0	0
					Plantation on forest land	Tropical	g CO2-e/MJ	58,8	333	58,8	333	0	0
Transport fuels	Short range road	13-20	Fossil diesel				g CO2-e/MJ	85,9	85,9	84,2	84,2	0,04	0
		20-35	Fossil diesel				g CO2-e/MJ	85,9	85,9	84,2	84,2	0,04	0
		35-50	Electricity - wind power				g CO2-e/MJ	14,2	14,2	13,3	13,3	0,04	0
		50+	Electricity - wind power				g CO2-e/MJ	14,2	14,2	13,3	13,3	0,04	0

Appendix L The GLOBIOM model

The function and characteristics of these SSPs are:

- SSP1: SUSTAINABILITY
  - economic growth: high (global GDP per capita reach 20 000 USD by 2050)
  - demographic growth: low (from current 7 B to 8 B in 2050); European population is highest here
  - education level: high
  - technological growth: fast
  - developed vs developing countries: convergence
  - international cooperation: high
  - sustainability concerns: high
  - to reflect better management of domestic waste in developed countries, consumption per capita assumed almost constant (for developed countries)
  - animal protein demand reduced in regions where more than 75 g protein/cap/d are consumed for animal and vegetable products, but min of 25 is ensured (from animal)
  - red meat reduced to 5 g protein/cap/d
  - developing countries: protein intake at 75 g protein/cap/d ensured, reduction of root consumption at a level of 100 kcal/cap/d

- SSP2: BAU
  - Demographic growth (from current 7 B to 9 B in 2050)
  - Future diet follow projections of (FAO 2006) for 2050

- SSP3: FRAGMENTATION
  - economic growth: slow (global GDP per capita < 10 000 USD by 2050)
  - demographic growth: high (from current 7 B to 10 B in 2050); European population is lowest here
  - low food demand per capita

Crop yields

- Econometric relationship between crop yield and GDP per capita established:
  - Crop yield from FAOSTAT fitted to GDP per capita over 1980-2009
  - Countries grouped based on world bank economic groups
  - Estimation carried out for each of the 18 crops of the database separately

- N utilization vs. yield:
  - SSP2: Proportional increase of N utilization to yield growth (elasticity = 1)
  - SSP1: decreasing N intensity (elasticity = 0.75)
  - SSP3: increasing N intensity (elasticity = 1.25)

(permanent increase of 1% in crop price result in an increase of 1%, 0.75% and 1.25% (respectively) of N utilization)

Table 0-1 Results of the runs of the baseline SSPs. All results for 2050, relative to 2000

	SSP1	**SSP2**	**SSP3**
Calorie comsumpt per capita, 2050	No change	+14%	+3%
Crop consumption	+12%	+10%	
Livestock consumption	+19%	+37%	
Demand for 1st gen biofuels	9% of all crop production, in terms of calories (largest)		
Crop price index, world	0.97	1.03	1.13
Land cover	Tot expansion ≈ **275 Mha**	175 Mha additional cropland 300 Mha additional grassland 150 Mha additional for short rotation tree plantations (total expansion = **625 Mha**: 35% in forest; 65% in other natural land) = 4.4 Mha deforestation/y	Tot expansion ≈ **575 Mha**
Yield change 2000-2050	+52	+70%	+55
N comsumpt	+40%	+60%	+61%
Irri water	+5%	+12%	+13%
GHG	-14%	+34	

Appendix M Literature

Note: this overview does not pretend to cover all bioenergy-related literature, but merely those publications that are of interest for this project. A classification of the references per category is here proposed, however, some references could also belong to other categories simultaneously. It is intended to further update this list as the project evolves (new references and trimming and/or re-categorization of the references below).

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