Report for
Xergi A/S
Sofiendalsvej 7
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Life Cycle Assessment of Biogas from Maize silage and from Manure

- for transport and for heat and power production under displacement of natural gas based heat works and marginal electricity in northern Germany

NB: Please note that the Life Cycle Assessment is being reviewed.
Final Assessment will be issued after completion of review

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REPORT INDEX

Executive summary

This report presents an environmental Life Cycle Assessment (LCA) of biogas produced from both maize silage (1) and animal manure (2) based on the technologies developed at Xergi A/S in Aalborg, Denmark. The LCA comprises both environmental impacts (with focus on global warming impacts) and impacts on resource consumption and covers utilisation of the produced biogas for either heat and power generation (A) or for transport (B) in an upgraded (cleaned) and compressed form. In biogas heat & power scenarios, the generated heat is assumed to replace natural gas based heat works, whereas the generated power will replace marginal power on the grid. The study is comparative and shows the environmental consequence of making biogas instead of the alternative use of the substrate. Biogas from manure is, thus, compared to the conventional storage and use of the manure as agricultural fertilizer, and biogas from maize silage is compared to using the same agricultural land for other bioenergy purposes, i.e. growth of maize for bioethanol production, growth of rapeseed for biodiesel production and growth of willow for heat and power production allowing to compare Xergi's biogas to other biofuels.

The assessment, thus, comprises:

1. Biogas made from whole-crop maize (silage)
   1A Biogas used for heat & power
   1B Biogas cleaned, compressed and used for transport

2. Biogas made from animal manure
   2A Biogas used for heat & power
   2B Biogas cleaned, compressed and used for transport

3. 1st generation biodiesel made from rapeseed

4. 1st generation bioethanol made from maize kernels

5. 2nd generation bioethanol made from whole-crop maize

6. Willow production for power and heat production

In this context, 1st generation biofuels are defined as biofuels based on raw materials that alternatively could be used as food, whereas 2nd generation biofuels are based on energy crops, residues and waste streams.

The environmental assessment is based on the EDIP method (Wenzel et al., 1997) and further up-dates of this method (Weidema et al. (2004), Weidema (2004), Stranddorf et al. (2005)) which are in agreement with the standards of the International Organisation for Standardisation, ISO.

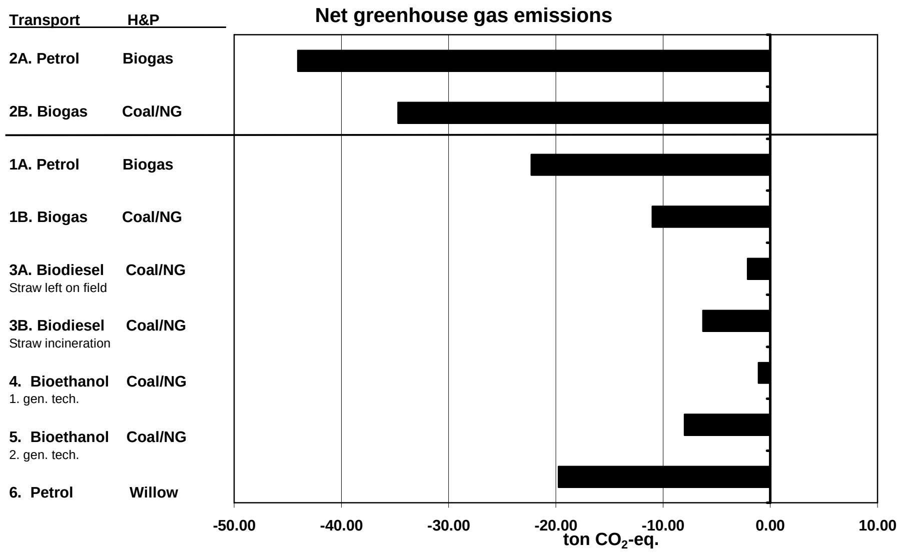
Moreover, the study is conducted according to the principles of consequential LCA, which is today's best scientific practice. It implies that the LCA is comparative and dedicated to identify the environmental consequence of choosing one alternative over the other. The consequential and comparative approach ensures that all compared alternatives are equivalent and provide the same services to society, not just regarding the primary service, which in this case is a specified transportation service together with a heat and power production, but also on all secondary services. Secondary services are defined as products/services arising e.g. as co-products from processes in the studied systems, and in the case of biofuels, such secondary services can typically be energy-services (electricity and/or heat) and animal feed. The consequential LCA ensures equivalence on all such services by identifying and including the displacements of alternative products that will occur when choosing one alternative over the other.

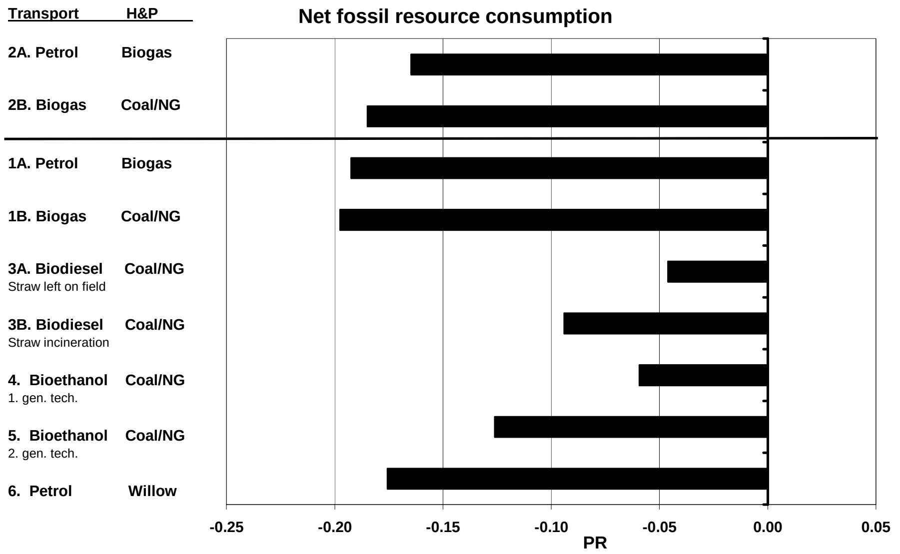
Biomass has become a priority resource to substitute fossil fuels in the energy sector (heat & power) and is increasingly seen to be so in the transport sector as well. In e.g. Denmark, wood chips, wood pellets, and straw are increasingly used to substitute fossil fuels for heat & power production. Moreover, it has been shown that the amount of biomass, that is or can be made available for energy purposes, is limited compared to the potential use of it for fossil fuel substitution in the energy (heat & power) and transport sector as a whole (Jensen and Thyø, 2007), and so is the fraction of agricultural land that can be made available for energy crops. Any area of land that is made available for energy purposes has, thus, a potential customer in both the heat & power sector and the transport sector. As such, any use of such biomass for transport fuels will happen at the expense of using it for heat & power and, thus, with the consequence of using an equivalent amount of fossil fuels there. Moreover, any use of biomass for biofuels will require subsidies for a long period ahead (and covering the time perspective of this study), and money to support a given biofuel or technological pathway is limited as well. Therefore, any use of biomass for energy purposes or of money to support biomass for energy purposes will happen at the expense of an alternative use of the same biomass, land, and/or the same money.

The situation to be modelled in a consequential LCA approach is, thus, clear: the use of the limited amount of agricultural land will happen at the expense of utilisation of agricultural land for alternative uses.

The Figures below show key results of the assessment. The unit for greenhouse gas emissions is ton CO_2-equivalents, and the unit for fossil fuel consumption is PR, standing for person reserves, which is a common unit for assessing resource consumption based on their scarcity and supply horizon.

The scenarios 2A and 2B of manure based biogas are included in the comparison, however, it should be emphasised that they are “stand alone”, while the rest of the scenarios are each others alternatives e.g. the prioritising of utilizing land for one option shall be seen to happen at the expense of the other options.





Biogas based on manure is not an alternative strongly correlated to the other scenarios, because it does not include any utilization of agricultural land. However, since it provides the same services to society as the other scenarios, it still compares to them and enters into the overall prioritisation of which type of bioenergy technology society should promote with subsidies and other incentives. The conclusion of this comparison is unambiguous: biogas from manure implies by far the highest reduction of greenhouse gas emissions per unit of services provided to society. This being due to the fact that it implies CO_2 reductions not only from the fossil fuel replacement by the generated biogas, but equally significantly from the reduced methane emissions from manure storage, reduced nitrous oxide emissions from soil application of the manure and improved plant availability of the nitrogen in the manure.

The brief and overall conclusions on manure based biogas can, thus, be expressed as:

> *Biogas from manure stands out as having very high reduction in greenhouse gas emissions and very high fossil fuel savings compared to the conventional storage and soil application of the manure. Environmentally and in terms of resource savings, manure should be utilised for biogas production prior to the soil application.*
>
> *Biogas from manure stands out as having much higher reduction in greenhouse gas emissions as the other bioenergy types and equal savings in fossil fuels. As cost aspects point to the same direction, manure based biogas should have the highest priority of all the compared bioenergy types.*

The other scenarios are strongly correlated by their competition for the same agricultural land. Based on the comparative approach, the LCA shows that environmentally and in terms of fossil fuel savings, energy crops should be prioritised for heat and power purposes either 1) through a preceding biogas generation or 2) by direct incineration or gasification, the two leading to almost equal CO_2 reductions and fossil fuel savings. Energy crops converted directly into a transport fuel implies significantly lower CO_2 reductions due to the energy losses in the conversion processes.

The brief and overall conclusions on maize based biogas can, thus, be expressed as:

> *Among the compared types of bioenergy requiring agricultural land and energy crops, biogas from maize silage and heat and power from willow imply the highest reductions in greenhouse gas emissions and the highest fossil fuel savings. Environmentally and in terms of fossil fuel savings, land for energy crops should, thus, be prioritised for crops for heat & power or for biogas.*

The explanation of this outcome of the LCA can be found within 3 main reasons:

1. The yield of the energy crop per hectare of land
2. The fossil fuel substitution efficiency, including the energy efficiency of the conversion of the calorific value of the crop's dry matter content
3. The energy infrastructure aspects of the bioenergy technology

The explanation within these 3 categories of why the rape seed biodiesel and the 1st and 2nd generation bioethanol comes out with lower CO_2 reductions and fossil fuel savings are given below.

Rape seed biodiesel: Rape has a very low energy yield per hectare, and this is the one reason for rape seed biodiesel to come out as the environmentally least preferable of the biofuels. Prioritising land for rape through choosing (and subsidising) rapeseed biodiesel for transport means depriving society the higher yield of other energy crops on the same land. There is no sign that this will change. The conversion efficiency of the rape seed oil to the biodiesel is comparably high, i.e. only 10% conversion loss or less. There are no infrastructure disadvantages.

Bioethanol: The yield of maize per hectare is the highest among the compared energy crops, and in this study, the bioenergy technologies using maize have for this reason an inherent advantage. For the first generation bioethanol, however, the advantage is of course lost when the stover is not used for energy purposes. On the energy conversion, however, the bioethanol technologies have large losses and an inherent disadvantage: Firstly (for the 2nd generation technology), a thermal pre-treatment of the maize stover is required, and this implies an energy consumption. Secondly, the metabolism of the ethanol fermentation is not as efficient as the methane fermentation, and much remains unconverted to ethanol in terms of metabolic side-products and un-degraded residues. It implies among other things that energy must be spent on drying/dewatering in order to render the residues suitable for subsequent incineration or gasification based energy conversions. Thirdly, energy is needed to separate the ethanol from the fermentation liquor, requiring a distillation process. The biogas has the inherent advantage of leaving the fermentation liquor voluntarily. On the infrastructure side, finally, the bioethanol technologies have an inherent requirement of being very large scale, mainly due to the necessity of the distillation to be large scale; in small scale the cost of bioethanol becomes much worse and detrimental to any real life implementation. It implies that bioethanol cannot enter into a decentralised heat & power production infrastructure and, thus, cannot, like biogas, realise the multiplication effect of full heat utilisation at the same time as delivering the electricity to the grid under marginal electricity replacement.

The assessment is robust to changes in boundary conditions including the key issues for the sensitivity of the results. The most crucial boundary condition behind the assessment in this LCA is the acknowledgement of the fact that energy crops/land for energy crops will be a constrained resource and require subsidies in order to reach any utilisation for energy purposes, with the implication that any use of land for energy crops should be assessed against the lost opportunity of using it for other purposes in the fulfilment of the same aims.

1. Introduction

This study was commissioned by Xergi A/S in April 2007.

Xergi A/S is a contractor and O&M (operation and maintenance) operator with more than 20 years of experience within development, delivery, operation and maintenance of turnkey energy and environmental plants (Xergi, 2007). The biogas and manure separation activities of the company are focused on exploitation of energy and nutrients in organic waste, while effective energy transformation of biogas, natural gas and landfill gas is the main element when it comes to power, heating and/or cooling solutions.

1.1 Aim of the study

The aim of this study is to make an environmental Life Cycle Assessment (LCA) of Xergi's biogas production based on 1) maize silage and 2) animal manure showing both environmental impacts and impacts on resource consumption. The study shall be comparative and show the environmental consequence of making biogas of maize silage and manure compared to alternatives. The biogas shall be assumed used for heat and power production in a situation where the produced heat displaces heat from a natural gas based heat works and the produced electricity displaces marginal electricity on the grid. This is believed to be the realistic situation in northern Germany. Under these conditions, the study shall compare the growing of maize for biogas to growing willow for heat & power, and it shall compare the biogas from manure to the alternative of conventional storing and use as fertiliser. Moreover, the study shall compare Xergi's biogas production with the use of other biofuels, i.e. biodiesel made from rapeseeds and bioethanol made from maize kernels and whole-crop maize.

A secondary aim is to identify and present a breakdown on sources of all induced and avoided environmental impacts related to making a biogas from maize silage/manure in order to support Xergi A/S in the understanding of proportions among the various sources of impacts.

The results of the study are intended for public dissemination.

2. Assessment methodology

The environmental assessment is based on the EDIP method (Wenzel et al., 1997) and further up-dates of this method (Weidema et al. (2004), Weidema (2004), Stranddorf et al. (2005)) which are in agreement with the standards of the International Organisation for Standardisation, ISO.

Moreover, the study is conducted according to the principles of consequential LCA, which is today's best scientific practice. It implies that the LCA is comparative and dedicated to identify the environmental consequence of choosing one alternative over the other. The consequential and comparative approach ensures that all compared alternatives are equivalent and provide the same services to society, not just regarding the primary service, which in this case is a specified transportation service and power and heat service, but also on all secondary services. Secondary services are defined as products/services arising e.g. as co-products from processes in the studied systems, as during the biogas production where fertilizer is produced or in the case of biofuels, such secondary services can typically be energy-services (electricity and/or heat) and animal feed. The consequential LCA ensures equivalence on all such services by identifying and including the displacements of alternative products that will occur when choosing one alternative over the other. See further explanation of comparative and consequential LCA in Wenzel (1998), Ekvall and Weidema (2004) and Weidema (2004).

2.1 Inventory analysis

In the inventory part of the study, data on inputs and outputs from the processes included in the study are collected taking into account all processes induced or displaced by the studied alternative including all processes induced or displaced by any co-products arising in the system. The resulting procedure of associating environmental inputs from and outputs to environment with the bioenergy production (n) being studied is, then, an algorithm summarizing inputs and outputs (Q_i) from all production processes (p) influenced (induced, displaced or changed):

$$Q_{i,\text{ bioenergy } n} = \sum Q_{i,p}$$

The results are summarised in an inventory of resource uses, emissions to air, water and soil (solid waste) induced and avoided per unit of transportation and energy service aggregated over the entire system.

2.2 Impact Assessment

The study, like any LCA, focuses on assessing the potential contributions to environmental impacts, and not the actual environmental effects. This is in accordance with both the ISO standards and international consensus, acknowledging that it is in practice impossible to know all sites of emissions to the environment and all actual exposure pathways of the emitted substances.

When calculating the potential environmental impacts ($EP(j)_{i,\text{ bioenergy } n}$) associated with specific substance emissions (i) induced or avoided as a result of choosing the particular resource for biogas production, the algorithm is a simple multiplication of total emissions of substances ($Q_{i,\text{ bioenergy } n}$) with specific equivalency factors ($EF(j)_i$) for specific impacts categories (j):

$$EP(j)_{i,\text{ bioenergy } n} = Q_{i,\text{ bioenergy } n} \cdot EF(j)_i$$

Subsequently, environmental impact potentials $EP(j)_{\text{bioenergy } n}$ are determined by summarizing contributions to environmental impacts from all induced, displaced or changed processes:

$$EP(j)_{\text{bioenergy } n} = \sum EP(j)_{i,\text{ bioenergy } n} = \sum (Q_{i,\text{ bioenergy } n} \cdot EF(j)_i)$$

Since the main environmental concern with respect to transport and energy systems is global warming, it has been decided to focus on global warming in the data presentation. However, data on other impact categories are available in appendix O, including:

- Acidification
- Nutrient enrichment
- Photochemical ozone formation

Contributions to stratospheric ozone depletion are considered insignificant in the studied systems and no assessment has been carried out on this impact category. Toxicity induced by application of pesticides during farming and changes in emission patterns of toxic substances induced could give good reason for including toxicity assessment in the study. Data on toxicity have, however, not been readily available and hence left to qualitative judgements in the discussion.

With respect to resource consumption, the use of fossil fuels, i.e. oil, natural gas and hard coal, have been considered. The consumption of a given resource is aggregated over the system as accounted for in the above section on inventory analysis. When the magnitude of consumption is found, it is subsequently weighted according to the scarcity of the resource.

In the EDIP-method, 2004 is currently used as reference year for weighting, where the weighted resource consumption, WR(j), can be expressed as:

$$WR(j) = \frac{RC(j)}{Known\,reserves\,of\,(j)\,per\ \ person_{2004}}$$

Where RC(j) is the consumption of the resource (j) in the product system for the functional unit (Nedermark et al., 1998).

As shown, the weighted resource consumption, WR(j), can be expressed as a fraction of the known global reserves per person in 2004. The unit for the weighted resource consumption is, thus, the 'person-reserve' PR_{2004}. Often, the weighted resource consumption is expressed in mPR_{2004}, i.e. in parts per thousand of known global person-reserves in 2004. For illustration, if e.g. the resource consumption associated with a given product is 20 mPR_{2004} (0.020 PR_{2004}), buying 50 products of the given type would correspond to using the ration of known reserves available for one person for the entire future of all subsequent generations, i.e. also that portion of the known reserves, which were otherwise available for one's children, grand children and subsequent generations. The weighting factors applied in the assessment is presented in table 1.

Table 1: Weighting factors applied in the assessment

Quantity	**Surply horizon (y)**	**Weighting factors (y^{-1})**	**$PR(j)_{2004}$ (kg/pers)^a**
Resource consumption			
Natural gas	67	0.015	23810
Crude oil	42	0.024	24510
Hard coal	125	0.008	73529

Source: Gabi4 (2006)

$PR(j)_{2004}$: known global person-reserves (in 2004), i.e. known reserves available per person for the entire future of all generations, i.e. also that portion of the known reserves, which are available for a persons children, grand children and subsequent generations.

As can be seen, the global availability of a given resource is measured in terms of the resource reserve. The *reserve* represents the fraction of resource, which it is *economically reasonable* to exploit. In contradiction, the so-called *reserve base* is the fraction of the resource which fulfils the requirements of ore grade, quality, quantity and depth defined by the current practice within mining and production. Hence, the reserve base is the fraction of the resource, which can be exploited *technically*. Ideally the reserve base should be used in the weighting of the resource consumption from the view point that it best describes the scarcity of the resource. However, data for the reserve base are often either lacking (e.g. oil, coal and manganese) or are too uncertain (e.g. iron, aluminium and coal). Therefore it is necessary to use data for the reserves as indicators of the resource scarcity instead (Nedermark et al., 1998).

The modelling and calculations of environmental impacts and resource consumption have been facilitated by modeling in the GaBi4 LCA software package.

3. Defining and modelling the scope of the compared systems

In agreement with the study commissioner, it was decided up front that the overall scope of the study was to assess Xergi's biogas production based on 1) maize silage and 2) animal manure and compare it with the following alternative uses of biomass for energy:

- 1st generation biodiesel made from rapeseed
- 1st generation bioethanol made from maize kernels
- 2nd generation bioethanol made from whole-crop maize

These biofuels are alternative fuels for transportation and each of them derives from a larger system of processes that together provide the fuel. In the comparison of alternatives, these systems and all influenced changes in adjoining systems are modelled (see section 3.5).

In this context 1st generation biofuels is defined as biofuels based on raw materials that alternatively could be used as food, whereas 2nd generation biofuels are based on energy crops, residues and waste streams. This seems to be a widely used definition. It should be noted, however, that energy crops competive with food crops with the same resulting influences on the food sector as when using food grade material directly for energy purposes.

3.1 Temporal, geographical and technological scope

The systems are geographically and technologically represented by northern European conditions (primary North German and Danish conditions) for the production of the bioenergy:

- Xergi's maize silage based biogas production is represented by Xergi's technology and data
- Xergi's animal manure based biogas production is represented by Xergi's technology and data
- Rapeseed biodiesel is represented by estimates based on technology and data from Jensen et al. (2007)
- Both 1st and 2nd generation bioethanol are represented by the technology developed by the Danish company DONG Energy A/S in terms of the so-called IBUS technology[1]

Moreover, the correlated heat and power systems are represented by the various heat and power technologies found within northern Germany. Note that the power production used in the models is the marginal power on the Northern German grid, which in turn is assumed to be the same as the Danish marginal power. The data for production and yields of the various agricultural crops and manure handling involved represents Danish agricultural practices. Data for the transportation, i.e. running the various types of cars, are general and derived from the EU Joint Research Centre, JRC. The remaining data for animal feed production, fertilizer production, chemical auxiliaries production, edible oil production and more, are less significant, and they all derive from one of the two LCA databases, the GaBi4 database or the Eco-Invent database. Greenhouse gas emissions and fossil fuel consumption associated with oil extraction and fossil petrol and diesel refining have been updated according to the process data given in JRC et al. (2006b).

However, except the data for agricultural operations, the data do not depend on the geographical location, but on the specific technology in question, and as such the study is of general applicability to any comparisons of the bioenergy types and technologies in question.

The most recent data are used for all parts of the systems and if possible data are projected to represent a near term future, i.e. about 10 years ahead. This is the case for the agricultural yields and the car technologies.

3.2 Primary service and functional unit

The primary service provided by, and equal for, all systems is a quantity of transportation and heat and power production, and hence the specified functional unit delivered by all alternative systems is:

98,851 km of transportation
in a typical European compact size 5-seat passenger car &
production of 82.2 GJ power and 85.0 GJ heat

with 2010+ (2010 and beyond) car configurations complying with EURO IV limits and presented in JRC et al. (2006a). The 98,851 km transportation is the distance made by the car when running on cleaned and compressed biogas from the maize silage from 1 ha·year of agricultural land. The 82.2 GJ power and 85.0 GJ heat is the heat and power generated in the co-generation of heat & power from biogas made from the maize silage from 1 ha·year of agricultural land (maize yield applied: 15 ton DW/ha·y).

3.3 Secondary services and system equivalence

For all bioenergy alternatives, the system providing the above mentioned primary transport service and energy production will, however, correlate with adjoining systems through the provision of co-products also

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[1] Integrated Biomass Utilisation System.

called secondary services. Such adjoining systems comprise essentially the provision of animal feed, human food, and fertilisers.

Through the system modelling, it is ascertained that all compared systems provide the same services for society. In practice, it is done by identifying the products on the market displaced by these co-products and by modelling the system of processes providing these displaced products and including them in the whole system as avoided processes (see section 3.5).

3.4 Modelling concept for comparing alternatives

The volume of biogas produced is determined based on the technology of Xergi's biogas plant. The biogas displaces either petrol for transport or displaces natural gas in German heat works and coal based electricity being the marginal on the Northern German electricity grid (equal to the Danish marginal).

Both agricultural land for energy maize production and the animal manure have, however, alternative uses. Only a limited amount of the agricultural land can be prioritised for energy crops (Jensen and Thyø, 2007), so one crop prioritised for one purpose will mean less land available for other crops for other purposes. It means that one choice happens at the expense of the others, and in turn it means that they have to be compared in order to include any attractive opportunities lost by the choice in question.

Biomass has become a priority resource to substitute fossil fuels in the energy sector and is increasingly seen to be so in the transport sector as well. In e.g. Denmark, wood chips, wood pellets, and straw are increasingly used to substitute fossil fuels for heat & power production, and much more could be used. Moreover, it has been shown that the amount of biomass, that is or can be made available for energy purposes, is limited compared to the potential use of it for fossil fuel substitution in the energy (heat & power) and transport sector as a whole (Jensen and Thyø, 2007) and so is the fraction, as mentioned, of agricultural land that can be made available for energy crops. Any area of land that is made available for energy purposes has, thus, a potential customer in both the heat & power sector and the transport sector, and any use of such biomass for e.g. transport fuels will happen at the expense of using it for heat & power and, thus, with the consequence of using an equivalent amount of fossil fuels there. Moreover, any use of biomass for biofuels will require subsidies for a long period ahead (and covering the time perspective of this study), and money to support a given biofuel or technological pathway is limited as well. Therefore, any use of biomass for energy purposes or of money to support biomass for energy will happen at the expense of an alternative use of the same biomass and/or the same money.

The situation to be modelled in the LCA is, thus, the choice of bioenergy technology in question (biogas from maize and manure) seen in the light of the lost alternatives. For the maize silage based biogas, the alternative of the same area of agricultural land for willow as energy crop for heat and power is chosen. For manure-based biogas, the alternative will be the conventional storage and soil application of the manure.

The other biofuels included for comparison, i.e. 1st generation biodiesel made from rapeseed, 1st generation bioethanol made from maize kernels, and 2nd generation bioethanol made from whole-crop maize, all depend on agricultural land, and for those, the use of willow for heat and power will also be an alternative.

Further background on this boundary condition is given in Jensen and Thyø (2007).

Based on this resource constraint of agricultural land, the modelling of each energy crop based scenario is therefore conducted under one and the same limitation:

1 ha·y of agricultural land available

This, however, does not apply to the use of manure where no land is utilised since the manure is a residue from farming. Instead, in the modelling of this scenario, the alternative use of the manure i.e. as a fertilizer is included.

3.4.1 Choice of energy crops

The following energy crops dedicated for bioenergy production are:

- Maize production, more specifically:
  - Whole-crop maize for silage for biogas production
  - Maize kernels for bioethanol production (1st generation technology)
  - Whole-crop maize (kernel and stover) for bioethanol production (2nd generation technology)
- Rapeseed for biodiesel production (1st generation technology)
- Willow for heat and power production

In the following, the relevance of considering the different energy crops and conversion technology is shortly given.

Maize for biogas and bioethanol (1st and 2nd generation technology) production: Based on discussions with Danish agricultural scientists, maize is a relevant energy crop under Danish conditions for both biogas and bioethanol production. Maize is usually grown in a warmer climate but new species have been developed that are able to stand the colder climate of Northern Europe. Maize is a C_4 plant, which means that the plant produces C_4 sugars directly and not via a step of C_3 sugar production, as other plants do. Thereby, maize is efficient in utilizing sunlight and has a high glucose production, which is important for the biofuel production. The lower part, the stover, resembles straw and mainly consists of ligno-cellulosic material. 2nd generation technology makes it possible to convert this ligno-cellulosic material thus enabling utilisation of the whole crop in fermentation processes (Bentsen et al., 2006). This means that a significantly higher yield can be obtained on a given amount of land for energy crop production.

Furthermore, the plant requires low amounts of energy and water when grown compared to many other crops. Maize also has practical advantages such as easiness to store compared to e.g. sugar beets which easily decay (Felby, 2006). Whole-crop maize can be ensiled on the agricultural field and preserved for up to 10-12 months with only a few percent losses in dry matter. The ensiled plant can then be collected when needed for bioethanol or biogas production. If the demand for maize feedstock for bioethanol or biogas production is in periods too low, maize the silage can be used as animal fodder. Furthermore, the harvest period is long, approximately 1 month depending on the weather, compared to e.g. wheat, which has a harvest period of approximately 10 days. Due to these properties, whole-crop maize is considered a stabile and flexible biomass feedstock supply for biogas and bioethanol production (Felby, 2006).

Through the last part of the 20th century, the biogas process has been implemented within a number of environmental and energy solutions utilizing the unique opportunity of combining treatment of organic waste with production of renewable energy (Xergi, 2007). Until 20 years ago, the process was mainly used in connection with treatment of waste water sludge (in Denmark). However, in recent years the farming sector has also gained an advantage from the potential of biogas technology in connection with handling of farmyard manure and energy crops.

Maize kernel based ethanol production (1st generation technology) is also a commercially available technology operated on large scale in e.g. the United States (IEA, 2004). Whole-crop maize for bioethanol production (2nd generation technology) is, however, still on a development stage, but the technology is receiving increasing worldwide focus, and it seems to have promising perspectives for commercialisation within the next few years (IEA, 2004).

Rapeseed for biodiesel production (1st generation technology): Rapeseed based biodiesel production, is a biodiesel technology currently operating at commercial scale. A significant amount of rapeseed based biodiesel is produced in Denmark and is currently being exported[2] (Teknologirådet, 2006).

Willow for heat and power production: Based on literature and information from Danish experts within the field of energy crop production, willow is assessed to be a highly relevant energy crop dedicated for heat and power production. The reasons and relevance of this crop choice are:

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[2] Emmelev Mølle produced 100 million litres rapeseed based biodiesel in 2005 (Teknologirådet, 2006).

- Willow provides a woody fuel which is easy to handle and is well suited for energy production (Jørgensen, 2006a), (Gylling, 2001)
- Production of willow is easy to establish and there is a solid experience with commercial willow production in Denmark (Jørgensen, 2006a)[3].
- Considerable progress has been achieved in improvement of willow species (Jørgensen, 2006b)
- Like elephant grass, willow is a perennial crop with a relatively low nitrogen requirement, which at the same time has a normal utilisation rate of both organic nitrogen (manure or waste water sludge) and inorganic nitrogen (fertilisers). This implies a very low leaching of both nitrogen types to the environment in the growth period (Gylling, 2001).

Energy crops produced in larger amounts can potentially be utilized at biomass based district heating or CHP plants or through co-firing at central plants (Gylling, 2001). Today, utilisation of willow for energy production occurs on commercial scale, primarily at decentralised district heating plants and at industrial plants (Skøtt, 2003).

3.4.2 Alternative energy conversion technologies

The technologies considered are biogas fermentation, bioethanol fermentation, esterification into biodiesel and gasification and subsequently incineration of biomass. A brief outline and, when relevant, a background for selection of each of the different technologies are given in the following.

Maize silage based biogas production

The input to the conversion process of maize silage to biogas consists of electricity and heat. Other chemical or enzymatic inputs can improve the decomposition of organic material and hence increase the biogas production, however, there is no confirmation of this in the case of maize silage, and therefore no other inputs are considered during the conversion process (Jensen, 2007).

The maize silage undergoes no pre-treatment before it is heated to approximately 50 °C in the oxygenfree process tank which sets of the methane producing bacteria. The biogas produced consists of 50 - 65% methane, 25 - 50% CO_2, 0 - 1% hydrogen sulphide together with a little hydrogen. The biomass not decomposed is utilized as fertilizer substituting artificial produced fertilizers (Xergi, 2007).

As in biogas, methane also makes up the main part of natural gas, and biogas can replace natural gas in boilers and engines. However, biogas has a lower calorific value than natural gas due to its content of CO_2, and further it may have to be cleaned for small amounts of unwanted gasses (primarily hydrogen sulphide) (Xergi, 2007).

The biogas produced in the anaerobic digestion tank and/or the post-digestion storage is used as fuel in a CHP module (Co-generation of Heat & Power) after cleaning of sulphur in either the post-digestion storage or a gas filter. The module consists of a 1.5 MW engine/generator unit and a boiler. The effect of the engine/generator sizes range from 500 kW and up, and the electricity efficiency is up to 42% (Jensen, 2007). The heat produced in the boiler (heat efficiency of 48% (Jensen, 2007)) is used for process heat at the biogas plant (with cooling down to 120 ˚C) as well as for heating of neighbouring buildings, while the electricity production is sold to the electricity grid (Xergi, 2007).

Table 2-4 below provides in- and output data on the biogas produced based on maize silage grown on 1 ha·y agricultural land, on the up-grading of biogas and on the heat and power production from the biogas.

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[3] However, the Danish scale of willow production is so far rather limited, i.e. around 400-500 hectares in 2003 (Skøtt, 2003).

Table 2: *Input and output data on maize silage grown on 1 ha·y agricultural land based biogas production*

Biogas production		**Substance**	**Original data**		**Energy units[a]**	
			Unit	**Quantity**	**Unit**	**Quantity**
Inputs	Raw materials	Maize silage (31% DM)	ton DW	15.0	GJ	218
	Energy	Power	kWh	1021	GJ	3.7
		Heat	kWh	2477	GJ	8.9
Outputs	Products	Biogas (52% methane)	Nm^3	10486	GJ	196
	Degassed biomass	Nitrogen	kg N	271	-	-
		Phosphorus	kg P	53	-	-
		Potassium	kg K	247	-	-

Source: Jensen (2007). The data have been verified by Xergi A/S.

[a] Lower heating values applied: biogas (52% methane) 18.7 MJ/Nm^3 (Jensen, 2007), maize silage 14.5 MJ/kg DW (Jensen and Thyø, 2007).

Table 3: *Inputs and outputs for the up-grading (cleaning and compressing) of biogas for transportation*

Upgrading of biogas		**Substance**	**Original data**		**Energy units[a]**	
			Unit	**Quantity**	**Unit**	**Quantity**
Inputs	Energy	Biogas (52% methane)	Nm3	2.13	MJ	40
		Power	kWh	0.80	MJ	2.88
Outputs	Products	Natural gas	Nm3	1.00	MJ	40
	Emissions	Methane	kg	0.03	-	-

Souce: Data based on Persson (2003).

[a] Lower heating values applied: biogas (52% methane) 18.7 MJ/Nm^3 (Jensen, 2007), Natural gas 39.77 MJ/ Nm^3 (Jensen and Thyø, 2007).

Table 4: *Inputs and outputs for the heat and power production from biogas*

Heat and power production		**Substance**	**Original data**	
			Unit	**Quantity**
Inputs	Energy	Biogas (52% methane)	MJ	1.00
Outputs	Products	Power	MJ	0.42
		Heat	MJ	0.48
	Emissions	NOx	mg	53.6
		UHC	mg C	112.5
		CO	mg	64.3
		Smell	LE	1607.0

Source: Jensen (2007)
UHC: Unburned Hydro Carbons.

The output of fertilizer replaces synthetic fertilizers. However application on the field gives others emissions to the surrounding environment than synthetic fertilizers. Appendix E presents the difference in emissions when applying the fertilizers.

Maize kernels for bioethanol production – the IBUS process

As mentioned, production of bioethanol from maize kernels is a 1st generation technology, which is available at commercial scale. Data for maize based bioethanol production in the present report are based on an estimated large scale production using the so-called IBUS process (Iversen, 2006b).

Together with bioethanol, a by-product in the form of Dried Distillers Grain Soluble (DDGS) is produced. DDGS is a protein rich fodder product, which will substitute soy meal since this is considered the marginal protein fodder product on the market (Schmidt and Weidema, 2006). For details regarding this fodder substitution, see Appendix D. Inventory data for maize kernel based bioethanol production using the IBUS process is given in Appendix B.

Considering use of 1st generation technology, the maize stover characterised as ligno-cellulosic biomass, cannot be converted to bioethanol. In a scenario where maize is produced for energy purposes, it would therefore be relevant to use the stover for some other form of energy utilisation. However, the maize stover part of the plant has very high water content, i.e. at least 75 % water (Mikkelsen, 2007). This makes the stover highly unsuitable as a fuel for combustion. In comparison, wood chips which is considered a wet biomass is typically fired with 40-45 % water as maximum (Bertelsen, 2007). In addition, due to the high water content, maize stover can be stored for only one month after harvest as a maximum. Thus, it constitutes a biomass supply which is available during approximately one month a year (around October or November depending on the climate and the choice time for harvest). Furthermore, no agricultural machines are currently available on the market, which facilitates collecting maize kernels and maize stover separately (Mikkelsen, 2007). Altogether, use of the maize stover for heat and/or CHP production seems unrealistic (Bertelsen, 2007). On the other hand, use of the stover for biogas production might prove to be a feasible option (Bertelsen, 2007), (Tafdrup, 2007).

Based on the above, in the base case scenario of 1st generation maize kernel based bioethanol production, the maize stover is assumed left on field for remoulding.

Whole-crop maize for bioethanol production – the IBUS process

Conversion of whole-crop maize to bioethanol is modelled based on an estimated large scale maize kernel based bioethanol production and maize stover based bioethanol production, respectively, using the IBUS process. In practice, the conversion will most likely be performed as a conversion of ensiled whole-crop. However, the conversion is modelled as two separate lines. Details for the two conversion lines are given in Appendix B. Apart from the bioethanol output, by-products in the form of solid biofuel and C_5-molasses (from maize stover conversion) as well as DDGS (from maize kernels conversion) are generated.

Rapeseed for biodiesel production

As mentioned, rapeseed based biodiesel production, is a biodiesel technology currently operating at commercial scale in Denmark. However, as the production is dependant on tax reductions compared to fossil fuel, the whole production has been exported, mainly to Germany, where such tax reductions are given. Apart from biodiesel called Rape-Methyl-Esther, RME, by-products in the form of glycerine and catalyst residues are produced (Andreasen, 2007). It is assumed that glycerine is used as fuel substituting natural gas in industrial boilers, however, glycerine from RME production is also likely to be used in the feed industry and chemical industry after an upgrading to pure glycerine. A typical average lower heat efficiency of approximately 89 % can be assumed for heat production based on glycerine fired in industrial boilers. The glycerine can be used as fuel in the natural gas fired boilers and thus displaces natural gas as fuel on the input side. For heat production based on natural gas, the typical average lower heat efficiency is 95 %. Thus, 1 GJ of glycerine substitutes approximately 0.94 GJ natural gas ($0.89/0.95 \approx 0.94$).

Input and output data for the esterification of rapeseed oil to RME is estimated based on data for esterification of animal fat to biodiesel (Jensen et al., 2007). Correspondingly, it is assumed that catalyst residues are used as fertiliser (as the case for catalyst residues produced from animal fat based biodiesel production). Inventory data used for rapeseed production and subsequent rapeseed pressing and esterification of rapeseed oil to biodiesel (RME) are given in Appendix A and B.

Applying 1st generation technology, only the rapeseeds and not the rape straw is utilised for biodiesel production. Considering use of rape as energy crop, it is nevertheless relevant to consider use of the straw for other energy purposes such as CHP production. Therefore, two sub-scenarios are set up: one scenario assuming that the rape straw is left on field for remoulding and one scenario assuming collection of the straw for CHP production.

Firing of straw at the existing central or decentralised natural gas fired boilers is not technically feasible as these boilers are not constructed for straw combustion. Among other factors, the high chlor-alkali content of straw sets specific requirements to the boiler construction (Sander, 2006).

Gasification of straw provides a possibility for obtaining a producer gas with a low content of chlor and alkali. Therefore, straw gasification and subsequent combustion of the producer gas at existing natural gas fired plants is a theoretically interesting option. However, experiments have revealed that straw gasification is highly problematic (Videncenter for halm- og flisfyring, 1998). Technologies for straw gasification are at the pilot stage and no development projects are being carried out which might indicate that the technology could become commercially available (Sander, 2006). As such, in a near term perspective (20 year perspective), there are no obvious solutions for utilizing straw for direct natural gas substitution at the plants. Thus, the only options which seem realistic in a near term perspective are 1) substitution through establishment of separate straw fired boilers in connection to existing natural gas fired plants or 2) establishment of new straw fired plants followed by limited operation or shutting down of existing natural gas fired units, i.e. natural gas substitution via the grid.

The amount of natural gas which through straw utilisation can realistically be displaced at central plants is very limited. Thus, large scale utilisation of straw for natural gas displacement would have to occur at the decentralised natural gas fired units (for details see Jensen and Thyø, 2007).

Through the implementation of decentralised straw CHP plants, existing decentralised natural gas fired plants could be replaced. Decentralised straw based CHP production is already demonstrated on commercial scale[4] using grate-firing and traditional steam turbine technology. Considering the investment costs, this solution is most obvious regarding decentralised natural gas fired plants which have outlived their life time (Ipsen, 2006b).

Based on data for the decentralised plants in Denmark, the share of decentralised natural gas fired units likely to have outlived their life time in a 20 year perspective, have been identified[5]. Among these, the share of plants with a heat generating capacity in the range feasible for biomass CHP production has been identified[6]. The average yearly net electricity efficiency and overall efficiency of the target group of decentralised natural gas based CHP plants is estimated to be 36 % and 87 %, respectively. Based on Energistyrelsen (2006), the corresponding efficiencies for the average decentralised straw fired CHP plant are estimated to be 25 % and 90 %, respectively. For further data see Appendix N.

Willow for heat and power production

Technical possibilities exist of utilising wood chips or wood pellets for direct fossil fuel substitution at some of the central plants in Denmark. However, this potential is limited and does thus not represent a large scale potential for especially natural gas displacement (Jensen and Thyø, 2007).

Establishment of separate decentralised biomass CHP plants and subsequent natural gas substitution through the energy grid constitutes another possible option. Decentralised wood chip based CHP production using grate-firing and the traditional steam turbine technology is already demonstrated at commercial scale[7]. However, as the case for separate straw based CHP plants, a lower electricity efficiency compared to natural gas fired CHP plants would have to be accepted.

From this perspective, other possible natural gas displacement routes become relevant. Gasification experiments have shown that gasification of woody chips is considerably less problematic than gasification of straw[8] (Videncenter for halm- og flisfyring, 1998). More experience exists with gasification of wood chips and the technology is more developed compared to straw gasification technologies (Sander, 2006). Thus, wood gasification technologies are considered to have significantly better future prospects than straw gasification technologies. Today, wood gasification is at the pilot and demonstration scale[9]. However, it is reasonable to expect that wood gasification technologies will become commercially available in a near term perspective (Henriksen, 2006).

Gasification of willow wood is technically possible and such gasification with subsequent incineration of the produced gas (in the following referred to as producer gas) at central natural gas plants could become a

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[4] Decentralised straw based CHP production is e.g. demonstrated at the plants: Grenå, Haslev, Maribo-Sakskøbing, Masnedø, Måbjerg, Rudkøbing and Slagelse (Energistyrelsen, 2000).

[5] The share of decentralised natural gas fired plants likely to expire until 2025 are identified based on data concerning plant implementation year (Energistyrelsen, 2006). A lifetime of 30 years for combined cycle gas turbines, a lifetime of 15 years for single cycle gas turbines and a lifetime of 10 years for gas engines is assumed (Elfor et al., 2000).

[6] The plant range feasible for biomass CHP production is assumed to be a range of 7.5-83 MW heat capacity corresponding to the heat capacity range between the smallest existing straw fired CHP plant, Rudkøbing, and the large straw fired CHP plant projected at Fynsværket.

[7] E.g. at the decentralised biomass based CHP plants Assens, Hjordkær, Masnedø, Måbjerg (Energistyrelsen, 2000).

[8] Among other factors, this is due to the granulate structure of wood chips and the forming of relatively stable wood coke.

[9] Demonstration plants in Denmark performing wood chip gasification are e.g. Ansager, Harboøre, and Høgild (Sørensen, 2003).

realistic option. In addition, willow gasification followed by combustion of the producer gas at the decentralised CHP plants could become commercially available. It would be technically possible to perform a flexible operation with up to 100 % producer gas at the existing natural gas installations (Henriksen, 2006). Utilizing the existing decentralised natural gas fired units would require a very clean producer gas in order to prevent damage of the equipment (Energistyrelsen, 2002), (Ipsen, 2006b). The so-called two-staged gasification is a probable choice of technology, due to the fact that it has documented to produce a clean producer gas (Bertelsen, 2006), (Henriksen, 2006). A 5 % energy loss during two-staged gasification will typically occur together with 1.8 % power loss due to the handling difficulties of willow wood chips (Henriksen, 2006). It is reasonable to assume that 1 GJ producer gas can substitute 1 GJ natural gas on the fuel input side. See Appendix N for details.

3.4.3 Alternatives for utilisation of animal manure

The technologies considered for utilisation of animal manure are:

- Animal manure based biogas production
- Animal manure for fertilizer displacement

A brief outline and, when relevant, a background for selection of each of the different technologies are given in the following.

Animal manure based biogas production

In recent years the requirements for addition of nitrogen to the crops and for exploitation of nitrogen have been increased substantially. These requirements make it difficult to achieve the legislated utilisation for nitrogen without alternative treatment of the manure. Therefore, the farmers have to increase the availability of nitrogen and thereby the exploitation. In this connection biogas production is an advantageous solution, both with regard to the above advantages as well as the opportunity of selling the electricity and heat produced and thereby gaining a financial benefit (Xergi, 2007).

The manure from pigs undertakes pre-treatment at the farm site where the fibres of manure (dry matter: 4.7 % in raw manure from pigs) and water fraction are separated. The fibre fraction contains 36.6 % dry matter after separation whereas the water fraction only contains 1.3 % (Kemira Miljø, 2007). This provides advantageous reduction of transport costs since the manure transported to the biogas plant takes up less space. An average of 15 km is applied for transport of the fibre fraction (Jensen, 2007).

Around 75% of the nitrogen content in raw manure from pigs is accessible for plants, whereas 60% is accessible for plants in manure from cattle (Nielsen et al., 2002). After the low-tech separation the nitrogen and phosphorus of the liquid phase is approximately 100% accessible for plants and thus the fraction can be spread on a smaller area than by using raw manure (Xergi, 2007). The digested manure after production of biogas has a content of nitrogen of 90% and 78% accessible for plants from pigs and cows, respectively (Nielsen et al., 2002). However, the nitrogen content is more concentrated since the produced biogas presents a loss of mass which do not influence the nutrient content of the manure (Jensen, 2007). When assuming the mineral fertilizer has 100% accessible for plants the substitution ratios when applying raw manure, the water fraction for manure from pigs or the digested manure on the field instead of mineral fertilizers can be estimated e.g. for raw manure from pigs: 1:0.75. The phosphorus and potassium are assumed to substitute mineral fertilizers in equal relations e.g. 1:1 (see also appendix E).

Due to the a lack of experience of biogas production based exclusively on manure (without other organic materials added to the produces) the manure input to the biogas fermentation is assumed to consist of one part dewatered manure from pigs and two parts raw manure from cattle (Jensen, 2007). Table 5 next page provides in- and output data on the biogas produced based on manure.

***Table 5:** In- and output data on manure based biogas production*

Biogas production		Substance	Original data		Energy units[a]	
			Unit	Quantity	Unit	Quantity
Inputs	Raw materials	Manure[b]	ton	131	-	-
	Energy	Power	kWh	2766	MJ	9958
		Heat	kWh	6712	MJ	24164
Outputs	Products	Biogas (62% methane)	Nm^3	8797	GJ	196
	Degassed biomass	Nitrogen	kg N	1110	-	-
		Phosphorus	kg P	395	-	-
		Potassium	kg K	514	-	-

Source: Jensen (2007). The data have been verified by Xergi A/S.

[a] Lower heating values applied: biogas (62% methane) 22.3 MJ/Nm^3 (Jensen, 2007).

[b] Manure mix of: one part dewatered manure from pigs and two parts raw manure from cattle (Jensen, 2007)

Table 6 below presents the applied data for separation of manure.

***Table 6:** In- and output data on separation of manure*

Separation of manure from pigs		Substance	Original data		Energy units	
			Unit	Quantity	Unit[a]	Quantity
Inputs	Raw materials	Manure from pigs	m^3	1.0	ton	1.0
		Water	l	30	-	-
		Polymer[b]	l	0.25	-	-
	Energy	Power	kWh	1.5	MJ	5.4
Outputs	Products	Liquid manure	m^3	0.9	ton	0.9
		Solid manure	m^3	0.1	ton	0.065

Source: Kemira Miljø (2007)

[a] Density applied: raw manure 1 ton/m^3, liquid manure 1 ton/m^3, solid manure 0.65 ton/m^3

[b] The polymer consist of acryl amide however the production of these are not included in the model due to lack of data.

The output of the liquid separated fraction and the digested manure replaces mineral fertilizers. However application on the field of the digested manure gives others emissions to the surrounding environment than mineral fertilizers. The liquid separated fractions are assumed to have approximately the same emissions as mineral fertilizers. Appendix E presents the difference in emissions when applying the fertilizers.

Animal manure for fertilizer displacement

The manure are already utilised today as substitutes for mineral fertilizer. However, as mentioned above, emissions of especially methane and nitrous oxide during application of raw manure as fertiliser are expected to exceed the emissions when applying mineral fertilizers. Since the farmer spread the manure only one or twice a year the manure is assumed to be stored however the emissions have been calculated ab stable to field. Appendix E presents the emission data when applying the raw manure on the field.

3.5 The scenario models

The main scenarios included in the comparative environmental assessment are numbered as follows:

1 Xergi's biogas production from maize silage
  A. Biogas for CHP production, petrol for transport
  B. Biogas for transport
2 Xergi's biogas production from animal manure (incl. alternative utilisation of manure)
  A. Biogas for CHP production, petrol for transport
  B. Biogas for transport
3 1st generation biodiesel from rapeseed
  A. Rape straw left on field
  B. Rape straw for incineration
4 1st generation bioethanol from maize kernels
5 2nd generation bioethanol from whole-crop maize
6 Petrol for transport and Willow for gasification and CHP production

In order to give an overview of the scenario models, the overall energy and mass flows characterising the respective scenarios are presented in process flow diagrams. The diagrams do not show all flows included in the environmental assessment. This simplification is made in order to clarify the most important differences between the scenarios.

In the transport sector, the reference (scenario 0) constitutes use of petrol or diesel as fuel depending on whether bioethanol, biogas or biodiesel is produced. In the energy sector the German marginal power and heat production is considered. Furthermore, the reference of scenario 2 constitutes an alternative utilisation of the given amount of manure which has to be included in order to account for all impacts of the scenario.

For each scenario, induced and avoided processes and flows compared to the reference scenario are indicated with the following colours:

Red: Induced processes/flows
Dashed Green: Avoided processes/flows
Blue: Changed processes/flows
Black: Unchanged services/processes/flows

The *functional unit* provided (98,851 km transport, 82.2 GJ power, 85.0 GJ heat) is given in the right side of the diagrams indicated with black **bold**. *Resource constraints* in the form of manure or land available for energy crops are also indicated with black bold.

0. Reference system. Petrol for transport and marginal German power and heat production

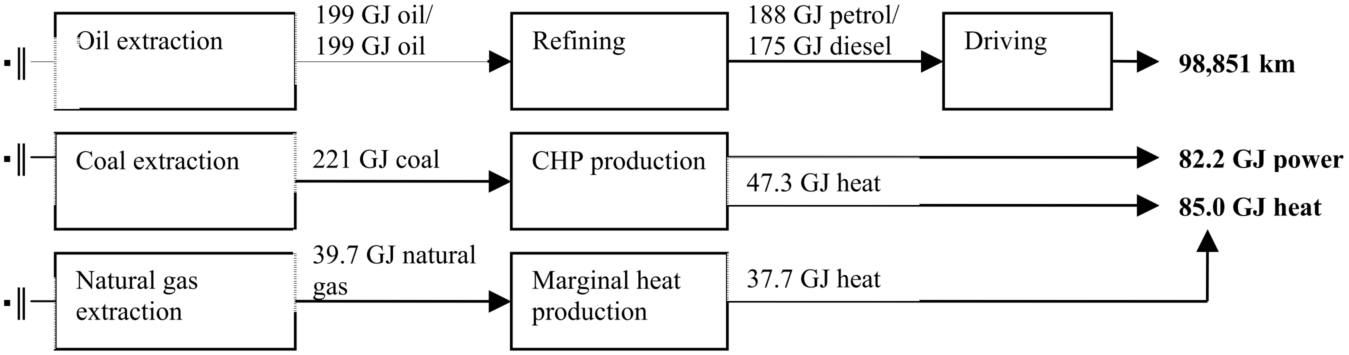

Figure 1: *Simplified flow diagram of the reference system providing 98,851 km of transport in a passenger car fuelled by petrol and diesel, respectively and provides from German marginal 82.2 GJ power and 85.0 GJ heat.*

1A. Xergi's biogas production from maize silage (biogas for CHP production)

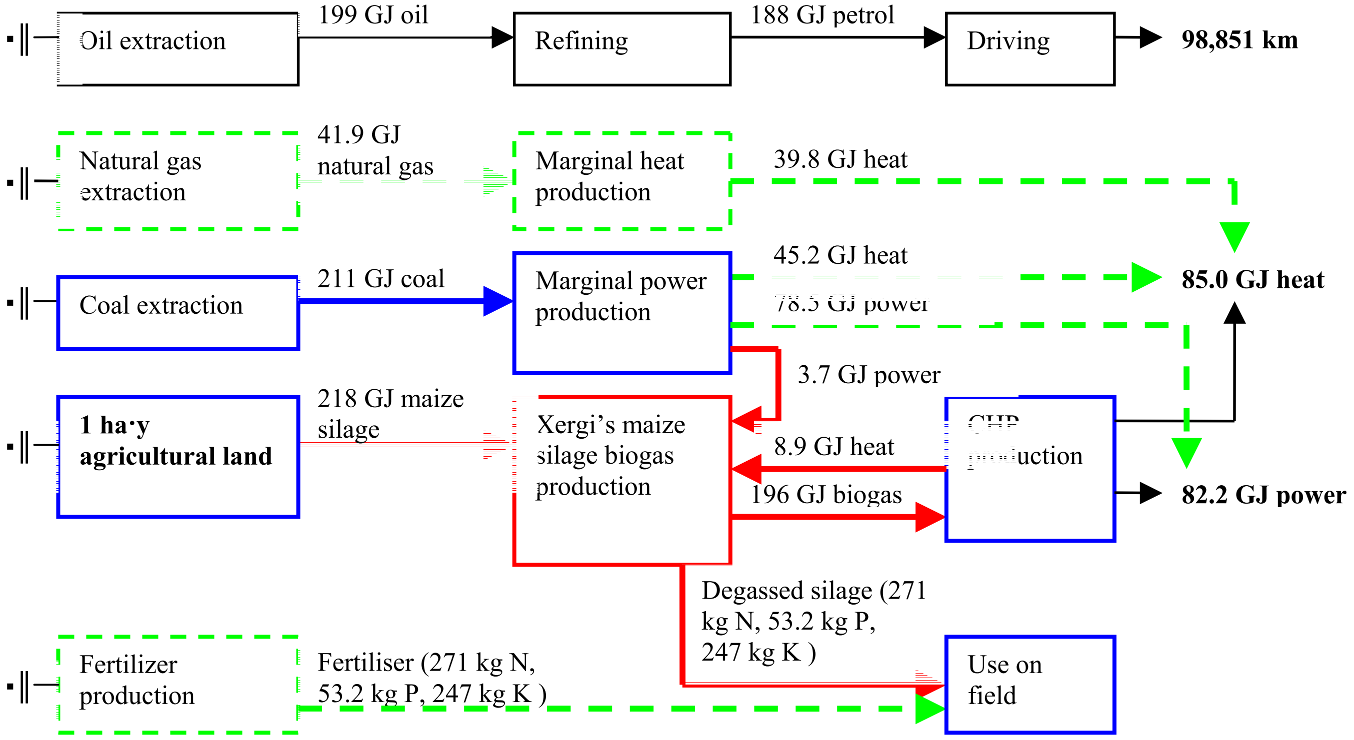

Figure 2: *Simplified flow diagram of the system providing 98,851 km of transport in a passenger car fuelled by petrol and energy output of 82.2 GJ power and 85.0 GJ heat. The heat produced from the biogas substitutes marginal district heat production based on natural gas whereas the power displace coal based CHP production. However this leads to induced production of heat which again substitute marginal district heat production based on natural gas.*

Figure 2 illustrates the main flows occurring when natural gas is displaced by the biogas produced from maize silage grown on 1 ha·y agricultural land through Xergi's biogas production. The power produced by the biogas displaces the Northern German marginal power production, which is based on coal and assumed to be the same as the Danish marginal electricity since it is exported from Denmark to Northern Germany. The heat produced at the biogas plant displaces a German marginal heat production at the location where the biogas plant is located, which is assumed to be based on natural gas.

1B. Xergi's biogas production from maize silage (biogas for transport)

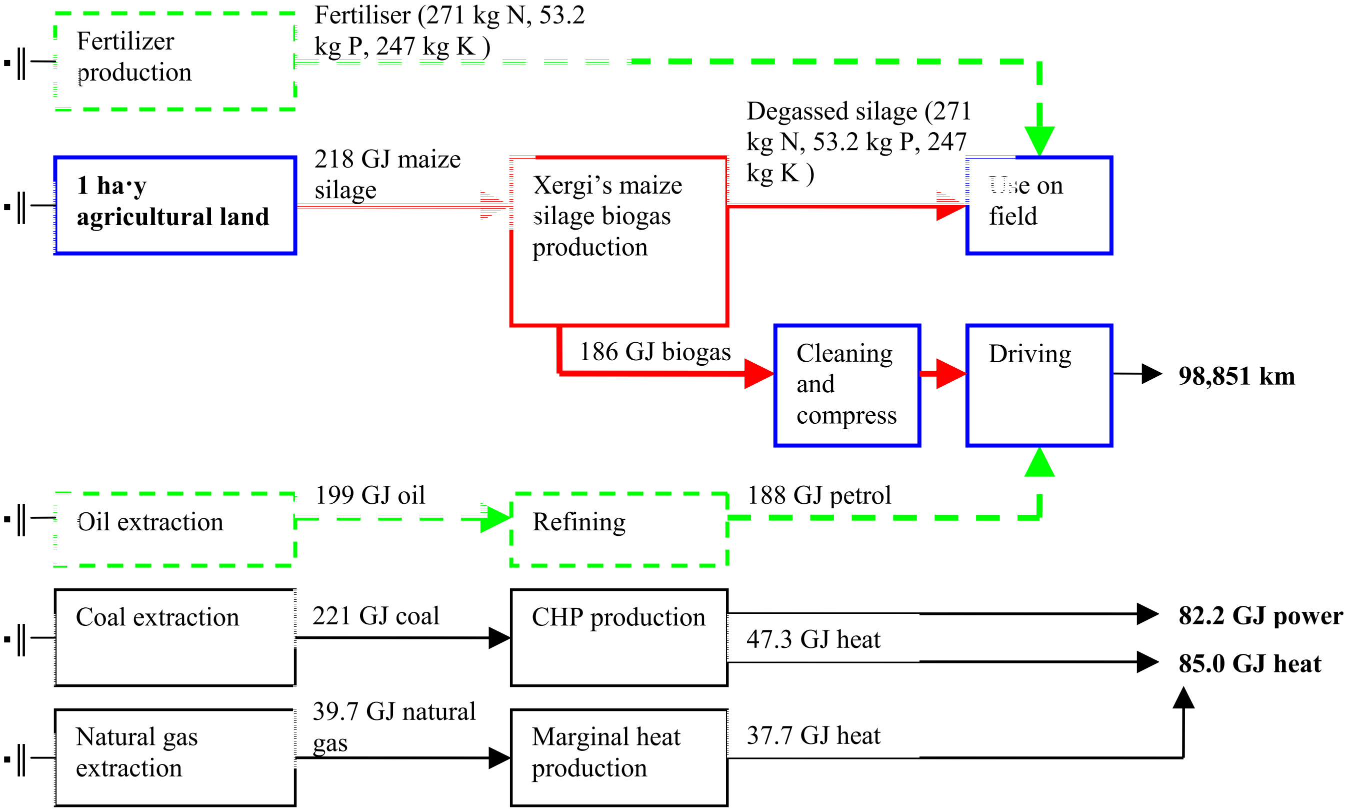

Figure 3: *Simplified flow diagram of the system providing 98,851 km of transport in a passenger car fuelled by biogas produced from maize ensilage and energy output of 82.2 GJ power and 85.0 GJ heat. The biogas substitutes fossil petrol.*

Figure 3 presents the main flows occurring as the consequence of choosing to use biogas made from maize ensilage for 98,851 km of transportation in a natural gas driven 5-seat passenger car (as specified in appendix F).

Figure 4 and 5 illustrates the same flows as figure 2 and 3 where the input consists of animal manure instead of agricultural land.

2A. Xergi’s biogas production from animal manure (biogas for CHP production)

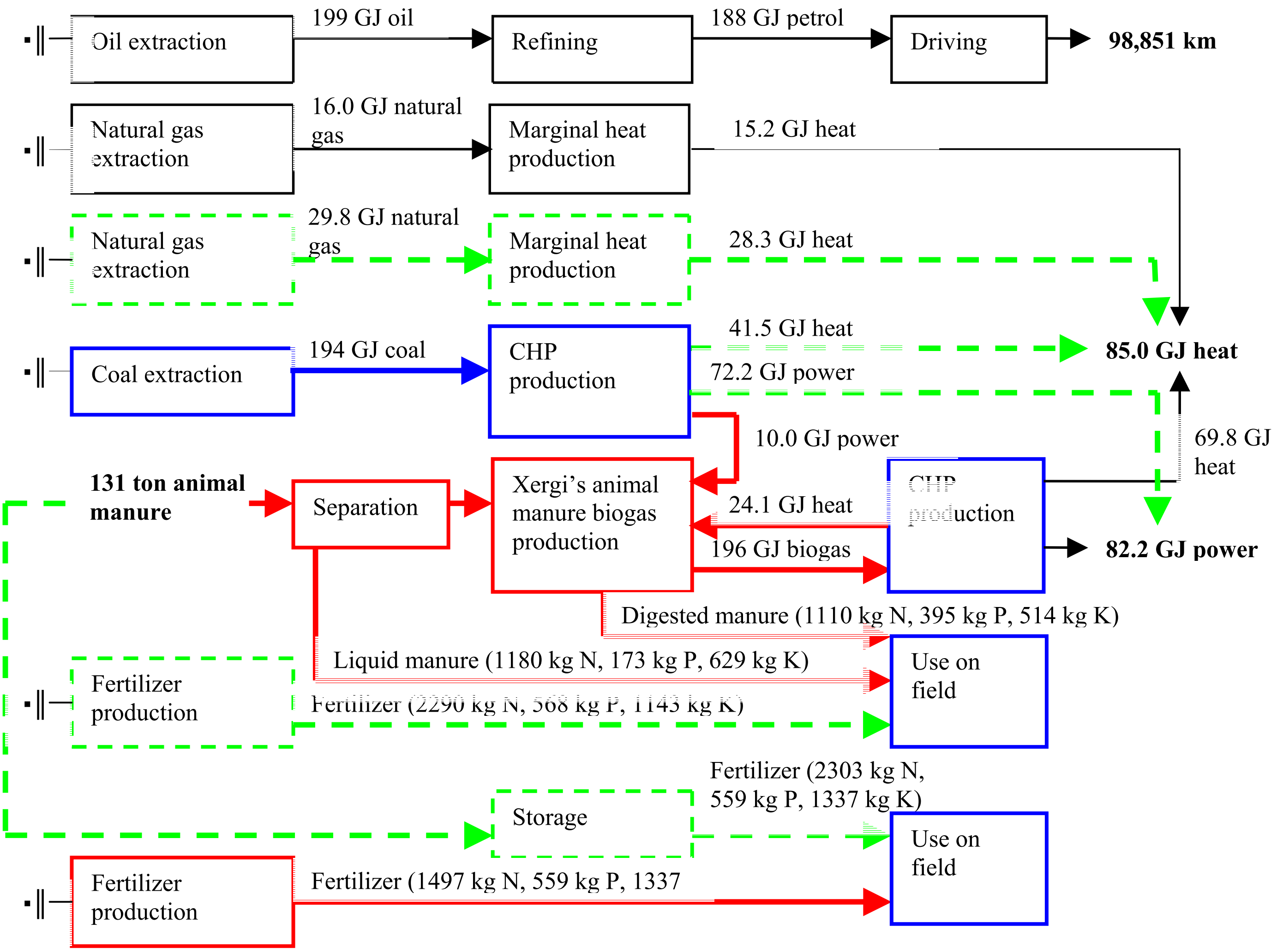

***Figure 4:** Simplified flow diagram of the system providing 98,851 km of transport in a passenger car fuelled by petrol and energy output of 82.2 GJ power and 85.0 GJ heat. The heat produced from the biogas substitutes marginal district heat production based on natural gas whereas the power displace coal based CHP production. However this leads to induced production of heat which again substitute marginal district heat production based on natural gas.*

2B. Xergi's biogas production from animal manure (biogas for transport)

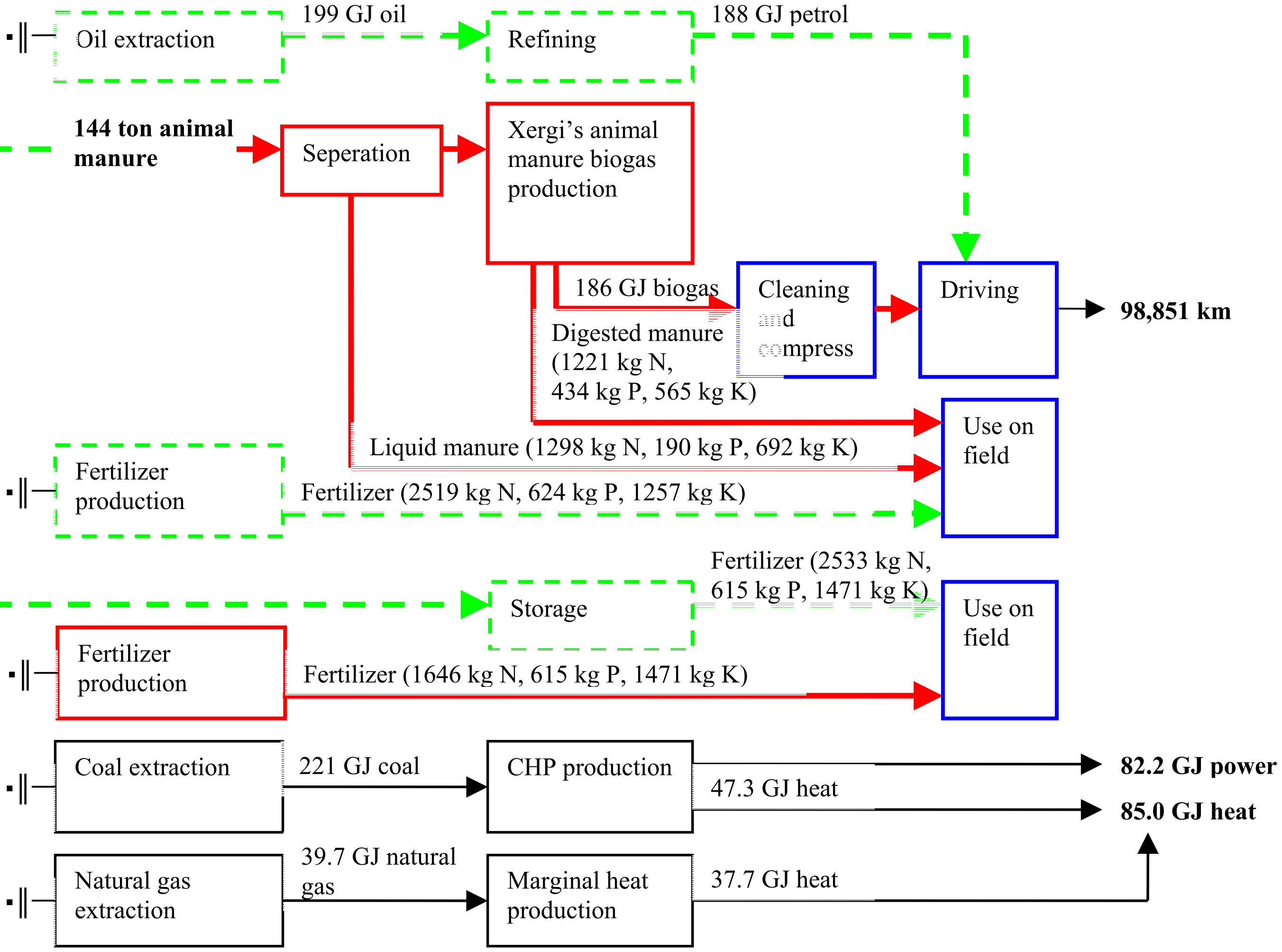

Figure 5: Simplified flow diagram of the system providing 98,851 km of transport in a passenger car fuelled by biogas produced from animal manure *and energy output of 82.2 GJ power and 85.0 GJ heat*. The biogas substitutes fossil petrol.

The scenario models 1A and 1B represents use of 1 ha·y agricultural land for maize silage production. The following figures of scenario models (3A, 3B, 4 and 5) present flow diagrams of the use of 1 ha·y agricultural land for rapeseed, maize kernels and whole-crop maize production, respectively. The biomass is sub-sequentially utilised for production of transport biofuel just as scenario model 1B. The last presented alternatively use of 1 ha·y agricultural land is given for production of willow utilized for energy purposes as scenario model 1A.

3A. Biodiesel from rapeseed (rape straw left on field)

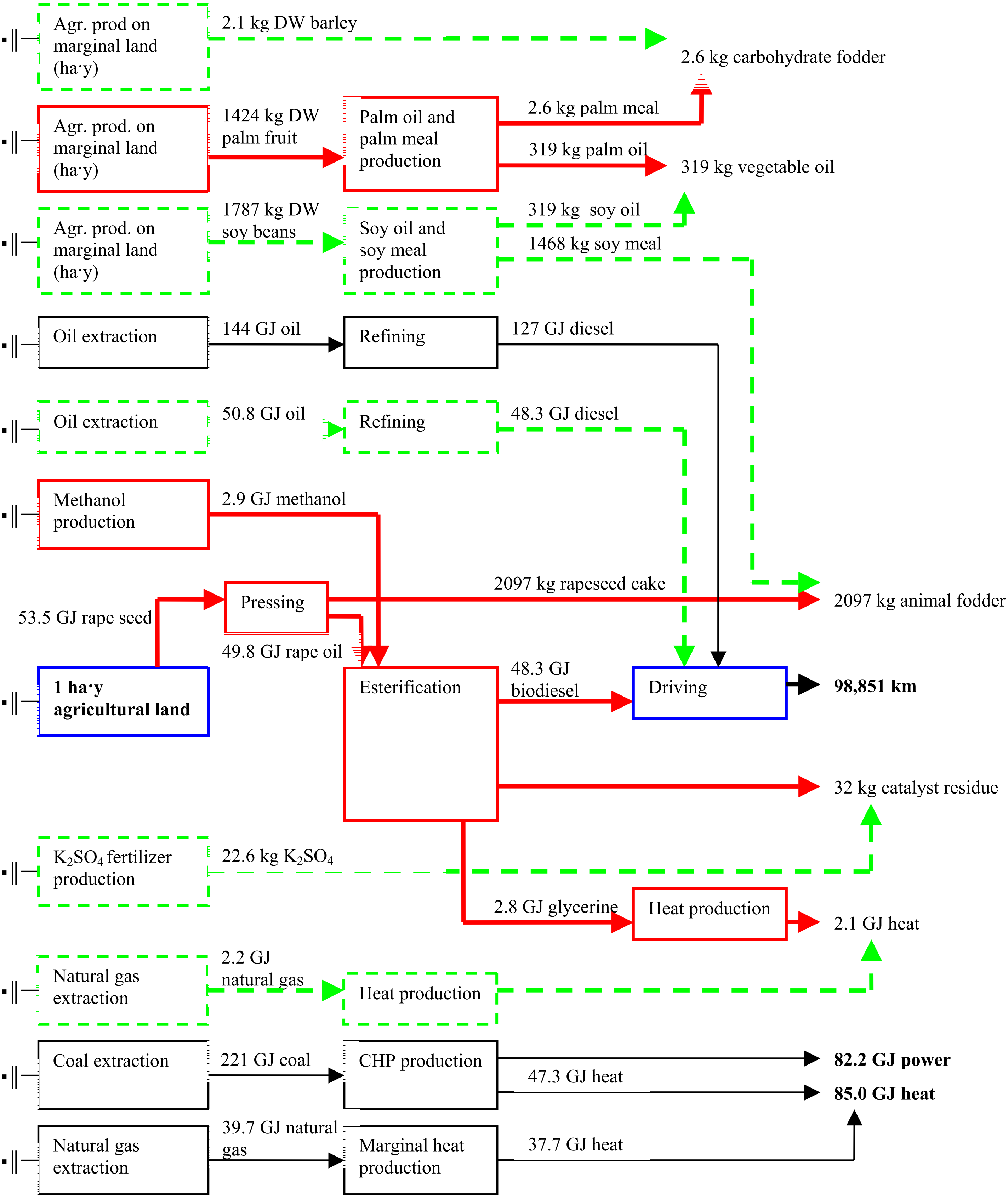

Figure 6: *Simplified flow diagram of the system providing 98,851 km of transport in a passenger car fuelled by biodiesel from rapeseeds and energy output of 82.2 GJ power and 85.0 GJ heat. The biodiesel substitute fossil diesel and rape straw is left on the ground. A reference in which energy crops for coal substitution is considered the lost opportunity is assumed*

The scenario of Figure 6 assumes that the biodiesel will displace fossil diesel in the transport service. As shown in the figure, the glycerine from the esterification process will be used for heat production in boilers displacing natural gas there. The small catalyst residue – being potassium sulphate – is assumed to substitute an equivalent production of this type of fertiliser. The rapeseed cake is assumed to be used as animal feed giving rise to a series of displacement/replacement reactions on the animal feed market, being of course increasingly insignificant for each iteration. The scenario assumes the rape straw to be left on the ground.

Figure 7, next page illustrates the same scenarios in which the rape straw is assumed utilised for heat & power with displacement of coal.

3B. Biodiesel from rapeseed (rape straw incineration)

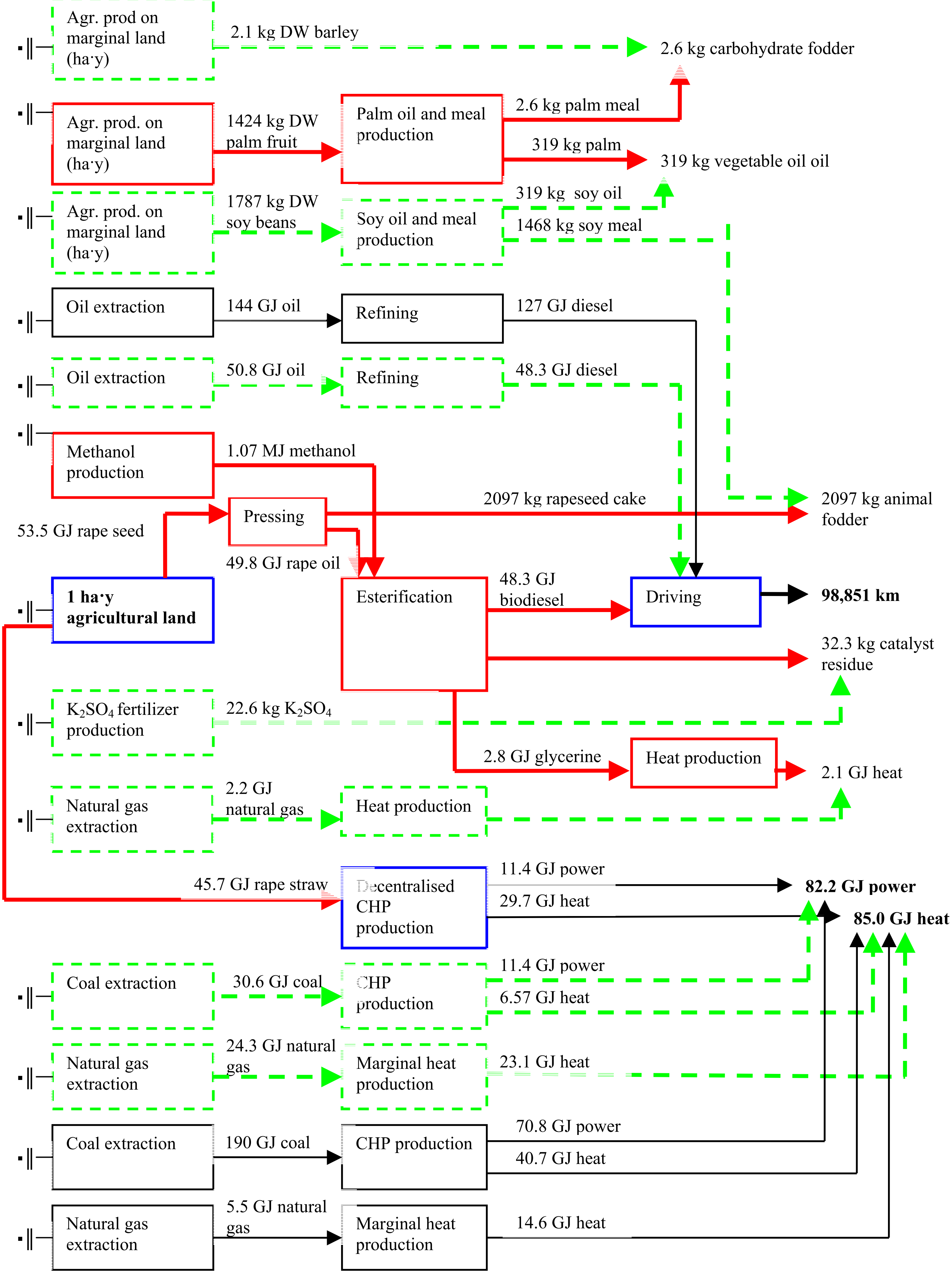

Figure 7: *Simplified flow diagram of the system providing 98,851 km of transport in a passenger car fuelled by biodiesel from rapeseeds and energy output of 82.2 GJ power and 85.0 GJ heat. The biodiesel substitutes fossil diesel, and rape straw is utilised for heat & power.*

4. 1st generation bioethanol from maize kernels

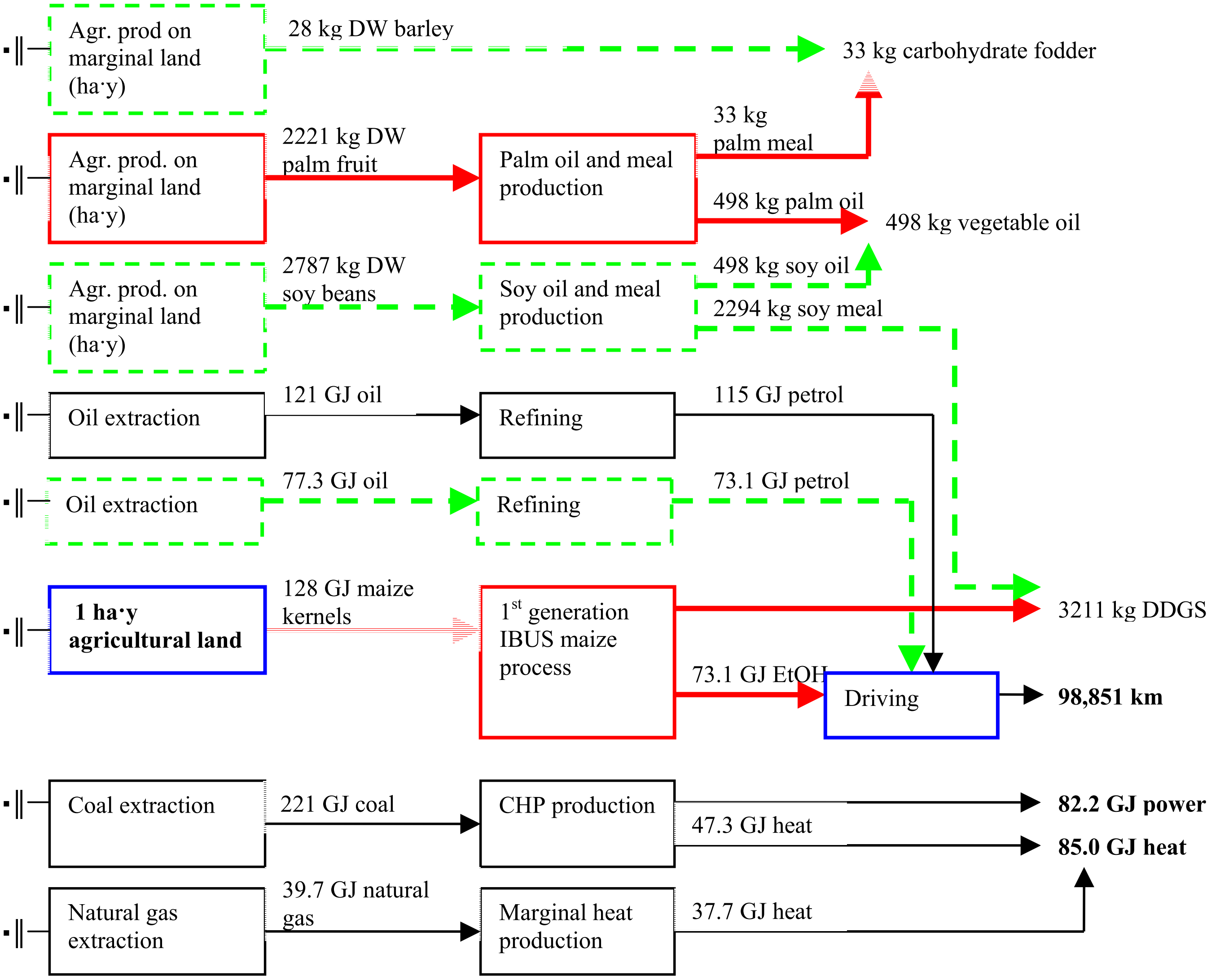

Figure 8: *Simplified flow diagram of the system providing 98,851 km of transport in a passenger car fuelled by 1st generation bioethanol from maize kernels and energy output of 82.2 GJ power and 85.0 GJ heat. The bioethanol substitutes petrol.*

The scenario of Figure 8 assumes that the bioethanol will displace petrol for the transport service. As shown in the figure, the DDGS from the bioethanol production is assumed used for animal feed displacing soy meal, which is the marginal feed on the protein feed market. As the Figure shows, the soy meal has a co-product of soy oil, and this gives rise to more displacement/replacement reactions on the edible oil and animal feed markets.

Figure 9 next page illustrates the main changes in techno-sphere occurring as the consequence of choosing to use bioethanol made from 1 ha·y whole-crop maize for 98,851 km of transportation in a conventional 5-seat passenger car (as specified in appendix F). The scenario assumes that the bioethanol will displace petrol for the transport service. As shown in the figure, both the DDGS and the C_5 molasses from the bioethanol production are assumed used for animal feed giving rise to displacement/replacement reactions on the edible oil and animal feed markets.

5. 2nd generation bioethanol from whole-crop maize

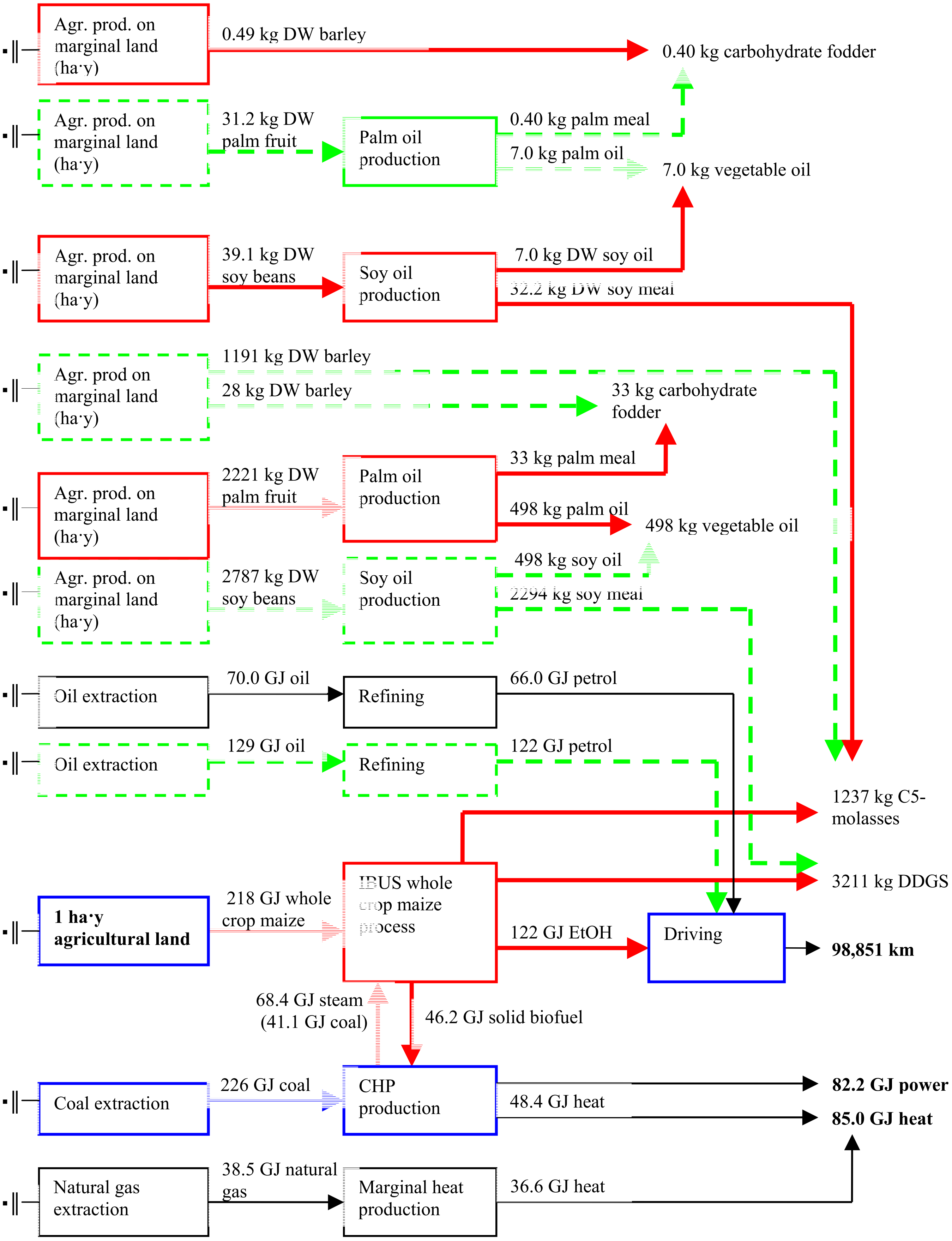

Figure 9: Simplified flow diagram of the system providing 98,851 km of transport in a passenger car fuelled by 2nd generation bioethanol from whole-crop maize and energy output of 82.2 GJ power and 85.0 GJ heat. The bioethanol substitutes petrol.

6. Petrol for transport & Willow for heat and power production

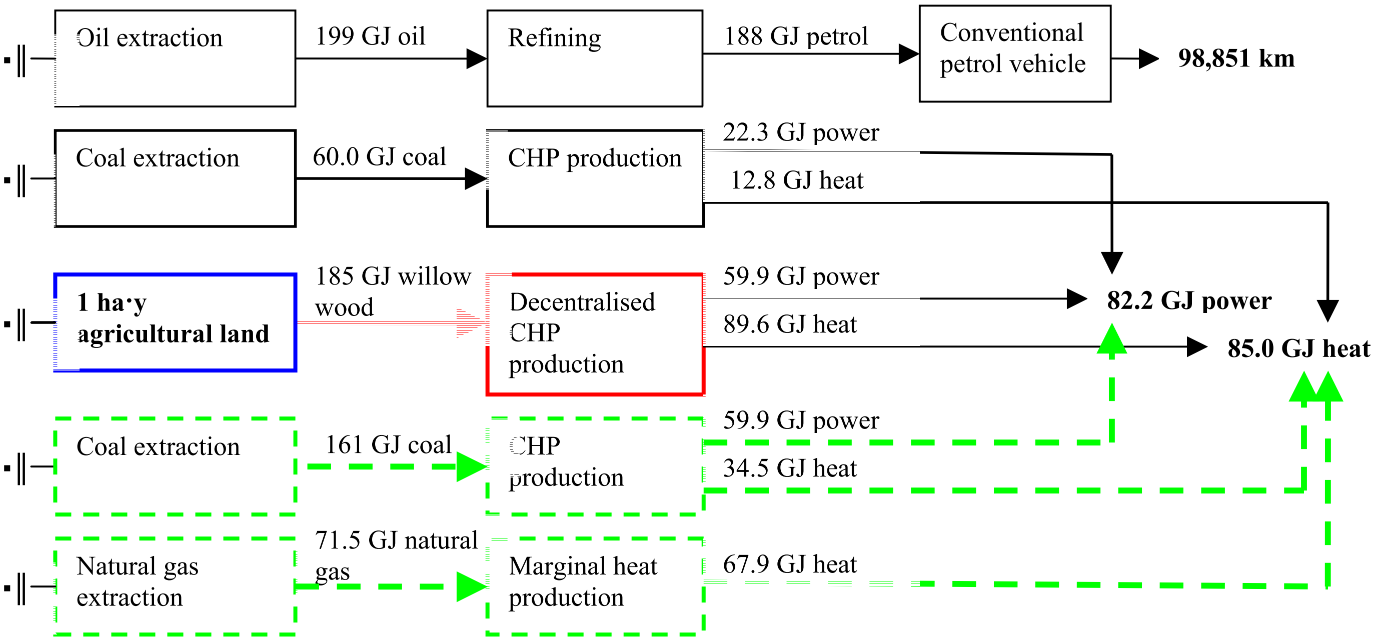

Figure 10: *Simplified flow diagram of the system providing 98,851 km of transport in a petrol passenger car and energy output of 82.2 GJ power and 85.0 GJ heat.* The agricultural land is used for willow production for heat and power production displacing German marginal power production (coal) and marginal heat production (natural gas).

4. Results

All scenarios are modelled in the GaBi4 LCA software, cf. enclosed CD in Appendix P.

4.1 Breakdown of the assessment of Xergi's maize silage based biogas production

Supporting the secondary aim of the study, a breakdown of results has been made showing the essential sources of greenhouse gas emissions and fossil fuel consumption related to Xergi's maize silage biogas production, the induced as well as the avoided emissions and consumptions, cf. Figure 11 and 12.

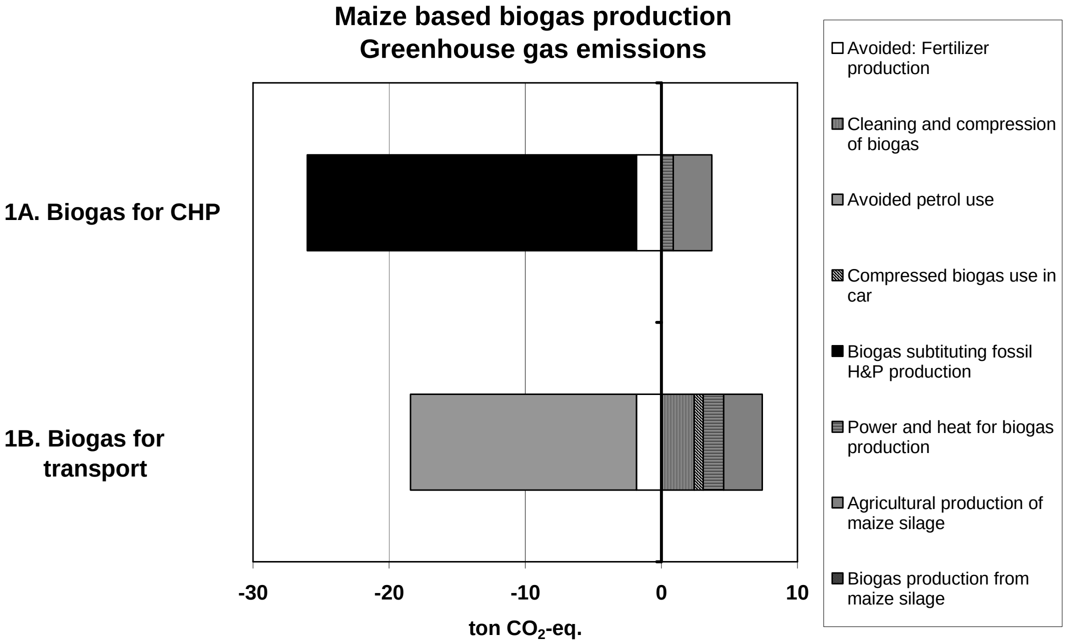

Figure 11: *A breakdown of induced and avoided global warming potentials when using maize silage at Xergi for biogas for CHP production and transportation. All data quantified per functional unit consisting of 98,851 km driven and energy output of 82.2 GJ power and 85.0 GJ heat within the scenarios 1A and1B as illustrated in Figures 2 and 3.*

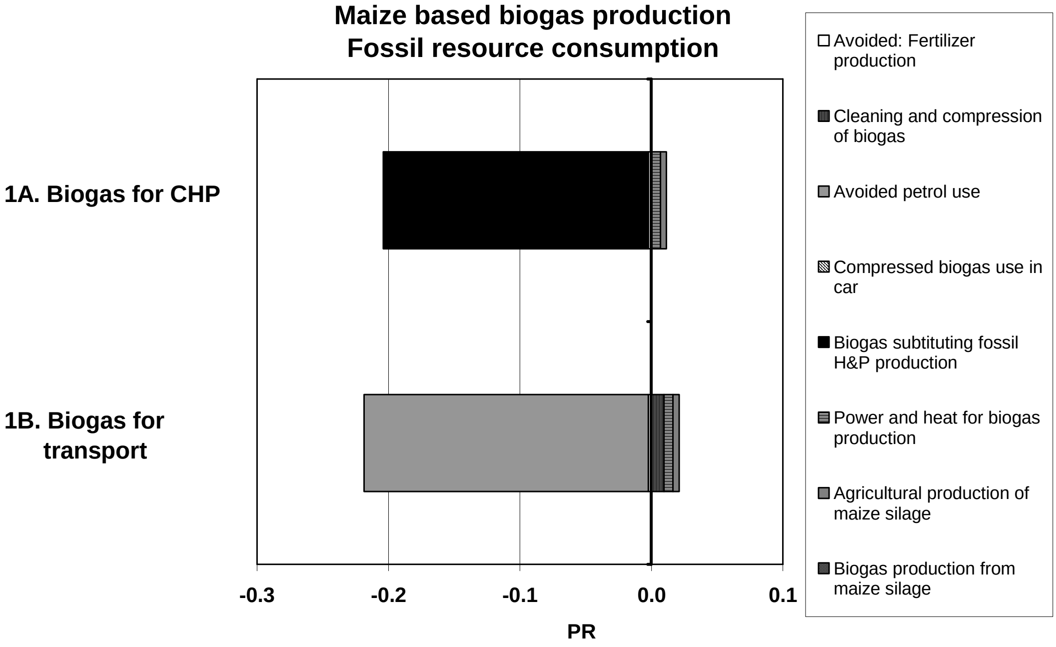

Figure 12: *A breakdown of induced and avoided resource consumption when using maize silage at Xergi for biogas for CHP production and transportation. All data quantified per 98,851 km driven and energy output of 82.2 GJ power and 85.0 GJ heat within the scenarios 1A and1B as illustrated in Figures 2 and 3.*
PR: known global person-reserves (in 2004), i.e. known reserves available per person for the entire future of all generations, i.e. also that portion of the known reserves, which are available for a persons children, grand children and subsequent generations.

As Figure 11 and 12 shows, the greenhouse gas emissions and resource consumptions avoided by displacing marginal heat and power (1A) and petrol in transportation (1B) are significant compared to other impact sources. Another source of avoided impacts of green house gas emissions is the avoided fertilizer production. Smaller induced impacts are based on the agricultural production of maize silage and heat and power production for the biogas production for both greenhouse gas emissions and resource consumption.

When utilizing the biogas for power and heat production there are significantly higher total avoided emissions compared to when utilizing the biogas for transportation. This is based on the higher avoided emissions obtained during displacement of coal and natural gas in the energy sector compared to substituting petrol in the transport sector but also because of the induced emissions occurring when utilizing the biogas in the car. Furthermore larger induced greenhouse gas emissions are obtained by the scenario where the biogas displace petrol since there is no production of power connected to the heat production needed for the biogas production process.

The resource consumption present a more equal picture since the displaced petrol (oil) are weighted higher than natural gas and coal when these different resources are compared based on a scarcity weighting as done in the EDIP method.

4.2 Breakdown of the assessment of Xergi's manure based biogas production

Figure 13 and 14 illustrates the breakdown related to Xergi's manure biogas production.

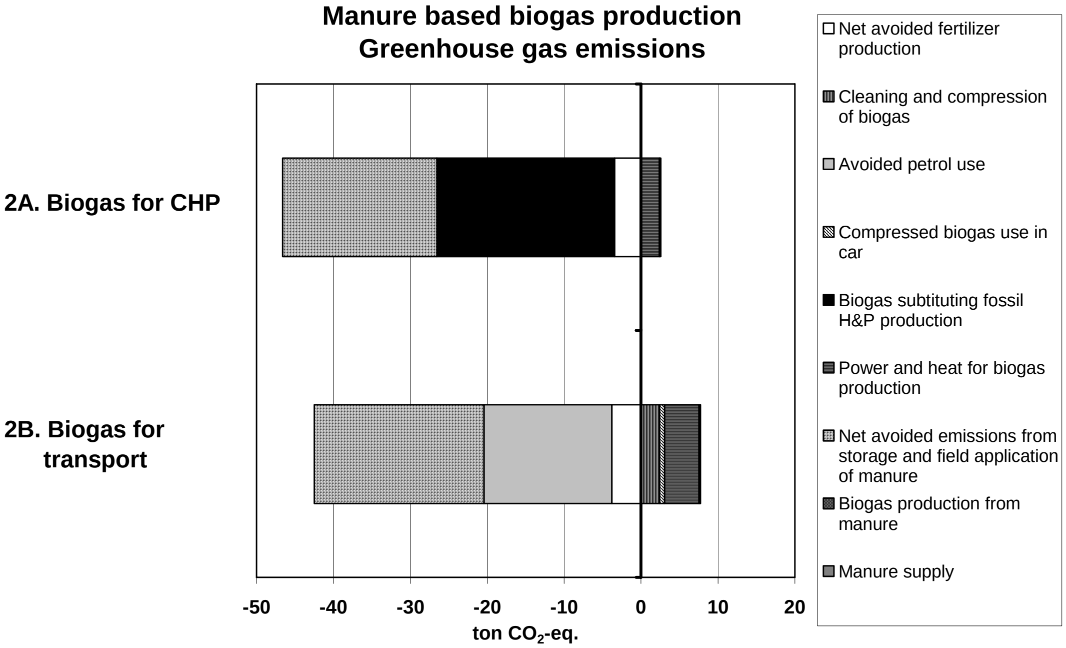

Figure 13: *A breakdown of induced and avoided global warming potentials when using manure at Xergi for biogas for CHP production and transportation. All data quantified per functional unit consisting of 98,851 km driven and energy output of 82.2 GJ power and 85.0 GJ heat within the scenarios 2A and 2B as illustrated in Figures 4 and 5.*

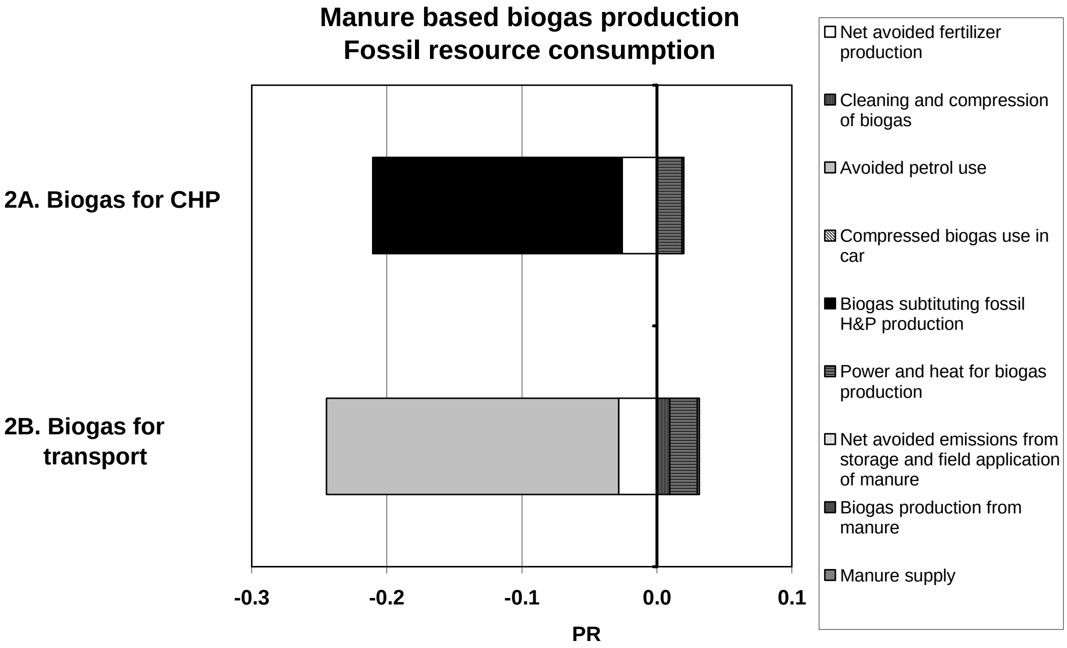

Figure 14: *A breakdown of induced and avoided resource consumption when using manure at Xergi for biogas for CHP production and transportation. All data quantified per 98,851 km driven and energy output of 82.2 GJ power and 85.0 GJ heat within the scenarios 2A and 2B as illustrated in Figures 4 and 5.*
PR: known global person-reserves (in 2004), i.e. known reserves available per person for the entire future of all generations, i.e. also that portion of the known reserves, which are available for a persons children, grand children and subsequent generations.

As Figure 13 and 14 shows, the greenhouse gas emissions and resource consumptions avoided by displacing marginal heat and power (2A) and petrol in transportation (2B) are significant as in the maize silage based biogas production. However, other impact sources when looking at greenhouse gas emissions are now added to the breakdown; the fertilizer production and emissions when applying the manure/fertilizer on the field. Since a little higher amount of manure is required in the scenario of utilizing the biogas for transport the avoided and induced impacts of fertilizer production and use of fertilizer/manure on the field are higher compared to utilizing the biogas for displacing marginal heat and power production.

4.3 Comparison with other biofuel technologies

Supporting the primary aim of the study, a comparison is made between the studied biofuel technologies. The scenarios of 2A and 2B are included in the comparison however it should be emphasised that they are “stand alone” while the rest of the scenarios are each others alternatives e.g. the prioritising of utilizing land for one option has to be seen on the benefit of the other options. Therefore the scenario of 2A and 2B are not discussed further in this comparison.

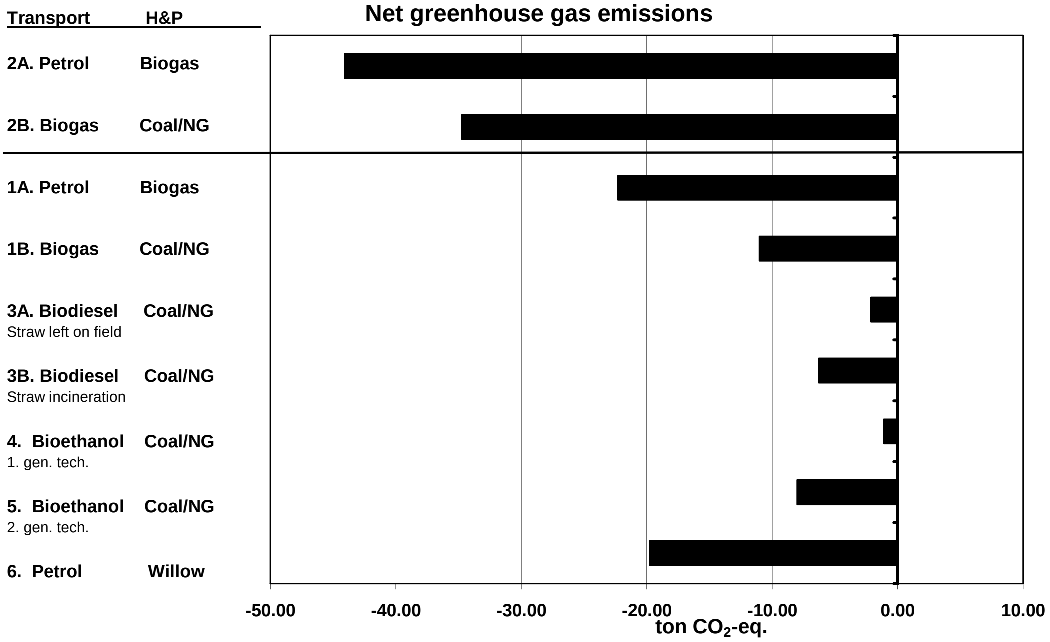

***Figure 15**: The greenhouse gas emissions of the studied biofuels. All data quantified per functional unit consisting of 98,851 km driven and energy output of 82.2 GJ power and 85.0 GJ heat.*

As Figure 15 show, using the biogas for marginal heat and power displacement (1A) is the scenario with the largest net reduction of greenhouse gas emissions. However, it is closely followed by utilizing the constrained land resource for production of energy willow for heat and power production (6). The differences of yield of maize and willow could be the reason for the differences seen in the avoided emissions. See further interpretation in next chapter.

Utilizing biogas for petrol displacement (1B) only provides approximately half the net reduction as utilising biogas for marginal heat and power displacement (1A). However, this obtains higher net reductions than when utilizing the land resource for rapeseed production followed by esterification to RME (3A) even when the rape straw is incinerated and displaces marginal heat and power (3B). The net reduction of the biogas substituting petrol scenario even exceeds the 2nd generation bioethanol production (5).

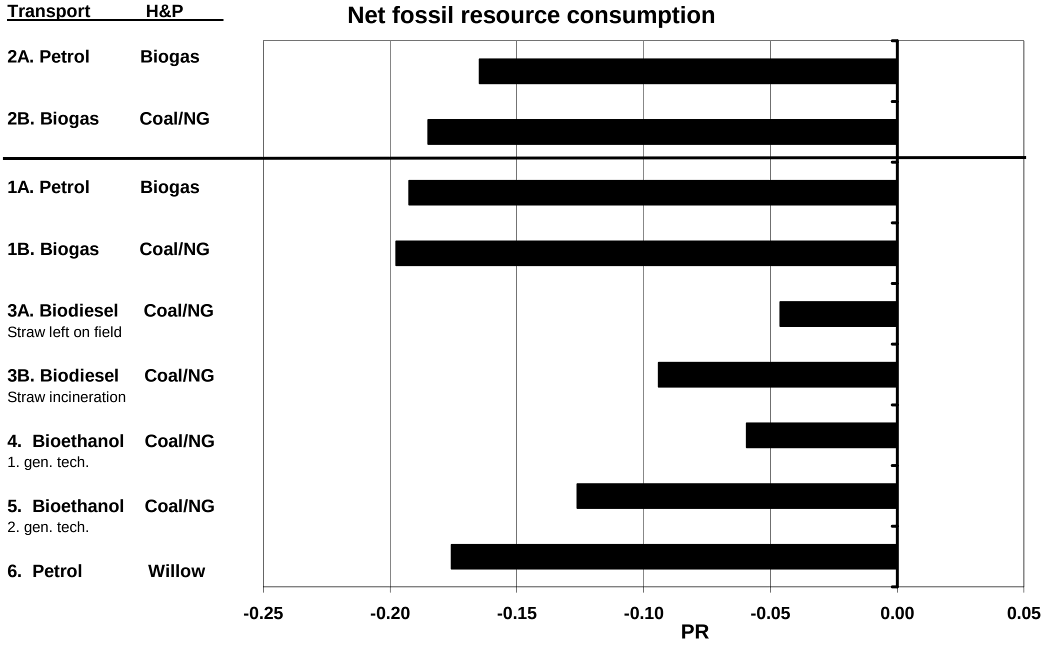

***Figure 16**: The fossil fuel consumption of the studied biofuels. All data quantified per functional unit consisting of 98,851 km driven and energy output of 82.2 GJ power and 85.0 GJ heat.*
PR: known global person-reserves (in 2004), i.e. known reserves available per person for the entire future of all generations, i.e. also that portion of the known reserves, which are available for a persons children, grand children and subsequent generations.

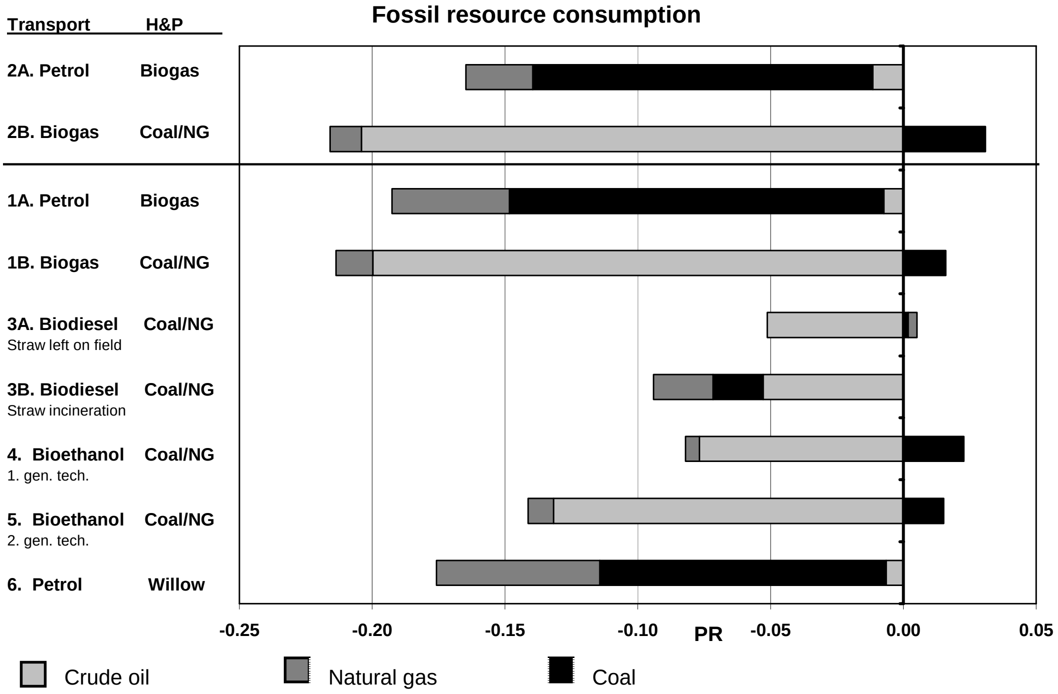

***Figure 17**: Breakdown of the fossil fuel consumption by the compared scenarios on crude oil, natural gas and coal. PR: known global person-reserves (in 2004), i.e. known reserves available per person for the entire future of all generations, i.e. also that portion of the known reserves, which are available for a persons children, grand children and subsequent generations.*

As Figure 16 and 17 shows, the crude oil savings when using the biomass in the transport sector strongly outweighs the coal and natural gas savings achievable by using the biomass in the heat & power production sector – when these different resources are compared in a weighted picture based on a scarcity weighting as done in the EDIP method.

5. Interpretation

In Figure 11 and 12, 13 and 14, the breakdown on sources of impacts is done for the maize silage and manure based biogas scenarios, respectively. This shows which sources are most significant and thereby also gives an indication of where the sensitivities of the results and conclusions of the assessment lie. Such a breakdown on sources is, of course, available for all studied bioenergy technologies when scrutinising the underlying modelling in the GaBi4 software, cf. Appendix P.

The sensitivity of the results and conclusions of the comparison, thus, depend on a set of key data and assumptions for each of the modelled technologies and scenarios. An extracted overview of these key issues for each biofuel is given in Table 7.

Table 7: *Key assumptions in the assessment of the various bioenergy technologies*

Scenario	Key issues
Biogas from maize silage	• The yield of maize versus the yield of alternative energy crops • The energy conversion efficiency of the biogas fermentation • The heat utilisation efficiency from the co-generated heat & power • The storage and field emissions
Biogas from manure	• The lost alternative use of the manure • The heat utilisation efficiency from the co-generated heat & power • The storage and field emissions • The differences in manure nutrient utilisation • The production of polymer for manure separation
Biodiesel from rapeseed	• The displaced fuel for transportation • The yield of rape versus the yield of alternative energy crops • The fate of the rape straw
1st generation bioethanol from maize kernels	• The yield of maize versus the yield of alternative energy crops • The fate of the maize stover • The fate of the DDGS by-product • The released agricultural land from the replacement of animal feed production • The long term effect of the IBUS correlation with a central CHP plant
2nd generation bioethanol from whole-crop maize	• The yield of maize versus the yield of alternative energy crops • The fate of the DDGS and C_5 molasses by-products • The released agricultural land from the replacement of animal feed production • The long term effect of the IBUS correlation with a central CHP plant
Willow for heat and power	• The yield of willow versus the yield of alternative energy crops • The energy efficiency of willow CHP versus biogas CHP

Some of these key issues have already been accounted for by the modelled scenarios, as they include the relevant variations in them. Others, for the 2 categories of bioethanol, have been substantially clarified in the recent study of Jensen and Thyø (2007) to which is referred. In the following, the key issues are discussed for each bioenergy technology in order to provide an understanding of the sensitivity/robustness of the results presented here.

5.1 Biogas made from maize silage

The yield of maize versus the yield of alternative energy crops

The yield of maize has been assumed higher than other energy crops including willow for heat & power production. This places an inherent advantage on the biofuel technologies making use of this crop (bioethanol and biogas). As discussed in Jensen and Thyø (2007), however, a too high difference in yield between the crop for fermentation (maize) and for burning (willow) cannot be allowed as assumption. Because if such differences would really be the case, it is not that difficult to burn maize for CHP either, and if needed for storage, drying e.g. superheated steam at CHP plants with subsequent utilisation of the energy in the evaporated water in condensing heat exchange allows for a very low – and insignificant – energy use. The yield of maize is set to 15 ton dry matter per ha·year, and the yield of willow to 11.9 ton dry matter per ha·year, i.e. the yield of maize is assumed around 25% higher than the yield of willow. Assuming maize – or another crop with similar yield – for CHP would then increase the benefits on CO_2-eq. reduction and fossil fuel savings for the CHP scenario by a magnitude of around 25%, or at least 20% leaving 5% for any necessary drying.

For the rapeseed biodiesel, it is another story. Rapeseed biodiesel needs rape, and this crop has an inherently lower yield.

The energy conversion efficiency of the biogas fermentation

As shown in Table 2, an energy conversion efficiency of 90% over the biogas fermentation has been assumed, i.e. 90% of the calorific value of the dry matter in the maize silage is assumed to be converted to methane. This is a high conversion efficiency compared to other fermentation processes like the ethanol fermentation. The assumption is based on both laboratory scale and full scale experience of Xergi A/S, the latter deriving from 7 weeks of full scale operation at a newly established biogas plant in Quarnbek, Germany (near Kiel). This plant is thermophilic with a hydraulic retention time of around 60 days, which is a quite normal retention time for German plants. The assumption is essential for the assessment and has been double checked with other Danish experts, i.e. Dr. Henrik Møller at the Faculty of Agricultural Sciences, Aarhus University (Møller, 2007) and Dr. Mattias Svensson at the Technical University of Denmark (Svensson, 2007). The high conversion efficiency when producing biogas from maize silage has been confirmed by these researchers and an uncertainty interval of 85% to 92% has been suggested, i.e. the uncertainty is not believed to be that high. The implication of changing the assumption to 85% and 92% respectively is evident from the result presentation figures.

The heat utilisation efficiency from the co-generated heat & power

A full heat utilisation of the co-generated heat has been assumed, i.e. the generated heat is utilised at heat works under substitution of natural gas at all times including the summer period. This situation requires that the magnitude of the heat is small compared to the overall capacity of the heat works, i.e. equal to or below the summer consumption. This is stated, by Xergi A/S, to be realistic in some cases, and the base case assumptions in this LCA are chosen to reflect this situation. Maize silage can be stored, and it is to a wide extent possible to operate the plant with a higher load and biogas production during winter and lower during summer. It is, therefore, possible to strive for a full utilisation of the calorific value of the ingoing biomass, but in many cases, however, it may be difficult to fully utilize the heat during summer. The heating period in Northern Germany is around 7 months a year, i.e. in 5 months a year, the heat demand is very low. If we as a worst case assume an equal load on the biogas plant (equal input of maize silage) over the year, then the heat part of the energy output would be lost in $5/12 \approx 40\%$ of the time. As the heat part is around 50% of the energy output, the energy loss would be around $0.4 \cdot 0.5 = 20\%$. The CO_2 reductions and fossil fuel savings from the electricity part are, however, much larger per energy unit than for the heat output, due to the electricity substituting marginal electricity being much more CO_2 and fossil fuel intensive per energy unit. Worst case is, therefore, a CO_2 and fossil fuel reduction of around 10-15% lower than assumed in the base case shown in the result figures, if the heat is not utilised during summer. The maize silage based biogas plant will, however, most probably always be operated with varying load trying to follow the changes in demand over the year. The resulting implication of the low demand for heat during summer is, thus, probably at maximum a 5-10% lower CO_2 and fossil fuel reduction than shown in the base case assuming fuel heat utilisation during summer.

The storage and field emissions

No emissions have been included from storage and field application of the digested maize silage. This is justified by the fact that the plant is a two stage plant ensuring a very low methane emission from storage due to the retention in the second reactor. Moreover, the very high carbon removal of around 90% ensures that the subsequent soil application of the digested silage does not lead to significantly increased N_2O emissions compared to the use of mineral fertiliser.

5.2 Biogas made from manure

The lost alternative use of the manure

At present, biogas stands out as the only alternative utilisation of manure compared to the conventional storage and soil application – and the volume of manure not being used for energy is huge. Some initiatives are made to use manure as substrate for ethanol fermentation as well, but to the knowledge of the authors, none have reached implementation. The making of biogas from manure is therefore compared to the existing alternative of conventional storage and soil application only. In case ethanol fermentation should be seen as an alternative, the comparison between maize based biogas and ethanol gives an indication of how the comparison would come out for manure as well.

The heat utilisation efficiency from the co-generated heat & power

Same comments as for maize based biogas, but with the exception that is may be more difficult to operate a manure based biogas plant with varying loading and gas production.

The storage and field emissions

The differences in storage emissions of methane and field emissions of nitrous oxide between conventional manure and digested manure are very large and have great influence on the results. As seen from figures 13 and 14, the reduced methane emissions from the digested manure and the reduced N_2O emissions from the field application of digested manure compared to conventional manure imply a reduction in greenhouse gas emissions of the same magnitude as the reduction from the biogas replacement of fossil fuels. The assumptions and emission factors used are presented in appendix E, and they have been reviewed by agricultural experts and compared to scientific literature.

The differences in manure nutrient utilisation

The increased availability of nitrogen in the digested manure implies as shown in figures 13 and 14 a net reduction in mineral fertiliser production and application. The assumptions on this aspect have also been taken from literature and are reviewed by agricultural experts. They are presented in Appendix E. The significance to the overall result and conclusion is not very large, and the uncertainty is believed to be small.

The production of polymer for manure separation

The energy consumption of the production of polymers for manure separation is insignificant to the results. If e.g. assuming 100 MJ of primary energy for production per kg polymer, it would imply approximately 8 kg CO_2 emitted per kg polymer (assuming just for the estimate that the energy all derives from oil). With a need of separating approximately 440 tons manure with 0.25 kg polymer per ton manure, it gives approximately 880 kg CO_2 emitted which is insignificant compared to the overall CO_2 reduction of 40 tons CO_2-eq. for the manure based biogas scenario.

5.3 Biodiesel made from rapeseed

The displaced fuel for transportation

The biodiesel may well substitute petrol based transport and not diesel based, as one should assume at first sight. The reason is that diesel has become the priority fuel among the two, but the correlation between them in the co-production at the refineries does not allow diesel to take over much more of the transport fuel market. Any diesel that can enter the market and take market shares without a co-produced petrol will tend to break the bottleneck for further diesel transport and consequentially result in petrol displacement on the long term. In LCA terminology it means that petrol cars are the marginal passenger transport vehicles on the passenger transport market. The overall significance to CO_2 reduction and fossil fuel savings by the biodiesel scenario are estimated to be a maximum of 10%, as the longer term difference in efficiency between the diesel- and petrol engine is around 7% (Jensen et al., 2007).

The yield of rape versus the yield of alternative energy crops

The main problem for the rape is the rather low yield compared to other energy crops. Prioritising land for rape through choosing (and subsidising) rapeseed biodiesel for transport means depriving society the higher yield of other energy crops on the same land. At present yields – rapeseed 3.1 tons DW/ha˙y, rape whole-crop 5.6 tons DW/ha˙y, whole-crop energy maize 15 tons DW/ha˙y and willow 11.9 tons DW/ha˙y – the approximately ratio between rape and other energy crops is around 1:5 for the rapeseed production and 1:3 for the rape whole-crop. There is no sign that this will change and the presented results are judged to be robust on this aspect.

The fate of the rape straw

The presented results include both scenarios with and without the use of the straw, and the issue is seen not to change the fact that the rapeseed biodiesel comes out as not environmentally preferable, due to the low energy output per hectare.

5.4 First generation bioethanol from maize kernels

The yield of maize versus the yield of alternative energy crops

Same comments as for biogas made from maize silage.

The fate of the maize stover

As described in this report previously, the maize stover is very wet, i.e. approximately 75% water, and the harvest lies within a month. It makes it difficult to collect and make use of the stover for CHP. But as described above, drying is possible with only little energy loss. If a drying and utilisation of the straw for CHP, as a supplement to the 1st generation bioethanol production, was assumed, the picture would change, and the greenhouse gas emissions and fossil fuel consumption of this biofuel technology would be closer to the ones of the 2nd generation bioethanol.

The fate of the DDGS by-product

As described in Jensen and Thyø (2007), the market for animal feed may not be able to take much more DDGS (or C_5 molasses), and these by-products may have to be used as fuels for CHP instead. This would imply a higher CO_2 reduction and higher fossil fuel savings of around 20-25% (Jensen and Thyø, 2007), and the reductions would, thus, still be much lower than for the alternative use of biomass for heat and power production or biogas.

The released agricultural land from the replacement of animal feed production

As a consequence of the fodder by-products generated in the maize based ethanol production, other animal feed products will be replaced, provided that there is still a market for the DDGS. This will, in turn, imply a reduction in the gain of land from nature at locations in the world where such land gains take place, i.e. the marginal land. As described in Jensen and Thyø (2007), this reduction in marginal land gain in the IBUS ethanol scenario is indeed significant and should be regarded as an important parameter in the comparison of the scenarios. However, it is considered highly unlikely that the reduced land gain will be utilized for energy crop production. Instead, it is more likely that the forest or nature areas will be left as they are, i.e. that the land gain for agricultural production will be delayed. The further implications of this trade-off in the assessment should be the target of further investigations. It does, however, also relate to the issue mentioned above, namely that the market for DDGS as animal feed may soon be saturated.

The long term effect of the IBUS bioethanol correlation with a central CHP plant

Behind the data for the bioethanol, both the 1st and 2nd generation, lies the boundary condition that a significant part of the needed thermal energy for the ethanol production derives from the surplus steam of a central CHP plant. On the long term, however, society will strive to improve the energy infrastructure in a direction away from the constraints that imply the huge losses of steam and towards higher overall energy efficiency – potentially by increased decentralisation and thereby increased used of the heat from heat & power co-generation, potentially by heat pumps, fuel cells, etc. A very large scale ethanol plant being locked to a large central CHP plant with a large heat loss available for the synergy between the CHP plant and the ethanol plant in the IBUS concept will lock the degrees of freedom to optimise the infrastructure and anchor the inefficiency of the central heat & power production. On the long term, therefore, it cannot be justified to ascribe the synergy (or the surplus steam) from the central CHP plant to the bioethanol, as done in the results presented here. Not ascribing the synergy/surplus steam to the bioethanol will increase greenhouse gas emissions and fossil fuel consumption of the bioethanol significantly.

5.5 Second generation bioethanol from whole-crop maize

The yield of maize versus the yield of alternative energy crops

Same comments as for biogas made from maize silage.

The fate of the DDGS and C_5 molasses by-products

Same comments as for 1st generation bioethanol, cf. Jensen and Thyø (2007).

The released agricultural land from the replacement of animal feed production

Same comments as for 1st generation bioethanol, cf. Jensen and Thyø (2007).

The long term effect of the IBUS correlation with a central CHP plant

Same comments as for 1st generation bioethanol, cf. Jensen and Thyø (2007).

5.6 Willow for heat and power

The yield of willow versus the yield of alternative energy crops

Same comments as for biogas made from maize silage.

The energy efficiency of willow CHP versus biogas CHP

The applied power and heat efficiencies of the biogas CHP (42% power and 48% heat) is given by Xergi A/S. The applied power and heat efficiencies of the willow chips based CHP (gasification and incineration of producer gas; 32% power and 48% heat) is based on the energy efficiencies estimated for the average decentralised natural gas CHP plant (36% power and 51% heat). Based on the assumed heat loss during gasification, the energy production is estimated to be 5 % lower per GJ wood and additionally 1.8 % loss in power efficiency due to power consumption when handling the willow wood chips compared to average decentralised natural gas fired CHP unit. The decrease in energy efficiencies due to utilizing producer gas from willow gasification is based on expert statements and assumed credible with the present state-of-the-art technologies, but it may be questioned if such differences would prevail on a longer term basis. If the same energy efficiencies were applied, except for the loss due to the willow gasification and handling, the differences between the two scenarios would rely only on the applied yield differences of maize and willow and the mentioned energy loss.

Conclusion

Biogas based on manure is not an alternative strongly correlated to the other bioenergy scenarios, because it does not include any utilization of agricultural land. However, since it provides the same services to society as the other scenarios, it still compares to them and enters into the overall prioritisation of which type of bioenergy technology society should promote with subsidies and other incentives. The conclusion of this comparison is unambiguous: biogas from manure implies by far the highest reduction of greenhouse gas emissions per unit of services provided to society. This being due to the fact that it implies CO_2 reductions not only from the fossil fuel replacement by the generated biogas, but equally significantly from the reduced methane emissions from manure storage, reduced nitrous oxide emissions from soil application of the manure and improved plant availability of the nitrogen in the manure.

The brief and overall conclusions on manure based biogas can, thus, be expressed as:

> *Biogas from manure stands out as having very high reduction in greenhouse gas emissions and very high fossil fuel savings compared to the conventional storage and soil application of the manure. Environmentally and in terms of resource savings, manure should be utilised for biogas production prior to the soil application.*
>
> *Biogas from manure stands out as having much higher reduction in greenhouse gas emissions than the other bioenergy types and equal savings in fossil fuels. As cost aspects point to the same direction, manure based biogas should have the highest priority of all the compared bioenergy types.*

The other scenarios are strongly correlated by their competition for the same agricultural land. Based on the comparative approach, the LCA shows that environmentally and in terms of fossil fuel savings, energy crops should be prioritised for heat and power purposes either 1) through a preceding biogas generation or 2) by direct incineration or gasification, these pathways leading to almost equal CO_2 reductions and fossil fuel savings. Energy crops converted directly into a transport fuel implies significantly lower CO_2 reductions due to the energy losses in the conversion processes.

The brief and overall conclusions on maize based biogas can, thus, be expressed as:

> *Among the compared types of bioenergy requiring agricultural land and energy crops, biogas from maize silage and heat and power from willow imply the highest reductions in greenhouse gas emissions and the highest fossil fuel savings. Environmentally and in terms of fossil fuel savings, land for energy crops should, thus, be prioritised for crops for heat & power or for biogas.*

The explanation of this outcome of the LCA can be found within 3 main reasons:

1. The yield of the energy crop per hectare of land
2. The fossil fuel substitution efficiency, including the energy efficiency of the conversion of the calorific value of the crop's dry matter content
3. The energy infrastructure aspects of the bioenergy technology

The explanation within these 3 categories of why the rape seed biodiesel and the 1st and 2nd generation bioethanol comes out with lower CO_2 reductions and fossil fuel savings are given below.

Rape seed biodiesel: Rape has a very low energy yield per hectare, and this is the one reason for rape seed biodiesel to come out as the environmentally least preferable of the biofuels. Prioritising land for rape through choosing (and subsidising) rapeseed biodiesel for transport means depriving society the 3-5 times higher energy yield of other energy crops on the same land. There is no sign that this will change. The conversion efficiency of the rape seed oil to the biodiesel is comparably high, i.e. only 10% conversion loss or less. There are no infrastructure disadvantages.

Bioethanol: The yield of maize per hectare is the highest among the compared energy crops, and in this study, the bioenergy technologies using maize have for this reason an inherent advantage. For the first generation bioethanol, however, the advantage is of course lost when the stover is not used for energy purposes. On the energy conversion, however, the bioethanol technologies have large losses and an inherent disadvantage: Firstly (for the 2nd generation technology), a thermal pre-treatment of the maize stover is required, and this implies an energy consumption. Secondly, the metabolism of the ethanol fermentation is not as efficient as the methane fermentation, and much remains unconverted to ethanol in terms of metabolic side-products and un-degraded residues. It implies among other things that energy must be spent on drying/dewatering in order to render the residues suitable for subsequent incineration or gasification based energy conversions. Thirdly, energy is needed to separate the ethanol from the fermentation liquor, requiring a distillation process. The biogas has the inherent advantage of leaving the fermentation liquor voluntarily. On the infrastructure side, finally, the bioethanol technologies have an inherent requirement of being very large scale, mainly due to the necessity of the distillation to be large scale; in small scale the cost of bioethanol becomes much worse and detrimental to any real life implementation. It implies that bioethanol cannot enter into a decentralised heat & power production infrastructure and, thus, cannot, like biogas, realise the multiplication effect of full heat utilisation at the same time as delivering the electricity to the grid under marginal electricity replacement.

The assessment is robust to changes in boundary conditions including the key issues for the sensitivity of the results. The most crucial boundary condition behind the assessment in this LCA is the acknowledgement of the fact that energy crops/land for energy crops will be a constrained resource and require subsidies in order to reach any utilisation for energy purposes, with the implication that any use of land for energy crops should be assessed against the lost opportunity of using it for other purposes in the fulfilment of the same aims.

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APPENDICES

Life Cycle Assessment of Biogas from Maize silage and from Manure

- for transport and for heat and power production under displacement of natural gas based heat works and marginal electricity in northern Germany

2nd draft
June 21st 2007
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APPENDICES

Appendix A: Energy crop production

The amount of CO_2 absorbed during growth of the crop is assumed submitted during incineration at the CHP plant or during fermentation at the bioethanol plant. Hence, no CO_2 uptake during growth is included, while accounting for zero CO_2 emissions during biomass combustion.

In the cases where rape straw or maize stover is not left for remoulding on field but is removed for energy purposes, a reduction in the carbon sink in soil can be expected to occur. The consequence will be that less CO_2 is sequestrated from the atmosphere compared to a situation where the biomass is left for remoulding. Against this background, a CO_2 emission accounting for this effect is included in the scenarios where rape straw or maize stover is removed from the field. Based on Marschalkerweerd (2006), considering af 20 year period, an average CO_2 emission of approximately 245 kg CO_2/ton straw DM removed (208 kg CO_2/ton straw, typically 15 % water), can be expected. It is reasonable to assume an equal CO_2 emission per ton DM maize stover removed from field (Marschalkerweerd, 2007).

No CO_2 emission accounting for removal of energy willow from the field is included. Due to factors such as a strong root system and the carbon addition resulting from leaves dropped during growth, energy willow production might as well result in a net increase as well as a net reduction in the carbon sink in soil. As a median estimate, it is therefore reasonable to assume an unchanged carbon sink in the soil for willow production (Marschalkerweerd, 2007).

The estimated energy crop yields and the inventory data for the production of the different energy crops are presented in the following.
For detailed information on agricultural production of whole crop maize and willow see Jensen and Thyø (2007). For detailed information on agricultural production of rape see Schmidt (2007).

Energy crop yields

Average yields in Danish agricultural practice, for the 25 % highest yielding share, for rape, energy whole-crop maize and energy willow, respectively are applied. The energy crop yields have been estimated based on statistics and communication with several relevant experts within agriculture and energy crop production. The consistent yield estimates are given in Table A1.

Table A1 Present yields and estimated average yields over the period 2006-2025 for rape, whole-crop maize and willow.

Yields on Danish soil		2005-6	Average annual yield increase (2006-2025)	Average yield over the period 2006-2025[c]
		ton DW/ha·y	% p.a.	ton DW/ha·y
Rape	Seed[f]	3.1	1.2	3.8
	Straw[g]	2.5	1.2	2.8
	Total	5.6		6.6
Whole-crop energy maize		11.9[a]	15[b]	15.0
Energy willow		11.0[d]	2.1[e]	11.9

[a] Based on average fodder maize yield of 10.64 ton DW/ha·y in practice for the 25 % highest yielding share in 2005/2006 (Landscentret, 2006c). Based on experiments carried out on Danish soil in 2005/2006, it is indicated that energy maize species developed towards a sugar optimized growth can obtain approximately 12 % higher yield compared to conventional fodder maize (Mortensen, 2006).

[b] Based on experiments carried out on Danish soil in 2005/2006, it is indicated that energy maize species can obtain approximately 15 % higher yield compared to the average present yield of fodder maize (Landscentret, 2007), (Bagge, 2007), (Jørgensen, 2007).

[c] Estimated based on the average annual yield increase.

[d] Average willow yield in practice of the 25 % highest yielding share in 2005/2006 (Bach, 2006).

[e] Estimated based on an expected overall 50 % willow yield increase realistically obtainable through improvement over a 20 year period for large scale application (Larson, 2006). Within the last 15 years, a 63 % willow yield increase has been achieved through improvement (Jørgensen, 2006b).

[f] Average Danish winter rapeseed yield of the 25 % highest yielding share in practice in 2005: 3.1 ton DM/ha·y (Landscentret 2006c) Based on Danish rapeseed yield statistics from 1990 to 2005, the average annual rapeseed yield increase is approximately 1.2 % p.a.

[g] Present rape straw yield of 2.93 ton/ha·y (Schmidt, 2007). Assuming a typical water content of 15 % for straw, this corresponds to 2.49 ton DM/ ha·y. An annual yield identical to the improvement for rapeseed, 1.2 % p.a., is assumed. This is an optimistic projection due to the fact that yield improvements will mainly apply for the rapeseed part of the plant (Gylling, 2007).

In the estimation of average willow yields over the period 2006 to 2025, it has been taken into account that willow is a perennial crop and that there is therefore a delay in the implementation of improved species in practice. This is the explanation for the relatively low average willow yield estimated for 2006-2025, in spite of the high annual yield increase (2.1 % p.a.) based on improvement. The extrapolation performed, has been verified by Gylling (2006) and is given in Table A2.

Table A2: Extrapolation of energy willow yield

	Obtainable yield for willow species available at given year																				
	2006	2007	2008	2009	2010	**2011**	2012	2013	2014	2015	**2016**	2017	2018	2019	2020	**2021**	2022	2023	2024	2025	**2026**
	11.0	11.2	11.5	11.7	11.9	**12.2**	12.4	12.7	12.9	13.2	**13.5**	13.8	14.0	14.3	14.6	**14.9**	15.2	15.5	15.8	16.2	**16.5**
	Average willow yield in practice [ton DW/ha y]																				
	2006	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
	11.0	11.0	11.0	11.0	11.0	**12.2**	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2
	11.0	11.0	11.0	11.0	11.0	**12.2**	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2
	11.0	11.0	11.0	11.0	11.0	**12.2**	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2
	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	**13.5**	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	**13.5**	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	**13.5**	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	**14.9**	14.9	14.9	14.9	14.9	14.9
	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	**14.9**	14.9	14.9	14.9	14.9	14.9
	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	**14.9**	14.9	14.9	14.9	14.9	14.9
	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	**16.5**
	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	**16.5**
	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	**16.5**
Average	**11.0**	**11.0**	**11.0**	**11.0**	**11.0**	**11.3**	**11.3**	**11.3**	**11.3**	**11.3**	**11.9**	**11.9**	**11.9**	**11.9**	**11.9**	**12.9**	**12.9**	**12.9**	**12.9**	**12.9**	**14.3**
Average over period	**11.9**																				

The obtainable yield for each willow plantation at a given year is given as the average yield for a production period of the given species starting in the given year.

The 25 % highest yielding willow in practice have an average yield in practice in 2006 of approximately 11 ton DW/ha·y (Bach, 2006).

A 50 % increase in the obtainable willow yield in practice through development over 20 years is reasonable to expect (Larson, 2006)

The obtainable annual yield increase is thus adjusted to obtain an overall yield increase through development of 50 %, i.e. from approximately 11 ton DW/ha y in 2006 to 16.5 ton DW/ha·y in 2026. The corresponding annual obtainable yield increase is 2.05 % p.a. (within the last 15 years an overall 63 % increase in yield corresponding to 3.3. % p.a. in average has been obtained through genetic improvement (Jørgensen, 2006a).

Typically, there is approximately a 5 year interval between introductions of new species. Willow has a production period of 20-30 years resulting in a delay in the utilisation of new species in practice. Considering a large-scale willow production at a fixed area it is reasonable to assume that over a 20 year period, approximately every 5 years, 25 % of the production area is planted with the newly introduced specie (Gylling, 2006).

Rape production

Table A4: Inventory data for agricultural production of rape

Agr. production of rape		**Substance**	**Unit**	**Quantity**
Inputs[a]	Resources	Land use	ha·y	1.00
		Rapeseeds	kg DW	5.00
	Fertilizers	Fertilizer N	kg N	140
		Fertilizer P	kg P	57.0
		Fertilizer K	kg K	99.0
		Pesticides	kg	0.27
	Transport		km	79.0
	Energy	Power (for drying)	MJ	0.05
		Diesel	MJ	3.61
Outputs	Products[b]	Rapeseed (9 % water)[c]	ton DW	3.79
		Rape straw (15 % water)[d]	ton DW	2.79
	Emissions to air[a]	NH_3	kg	9.50
		N_20	kg	4.90
		NO	kg	2.90
		CO_2 (if straw removed from field)	kg	656
	Emissions to water[a]	NO_3	kg	162

[a] Source: Schmidt (2007)

[b] Source: Statistikbanken (2007)

[c] LHV of dry rapeseed assumed equal to LHV of energy grain: 17 MJ/kg DM. Source: Gylling (2001). Corresponding LHV of rapeseed (9 % water): 15.3 MJ/kg.

[d] LHV of rape straw (15 % water) assumed equal to typical LHV of straw: 14.5 MJ/kg. Source: Energistyrelsen (2005b).

Emissions to soil are not included in the inventory data and among emissions to water, only nitrate emissions are included. CO_2 emission resulting from removal of straw accounts for the effect of lost remoulding, leading to a reduction of the carbon sink in the soil. 245 kg CO_2/ton DM straw assumed based on Maarschalkerweerd (2006).

Production of rapeseed oil and cake are performed by a full press process which is presented in Table A5.

Table A5: Full press production of rapeseed

Rapeseed oil and cake production		**Substance**	**Unit**	**Quantity**
Inputs	Resources	Rape seed (9 % water)	ton	2.60
		Area	ha	0.75
	Energy	Heat	GJ	0.85
		Electricity	GJ	0.47
Outputs	Products	Rape seed cake	ton DW	1.56
		Rape seed oil[a]	ton DW	1.00
		Water	ton	0.04

The table is based on data collected from Scanola A/S by Schmidt (2007)

[a] LHV of rapeseed oil: 37 MJ/kg. Source: Gabi (2007).

Maize production

The data applied for agricultural production of whole-crop maize are based on communication with a number of relevant experts. Overall, it has been assumed that reasonably sound agricultural practice is applied e.g. concerning pesticide and fertiliser use. The inventory data applied is given in Table A6, together with the references used.

Table A6: Inventory data for agricultural production of whole-crop maize

Agr. Production of maize		Substance	Unit	Quantity
Inputs	Resources	Arable land use	ha/y	1.00
		Maize seed[b]	kg	50.0
	Fertilizer	Nitrogen[a b]	kg N	50.0
		Phosphate[b]	kg P	5.00
		Lime (CaCO3)[e]	kg Ca	200
		Potasium[b]	kg K	30.0
		Magnesium[b]	Kg Mg	10.0
		Sulphur[b]	Kg S	8.00
	Manure[c]	Nitrogen	kg N	50.0
		Phosphate	kg P	17.3
		Potasium	kg K	54.3
	Pesticides[d]	Herbicides		
		Bentazon	g	250
		Fluropyr	g	135
		Foramsulfuron	g	45.0
		Iodosulfuron-Na	g	1.50
		Mesotroine	g	75.0
		Pendimethalin	g	800
		Pyridat	g	450
		Terbuthylazin	g	575
		Thifensulfuron methyl	g	3.75
		Insecticides		
		Alpha-cypermethrin	g	6.25
		Cypermethrin	g	10.0
		Dimethoat	g	150
		Lambda-cyhalothrin	g	7.50
	Energy[e]	Electricity	MJ	24.0
		Diesel	kg	66.6
Outputs	Products	Maize kernels (35% water)	ton DW	6.87
		Maize stover (75% water)[f]	ton DW	8.13
	Emission to air[a]	N_2O	kg	1.43
		NH_3	kg	3.99
		Pesticides		Treated separately
	Emissions to water	NO_3[a]	kg	81.0
		Phosphate[e]	kg	0.5
		Pesticidies		Treated separately
	Emissions to soil	Pesticides		Treated separately

[a] 70 % of applied N in form of manure and 50 % of commercial N is emitted to the surroundings (Felby, 2006). The distribution of emitted N in the form of N_2O, NH_3 and NO_3 is estimated based on American maize production in Nielsen & Wenzel (2005)

[b] Landscentret (2006a)

[c] Bentsen et al. (2006)

[d] Miljøstyrelsen (2006), Forchhammer (2006)

[e] Felby (2006) (2007)

[f] LHV of dry maize kernels assumed equal to energy grain: 17 MJ/kg DM. Source: Gylling (2001). LHV of maize kernels (35 % water): 10.2 MJ/kg.

[g] LHV of dry maize stover: 16.5 MJ/kg DM. Source: Domalski et al. (1986). LHV of maize stover (75 % water): 3.9 MJ/kg.

CO_2 emission resulting from removal of stover accounts for the effect of lost remoulding, leading to a reduction of the carbon sink in the soil. 245 kg CO_2/ton DM stover assumed based on Maarschalkerweerd (2006).

The agricultural outputs of maize stover and kernels are estimated from the estimated whole-crop yield of approximately 13.1 ton DW/ha·y. It can be assumed that approximately 55 % of the crop is stover and approximately 45 % kernels, on dry weight basis (Felby, 2006) (output of maize kernels and stover are given in DW).

The input of N, P, K, Mg and S is based on general guidelines for cultivation of maize given by the Danish Agricultural Advisory Service, National Centre (Landscentret, 2006a). Based on Felby (2006), the input of N has been assumed supplied as 50 % commercial fertilisers and 50 % manure. The use of manure reflects the practical application in Denmark where large scale production of pigs and cow provide significant amounts of manure (Felby, 2007). Assuming the manure to be slurry from cows or pigs, the nitrogen content ranges from 3.93 to 6.93 kg N/ton slurry. The need of 50 kg N requires in average 13.5 kg slurry per ha·y to be applied on the field. The slurry also contains 0.72-1.91 kg P/ton slurry and 1.78-6.47 kg K/ton slurry (Bentsen et al., 2006). The commercial fertilisers are assumed applied in remaining quantities to match the amount for maize recommended by the National Centre. Based on Felby (2006), 70 % of applied N in form of manure and 50 % of commercial N is assumed emitted to the surroundings. The emission of phosphate is the average phosphate emission per ha·y on Danish agricultural land (Felby, 2007).

Each of the various pesticides used are treated separately. The assumed amounts of pesticides used are based on the Danish EPA standard guide in agricultural production of maize (Miljøstyrelsen, 2006). The quantities applied in the LCA are half the quantities given in the standard guideline, based on the fact that the guideline concerns food/fodder maize production, while the inventory data concern maize for energy crop use. A lower amount of pesticides are required for energy crop production (Forchhammer, 2006). Still, the doses are considered in the high end of actual practical application on Danish agricultural land (Felby, 2007).

The pesticide emissions are calculated based on the PESTLCI distribution model developed by Birkved and Hauschild (2003). When the pesticides are sprayed on the field, several parameters influence the fate of the pesticides. The model calculates emission fractions to air, water, soil, and groundwater compartments of the environment, based on generally available information about: type and time of application, crop species, development stage and properties of the pesticide active ingredients. The individual modules for PESTLCI have been chosen as a compromise between environmental realism and feasibility in terms of data need. The model methodology assumes that the farmer follows the recommended pesticide application (time of application, dosing, etc.) (Birkved and Hauschild, 2003).

The results from the modelling are given in Table A7 in the form of emitted fractions of the active substances in the pesticides.

Table A7: Active substances from pesticide use emitted from agricultural production of energy maize on 1 ha·y based on modelling in PESTLCI (Birkved and Hauschild, 2003)

Pesticides	**Applied amount[a] (g)**	**Fraction emitted**		**Mass emitted per ha**	
Active substance		to air	to water	to air (g)	to water (g)
Herbicides					
Bentazon	250	0.04	1.7E-02	10.5	4.3E+00
Fluropyr	135	0.03	3.5E-05	3.92	4.7E-03
Foramsulfuron	45.0	0.03	3.5E-05	7.27	8.7E-03
Iodosulfuron-Na	1.50	0.03	2.2E-02	0.04	3.3E-02
Mesotroine	75.0	0.97	1.3E-07	242	3.3E-05
Pendimethalin	800	0.46	6.4E-02	369	5.2E+01
Pyridat	450	0.03	1.2E-05	13.1	5.2E-03
Terbuthylazin	575	0.04	6.1E-02	21.4	3.5E+01
Thifensulfuron methyl	3.75	0.03	2.1E-05	0.1	7.9E-05
Insecticides					
Alpha-cypermethrin	6.25	0.89	1.2E-02	5.59	7.5E-02
Cypermethrin	10.0	0.89	2.8E-06	8.94	2.8E-05
Dimethoat	150	0.89	2.0E-20	134	3.0E-18
Lambda-cyhalothrin	7.50	0.89	6.2E-04	6.70	4.6E-03

[a] Miljøstyrelsen (2006)

Willow production

The inventory data applied for agricultural production of energy willow are based on communication with experts within agricultural production and willow production. The data applied are presented in Table A8 together with the references used.

Table A8: Inventory data for agricultural production of energy willow

Agr. production of energy willow		**Substance**	**Unit**	**Quantity**
Inputs	Resources	Arable land use	ha y	1.00
		Stiklinger[a]	pieces/y	600
	Manure[b]	Nitrogen	kg N	100
		Phosphate	kg P	20.0
		Potasium	kg K	67
	Pesticides[c]	Pendimethalin	g	93.4
		Haloxyfop-ethoxyethyl	g	0.04
		Glyphosat	g	12.0
	Energy[d]	Diesel	kg	25.2
		Electricity	MJ	24.0
Outputs	Products	Willow (50 % water)[f]	ton DW	11.9
	Emission to air[e]	N_2O	kg	0.19
		NH_3	kg	0.52
		Pesticides		Treated separately
	Emissions to water	NO_3[e]	kg	10.7
		Phosphate[d]	kg	0.50
		Pesticidies		Treated separately
	Emissions to soil	Pesticides		Treated separately

[a] Landscentret (2006b)

[b] Quantities taken from Landscentret (2006b) and increased by 33 % based on expectations of what quantities that will be allowed in the future based on the large uptake from the willow roots (Bach, 2006)

[c] Bach (2006)

[d] Felby (2006)

[e] 5 % of applied N is emitted to the surroundings (Felby, 2006). The distribution of emitted N in form of N_2O, NH_3 and NO_3 is estimated based on American maize production in Nielsen & Wenzel (2005)

[f] The LHV of willow wood is similar to other wood types, i.e. approximately 18 GJ/ton DM. Source: Videncenter for halm- og flisfyring (1999b). LHV of energy willow (50 % water): MJ/kg.

The use of fertiliser in the form of manure is based on guidelines for cultivation of willow set up by the Danish Agricultural Advisory Service, National Centre (Landscentret, 2006b). The quantities have been increased by 33 % based on expectations concerning the quantities, which is expected to be allowed in the future due to the large nutrient uptake from the willow roots (Bach, 2006). This also ensures consistency in the sense that willow and maize receive the same amount of N. 5 % of the N added to the soil, is emitted to the surroundings since the roots of willow will take up large amounts of N (Felby, 2006). Furthermore, the phosphor emission is in the same range as the phosphor emitted during maize production. The phosphor emissions applied for willow are considered to be rather high because practically no uptake from the roots has been included due to lack of research completed on the subject (Felby, 2006).

The emissions of active substances in pesticides emitted per ha·y are presented below, based on results from the PESTLCI model.

Table A9: Active substances from pesticide use emitted from agricultural production of energy willow on 1 ha·y based on modelling in PESTLCI (Birkved and Hauschild, 2003)

Pesticides	**Applied amount[a] (g)**	**Fraction emitted**		**Mass emitted per ha**	
Active substance		to air	to water	to air (g)	to water (g)
Pendimethalin	66.7	0.46	6.5E-02	30642	4.3E+03
Haloxyfop-ethoxyethyl	0.04	0.76	2.6E-03	28.9	1.0E-01
Pendimethalin	26.7	0.46	6.5E-02	12250	1.7E+03
Glyphosat	12.0	0.03	1.8E-03	348	2.1E+01

[a] Bach (2006)

Appendix B: Biofuel conversion

Data for the various biofuel conversion processes for the comparison with Xergi's biogas production are presented below in the following.

Biodiesel from rapeseed

Waster water emissions (COD, methanol, methyl-esther) from the rapeseed based biodiesel production are not included in the impact assessment, since the waste water is assumed processed in a sludge treatment plant with subsequent use of the sludge for biogas production (as the case for the animal fat based biodiesel production). It can reasonably be assumed that the energy required for waste water treatment more or less equals the energy produced in the form of biogas (Andreasen, 2007). Thus, no net energy requirement or net energy production associated with the waste water treatment is assumed.

Table B1: Black box data of esterification of rapeseed oil

Rapeseed based biodiesel production - Esterification		**Substance**	**Original data**		**Energy units**[a]	
			Unit	**Quantity**	**Unit**	**Quantity**
Inputs	Raw materials	Rapeseed oil	kg	1000	GJ	37.0
		H_2SO_4 (96%)	kg	12	-	-
		Methanol (natural gas based)	kg	109	GJ	2.17
		KOH (88%)	kg	15	-	-
		H_3PO_4 (75%)	kg	1.0	-	-
		Nitrogen	kg	4.0	-	-
		Water	kg	51	-	-
	Energy	Power	MJ	133	GJ	0.133
		Power (water treatment)	MJ	3.2	GJ	0.0032
		Natural gas	MJ	2059	GJ	2.059
Outputs	Products	RME biodiesel	kg	975	GJ	35.9
		Catalyst residue (fertiliser use)	kg	24	-	-
		Glycerin (fuel use)	kg	123	GJ	2
	Water	Water	kg	40.6	-	-
	Emission to air	Nitrogen	kg	3.96	-	-
		Methanol	kg	0.010	-	-

Power consumption assumed to be 10 % lower and steam consumption assumed to be 20 % lower per ton biomass input compared to animal fat based biodiesel production. This is based on the fact that one less process step is necessary for rapeseed based biodiesel production compared to the animal fat based esterification process. Same relation between biomass and methanol input and biodiesel and glycerine output on mass basis can be assumed. No distillation residue will occur. Source: Andreasen (2007).

[a] Lower heating values applied: Animal fat: 35 MJ/kg; Glycerin: 16.8 MJ/kg, Distillation residues: 35 MJ/kg. Source: Andreasen (2007).

Methanol: 19.9 MJ/kg; RME biodiesel: 36.8 MJ/kg. Source: JRC et al. (2006a).

Inventory data for methanol production are given in Table B2.

Table B2: Inventory data for natural gas based methanol production.

Methanol production -		**Substance**	**Unit**	**Quantity**
Inputs	Raw material	Natural gas	MJ	25.75
	Energy	Heat (natural gas based)	MJ	7.32
		Electricity	MJ	0.27
	Water	Deionat water	kg	0.85
		Cooling water	kg	8.16
Outputs	Products	Methanol (CH_3OH)[a]	kg	1.0
			MJ	19.9
	Emissions to water	Biological Oxygen Demand (BOD)	g	0.18
		Chemical Oxygen Demand (COD)	g	0.49
		Dissolved organic carbon	g	0.24
		Formaldehyde	g	0.10
		Methanol (CH_3OH)	g	0.030
		Phenol (hydroxy benzene)	g	0.010
		Phosphorous	g	0.010
		Solids (suspended)	g	0.020
		Total Organic Carbon (TOC)	g	0.24
	Emissions to air	CH4	g	1.0
		Methanol (CH_3OH)	g	0.53
		NO_x (as NO_2)	g	0.15
		SO_2	g	0.014

Source: Eco-Invent database (2007).

[a] LHV of methanol: 19.9 MJ/kg (JRC et al., 2006a).

Bioethanol from maize stover

Table B3: Black box data of IBUS maize stover line

IBUS maize stover		**Substance**	**Original data**		**Energy units**[b]	
			Unit	**Quantity**	**Unit**	**Quantity**
Inputs	Raw materials	Maize stover (14 % water)	kg	1000	GJ	13.66
		Additives and enzymes[a]	kg	16.7	-	-
	Water	Raw water	kg	8.00	-	-
	Energy	Electricity	MWh	0.18	GJ	0.65
		Steam	MWh	1.14	GJ	4.10
		Cooling	MWh	1.12	GJ	4.03
	Fuels	Propane gas	kWh	5.89	-	-
Outputs	Products	Ethanol	kg	235	GJ	6.30
		Solid biofuel (10 % water)	kg	339	GJ	5.93
		C_5 molasses (30 % water)	kg	227	GJ	1.63
		Biogas	kWh	3.29	GJ	0.012
	Air emissions after emission reduction	CO_2	kg	226	-	-
		TOC	kg	0.01	-	-
		CO	kg	0.02	-	-
		NOx	kg	0.02	-	-
	Waste water emissions after treatment	COD	mg	8.64	-	-
		BOD_5	mg	1.73	-	-
		N-total	mg	0.58	-	-
		P-total	mg	0.02	-	-

Source: Iversen (2006b). The data have been verified by DONG Energy A/S.

[a] Actual amounts used in the process are confidential. Source used: Bentsen et al. (2006) (see Table B4)

[b] Lower heating values applied: Maize stover dry: 16.5 MJ/kg DM (Domalski et al. (1986); Maize stover (15 % water): 13.7 MJ/kg.; Ethanol: 26.8 MJ/kg (JRC et al. (2006a); Solid biofuel: 17.5 MJ/kg; C_5-molasses: 7.2 MJ/kg. (Iversen, 2006b).

Table B4 presents the data for consumption of enzymes and additives used in the modelling.

Table B4: Inventory data applied for consumption of enzymes and additives in the IBUS straw line.

IBUS straw enzymes and additives		**Substance**	**Unit**	**Quantity**
Inputs	Enzymes	Cellulasse	kg	1.1
	Additives	Sulphuric acid (H_2SO_4) (94 %)	kg	7.3
		Phosphorous acid (H_3PO_4) (74 %)	kg	1.7
		Sodium hydroxide (NaOH) (49 %)	kg	1.1
		Ammonia water (NH_3OH) (25 %)	kg	3.5
		Urea ($CO(NH_2)_2$) (45 %)	kg	1.70
		Calcium chloride ($CaCl_2.2H_2O$) (68 %)	kg	0.35

Source: Bentsen et al. (2006)

Bioethanol from maize kernels

Table B5: Black box data of IBUS maize kernels line

IBUS maize kernels		**Substance**	**Original data**		**Energy units[b]**	
			Unit	**Quantity**	**Unit**	**Quantity**
Inputs	Raw materials	Maize kernels (15 % water)	kg	1000	GJ	14.08
		Additives and enzymes	kg	16.3[a]	-	-
	Water	Raw water	kg	624	-	-
	Energy	Electricity	MWh	0.14	GJ	0.51
		Steam	MWh	0.97	GJ	3.50
		Cooling	MWh	0.66	GJ	2.37
	Fuels	Propane gas	MWh	0.01	-	-
Outputs	Products	Ethanol	kg	285	GJ	7.64
		DDGS (10 % water)	kg	373	GJ	5.60
		Biogas	kWh	10.5	GJ	0.038
	Air emissions after emission reduction	CO_2	kg	306	-	-
		TOC	kg	0.01	-	-
		CO	kg	0.02	-	-
		NO_x	kg	0.02	-	-
	Waste water emissions after treatment	COD	g	4.70	-	-
		BOD_5	g	0.94	-	-
		N-total	g	0.31	-	-
		P-total	g	0.01	-	-
		Ca	g	29.7	-	-
		Mg	g	4.61	-	-
		Na	g	49.4		
		K	g	1.94		
		HCO_3	g	43.1		
		Cl	g	100		
		SO_4	g	19.7		
		SiO_2	g	4.02		
	Water emissions to recipient	Phosporous (P)	g P	0.07		
		Nitrogen (N)	g N	0.02		

Source: Iversen (2006b). The data have been verified by DONG Energy A/S.

[a] Actual amounts are confidential. Source used: Nielsen and Wenzel (2005) and Bentsen et al. (2006) (see Table B6)

[b] Lower heating values applied: Maize kernels dry (assumed equal to LHV of energy grain): 17 MJ/kg DM (Gylling, 2001); Maize kernels (15 % water): 14.1 MJ/kg; Ethanol: 26.8 MJ/kg (JRC et al., 2006a); DDGS: 15.0 MJ/kg (Iversen, 2006b).

Data for consumption of additives is based on Bentsen et al. (2006), whereas enzyme data are based on information for maize kernel based ethanol production given in Nielsen and Wenzel (2005). Table B6 presents the data used in the modelling.

Table B6: Enzymes and additives utilized in the modelling

IBUS maize kernels enzymes and additives		**Substance**	**Unit**	**Quantity**
Inputs	Enzymes[a]	Termamyl SC DS	kg	0.17
		Spirizyme plus FG	kg	0.7
	Additives[b]	Sulphuric acid (H_2SO_4) (94 %)	kg	7.3
		Phosphorous acid (H_3PO_4) (74 %)	kg	1.7
		Sodium hydroxide (NaOH) (49 %)	kg	1.1
		Ammonia water (NH_3OH) (25 %)	kg	3.5
		Urea ($CO(NH_2)_2$) (45 %)	kg	1.70
		Calcium chloride ($CaCl_2.2H_2O$) (68 %)	kg	0.35

[a] Nielsen and Wenzel (2005) .[b] Bentsen et al. (2006).

Appendix C: Fodder production

On the global market, the marginal production of barley is likely to occur in Canada, the marginal production of soy beans in Argentina and the marginal palm fruit production in Malaysia and Indonesia (Schmidt and Weidema, 2006). Against this background, the marginal production of barley, soy beans and palm fruit is represented by productions in these countries. The agricultural production of the marginal fodder products are presented below, including further treatment processes.

Barley production

Table C1: Marginal production of barley

Agr. production of spring barley		**Substance**	**Unit**	**Quantity**
Inputs	Resources	Fertilizer N	kg N	0.0261
		Fertilizer P	kg P	0.0043
		Fertilizer K	kg K	0.0136
		Total fertilizer	kg	0.044
		Chemicals inorganic	kg	0.0027
	Energy	Natural gas	MJ	0.863
		Heavy oil	MJ	0.142
		Coal	MJ	0.157
		Power	MJ	0.0176
		Diesel	kg	0.0254
Outputs	Products	Barley	kg DW	1.0
		CO_2	kg	0.671
		SO_2	kg	0.0058
		NO_3	kg	0.053
		Ethene	kg	0.0002
	Land use	Land use	m^2·year	2.0

Source: LCA food (2006).

Soy bean production

Table C2: Marginal production of soy bean

Agr. production of soy beans		**Substance**	**Unit**	**Quantity**
Inputs	Resources	Fertilizer N	kg N	0.0261
		Fertilizer P	kg P	0.00428
		Fertilizer K	kg K	0.0136
		Total fertilizer	kg	0.04398
		Chemicals inorganic	kg	0.00265
	Energy	Natural gas	MJ	0.863
		Coal	MJ	0.157
		Heavy oil	MJ	0.142
		Power	MJ	0.0176
		Diesel	kg	0.0254
Outputs	Products	Soy bean	kg DW	1.0
		CO_2	kg	0.62
		SO_2	kg	0.0007
		NO_3	kg	0.006
		Ethene	kg	0.00012
	Land use	Land use	m^2·year	3.3

Source: LCA food (2006).

The soy beans further have to be treated into soy oil and soy meal. The process is presented below.

Table C3: Marginal production of soy oil and meal

Soya-bean oil and soy meal production		**Substance**	**Unit**	**Quantity**
Inputs	Resources	Soya beans	ton	5.6
		Hexane	g	376
	Energy	Heat	MJ	2240
		Electricity	kWh	64.7
Outputs	Products	Soy meal	ton DW	4.6
		Soy oil	ton	1.0
	Emission to air	Hexane	g	376
		CO_2	kg	140
		CO	g	22.7
		NO_x	g	169
		VOC	g	66.1
		SO_2	g	12.1
	Emissions to water	BOD	g	0.09
		COD	g	0.32
		Nitrate	g	0.02

Source: LCA food (2006).

The rest of the soy bean plant is not taken into consideration in model since it is left at the field to decay (Felby, 2007).

Palm fruit production

Table C4: Marginal production of palm fruit

Agr. production of palm fruits		Substance	Unit	Quantity
Inputs	Resources	Fertilizer N	kg N	0.0261
		Fertilizer P	kg P	0.00428
		Fertilizer K	kg K	0.0136
		Total fertilizer	kg	0.04398
		Chemicals inorganic	kg	0.00265
	Energy	Natural gas	MJ	0.863
		Coal	MJ	0.157
		Heavy oil	MJ	0.142
		Power	MJ	0.0176
		Diesel	kg	0.0254
Outputs	Products	Palm fruit[a]	kg DW	1.0
		CO_2	kg	0.62
		SO_2	kg	0.0007
		NO_3	kg	0.006
		Ethene	kg	0.00012
	Land use[a]	Land use	m^2·year	1.94

Source: LCA food (2006).
[a] Source: Schmidt (2007).

The Palm fruit further have to be treated into palm oil and palm meal. The process is presented below.

Table C5: Marginal production of palm oil and meal

Palm oil and palm meal production		Substance	Unit	Quantity
Inputs	Resources[a]	Palm fruit	ton	4.463
	Energy	Heat	MJ	2240
		Electricity	kWh	64.7
Outputs	Products[a]	Palm meal	ton DW	0.122
		Palm oil	ton DW	1
	Emission to air	Hexane	g	376
		CO_2	kg	140
		CO	g	22.7
		NO_x	g	169
		VOC	g	66.1
		SO_2	g	12.1
	Emissions to water	BOD	g	0,09
		COD	g	0.32
		Nitrate	g	0.02

Source: LCA food (2006).
[a] Source: Schmidt (2007).

The palm oil mill produces electricity to cover the processes own electricity need but it is assumed that the net quantity of electricity is minimal compared to the whole scenario and thereby is not included.

Appendix D: By-products substituting fodder products

Dried distillers grain soluble (DDGS) and C_5-molasses are produced as by-products from the IBUS bioethanol process. In the baseline scenarios, these fodder products are sold as animal fodder on the global market. Following the consequential LCA thinking, the produced fodder products will substitute other products on the market, which will then again substitute other fodder products. Down the line, production of the marginal fodder products will be prevented. This production would otherwise have taken place at the frontier between agricultural land and nature, where new land is gained from nature. This reduced land gain for agricultural production is the result of system expansion performed in the IBUS ethanol scenarios.

C_5-molasses is the fodder by-product generated from straw and maize stover based ethanol production. The content of molasses from straw based ethanol does not differ much from the content of maize stover molasses so the same content is assumed. C_5-molasses is high in feed energy content (14.2 MJ/kg DW (Elsam, 2006d)) and will substitute fodder barley (15.2 MJ/kg DW (Landscentret, 2005)), since this is the marginal product on the market regarding fodder energy content (Schmidt and Weidema, 2006). However, fodder barley contains a little higher content of protein (10.8 % of DW (Landscentret, 2005)) compared to molasses (5.9 % of DW (Elsam, 2006d)). This results in lack of protein in the fodder when substituting barley with molasses.

In order to obtain a reasonable substitution concerning both fodder energy and protein content, supplemental protein is supplied in the substitution relation. This is done in the form of soy meal, which has a high content of protein (48.7 % of DW (Landscentret, 2005)) and is the marginal source of fodder protein on the market (Schmidt and Weidema, 2006).

DDGS is produced from the maize kernel based bioethanol production. Since no IBUS plant currently exists performing this fermentation, the protein content of the DDGS has been estimated based on American studies (30.2 % of DW (Shurson, 2001)). The protein content is high and substitutes soy meal being the marginal source of fodder protein (Schmidt and Weidema, 2006). The energy content is neglected in the substitution relation, since protein content is most important when dealing with these fodder products.

The agricultural production of barley, soy bean and palm oil and further production of soy meal, soy oil, palm meal, and palm oil are given in Appendix C. Data for production of these products have not been verified to the same extent as the Danish production of willow and maize but are based on data from the LCA food database (2006).

The following tables present the substitution relations applied.

Table D1: C_5-molasses and barley content and their substitution relation

C_5-molasses	**Unit**	**Quantity**
Scandinavian food unit[a]		1.03
Energy[b]	MJ/kg DW C_5-molasses	14.2
Crude protein[a]	% DW/kg DW C_5-molasses	5.90
Barley[c]	**Unit**	**Quantity**
Scandinavian food unit		1.11
Digestable energy	MJ/kg DW barley	15.2
Crude protein	% DW/kg DW barley	10.8
Digestable crude protein	% DW/kg DW barley	7.00
Substitution relation[d]	**Unit**	**Quantity**
Protein related substitution		
To cover protein, induced	kg DW soy meal/kg DW C_5-molasses	0.03
Energy related substitution		
Energi from soy meal, induced	MJ/kg DW C_5-molasses	0.46
Total energy induced	MJ/kg DW C_5-molasses	14.6
To cover rest energy, avoided	kg DW barley/kg DW C_5-molasses	0.96

[a] Elsam (IV) (2006)
[b] Bentsen et al. (2006)
[c] Landscentret (2005)
[d] Assumed same amino acid content for C5-molasses as for barley.

Fodder barley contains a little higher content of protein compared to molasses. This results in lack of protein in the fodder when substituting barley with molasses. In order to obtain a reasonable substitution concerning both fodder energy and protein content, supplemental protein is supplied in the substitution relation. This is done in the form of soy meal, which has a high content of protein.

Table D2: DDGS and soy meal content and their substitution relation

DDGS	**Unit**	**Quantity**
Scandinavian food unit[a]		1.24
Energy[b]	MJ/kg DW DDGS	16.6
Crude protein[b]	% DW/kg DW DDGS	30.22
Soy meal[c]	**Unit**	**Quantity**
Scandinavian food unit		1.36
Digestable energy	MJ/kg DW soy meal	17.8
Crude protein	% DW/kg DW soy meal	48.7
Digestable crude protein	% DW/kg DW soy meal	42.3
Substitution relation - protein related[d]	**Unit**	**Quantity**
To cover protein, avoided	kg DW soy meal/kg DW DDGS	0.71

[a] Bentsen et al. (2006)
[b] Shurson (2001)
[c] Landscentret (2005)
[d] Assumed same amino acid content for DDGS as for soy meal.

The energy content is neglected in the substitution relation, since protein content is most important when dealing with these fodder products. This also applies for rape cake and soy meal substitution.

Table D3: Rape cake and soy meal content and their substitution relation

Rape cake[a]	**Unit**	**Quantity**
Scandinavian food unit		1.08
Digestable energy	MJ/kg DW rape cake	15.2
Crude protein	% DW/kg DW rape cake	35
Soy meal[b]	**Unit**	**Quantity**
Scandinavian food unit		1.36
Digestable energy	MJ/kg DW soy meal	17.8
Crude protein	% DW/kg DW soy meal	48.7
Digestable crude protein	% DW/kg DW soy meal	42.3
Substitution relation - protein related[c]	**Unit**	**Quantity**
To cover protein, avoided	kg DW soy meal/kg DW rape cake	0.70

[a] Scanola (2007)

[b] Landscentret (2005)

[c] Assumed same amino acid content for rape cake as for soy meal.

Appendix E: Fertilizer substitution relation and field emissions

Field emissions and mineral fertilizer substitution relations applied are presented below for each manure fraction (raw manure, degassed manure, liquid manure) and degassed maize silage. Further emission data for application of mineral fertilizers are given.

Raw manure

The raw manure have been assumed one third of pig manure and two-thirds of cattle manure.
The substitution relation between raw manure and mineral fertilizer can be calculated based on the content of degradable nitrogen in the manure. Around 75 % of the nitrogen content in raw manure from pigs is easily degradable, whereas 60 % is easily degradable in manure from cattle (Nielsen et al., 2002). The applied relation is thus: 0.65 kg N of mineral fertilizer per 1 kg N in the raw manure. The degradable nitrogen is thereby assumed to be equal to the content of mineral nitrogen in the mineral fertilizer.

When applying the raw manure through storage on the field emissions compared to mineral fertilizer are higher. The table below presents emission factors of methane and nitrous oxide in CO_2-eq. of raw and degassed manure from pig or cattle, respectively, including mineral fertilizer.

Table E1: Methane and nitrous oxide emissions in CO_2-eq. per 1 kg VS

Emission factors[a]	kg CO_2-eq./kg VS[b]		
	Stable CH_4	Storage CH_4	Field N_2O[c]
Raw pig manure	0.3737	0.7744	0.01
Raw cattle manure	0.7236	0.4222	0.01
Degassed pig manure	0.3737	0.1902	0.01
Degassed cattle manure	0.7236	0.0772	0.01
Applied factors of degassed manure[d]	0.6070	0.1149	0.01
Mineral fertilizer	0	0	0.01

Source: Sommer et al. (2001)
[a] The emission factors applied are based on several assumptions of storage time, temperatures in stable and storage, etc. See Sommer et al. (2001) for further elaboration.
[b] Global warming potentials: 1 kg CH_4 equals 25 kg carbon dioxide, 1 kg N_2O equals 298 kg carbon dioxide (time horison of 100 years) (Solomon et al., 2007)
[c] IPCC emission factor. The value of the emission factor has been changed from 1.25% to 1%, as compared to the *1996 IPCC Guidelines*, as a result of new analyses of the available experimental data (Klein et al., 2006)
[d] Based on the content of applied manure of one third of pig manure and two-thirds of cattle manure
VS: Volatile Solids

The content of VS in the raw manure is based on the content of dry matter. It is assumed that approximately 80 % of the dry matter is VS (Sommer, 2007). The content of dry matter in raw manure from pigs and cattle are assumed approximately 4.7 % and 7.0 %, respectively (Kemira Miljø, 2007), thus an average of 5.85 % is used when dealing with the applied mixture of pig and cattle manure. This provides a VS content of 46.8 kg per ton mixture of manure.

Degassed manure

The emissions when applying the degassed manure have been assumed one third of degassed pig manure and two-thirds of degassed cattle manure which is the amounts of raw manure used as input for biogas production.
The degassed manure after production of biogas has a degradable content of nitrogen of 90 % and 78 % from pigs and cows, respectively (Nielsen et al., 2002). The applied relation is thus: 0.82 kg N of mineral fertilizer per 1 kg N in the degassed manure.

Table E1 presents the emissions of methane and nitrous oxide of degassed manure in CO_2-eq. per kg VS. The content of dry matter in the applied mixture of degassed manure is assumed to be 6.44 % (Kemira Miljø, 2007), thus the VS content per ton gassed manure is calculated to be 51.5 kg.

Liquid manure

The liquid separated fractions are assumed to have approximately the same emissions as mineral fertilizers and thus the relation of 1 kg N of mineral fertilizer per 1 kg N in the liquid manure is applied (Sommer, 2007). The emissions when applying the liquid manure are also assumed to be the same as for mineral fertilizer (emission factor 1.0 % (Klein et al., 2006)) and thereby no additional emissions are applied in the modelling. It could be argued that a methane emission would occur from the liquid manure during storage but due to lack of data on the subject of liquid manure this emission is not included in the scenario.

Degassed maize silage

The methane and nitrous oxide emissions when applying the degassed maize silage are as well as for the liquid manure assumed to be the same as for mineral fertilizer. Thus the relation of 1 kg N of mineral fertilizer per 1 kg N in the degassed maize silage is applied and no further emissions are included in the modelling (Sommer, 2007).

Mineral fertilizer

The emission of nitrous oxide when mineral fertilizer is applied on the field has the emission factor of 1.0 % (Klein et al., 2006) which is the same as when manure is applied (Sommer et al., 2001). It is assumed that there is no emission of methane when mineral fertilizer is applied.

Appendix F: Transport technologies

Diesel and biodiesel as transport fuel

Table F1: Fuel consumption and emission data for use of diesel and biodiesel, respectively, in passenger cars.

Data for use of diesel and biodiesel in passenger cars	Unit	**Diesel**				**Biodiesel**
		INFRAS (2004)	JRC et al. (2006a)	EURO4 limits[a]	Applied data for 2010+ vehicle	Applied data for 2010+ vehicle[c]
Fuel consumption	MJ/km		**1.767**		**1.767**	**1.767**
CO	g/km	0.091	n.a.	**0.05**	**0.050**	**0.015**
CO_2 (fossil)	g/km	163	**129.4**	-	**129.4**	**4.3**
HC	g/km	**0.020**	n.a.	0.05	**0.020**	**0.0061**
CH_4	g/km	0.00049	**0.010**	-	**0.010**	**0.010**
NMHC	g/km	**0.020**	n.a.	-	**0.020**	**0.0059**
Benzene	g/km	**0.00034**	n.a.	-	**0.00034**	**0.00010**
Toluene	g/km	**0.000065**	n.a.	-	**0.000065**	**0.000019**
Xylene	g/km	**0.00016**	n.a.	-	**0.00016**	**0.000049**
Unspecified NMHC	g/km	**0.019**	n.a.	-	**0.019**	**0.0058**
NOx	g/km	0.33	n.a.	**0.25**	**0.250**	**0.13**
NH3	g/km	**0.0010**	n.a.	-	**0.0010**	**0.0010**
N_2O	g/km	0.0055	**0.0051**	-	**0.0051**	**0.0051**
PM (exhaust)	g/km	**0.016**	n.a.	0.025[b]	**0.016**	**0.0032**
SO_2	g/km	0.031	n.a.	-	**0.00082**[d]	**0.0**

[a] Source: Arcoumanis (2000).

[b] EURO5 limits for particulate matter. Source: Schmidt (2003).

[c] EURO4 emission factors for FAME (30 D) vehicle. SO2 emission assumed zero due to negligible sulphur content in biodiesel. The fossil CO_2 emission originates from the fossil methanol share of biodiesel (see Table F3).

d Estimated based on sulphur content limits for diesel according to European fuel standard (see Table F6).

Table F2: EURO4 emission factors for biodiesel use in cars.

	Biodiesel/diesel vehicle (FAME 30D[a])
HC	0.30
NO_x	0.50
CO	0.30
PM_{10}	0.20

[a] Mixture of 30 % Fatty Acid Methyl Esther (FAME) in diesel.
Source: Arcoumanis (2000).

Table F3: Estimation of CO_2 emission from fossil methanol share in biodiesel

CO_2 emission from fossil methanol in biodiesel	**kg CO_2/kg**	**kg/10 km**	**kg CO_2/10 km**
Animal fat[a]	-2.78	0.49	-1.36
Methanol[b]	1.38	0.05	0.07
Biodiesel[c]	2.8	0.48	1.33
Net fossil CO_2 emission			**0.043**

[a] Andreasen (2007).

[b] JRC et al. (2006a).

[c] Same CO_2 emission as for RME assumed: 2.8 kg CO_2/kg RME (JRC et al., 2006a).

Petrol and ethanol as transport fuel

Table F4: Fuel consumption and emission data for use of petrol and bioethanol, respectively, in cars.

Data for use of petrol and bioethanol in passenger cars	Unit	**Petrol**				**Bioethanol**
		INFRAS (2004)	JRC et al. (2006a)	EURO4 limits[a]	Applied data for 2010+ vehicle	Applied data for 2010+ vehicle[c]
Fuel consumption	MJ/km		**1.90**		**1.90**	**1.90**
CO	g/km	1.2	n.a.	**1**	**1**	**0.3**
CO_2 (fossil)	g/km	154	**139.4**	-	**139.4**	**0**
HC	g/km	0.013	n.a.	**0.10**	**0.10**	**0.04**
CH_4	g/km	0.0011	**0.02**	-	**0.020**	**0.008**
NMHC	g/km	**0.012**	n.a.	-	**0.012**	**0.00488**
Benzene	g/km	**0.0017**	n.a.	-	**0.0017**	**0.00068**
Toluene	g/km	**0.0012**	n.a.	-	**0.0012**	**0.00048**
Xylene	g/km	**0.0010**	n.a.	-	**0.0010**	**0.0004**
Unspecified NMHC	g/km	**0.0083**	n.a.	-	**0.0083**	**0.00332**
NOx	g/km	**0.050**	n.a.	0.08	**0.050**	**0.015**
NH3	g/km	**0.023**	n.a.	-	**0.023**	**0.023**
N_2O	g/km	0.0013	**0.0017**	-	**0.0017**	**0.0017**
PM (exhaust)	g/km	**0.0000**	n.a.	0.005[b]	**0.00**	**0.00**
SO_2	g/km	0.0068	n.a.	-	**0.00088**[d]	**0.00000**

[a] Source: Arcoumanis (2000).

[b] EURO5 limits for particulate matter. Source: Schmidt (2003).

[c] EURO4 emission factors for a Flexible Fuel Vehicle (FFV, 85 % ethanol, 15 % petrol on volume basis) applied. SO_2 emission assumed zero due to negligible sulphur content in bioethanol. CO_2 emission set to zero since bioethanol is produced from renewable raw materials (biomass).

[d] Estimated based on sulphur content limits for petrol according to European fuel standard (see Table F6).

Table F5: EURO4 emission factors for bioethanol use in cars.

	FFV (E85)[a]
HC	0.40
Nox	0.30
CO	0.30
PM_{10}	0.40

[a] Flex Fuel Vehicle (FFV) with 85 % ethanol and 15 % petrol on volume basis.
Source: Arcoumanis (2000).

Table F6: Estimation of SO_2 emissions from petrol and diesel vehicle configurations.

SO_2 emissions for 2010+ petrol/diesel vehicle configurations	**Unit**	**Quantity**	
		Petrol vehicle	**Diesel vehicle**
Sulphur content of petrol/diesel according to European fuel standard[a]	mg S/kg fuel	10	10
Fuel consumption for 2010+ vehicle[b]	kg fuel/km	0.044	0.041
SO_2 emission assuming full oxidation of sulphur to SO_2	mol SO_2/km	0.000014	0.000013
SO_2 emission assuming full oxidation of sulphur to SO_2	g SO_2/km	**0.00088**	**0.00082**

[a] From January 1, 2009 petrol and diesel is allowed to be sold and imported with the intention to be used in motor vehicles in Denmark, only if the sulphur content is maximum 10 mg/kg fuel (Schmidt, 2003).

[b] Source: JRC et al. (2006a).

Compressed Natural Gas (CNG) and biogas as transport fuel

When the biogas is upgraded it can be assumed to have the same quality as natural gas.

Table F7: Upgrading of biogas to natural gas

Upgrading of biogas		Substance	Original data		Energy units[a]	
			Unit	Quantity	Unit	Quantity
Inputs	Energy	Biogas (52% methane)	Nm3	2.13	MJ	40
		Power	kWh	0.80	MJ	2.88
Outputs	Products	Natural gas	Nm3	1.00	MJ	40
	Emissions	Methane	kg	0.03	-	-

Souce: Data based on: Persson (2003).

[a] Lower heating values applied: biogas (52% methane) 18.7 MJ/Nm^3 (Jensen, 2007), Natural gas 39.77 MJ/ Nm^3 (Jensen and Thyø, 2007).

Natural gas is compressed before use as transport fuel in the CNG (Compressed Natural Gas) bi-fuel vehicle applied in some of the scenarios setups[1]. Data from JRC et al. (2006a) have been used for the compression process.

Table F8: Inventory data applied for compression of natural gas.

Compression of natural gas		Substance	Unit	Quantity
Inputs	Media	Natural gas	GJ	1
	Energy consumption	Power	GJ	0.022
Outputs	Product	Compressed natural gas (CNG)	GJ	1
	Emissions	CH_4	kg	0.01

The compression is assumed to occur at Danish fuel stations. The power consumption is estimated based on data for primary energy consumption (0.04-0.08 GJ/GJ natural gas, best estimate: 0,06GJ/GJ natural gas). Applying the average yearly electricity efficiency of Danish marginal power plants of 37 % (see section 11.8), the corresponding power consumption for the compression process is estimated to 0.022 GJ/GJ natural gas.
Emissions of CH_4 are assumed to originate from leaching during the process.
Source: JRC et al. (2006a), Appendix 2.

Emission factors are given for bi-fuel vehicle applied according to CNG/petrol ratio of 57%/43 % on an energy basis.

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[1] Scenario A3, AA3, B3 and BB3.

Table F9: Fuel consumption and emission data for use of CNG in cars.

Data for use of CNG in passenger car	**Unit**	**CNG**
		Applied data for 2010+vehicle[a]
Fuel consumption	MJ/km	**1.88**
CO	g/km	**0.2**
CO_2 (fossil)[d]	g/km	**106**
HC[b]	g/km	**0.009**
CH_4	g/km	**0.01**
NMHC	g/km	**0.001**
Benzene	g/km	**0.0002**
Toluene	g/km	**0.0001**
Xylene	g/km	**0.0001**
Unspecified NMHC	g/km	**0.0008**
Nox	g/km	**0.01**
NH_3[e]	g/km	**0.02**
N_2O[c]	g/km	**0.02**
PM (exhaust)	g/km	**0**
SO_2	g/km	**0.001**

[a] Source: JRC et al. (TTW) (2006), Arcoumanis (2000), Nielsen & Wenzel (2005)

[b] Emission factor for Biofuel (E85G) of 0,40 for HC in general applied for CH_4 emissions (JRC et al. (TTW), 2006)

[c] N_2O emissions assumed equal to emissions from a conventional gasoline vehicle and a neat ethanol vehicle. This is reasonable since identical magnitudes of these emissions are applied for gasoline and neat ethanol vehicle in JRC et al. (TTW) (2006)

[d] CO_2 (fossil) emission estimated from gasoline share (15 % vol.) corresponding to 40 MJ gasoline/100 km and CO_2 emission of 73.38 g CO_2/MJ for 2010 vehicle.

[e] NH_3 emissions assumed equal to NH_3 emissions from a conventional petrol vehicle

Table F10: EURO4 emission factors for CNG use in cars.

Euro II	**Bi-fuel vehicle (CNG)**
HC	1,7 (NMHC)
Nox	0.5
CO_2 (vehicle)	0.8
CO	0.4
PM_{10} (exhaust)	0.6

Source: Arcoumanis (2000).

Table F11: Estimation of SO_2 emissions from CNG vehicle configurations.

Bi-fuel vehicle (57 % CNG/43 % petrol)	**Unit**	**Quantity**
Sulphur content in Danish natural gas	mg S/m3	10.5
	mg S/MJ	0.26402
CNG consumption for reference vehicle[a]	MJ/km	1.883
SO2 emission assuming full oxidation of sulphur to SO2	mol S02/km	0.000015
SO2 emission assuming full oxidation of sulphur to SO2	g SO2/km	**0.00099**

[a] Source: JRC et al. (2006a).

Appendix G: Extraction of oil, natural gas and coal

Applying the concept of consequential LCA, a marginal approach has been applied when modelling the extraction of coal, natural gas and oil. Crude oil, natural gas and coal are all internationally traded goods.

Crude oil extraction and refining

In the environmental assessment, the crude oil extraction step is primarily relevant in modelling of petrol displacement[2]. The question in this matter is therefore to identify the marginal, in terms of avoided crude extraction and refining resulting from a decreased petrol demand.

Since year 1997, Denmark has been self sufficient in oil supply, and the self sufficiency is expected to remain some years to come (Energistyrelsen, 2001). However, it is not reasonable to expect that the volume of the Danish oil production reacts to changes in the Danish petrol demand. Therefore, crude oil extraction in Denmark is not likely to be characterized the marginal for a reduced Danish petrol demand (Trier, 2006). On the contrary, the marginal crude oil supplied to Europe is generally likely to originate from the Middle East. Traditionally, crude oil is transported and refined near the markets. The bulk of the oil based fuels solid in Europe is manufactured in European refineries (JRC et al., 2006a).

Against this background, it is assumed that crude oil extraction occurs in the Middle East and oil refining takes place at European refineries. Aggregated EDIP 1997 data from the Gabi4 database, for European petrol manufacturing has been applied. In order to achieve a high reliability on data concerning energy consumption and green house gas emission (GHG) data, these have been adjusted according to JRC et al. (2006a). The data applied are presented in Table G1 and G2.

Table G1: Energy consumption data applied for oil extraction and refining for petrol and diesel production, respectively

Energy consumption for crude oil pathways	**Petrol**	**Diesel**
	MJ/MJ fuel	MJ/MJ fuel
Crude oil extraction and conditioning at source[a]	0.025	0.025
Transportation to markets	0.010	0.010
Refining	0.080	0.100
Total	**0.115**	**0.135**

Source: JRC et al. (2006a).

Table G2: Green house gas emission data applied for oil extraction and refining for petrol and diesel production, respectively.

	Petrol	**Diesel**
GHG emissions for crude oil pathways	g CO_2-eq./MJ fuel	g CO_2-eq./MJ fuel
Crude oil extraction and conditioning at source	3.3	3.3
Transportation to European markets	0.8	0.8
Refining	6.5	8.6
Total	**11.6**	**13.7**

[a] An interval of 2.9-3.9 CO_2-eq./MJ petrol is given in JRC et al. (2006a) for a number of CONCAWE member states. As in JRC et al. (2006a), the median of 3.3 is applied as average estimate.
Source: JRC et al. (2006a).

Natural gas extraction

For the moment, Denmark is self-sufficient in natural gas supply. However, it is not likely that the magnitude of the Danish natural gas production is affected by changes in the Danish demand. In contradiction, the

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[2] Petrol displacement occurs in the IBUS ethanol scenarios A1 and B1. In addition, crude oil extraction is relevant for processes which use oil based fuels as input.

marginal natural gas producer to Europe is likely to be Norway or Russia, since these are currently the main natural gas suppliers to the European market (Pockenauer, 2006).

Aggregated 1997 data from the Gabi4-database for a natural gas mix to the German market has been applied. In this fuel mix, significant parts of the natural gas originate from Norway, C.I.S[3], Germany and the Netherlands. The technology level of the applied natural gas extraction mix is thus considered a well representative for the marginal.

Coal extraction

Coal extraction is mainly included in the model in connection to induced or avoided coal based power production, CHP production and steam production. Aggregated EDIP 1997 data from the Gabi4-database have been applied.

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[3] Commonwealth of Independent States (CIS): 11 former Soviet Republics: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Ukraine, and Uzbekistan (Wikipedia, 2006).

Appendix H: Fuel distribution

Environmental exchanges associated with distribution of petrol, diesel, ethanol and biodiesel to the fuel stations in Denmark is included in the environmental assessment. Also, exchanges connected to natural gas distribution through the grid are included.

Petrol, diesel, bioethanol, and biodiesel distribution

The transport work for inland transport fuel distribution is adjusted to imply a green house gas emission equivalent to the emission of 1 g CO_2-eq. given in JRC et al. (2006a). This corresponds to a transport work of approximately 60 kg·km when transport by van (3.5 t, EURO2, 25% load, mixed local traffic) is assumed. A transport work of 60 kg·km per kg fuel is thus assumed for petrol, diesel, bioethanol and biodiesel distribution, respectively. Due to differences in the energy density of these transport fuels, the transport work required to distribute a given amount of fuel on energy basis varies. However, the transport fuel distribution constitutes only a diminishing share of the energy consumption and green house gas emissions in the full life cycle considered.

Natural gas distribution

The environmental impacts associated with natural gas distribution primarily consists of three areas: Direct emission of natural gas from the distribution grid, consumption of natural gas and use of propellants at monitoring and regulation stations and the compulsory addition of odorant (Ipsen, 2006a).

Average data in Ipsen (2006a) for the environmental exchanges associated with natural gas distribution have been applied. Based on data for the total Danish natural gas transport through the grid[4], the average environmental exchanges per GJ natural gas distribution have been estimated. Eventual further distribution of CNG by road transport to areas not covered by the natural gas grid is not included.

Average data for the environmental exchanges per 1 GJ natural gas distribution are estimated based on data for the total Danish natural gas transport through the grid (approximately $7.6 \cdot 10^9$ m^3 natural gas in 2005 corresponding to 93 TWh (Ipsen, 2006b)).

There is a natural gas leakage of 0.0019 % in the grid. This result in the required input of 1.000019 GJ natural gas per GJ natural gas delivered. The leakage is included as an emission on the output side as methane (CH_4).

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[4] Approximately $7.6 \cdot 10^9$ m^3 natural gas in 2005 corresponding to 93 TWh (Ipsen, 2006a).

Table H1: Inventory data for natural gas distribution.

Natural gas distribution in Denmark		**Substance**	**Unit**	**Quantity**
Inputs	Distribution media	Natural gas	GJ	1.000019
	Odorant consumption	C_4H_8S	litre	0.00018
	Fuel for heating of natural gas	Natural gas	GJ	0.00064
Outputs	Distibution media	Natural gas	GJ	1
	Emissions from the grid[a]	CH_4	g	0.35
	Heating of natural gas	CO_2	kg	0.037
		CH_4	g	0.010
		N_20	g	0.00065
		CO	g	0.018
		NMVOC	g	0.0013
		SO_2	g	0.00019
		NO_x	g	0.027
	Emissions due to odorant use	SO_2	g	0.13

Heating of natural gas is required in order to compensate for pressure drop

Natural gas and thus natural gas emissions are for the dominating part methane (CH_4). The natural gas emission is assumed to be in the form of CH_4 alone.

The CH_4 emission of 0.35 g/MJ natural gas is estimated based a volumetric emission of $4.89*10^{-4}$ Nm^3 natural gas/GJ natural gas distributed. In the estimation, a molar weight of 0.016 kg/mol CH_4 is applied together with the fact that 1 mole of inert gas takes up a volume of approximately 0.0224 m^3 at standard temp and pressure (STP), i.e. 0.0224 Nm^3 (Colls, 2002).

Source: Ipsen (2006b)

Appendix I: Marginal power production

Based on a consequential LCA approach, the marginal power production resulting from an increased or decreased Danish power demand is identified. Inventory data for marginal power production are used for all the electricity consuming processes in the scenarios, which take place in Denmark.

As described below, the Danish marginal power is assessed to be based on coal firing at central CHP plants (Behnke, 2006). The inventory data for coal based CHP production are therefore also used to represent the environmental exchanges of coal based CHP production.

Based on data reported from Danish power and heat producers for 2005, seven marginal power plants have been identified. The power plants are all coal fired and can be considered marginal power plants in June 2006. A theoretical average "Danish marginal coal fired power plant" has been estimated based on data from these seven marginal plants. An environmental product declaration for the power from this theoretical plant has been developed (Behnke, 2006).

The seven marginal plants are CHP plants and thus produce both power and heat. In the product declaration given in Behnke (2006), the environmental exchanges for the CHP production are allocated to the power production, applying the principle of exergy allocation. However, for the scenario modelling in the environmental assessment, unallocated data for the CHP production is required. Therefore, based on background data for the environmental product declaration, unallocated data have been estimated. The correctness of the estimates has been verified by Ipsen, K. and Nielsen, C.F.B. in November, 2006 at Energinet.dk. Table I1 presents the resulting data estimates applied. The environmental exchanges per 14.5 GJ coal (LHV) are also indicated, in order to support comparison with the inventory data per ton straw combustion (LHV of straw is 14.5 GJ/ton).

Table I1: Unallocated environmental exchange data for theoretical Danish marginal power plant.

CHP production at theoretical Danish marginal power plant			**Per 1 kWh power**		**Per 14.5 GJ coal**	
		Substance	**Unit**	**Quantity**	**Unit**	**Quantity**
Inputs	Primary fuel	Coal	g	393	kg	589
			kWh	2.68	GJ	14.5
	Secondary fuel	Oil	g	4.41	kg	6.6
Outputs	Products[a]	Power, net	kWh	1.0	GJ	5.4
		Heat, net	kWh	0.57	GJ	3.1
	By-products for reuse[b]	Gypsum	g	18.0	kg	26.9
		TDP	g	2.3	kg	3.5
		Coal fly ash	g	45.1	kg	67.6
	By-products for deposit	Coal bottom ash	g	5.2	kg	7.8
	Emissions to air (after emission control)	CO$_2$	g	939	kg	1408
		CH$_4$	g	0.011	kg	0.016
		N$_2$0	g	0.008	kg	0.012
		SO$_2$	g	0.31	kg	0.46
		NO$_x$	g	1.31	kg	1.97
		CO	g	0.091	kg	0.14
		NMVOC (unburnt)	g	0.009	kg	0.013
		Particles	g	0.04	kg	0.07

The data represent and average based on data reported by seven marginal coal fired CHP plants in Denmark in 2005.

[a] Net power and heat production ex plant is given, i.e. net energy delivered to the grid. Transmission and distribution losses in the power grid and heat losses in the district heating grid are thus not included. Electricity consumption for coal mills, pumps and emission control equipment etc. has been subtracted. Heat delivered to the grid is assumed equal to the gross heat produced for the grid, since heat losses at the plant are negligible (Nielsen, 2007).

Source: Nielsen (2006).

[b] Gypsum and Total desulphurisation product (TDP) are by-products from desulphurisation. Gypsum is typically reused for e.g. manufacturing of gypsum plates, and TDP e.g. reused in fertiliser for agriculture (Olsen, 2002). Coal fly ash is normally reused for cement or concrete production (Videncenter for halm- og flisfyring, 1998).

Based on measurements from Nordjyllandsværket, the amounts of heavy metals emitted from coal fired power production are considered insignificant (Behnke, 2006). Furthermore, heavy metal emissions are associated with high uncertainties, since the heavy metal content can vary considerably in between coal fraction (Hundebøl, 2006). Moreover, the data in Behnke (2006) do not include waste water emissions, e.g. resulting from air emission control. The reason is that waste water emission data for the marginal power production have not been the primary focus among the members and external co-operation partners of Energinet.dk (Nielsen, 2007).

From Table I1, it can be seen that the theoretical marginal power plant, has a yearly net electricity efficiency of approximately 37 %[5]. Correspondingly, an average yearly total net efficiency of approximately 59 % can be estimated[6].

In the LCA, avoided environmental exchanges resulting from reuse of by-products (gypsum, TASP and coal fly ash) is not included. The reuse is merely credited for in terms of a reduced amount of waste for deposit.

It should be noted, that some people have doubts concerning to which extent coal based power production can be characterised as the marginal. Thus, some claim that in some cases wind based power production might be the marginal (Ipsen, 2006b). Nevertheless, it has been chosen to use the data from Behnke (2006) concerning marginal coal based power production as reference. Finally, regarding assessments of large changes in the energy system, it can be noted that it is not necessarily appropriate to use a marginal approach based on the existing system (Lund, 2006).

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[5] 1 kWh power / 2.68 kWh coal ·100 % ≈ 37 %.

[6] (1 kWh power + 0.57 kWh heat) / 2.68 kWh coal ·100 % ≈ 59 %

Appendix J: Marginal district heat production

Data for marginal district heat production is used in scenarios where district heat production is avoided. This occurs when certain system expansions are required in order to secure fulfilment of the functional unit.

An environmental product declaration in Duhn (2006a) developed for Danish district heat production has been used. The product declaration can be used for assessment of an either increased or reduced district heat demand (Duhn, 2006b). In the scenarios involving avoided district heat production, the avoidance arises as a function of surplus district heat production (surplus district heat production compared to the required functional unit) from central CHP plants. Therefore, data for district heat production to the central district heat grid has been applied.

The data are weighted according to the average yearly district heat supplied by each of the 12 central Danish district heat grids[7]. The inventory data for the average marginal district heat production are given in Table J1. As in the environmental product declaration for marginal power production, waste water emissions are not included.

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[7] Aabenraa Fjernvarme, Aalborg Kom. Forsyningsvirksomhederne, Århus Kommunale Værker, Esbjerg Kommune Forsyningen, Vestforsyning Varme A/S, Horsens Varmeværk a.m.b.a., Nyborg Forsyning og Service A/S, Odense Kommunale Fjernvarmeforsyning, Vejen Varmeværk a.m.b.a., Vordingborg Fjernvarme, Fredericia Fjernvarme a.m.b.a., and Kalundborg Kommune Varmeforsyningen.

Table J1: Inventory data for marginal district heat production in Denmark.

Marginal Danish district heat production		Substance	Unit	Quantity
Inputs	Fuels	Coal	kWh	-0.59
		Natural gas	kWh	0.10
		Gas oil	kWh	0.20
		Fuel oil	kWh	0.31
		Bio oil	kWh	0.0028
		Waste	kWh	0.34
		Wood	kWh	0.0068
		Straw	kWh	0.020
Outputs	Products	District heating	kWh	1
	By-products for reuse	TDP	g	0.024
	Emissions to air (after treatment)	CO_2	kg	0.24
		NO_x	g	0.47
		SO_2	g	0.77
		CH_4	g	-0.31
		NMVOC	g	-0.061
		CO	g	-0.064
		PM_{10}	g	0.008
		PM_{25}	g	0.018

Duhn (2006a) and Duhn (2006b). The database on which the information is based has not yet been verified.

Total desulphurisation product TDP is e.g. reused in fertiliser for agriculture (Olsen, 2002). PM_{10}, PM_{25}: Particulate matter with a dimensional diameter lower than 10 and 25 μm, respectively.

The district heating supplied to the central grid is in many cases co-produced with power (CHP operation). The relation between the power and heat production depends on whether the plant is operated in *back-pressure mode* or *extraction mode*[8]. For operation in back-pressure, the surplus heat generated during electricity production is cooled of for district heat supply. Therefore, there is a linear connection between heat and power production, i.e. if the heat production is increased, the power production will also increase[9]. In extraction mode, heat is extracted before it has lost all its energy in the steam turbine of the plant. In this case, an increased district heat production results in a reduced power production at the plant[10] (Duhn, 2006a).

Regarding back-pressure operation, a system expansion is performed, in which heat is considered the main product and power the by-product. As such, all environmental exchanges (resource consumptions and emissions) associated with the CHP production is attributed to the district heat production. Next, the power produced will displace marginal power production elsewhere in the grid. Therefore, the environmental exchanges associated with this displaced marginal power production are subsequently subtracted. The power is produced at central CHP plant where the environmental exchanges are exclusively attributed to the power production (Duhn, 2006a), (Duhn, 2006b).

In extraction mode, an increased district heat production does not cause an increase in the fuel supply. As such, the district heat production does not induce resource consumptions or emissions at the plant. On the other hand, the power production is reduced as a result of the heat production. Therefore, the emissions are attributed to the power which in compensation has to be produced at another plant. The fuel consumption at this plant is then exclusively attributed to the power production.

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[8] In Danish: Modtryksdrift eller udtagsdrift.

[9] The relation between power and heat production is described by the C_m value of the plant which typically can have a value of 0.6.

[10] The relation between the increased heat production and the reduced power production is characterised by the C_v value of the plant is typically e.g. 0.14.

Some of the central CHP plants operate in back-pressure mode, while some have possibility of operating in either back-pressure or extraction mode. For the last mentioned plants, the relation between the two different operation modes can not immediately be determined. For that reason, an equal distribution between the two operation modes has been assumed (Duhn, 2006a).

Data for the marginal power production, presented, are used as reference for the environmental exchanges associated with power production. Coal consumption is thus avoided in cases with displaced power production. This is the explanation for the negative coal consumption on the input sided in Table J1. Due to the displaced marginal power production, avoided emissions also occur on the output side.

The database, on which the environmental production declaration for marginal district heat consumption is based, has not yet been verified. Therefore, the data should be interpreted with some reservations (Duhn, 2006b).

Appendix K: Natural gas based CHP production

Natural gas based CHP production is avoided in the scenarios involving use of biomass for CHP production displacing natural gas as fuel. The average electricity efficiency and overall efficiency for the decentralised natural gas based CHP plants considered[11] is estimated to be 36 % and 87 %, respectively. The estimate is based on 2005 production data for decentralised plants in Denmark given in Energistyrelsen (2006).

Emissions are estimated based on emission data of Energistyrelsen et al. (2005) for different types of decentralised natural gas CHP plants: Gas engines, single cycle gas turbines and combined cycle gas turbines. Emissions for an average natural gas based CHP plant are estimated as a weighted average depending on the distribution between the different types of plants in the target group of plants identified. The estimation and resulting inventory data are presented in Table K1.

The inventory data applied for natural gas based CHP production are given in Table M1. The estimation of emissions and by-products for an average decentralised natural gas based CHP plant is presented in Table M2.

Table K1: Inventory data for decentralised natural gas based CHP production.

Decentralised natural gas based CHP production		**Substance**	**Unit**	**Quantity**
Inputs	Fuel	Natural gas	GJ	1
Outputs	Products[a]	Power, net	GJ	0.36
		Heat, net	GJ	0.51
	Emissions to air[b]	CO_2[c]	kg	57.12
		NO_x	kg	0.14
		CH_4	kg	0.24
		N_2O	kg	0.0013
		Particles	mg	1845
		Ashes	kg	0
		SO_2	kg	0

[a] Based on an average net electricity efficiency of 36 % and average overall efficiency of 87 % estimated for the group of decentralised natural gas based CHP plants considered. The estimate is based on 2005 production data for the decentralised plants in Denmark. Source Energistyrelsen (2006).
[b] Emissions for average decentralised natural gas fired CHP plant (see estimation in Table K2).
Source: Energistyrelsen et al. (2005).
[c] Source: Energistyrelsen (2005a).

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[11] The average energy efficiencies estimated for the existing Danish decentralised natural gas based CHP plants which are in the heat capacity range feasible for biomass CHP production and which are at the same time likely to expire within a 20 year perspective.

Table K2: Estimation of inventory data for average decentralised natural gas based CHP plant.

		Unit	**Gas turbine combined cycle**	**Gas turbine single cycle**	**Gas engines**		**Weighted average**
Plant data	Natural gas consumption in 2005[a]	TJ/y	3015	4432	5151		
	Weight[b]		**0.24**	**0.35**	**0.41**		
	Generating capacity	MWe	10-100	5-40.	0.5-16.	1-5.	
Emissions and bi-products[c]	**SO_2**	kg/GJ fuel			0		**0**
	NO_x	kg/GJ fuel	<0.05	0.12	0,15-0.20	0.17	**0.14**
	CH_4	kg/GJ fuel	0.005.	0.0015		0.26-0.58	**0.24**
	N_2O	kg/GJ fuel		0.0022		0.0013	**0.0013**
	Particles	mg/GJ fuel		0	0-6000	0-3000.	**1845**
	Ashes	kg/GJ fuel		0			**0**
	Other residuals	kg/GJ fuel		0	0		**0**

[a] Natural gas consumption within natural gas fired CHP plants in the group considered. Source: Energistyrelsen (2006).

[b] Weight according to natural gas consumption.

[c] Source: Energistyrelsen et al. (2005). Emissions data for technologies in 2004/2005 is assumed representative for the existing natural gas fired CHP plants. The high end in the emission range given for NO_x, CH_4 and particle emissions for 2004 technology level is applied in order to approximate the assumed generally lower technology level of existing decentralised natural gas fired plants.

Appendix L: Natural gas and oil based heat production

Table L1: Natural gas based heat production at industrial boiler.

Natural gas based heat production, Industrial boiler		**Substance**	**Unit**	**Quantity**
Inputs	Fuel	Natural gas	GJ	1
Outputs	Products[a]	Heat, net	GJ	0.95
	Emissions to air	CO_2[b]	kg	57.12
		NO_x[c]	kg	0.055
		CH_4[d]	kg	0.24
		N_2O[d]	kg	0.0013
		Particles[c]	g	0.91
		SO_2[d]	kg	0

[a] Typical average heat efficiency of 95 % is applied. Source: Andreasen (2007).
[b] Source: Energistyrelsen (2005a).
[c] Based on emission measurements performed for natural boilers at Daka Randers in 2006. Source: Andreasen (2007).
[d] Average emission data for decentralised natural gas CHP plants applied. Source: Energistyrelsen et al. (2005).

For oil based heat production at an industrial boiler, the typical average heat efficiency can be assumed to be equal to the heat efficiency for animal fat based heat production, i.e. approximately 89 %. Boilers dimensioned for animal fat incineration will in practice also be capable of using fuel oil, in addition to gas oil (diesel oil). Since fuel oil is less expensive compared to gas oil, animal fat can be expected to substitute fuel oil at the given industrial boilers (Andreasen, 2007).

Due to the fact that the impact assessment in the present LCA focuses on green house gas emissions and fossil resource consumption, only CO_2 emissions are included in the inventory data for oil based heat production (see Table L2).

Table L2: Oil based heat production at industrial boiler.

Oil based heat production, Industrial boiler		**Substance**	**Unit**	**Quantity**
Inputs	Fuel	Fuel oil	GJ	1
Outputs	Products[a]	Heat, net	GJ	0.89
	Emissions to air	CO_2[b]	kg	78

[a] Typical average heat efficiency of 89 % is applied. Source: Andreasen (2007).
[b] Source: Energistyrelsen (2005a).

Appendix M: Heat production from glycerine

The inventory data applied for heat production based on animal fat given in Table M1. Identical inventory data are assumed for heat production based on the fat constituting the distillation residue from the esterification process. This is a reasonable assumption (Andreasen, 2007).

Table M1: Heat production based on animal fat at industrial boiler.

Animal fat based heat production, Industrial boiler		**Substance**	**Unit**	**Quantity**
Inputs	Fuel	Animal fat	GJ	1
Outputs	Products[a]	Heat, net	GJ	0.89
	Emissions to air	CO_2[b]	kg	0
		NO_x[c]	kg	0.086
		CH_4[b]	kg	0
		N_2O[b]	kg	0
		Particles[c]	g	0.0067
		SO_2[d]	kg	0

[a] Source: Andreasen (2007).

[b] Green house gas emissions, i.e. CO_2, CH_4 and N_2O, are assumed zero since animal fat is considered CO_2-neutral.

[c] Based on emission measurements performed for natural boilers at Daka Randers in 2006. Source: Andreasen (2007).

[d] SO_2 emissions are assumed zero, due to a negligible sulphur content in animal fat.

For glycerin based heat production at an industrial boiler, the heat efficiency is approximately 20 % lower than for an industrial natural gas fired boiler, i.e. approximately 76 % ($0.80 \cdot 0.95 = 0.76$) (Andreasen, 2007). Same emission data as for animal fat based heat production is assumed.

Appendix N: Biomass based CHP production

Grate firing of straw at decentralised CHP plants

Power and heat production data for decentralised straw based CHP production is based on an electricity efficiency of 25 % and an overall efficiency of 90 % for an average decentralised straw fired CHP plant.

Due to the low sulphur content in straw, separate straw fired CHP plants are normally not equipped with dedicated desulphurisation equipment[12]. In addition, separate straw fired CHP plants are typically not equipped with de-NO_x-installations (Sander, 2006). The reason is most likely lower levels of NO_x generated during combustion, due to the lower combustion temperatures compared to a coal fired plant. Based on the differences in emission control, emission levels of separate straw fired CHP plants will differ from the emission levels of suspension firing straw at central coal CHP plants. Data for Masnedø CHP plant which is primarily straw fired are used as reference. Table N1 presents the inventory data applied.

Table N1: Inventory data for decentralised straw based CHP production.

Decentralised straw based CHP production		**Substance**	**Unit**	**Quantity**
Inputs	Primary fuel	Straw	GJ	14.5
	Supplemental fuel	Diesel oil[a]	GJ	0.0065
Outputs	Products[b]	Power, net	GJ	3.625
		Heat, net	GJ	9.425
	By-products[c]	Fly ash (deposit)	kg	8.3
		Slag (return to farmland)	kg	54
	Emissions to air (after treatment)	CO_2 (fossil)[d]	kg	0.48
		SO_2	kg	0.68
		NO_x	kg	1.9
		CO	kg	0.91
		HCl	kg	0.67
		N_2O	kg	0.02
		Dioxin	ug	0.32

[a] Diesel oil consumption on energy basis is estimated based on a given consumption of 75 litre diesel oil per 1 ton straw LCA Food (2006). A density of 0.84 kg/litre and a LHV of 42.7 GJ/ton is applied. Source: Energistyrelsen (2005a).

[b] Power and heat production is estimated based on a yearly net electricity efficiency of 25 % and overall net efficiency of 90 % for an estimated average decentralised straw based CHP plant.

[c] Slag is returned to agricultural land and used as fertiliser. Phosphor (P): 0.8 -2.1% (w/w), sulphur (S): 0.1 - 0.7% (w/w) calcium (Ca): 6-13% (w/w) nitrogen: 0.05 - 0.08 (w/w). Fly ash is deposited due to a high content of heavy metals (Videncenter for halm og flisfyring, 1999b). Avoided environmental exchanges resulting from by-product reuse are not included.

[d] CO_2 emission from diesel oil combustion. Estimated based on a CO_2 content of 74 kg CO_2/GJ diesel oil. Source: Energistyrelsen (2005a).

The data for supplemental fuel use, by-products and emissions to air are refer to straw fired CHP production at Masnedø CHP plant in 1999. The plant is dimensioned to 10 MW electricity and 23 MJ heat/sec and is primarily fired with straw (about 40.000 t/year). The plant is equipped with electrical filter for reduction of fly ash emission but no desulphurisation or de-NOx installation has been implemented.

Source: LCA Food (2006).

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[12] However, if flue gas condensation is installed this can function as desulphurisation device (Friborg, 2006).

Willow wood gasification and combustion at decentralised plants

Willow wood gasification takes place in the reference scenarios where willow wood is utilized for natural gas substitution in the energy sector. Willow wood chips gasification is assumed at decentralised natural gas based CHP units with subsequent firing of the producer gas at the existing plants. The technology of two-staged gasification is assumed applied.

Producer gas from wood gasification can flexibly be co-fired with natural gas in shares up to 100 % of the gas fuel mix. 5 % of the LHV of wood can be expected to be lost as heat during gasification and additionally 1.8 % loss in power efficiency due to power consumption when handling the willow wood chips (Henriksen, 2006).

The power and heat production per GJ wood is estimated based on the energy efficiencies estimated for the average decentralised natural gas CHP plant. Based on the assumed heat loss during gasification, the power and heat production is estimated to be 5 % lower per GJ wood compared to average decentralised natural gas fired CHP unit. Regarding emissions and by-products, data for staged gasification of wood chips given in Energistyrelsen et al. (2005) are referred to.

The inventory data for the gasification of willow wood are given in Table N2.

Table N2: Inventory data for willow wood gasification and subsequent CHP production at decentralised natural gas based plants

Willow wood gasification		**Substance**	**Unit**	**Quantity**
Inputs	Fuel	Willow wood chips (50 % W/W)	GJ	1
Outputs	Products[a]	Power, net	GJ	0.32
		Heat, net	GJ	0.48
	Air emissions and by-products[b]	NO_x	kg	0.1
		SO_x	kg	0
		Particles	mg	360
		Ashes (return to farmland)	kg	0.25

[a] Power and heat production per GJ wood is estimated based on an expected 5 % loss in LHV during two-staged gasification and additional loss of 1.8 % of the power efficiency. Source: Henriksen (2006).

[b] Data are for down-draft staged gasification system including a gas engine. The data are given are identical for 2004, 2010-25 and 2020-2030 technology level. Source: Energistyrelsen et al. (2005). The emission data given are identical for technology level in 2004 and expected technology level in 2010-15 and 2020-2030.

Waste water emissions given in the form of NH_4 condensate are excluded from the inventory since waste water emissions from CHP production processes are not included in the LCA.

No drying of the willow prior to gasification is assumed. Drying might be required, but the energy consumption associated with such drying process is assumed very limited and thus acceptable to exclude.

Willow wood pellet processing

Wood pellet processing is included in the scenarios which involve utilisation of willow wood for coal substitution in the energy sector. It is assumed that willow wood chips are processed into pellets prior to suspension firing in combination with coal at the central coal based CHP plants.

Power and steam is consumed for drying, crushing and pressing in the wood pellet processing.
Based on data for traditional forest wood pellet processing, estimates for willow wood pellet processing have been made.

Due to differences in content of willow wood chips compared to other wood chips, relatively larger power consumption is expected for pressing the wood dust into pellets. Steam consumption similar to the steam consumption for forest wood pellets can be expected for drying of willow wood pellets (Poulsen, 2006). Inventory data for willow wood pellet processing is given in Table N3.

Table N3: Inventory data for willow wood pellet processing

		Substance	**Unit**	**Quantity**
Inputs	Raw material	Willow wood chips (50 % w/w)	GJ	1.00
	Crushing, drying and pelleting	Power[a]	GJ	0.040
	Drying	Steam[b]	GJ	0.0067
Outputs	Product	Wood pellets (10 % w/w)	GJ	1.00

[a] The power consumption for willow wood pellet processing is assumed to be similar to the typical power consumption for straw pellet processing of 0.040 GJ/GJ straw. Source: (Sander, 2006).
In comparison, the typical power consumption for forest wood pellet processing is 0.016 GJ/GJ wood chips.

[b] 25 % higher steam consumption for drying of willow wood chips is assumed compared to drying of other wood chips. This is based on the fact that willow wood has a water content of 55-58 % from harvest while, forest wood chips has a water content of 35-55 % (Videnscenter for halm- og flisfyring, 1999b).
The steam will most in most cases be produced in a natural gas fired boiler at the pellet processing plant.
Source: Poulsen (2006).

Appendix O: Environmental impact potentials

Results regarding acidification, nutrient enrichment and photochemical ozone formation potential are given in Table O1 and O2. Positive values express net induced impact potentials and correspondingly, negative values express net avoided impact potentials.

Table O1: Environmental impact potentials on characterisation level.

Environmental impact potentials **Normalisation level**		**Acidification**	**Nutrient enrichment**	**Photochemical ozone formation**
		PE	PE	PE
1A	Maize silage based biogas for CHP	-3.4E-01	6.1E-01	-2.0E-02
1B	Maize silage based biogas for transport	-3.5E-01	6.7E-01	-9.2E-01
2A	Manure based biogas for CHP	-4.8E-01	-3.9E-01	-2.6E-02
2B	Manure based biogas for transport	-4.9E-01	-3.3E-01	-9.3E-01
3A	Rapeseed based biodiesel (straw left on field)	1.9E-01	1.8E+00	-2.1E-01
3B	Rapeseed based biodiesel (straw incinerated)	1.8E-01	1.8E+00	-2.2E-01
4	1st generation bioethanol from maize kernels	-1.2E-02	1.0E+00	-3.7E-01
5	2nd generation bioethanol from whole-crop maize	-2.0E-01	3.1E-01	-6.2E-01
6	Willow for CHP	-3.3E-01	-1.0E-02	-4.6E-02

Note: eq.: equivalents.

Table O2: Normalised environmental impact potentials.

Environmental impact potentials **Characterisation level**		**Acidification**	**Nutrient enrichment**	**Photochemical ozone formation**
		kg SO_2-eq.	kg NO_3-eq.	kg Ethene-eq.
1A	Maize silage based biogas for CHP	-25.2	73.1	-0.5
1B	Maize silage based biogas for transport	-26.0	80.0	-22.9
2A	Manure based biogas for CHP	-35.7	-46.6	-0.7
2B	Manure based biogas for transport	-36.4	-39.4	-23.3
3A	Rapeseed based biodiesel (straw left on field)	14.3	215.1	-5.2
3B	Rapeseed based biodiesel (straw incinerated)	13.6	212.4	-5.5
4	1st generation bioethanol from maize kernels	-0.9	120.7	-9.3
5	2nd generation bioethanol from whole-crop maize	-15.1	36.9	-15.6
6	Willow for CHP	-24.3	-1.2	-1.1

Note: PE: Person Equivalents.

Appendix P: Models in Gabi4 LCA software

CD with Gabi-model to be inserted when the report is sent to review.