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Abstract

The purpose of this study is to carry out updated and developed life cycle assessments of biofuels produced and used in Sweden today. The focuses are on making the assessments as relevant and transparent as possible and to identify hot spots which have significant impacts on the environmental performance of the specific biofuel production chains. The study includes sensitivity analyses showing the impact on changed future conditions. The results should be seen as current and average environmental performance based on updated calculation methods. Thus individual systems developed by specific companies may have somewhat different performances. The biofuels analysed are ethanol from wheat, sugar beet and sugar cane (imported from Brazil), RME from rapeseed, biogas from sugar beet, ley crops, maize and organic residues, such as municipal waste, food industry waste and liquid manure. The study also includes co-production of ethanol and biogas from wheat. Final use in both light and heavy duty vehicles, and related emissions, are assessed. Environmental impact categories considered are climate change, eutrophication, acidification, photochemical oxidants, particles and energy balances. The calculations include emissions from technical systems, e.g. energy input in various operations and processes, and biogenic emissions of nitrous oxide and carbon dioxide from direct land use changes (LUC). The potential risk of indirect land use changes (ILUC) is also assessed. By-products are included by three different calculation methods, system expansion, energy allocation and economic allocation. The results are presented per MJ biofuel, but the alternative functional unit per hectare cropland is also used regarding the greenhouse gas performance of crop-based biofuels. Finally, estimations are carried out regarding the current environmental performance of the current various biofuel systems based on system expansion, recommended by the ISO-standardisation of LCA, and energy allocation, utilised in the standardisation of biofuels within the EU's Renewable Energy Directive (RED).

Keywords

Biofuels, life cycle assessment, environmental aspects, Sweden

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Foreword

This report was initiated by the Swedish Gas Centre (SGC), which has also served as coordinator for the project. Funding, which we wish herewith to acknowledge, has been received from AGA Gas AB, Ageratec, Swedish Waste Management [Avfall Sverige], BioAlcohol Fuel Foundation (BAFF), Energigårdarna, E. ON Gas Sweden AB, Flotech/Green Lane Biogas, Fordonsgas Sverige, Airport Coaches [Flygbussarna], Göteborg Energi AB, Kraftringen Produktion AB, LRF, Lantmännen Energi, Läckeby Water AB, Malmberg Water AB, Norups Gård, Perstorp Bioproducts, Preem Petroleum, SEKAB, SL, Stockholm Gas, Svensk Biogas AB, Svensk Raps, Öresundskraft and the Swedish Energy Agency [Energimyndigheten].

A reference group, linked to the project has contributed with valuable and constructive comments and viewpoints during the course of the work. We would especially like to thank Kristina Birath (Swedish Association of Green Motorists [Gröna Bilister]), Johan Biärsjö (Svensk Raps), Mats Björsell (Swedish Environmental Protection Agency [Naturvårdsverket]), Maria Edlund (SEKAB), Tula Ekengren (Fordonsgas Sverige), Sven-Olov Ericson (Ministry of Enterprise, Energy and Communications [Näringsdepartementet]), Håkan Eriksson (E.ON), Sören Eriksson (Preem Petroleum), Linus Hagberg (IVL), Erik Herland (LRF), Anders Hultgren (Perstorp), Olle Hådell (the Swedish Transport Administration [Vägverket]), Sofie Karlsson (Lantmännen), Lars-Gunnar Lindfors (IVL), Marita Linné (Biomil), Lena Nordgren (BAFF), Claes Ramel (Energigårdarna), Jan Svensson (Airport Coaches [Flygbussarna]), Nanna Wikholm (Swedish Environmental Protection Agency [Naturvårdsverket]), Eric Zinn (Göteborg Energi), Andreas Öman (IVL) and finally Mattias Svensson (SGC, coordinator).

A critical review of the report has been made by IVL (see Appendix).

Lund, May 2010

The authors

Table of contents

Summary *(extended)*

All biofuels produced and used in Sweden today are assumed to lead to significant climate benefits compared to fossil fuels when also direct land use change is included. The reduction of greenhouse gas emissions compared to fossil fuels is estimated to be between 67% and 148% depending on the fuel chain, but there are also wide variations within each system due to local conditions and calculation methodology. Today's production is not expected to cause any significant negative net effect of indirect land use changes outside of Sweden.

Direct land use changes are assumed to take place on one fourth of agricultural land due to the cultivation of annual crops for biofuels taking place on previous grassland. This assumption is probably an overestimate rather than an underestimate. Today, approximately 5% of Swedish cropland is used for biofuel production. For future expansion of biofuels from annual crops, the share of grassland used may increase, resulting in increased biogenic emissions of greenhouse gases. This may, on the other hand, be countered by various measures to increase efficiency throughout the production chain. An example is the implementation of nitrous oxide cleaning equipment in the production of mineral nitrogen fertilisers that can increase the climate benefits several percentages.

Today not all agricultural land in Sweden is used for crop cultivation and the intensity of current crop production is also expected to increase, particularly for the cultivation of ley crops. This allows some expansion of domestic biofuel production from field crops without negative indirect land use change effects (at a constant food and feed production), provided, however, that the rate of expansion is balanced so that these potential dynamic effects are exploited. Today's combined production of biofuel and protein cattle feed can also lead to positive indirect land use change effects by a decreased use of imported soy feed.

In the base case, all calculations are based on the method called system expansion whereby the indirect effects of the by-products are included, as recommended by the ISO standard for life cycle assessments (LCA). The variation in the result is also shown for different methods to allocate the emissions between biofuels and by-products according to their energy content or economic value. Crop residues, such as straw, are excluded in the base cases but included in alternative calculations. As reference, petrol and diesel are used, which have the same greenhouse gas emissions of 83.8 g CO_2 per MJ.

Wheat-based ethanol is considered to lead to a climate benefit of 71% compared to fossil fuel, when system expansion is applied (excluding straw). Today, the by-product, distillers waste, is used as feed and the domestic market is estimated to be equivalent to 1-2 TWh of ethanol. This in turn corresponds to 2.5 to 5 % of the current petrol consumption in Sweden (about 42 TWh of petrol and a total of 84 TWh including diesel). In addition, there is an export market, for example within the EU, where the total market for distillers waste used as feed is also estimated to correspond to an ethanol production of 5% of Europe's current petrol consumption. When energy allocation is applied climate benefits of today's grain-based ethanol is 63% (excluding straw).

An alternative to using distillers waste as protein feed is to use it for biogas production. The climate benefits of combined ethanol and biogas production from grain is estimated to be 67% when system expansion is applied, i.e. when the residues of the digestion are assumed to replace mineral fertilisers.

Ethanol production from sugar beet is considered to have a climate benefit of 80 % under today's conditions, and of 74% using energy allocation. If all land used for sugar-beet production in Sweden were used only to produce ethanol, around 2 TWh of ethanol could be produced annually. Ethanol produced from sugar cane currently imported from Brazil is expected to generate a climate benefit of 79%, and of 77% if energy allocation is applied. How the climate benefits are altered with continued expansion depends largely on the type of land that would then be used, i.e. low productive pasture, cultivated pasture and/or open cropland, and how much of this increased land use is compensated for by increased grazing and cropping intensity. When ethanol is used in heavy duty vehicles additives are required (ED95) which produce a climate load of just less than 4% of that of fossil fuel.

The climate benefit of today's RME is estimated to be 68% compared to fossil fuels. One important parameter is how much soy meal can be replaced by the by-product rapeseed meal and, if this share decreases or increases by 25%, the climate benefits change from 64% to 72%. When energy allocation is applied the climate benefit is 53% (excluding straw). The maximum production of RME from rapeseed grown in Sweden is expected to be around 1 TWh per year based on the possible increase of the area of land under oilseed cultivation due to restrictions in crop rotation. The production may increase with imported rapeseed or rapeseed oil.

Biogas from ley crops, sugar beets (including tops) and maize are assessed in the current situation to provide a climate benefit of 86%, 85% and 75%, respectively, compared to fossil fuels. If the share of the cultivation on former grassland increases in the future, this does not affect the climate performance of biogas based on ley crops. Another important parameter is the losses of methane in the production and upgrading of biogas and if this increases from the assumed 0.5% to 1.5% the climate benefits are reduced by an equivalent of 5 percentage points. When energy allocation is applied using current conditions, the climate benefit will be 68%, 74% and 61% for biogas from ley crops, sugar beet and maize, respectively. If the maximum potential of land in Sweden used for producing sugar beets is used solely for biogas production, it was estimated that around 3.5 TWh of biogas per year could be produced. The agricultural land suitable for maize production is also expected to be limited but here no quantitative estimations were made.

If residues such as manure, waste from food industries and organic household waste are used for biogas production they are assessed to provide a climate benefit of 148%, 119% and 103%, respectively, compared to fossil fuels. The reason that the climate benefit exceeds 100% is the indirect effects obtained through increased recycling of nutrients reducing the need for fertilisers, and the increased recycling of organic matter to the soils etc.

In the case of manure, the main indirect benefit is that the methane and nitrous oxide leakage from traditional manure storage decreases. However, there is considerable uncertainty as to how big this benefit is, since Danish studies and also the IPCC's methodology result in increased indirect benefits while Swedish measurements indicate a decreased indirect benefit. If these different bases for calculation are applied, the climate benefits of manure-based biogas are changed to 176% and 122%, respectively, compared to fossil fuels. This indirect climate benefit in terms of reduced leakage of methane and nitrous oxide from manure storage decreases from south to north of Sweden, since it is temperature-dependent.

The amount of biogas that can be produced from food waste and household waste is estimated to be about 1 TWh each per year, while the corresponding amount from manure is estimated to be about 3 TWh per year. When local biogas distribution grids are built, this will result in a slightly increased contribution of greenhouse gases, about 1%, compared to the load from fossil fuels. The energy input is also equivalent to about 1% of the energy content in the biogas.

When climate benefits of biofuels based on cultivated crops are expressed per hectare and year, which is an alternative to the functional unit per MJ of fuel, the ranking slightly changes. The best climate benefit per hectare and year comes from biogas produced from sugar beet, including tops (12-14 tonnes of CO_2-equivalents using energy allocation and system expansion, respectively), followed by biogas from maize and ethanol from sugar beet (6-7 tonnes), biogas from ley crops (5-6 tonnes), ethanol and biogas from wheat (4-5 tonnes), ethanol from wheat (3-4 tonnes) and finally RME (2-3 tonnes of CO_2-equivalents per hectare and year).

In addition to climate change the contribution to eutrophication is also an important aspect to be considered in the case of biofuels from crops and agricultural residues. When system expansion is applied the contribution to eutrophication for ethanol from wheat and biogas from waste products is almost equal. The reason for this is that the ethanol gives rise to an indirect positive effect when the distillers waste replaces other feed crops, while the biogas gives rise to a negative indirect effect when the digestate replaces mineral fertilisers, resulting in slightly increased nitrogen losses. Ethanol from sugar beet is even better concerning eutrophication due to a relatively high output of biofuel per hectare in combination with indirect benefits when the by-product pulp that replaces grain is used for feed. The contribution to eutrophication is slightly higher for biogas based on sugar beets or ley crops and ethanol from sugar cane, and even higher for biogas from maize as well as biogas and ethanol from wheat. RME gives the highest contribution to eutrophication.

The contribution to eutrophication from emissions from final use in heavy duty vehicles is considered to be the same order of magnitude as that in the production of ethanol from wheat and biogas from waste residues. For other biofuels the emissions from fuel production are at least twice as high as those from final use in heavy duty vehicles. Emissions from light duty vehicles that contribute to eutrophication are much lower and usually they result in only one or a few percent of those from the fuel production. An exception is RME where emissions from the vehicle represent roughly one third. If energy allocation is applied as the calculation method the ranking between the contribution to eutrophication of biofuels is changed since no indirect environmental effects are included. In this case, biogas from residues performs much better than all other biofuels, followed by biogas from ley crops and sugar beets where also the nitrogen-rich tops and leaves are harvested and then ethanol from sugar cane and sugar beet. The highest contribution to eutrophication comes from RME, while biogas from maize and ethanol and biogas from wheat make a slightly lower contribution.

The production system for RME and ethanol from wheat contributes the least to acidification, followed by ethanol from sugar beets. The reason for this is the indirect benefits accruing when soy meal and grain used as feed are replaced by rape-seed meal and distillers waste, respectively. Biogas from residues and crops makes a higher contribution to acidification, mainly due to increased emissions of ammonia when the digestate replaces mineral fertilisers. The highest contribution comes from ethanol produced from sugar cane; this is mainly due to the boat transport across the Atlantic for which fuel oil containing sulphur is used. When energy allocation is applied the variation between the different biofuels becomes much smaller, with the exception of ethanol from sugar cane that still contributes more than the others.

The emissions contributing to acidification from light duty vehicles are relatively low and are often about one-tenth of those from the production of the fuel, with some variation. One exception is RME for which vehicle emissions are significantly higher than from the fuel production. The emissions contributing to acidification from heavy duty vehicles are almost always higher than from the fuel production. The lowest emissions come from the vehicles running on biogas, followed by ethanol vehicles, while heavy duty vehicles running on RME give the highest emissions.

Emissions contributing to the photochemical ozone creation potential (for example ground-level ozone) are comparable for the different production systems, with slightly higher emissions for the biogas systems. One exception is ethanol from sugar cane that makes about a ten times higher contribution, mainly due to the boat transport across the Atlantic. The emissions from heavy duty vehicles are of the same order of magnitude as the fuel production for biogas and RME, and 2-3 times higher than the production of ethanol. The emissions from light duty vehicles are about the same, independent of the fuel used but the level is often 5-10 times higher than the emissions from the fuel production.

The biogas production systems have the lowest emissions of particles and RME makes the highest contribution, with ethanol intermediate, when system expansion is applied. When energy allocation is applied the differences become smaller. The emissions of particles from the production of the fuel are normally higher than from the final use of the fuels in both light and heavy duty vehicles.

An exception is RME for which the use in vehicles gives roughly the same emissions as in the production of the fuel. Vehicles run on biogas are estimated to give somewhat lower emissions of particles than vehicles run on ethanol.

Regarding energy efficiency in various production systems for biofuels, expressed as the ratio of biofuel yield and energy input in terms of primary energy, this is about 5-6 for RME, biogas from waste and ethanol from sugar cane, when system expansion is applied. For other biofuel systems the energy balance is about 2 to 3. When energy allocation is applied the differences in energy balance are smaller and all systems are between 2 and 4, with the exception of ethanol from sugar cane, which is above 5.

1. Background

There is currently an urgent need to update and complement the life cycle assessments (LCA) of biofuels that are produced and used in Sweden (Linné, 2007). Most existing LCAs were made between five and ten years ago and, furthermore, were made using different assumptions in the calculations. There are some newer LCAs but these are often restricted to include only greenhouse gases or do not include the end-use in vehicles. At the European level there are often references to the so-called Well-to-Wheel studies carried out by Concawe, Eucar and JRC (JRC, 2007), which include several different fuel systems, fossil as well as biofuel. These studies focus on greenhouse gases, energy balances and costs, i.e. no other forms of pollution, and are of a more general character, where national conditions are not fully taken into account.

Another aspect that has received increased attention is the possible direct and indirect impacts of the change of land use due to the increased production of biofuels. Within the EU work is at present being carried out to present a calculation methodology within the Renewable Energy Directive, RED, to assess the climate benefit of biofuels compared to fossil fuels and in this methodology direct land use impacts are included. In previous LCAs of biofuels this aspect was not included. There is, in addition, an ongoing discussion about also including possible indirect effects beyond national borders (or the boundaries of the EU within the RED), but due to great uncertainties concerning these possible aspects (which can be both positive and negative) they are currently not included.

2. Objective

The objective of this project is to make updated and developed life cycle assessments of biogas, ethanol and RME as fuels based on current Swedish conditions. Focus is on making the comparisons as transparent and relevant as possible and to highlight the parts of the life cycle which significantly affects the environmental performance of each biofuel. In the study, sensitivity analyses are also made, showing the effects of, for instance, future changes in production conditions. The results of the study should be interpreted as the current and average environmental performance found for each biofuel, using the calculation methods developed and used today, i.e. there may be some differences between specific production systems that different companies use today.

3. Method and limitations

The calculations in this study follow the ISO standard for life cycle assessment, i.e. ISO 14 044 (ISO, 2006). The general conditions for the calculations are described below, while specific conditions for individual biofuel systems are listed in the Appendix or alternatively in the referenced literature.

3.1. The systems analysed

In the present study the following biofuel chains, based on biomass produced in Sweden, (apart from ethanol made from sugar cane) are included:
Ethanol from wheat.
Ethanol from sugar beets.
Ethanol and biogas from wheat.
Biogas from waste (food industry and household).
Biogas from manure.
Biogas from crops (sugar beets, ley crops and maize).
RME from rapeseed.
Ethanol from sugar cane *(Imported from Brazil).*

The use of biofuel is to be used in both light as well as heavy duty vehicles. The results will be compared to fossil fuels such as petrol and diesel regarding climate benefit.

3.2. Methodology

3.2.1 Functional unit

The functional unit (FU) of this study will be: ”environmental impact per MJ fuel”.

There are other options, such as “environmental impact per kilometre of transport service”. One advantage of this FU is that differences in fuel efficiency of different vehicles are also included and considered. A disadvantage is, however, that the uncertainty in the results increases when, for instance, improvements in the fuel efficiency of different vehicles are implemented rapidly and new technologies are introduced, such as electric hybrid technology. In addition, differences in vehicle fuel efficiency of different vehicles with regard to different fuels, change with technological development. By presenting the results in MJ of fuel the reader can convert these into per kilometre of transport service for the specific vehicles in question. We believe that the usefulness of the study is increased by selecting this FU.

The results regarding energy balance and climate benefit are additionally presented per hectare for fuels based on crops in order to reflect the area efficiency. This functional unit is expected to become more important in the future with an increased competition of cropland for food, feed, energy, etc. In the world of LCA it is increasingly being advocated that the functional unit for biofuels per hectare and year should be used in parallel with per MJ fuel (and if possible per km transport service) (see e.g. Cherubini et al., 2009; Kim and Dale, 2009).

3.2.2 Data

Data are collected from current sources of data and studies, and are processed in order to get the best possible comparability. The aim is that the data refer to the "best available technology" (BAT) commercially available today, or the equivalent for the systems not yet built on a commercial scale. Depending on the number of existing biofuel plants and their scale-size the character of the data set varies. When only a few large facilities exist the analyses are more based on site-specific data, while more general data are used for smaller facilities existing in larger numbers. Some systems have not yet been built in Sweden. In these cases data from different preliminary studies, international data etc. are used. In other words, the nature of the data varies, giving a factor of uncertainty which is analysed in sensitivity analyses. Moreover, it is not possible to obtain data of exactly the same character for the various fuel systems since there are inherent differences in, for example, scale-size and number of units. In Table 1 a summarised description is given of the type of data used for the various systems.

Table 1. Type of data used in the analyses of the different fuel systems.

Biomass	**Biofuel**	**Nature of data**		
		Raw material	***Transformation***	***End-use***
Wheat	Ethanol	General – Processed official statistics	Mainly site-specific – Norrköping – Existing	General – Processed data – Literature studies
	Biogas	General – Processed official statistics	Mainly general – Preliminary studies	General – Processed data – Literature studies
Sugar beets	Ethanol	General – Processed official statistics	Mainly general – Preliminary studies & International	General – Processed data – Literature studies
	Biogas	General – Processed official statistics	Mainly general – Preliminary studies	General – Processed data – Literature studies
Rapeseed	RME	General – Processed official statistics	Mainly site-specific – Karlshamn & Stenungsund – Existing	General – Processed data – Literature studies
Ley crops	Biogas	General – Processed official statistics	Mainly general – Existing & Preliminary studies	General – Processed data – Literature studies
Maize	Biogas	General – Processed data - Practical cultivations	Mainly general – Preliminary studies & International	General – Processed data – Literature studies
Manure	Biogas	General – Processed data – Literature studies	Mainly general – Existing & Preliminary studies	General – Processed data – Literature studies
Waste	Biogas	General – Processed data – Literature studies	Mainly general – Existing & Preliminary studies	General – Processed data – Literature studies
Sugar cane	Ethanol	General – Literature studies	Mainly general – Brazil – Existing	General – Processed data – Literature studies

3.2.3 System boundaries and allocations

The length of the life cycle consists of the cultivation of the raw material (or alternatively the collection and handling of the waste product), the transportation of the raw material to the fuel plant, the production of the fuel and its end-use in vehicles. The distribution of the fuel is not included. However, the relevance of the energy input and emissions from the building of infrastructure for local biogas grids is assessed, for example, for linking production facilities to a common facility for upgrading. The transportation of sugar cane ethanol from Brazil to a Swedish port is included. The width of the life cycle includes all essential activities, processes and material inputs which have a significant impact on the result. Inputs consisting of buildings and other infrastructure are not included.

For biofuel systems that generate by-products a system expansion is applied where possible, i.e. when the by-products replace a clearly identified alternative product, and when life cycle inventory data (LCI-data) are obtainable for this. This means the system boundaries are expanded so that the indirect environmental benefits of the by-products are included in the analyses. With this type of system expansion it is also necessary to estimate the volumes of biofuel that can be produced before the market for the actual by-product becomes saturated. After that a new alternative product must be identified or other methods of calculation must be used. Therefore, the present study includes an estimate of the market volumes of the by-products at issue and shows under what conditions the current system expansions are relevant.

Table 2 shows the system expansions made in the present study. They are also illustrated in Figure 1 and 2. In the case of crop residues in the form of straw and tops and leaves, their use for energy purposes is today of limited extent. For this, the utilisation of crop residues is not included in the base cases except for biogas from sugar beets where tops and leaves are included ("whole-crop harvest"). In alternative calculations for biofuels from wheat, rapeseed and sugar beets (ethanol) however, the importance of also using crop residues for energy purposes is described. In these alternative calculations it is always assumed that a sufficient proportion of straw (between 40-50%) is left to maintain the fertility of the soil.

Table 2. Description of system expansions made in the present study.

Biomass	**Biofuel**	**By-product**	**Replacement product**
Wheat	Ethanol	a) distillers waste b) straw	a) soybean meal and barley[1] b) wood chips[2]
	Ethanol Biogas	a) digestate	a) mineral fertiliser[3]
Sugar beets	Ethanol	a) pulp	a) barley[4]
	Biogas	a) digestate	a) mineral fertiliser[3]
Rapeseed	RME	a) rapeseed meal b) glycerol c) straw	a) soybean meal and barley[5] b) fossil- and bio-based chemicals[6] c) wood chips[2]
Ley crops	Biogas	a) digestate	a) mineral fertiliser[3]
Maize	Biogas	a) digestate	a) mineral fertiliser[3]
Manure	Biogas	a) digestate	a) mineral fertiliser[7]
Waste	Biogas	a) digestate	a) mineral fertiliser[3]
Sugar cane	Ethanol	a) electricity b) bagasse	a) fossil electricity[8] b) biofuels[9]

[1] 1 kg distillers waste (dry matter) is replacing 0.4 kg soybean meal and 0.6 kg barley (see Appendix).

[2] 1 kg straw (dry matter) is replacing 0.9 kg wood chips (see Appendix).

[3] 1 kg nitrogen in the original raw material is replacing 0.7 kg mineral fertiliser nitrogen (equivalent of nitrogen accessible to plants including losses in the handling of digestate) and 1 kg phosphorus and potassium, respectively, in the digestate is replacing 1 kg phosphorus and potassium, respectively, in mineral fertiliser (see Appendix).

[4] 1 kg pulp (dry matter) is replacing 1 kg barley (see Appendix).

[5] 1 kg rapeseed meal (dry matter) is replacing 0.7 kg soybean meal and 0.3 kg barley (see Appendix).

[6] 1 kg glycerol is replacing 0.5 kg fossil-based and 0.5 kg bio-based chemicals (see Appendix).

[7] 1 tonne of digested manure implies a decreased demand of 0.5 kg N from the mineral fertiliser per tonne of substrate when the content of ammonium (i.e. nitrogen accessible to the plant) increases from 70% in undigested manure to 85% in digested manure while digestion of manure does not affect phosphorus and potassium (see Appendix).

[8] Excess electricity is replacing electricity based on natural gas (see Appendix).

[9] Excess bagasse is replacing other biofuels for heat production (see Appendix).

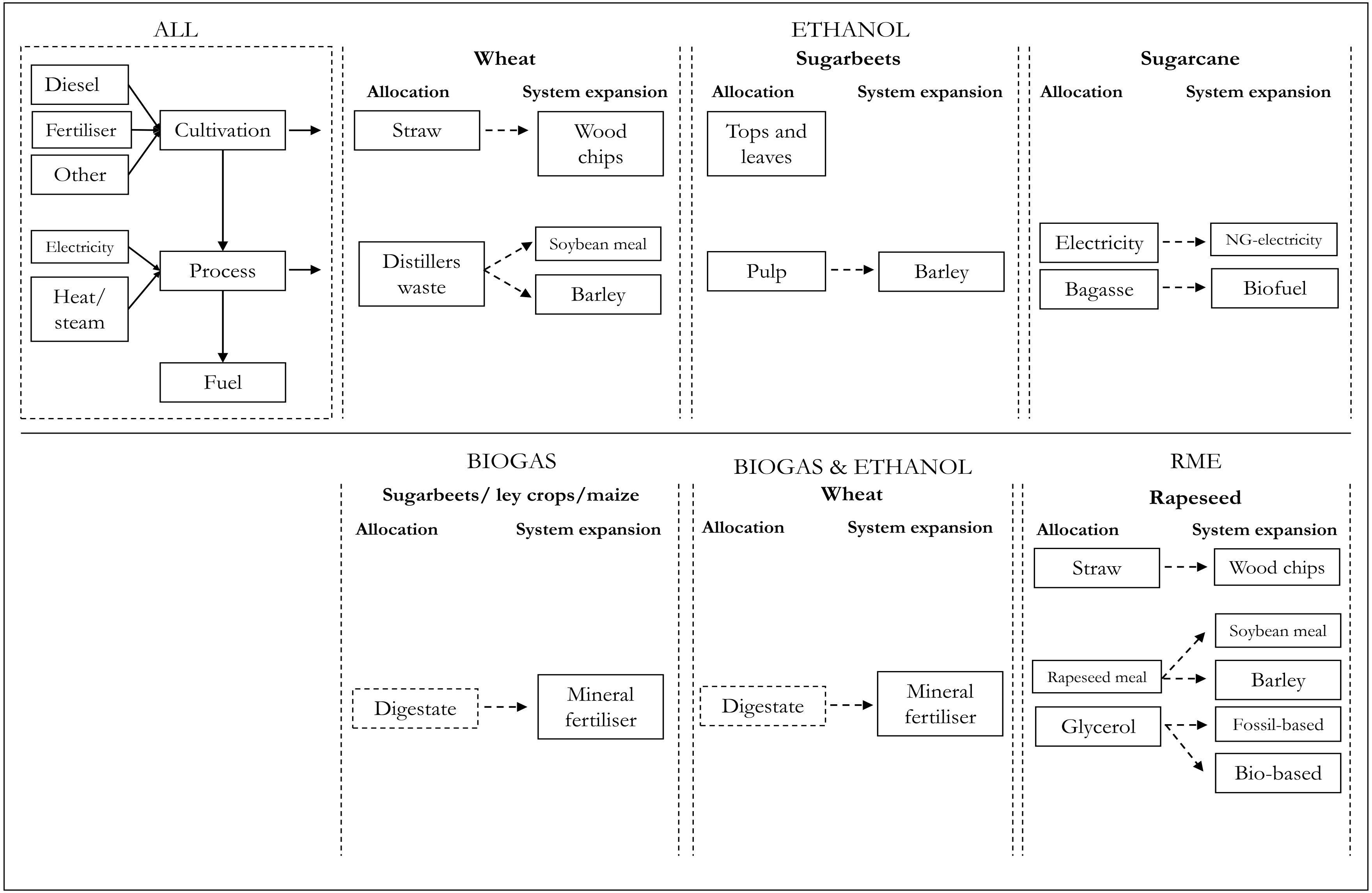

Figure 1. Flow chart of biofuel systems based on crops that are included in this study.

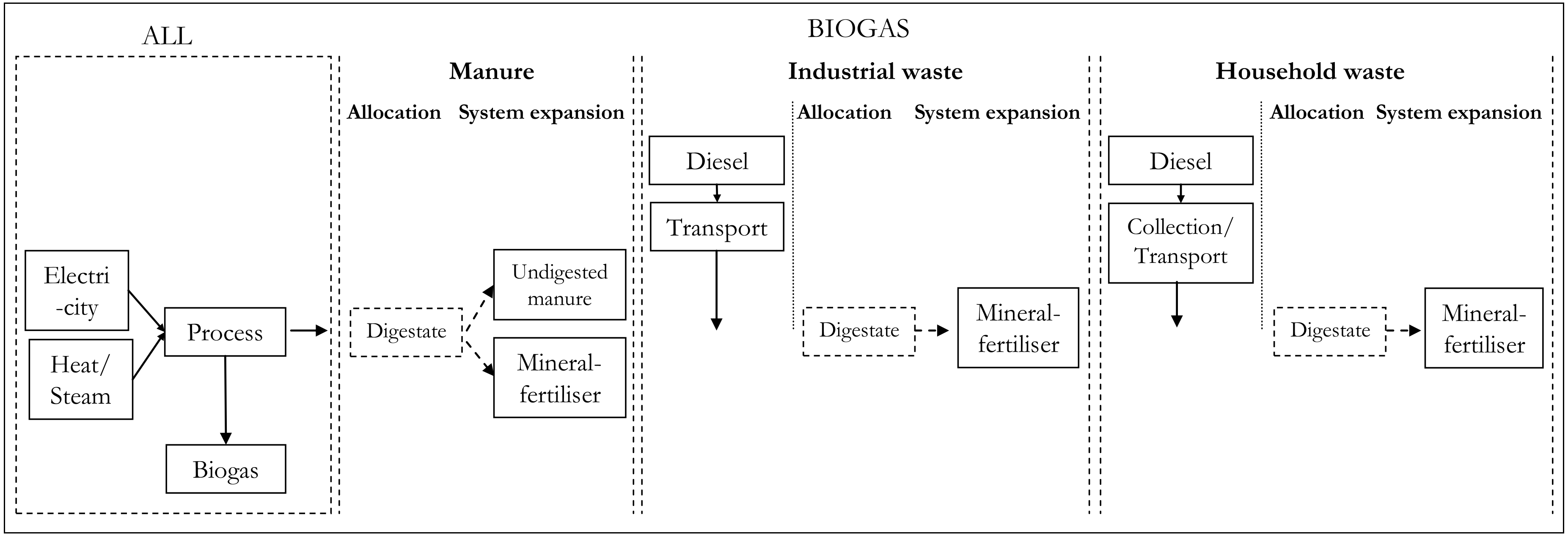

Figure 2. Flow chart of biofuel systems based on waste products that are included in this study.

In parallel with the system expansion, an allocation is also made by which the environmental impacts of the production system are divided between biofuel and by-products according to their energy content or their economic value. Moreover, the results when no allocation is made are presented, i.e. when the whole environmental impact is allocated to the biofuel. One advantage of energy allocation is that this method is constant over time. Within the RED of the EU a decision is made that energy allocation is to be used when calculating the environmental performances of biofuels. A disadvantage of energy allocation is that misleading results can be obtained if large quantities of low-grade by-products are generated in proportion to the more high-grade biofuel. For example, if straw is included as a by-product in the production of grain ethanol, the straw will bear the greatest environmental load since the amount of energy in the form of straw is greater than the amount of energy in the form of ethanol. In these cases an economic allocation is advocated instead, reflecting the value of each product. A disadvantage of economic allocation is that it changes over time as the prices of the different products vary. In RED it has been decided that only by-products from the biofuel processes are to be included through energy allocation and not by-products from cultivation (i.e. crop residues like straw) to limit the disadvantage of energy allocation discussed above. In the Appendix data for energy and economic allocation are presented.

The geographical system boundaries refer to cultivation of energy crops in southern Sweden on good cropland (and the handling and storage of waste and manure in southern Sweden). Much attention has been paid to obtain comparable levels of harvest for different crops, i.e. they are grown on equal cropland and with equal intensity of cultivation. Harvest levels may therefore be both higher in the more high-yielding areas and lower in the areas yielding less. Harvest levels and energy inputs for each crop are shown in the Appendix. Inputs in the form of electricity consists of the Swedish electricity mix (see the Appendix for emission data). Inputs in the form of fuels in the fuel plants consist of biofuels, i.e. biogas in biogas plants and forest fuels in ethanol and RME facilities (see the Appendix for emission data). Emissions of methane from biogas plants are assumed to be equivalent to 0.5% of the biogas production, based on the current best technology. It is assumed that the mineral fertiliser used is partly being produced in Western European plants (about 60%) with the current level of cleaning equipment etc, and are partly imported from countries outside of Europe (40%). This means that approximately 30% of the production of mineral fertiliser nitrogen takes place in plants with nitrous oxide cleaning in which the emissions of nitrous oxide are reduced by about 80% (see the Appendix). The emission data for vehicles are based on a compilation of literature where the input data are evaluated in terms of how well they correspond to current vehicle and emission control technology and fuel quality. The selection of emission data has been made in consultation with vehicle experts to get as correct emission levels as possible for each fuel and which correspond to current and new vehicles sold on the Swedish market today. The temporal system boundaries thus refer to modern and current technologies for the production of material inputs and cultivation methods as well as for processes for biofuel production and vehicle technologies. The fuel-cycle emissions of greenhouse gases for petrol and diesel are assumed to be the same, 83.8 g CO_2 per MJ, based on RED of the EU.

When energy crops are cultivated on cropland the alternative land use must be determined as reference in the calculations. The choice of reference affects the amount of emissions from the land in the form of carbon dioxide and nitrous oxide, called biogenic emissions. For this reason more than one type of land use reference should be included. In this study the following two different land use references are included: 1) unfertilised grassland, and 2) wheat cultivation without harvest of straw (see Appendix). These references are assessed to give a good illustration of the potential importance of the direct land use effects, i.e. both in the form of significant impact and marginal impact. In previous studies of fuel-cycle emissions of biofuels differences in biogenic emissions of carbon dioxide are usually not included, i.e. how the cultivation systems influence the content of carbon in the soil. On the other hand, biogenic emissions of nitrous oxide are normally included but usually without taking an alternative land use reference into account. The calculation methods used in this study are therefore new in the sense that biogenic emissions of carbon dioxide as well as nitrous oxide are based on the same land use reference in order to to get consistent comparisons.

In the calculation methodology being developed in the Renewable Energy Directive of the EU, it is, as previously mentioned, proposed that carbon stock changes due to changes in cultivation systems are to be included, i.e. direct land use effects, where relevant. This proposal is in turn based on the current international research on LCA of biofuels that describes the need to consider this aspect (see e.g. Kendall and Chang, 2009; Menichetti and Otto, 2009; Reijnders and Huijbregts, 2008; Tufvesson and Börjesson, 2010). In addition, biogenic emissions of nitrous oxide are to be included independently of land use reference as these emissions are usually calculated on the basis of the amount of nitrogen fertiliser applied. Hence the results of the present study are also presented using this methodology. For this an assessment has also been made of the proportions of grass-covered fields lying uncultivated for a long period of time and existing open cropland that are used for biofuel production in Sweden today, based on the land use statistics of the past five years. This assessment, however, is marred by uncertainties and is mainly to be seen as an attempt to minimise the risk of underestimating the effects of direct land changes. Another uncertainty is the large variation in the size of the carbon losses from grasslands, which among other things, depend on how long the ground has been grass-covered. Carbon stock changes are slow processes that may proceed for 30-50 years before new states of equilibrium are reached (Börjesson, 1999). If ley crop cultivation is part of a traditional crop rotation with annual crops, the differences between this grass-covered land and open cultivation regarding carbon stock changes are significantly lower than when cultivation of annual crops is started on grass-covered lands lying unused for a long period of time (where states of equilibrium have been reached). Within the RED of the EU it is stated that fallow land is always to be regarded as open cropland even if it is grass-covered, i.e. it is assumed that no carbon stock changes occur by cultivation.

In addition to the direct land use changes described above, there may also be environmental impacts from indirect land use changes, called displacement effects. In these cases it is assumed that an increased cultivation of energy crops always leads to the displacement of food or feed production, which in turn leads to land reclamation of cropland in another part of the world. There is, however, a large scientific uncertainty inherent in these possible indirect effects, both in terms of defining their scope and also in the calculation methodology to include these possible effects in different types of systems studies (see e.g. Kim and Dale, 2009; Cornelissen and Dehue, 2009). The conclusion is therefore that indirect displacement effects neither should, nor can, be included in an LCA of biofuels at present. These possible effects which are a possible result of a future rapid and extensive increase in the production of biofuels from agricultural crops, combined with increased food production, meat consumption, etc. must be handled using other methods and approaches, and also be assessed from a holistic perspective where all land use is included. For a more detailed discussion regarding this question references are made to Börjesson and Tufvesson (2010) as well as to Berndes et al. (2010). This study however, analyses how the use of Swedish cropland has changed over the past five years, and what potential dynamic effects exist in Swedish agriculture with a further increase in order to describe the relevance of taking into account indirect land use changes for Swedish-produced biofuels of today in any other potential types of studies and modelling.

3.2.4 Environmental impact categories

The emissions included in the study are: 1) carbon dioxide - fossil from fuels and biogenic from cropland (CO_2), 2) methane (CH_4), 3) nitrous oxide - from technical processes and biogenic from cropland (N_2O), 4) nitrogen oxides (NO_x), 5) ammonia (NH_3), 6) sulphur dioxide (SO_2), 7) hydrocarbons – excluding methane (HC), 8) particles and 9) nitrate (NO_3) and phosphate (PO_4) – to water.

The environmental impact categories considered are: 1) the greenhouse effect (Global Warming Potential, GWP), 2) eutrophication potential (EP), 3) acidification potential (AP), 4) formation of photochemical oxidants (Photochemical Oxidant Creation Potential, POPC), 5) particles and 6) energy balance. The characterization factors used in the conversion of separate emissions to environmental impact categories are presented in the Appendix.

In particular, the greenhouse gas balance and eutrophication potential are investigated, as shown in extra detail in the Appendix, since these two environmental effects are considered to be the most critical for biofuels today (see Börjesson and Tufvesson, 2010).

4. Results

The following chapter presents the results in terms of overall environmental impact of each biofuel system and in comparison with fossil fuels regarding climate performance. For each environmental impact category a summarised assessment of the current level of environmental impact is made based on current conditions. The underlying input data and the calculation methodology are shown in the Appendix. By way of introduction an assessment of possible limitations of the production volume for each biofuel system is presented, based on the limits in the market for by-products when system expansion is applied in the calculations and also limits on the cultivated area. In addition an analysis is made of how biofuel production leads to changes in land use, directly and indirectly.

4.1. Limitations in production volumes

According to the ISO standard for LCA (ISO, 2006), system expansion is to be applied when possible. In Figures 1 and 2 the alternative products that are assumed to be replaced by the by-products generated in each biofuel system are described. When it comes to distillers waste and rapeseed meal as protein feed and as a replacement for imported soy protein feed a previous theoretical calculation has shown that ethanol and RME equivalent of a maximum of approximately 4 TWh could be produced before this market becomes saturated in Sweden (Börjesson, 2007). Since however, there are different types of restrictions, the practical potential is assessed to be lower in the current situation. In the present study it is assessed that the market limit for distillers waste as protein feed could reach between 100,000-120,000 tonnes (DM) per year on the Swedish feed market today in terms of its protein feed quality. This volume of distillers waste represents approximately 4% of the total feed consumption of Swedish dairy cows (Emanuelson et al, 2006). By improving the quality of the distillers waste for feed, changing diets, etc. the domestic market limit is expected to increase in future. In addition, a part of the distillers waste can be used for beef cattle and pig production, corresponding to approximately 30% of the amount assessed to be of use in the dairy industry (Börjesson, 2007). In the well-to-wheel study by Concawe et al. (JRC, 2007) it is assessed that distillers waste equivalent to 15-20% of the feed consumption in the EU could be marketed before the market is saturated, i.e., their assessment is considerably higher.

In ethanol terms, the domestic market limit for distillers waste as feed is equivalent to approximately 1 to 2 TWh of ethanol, when the equivalent 4% to 8% of the total domestic feed consumption consists of distillers waste. This amount of ethanol is in turn equivalent to approximately 2.5 to 5% of the current use of petrol (which amounts to 42 TWh per year and which, together with 42 TWh of diesel, gives a total consumption of fossil fuels for road transport of 84

TWh per year). As a comparison Concawe et al. assess that ethanol equivalent to a maximum of approximately 6% of the current consumption of petrol in the EU could be produced from grain before the feed market in the EU becomes saturated (JRC, 2007). The ethanol production in the extended Agroetanol plant in Norrköping amounts to about 1.2 TWh when in full production. The distillers waste produced here can thus primarily be disposed of in Sweden but can also be exported to countries in the EU. The export potential for distillers waste as feed is assessed to be relatively large in the current situation and especially as a replacement of, for example, soy protein feed. The most likely outlet for distillers waste when not used as feed is for biogas production, which today is already taking place on a small scale in the ethanol plant of Agroetanol.

As rapeseed meal is assessed to be a protein feed of higher quality than distillers waste the admixture of this in feed could be increased (Emanuelson et al., 2006). The production capacity of RME in Sweden today is equivalent to approximately 2.3 TWh per year all in all, for which the plant of Perstorp in Stenungsund is the largest, approximately 1.7 TWh (Hultgren, 2010), followed by the plant of Lantmännen Ecobränsle in Karlshamn, with approximately 0.5 TWh (Börjesson, 2007). There are in addition a number of smaller plants in Sweden. It has been estimated that a maximum of close to 300,000 tons (DM) of rapeseed meal (including rapeseed cake) is generated from this production, most of which is generated abroad, since Perstorp imports rapeseed oil. It has been assessed that potentially approximately 70,000 tonnes (DM) can be produced in Sweden and this amount of rapeseed meal is equivalent to approximately 2% of the current total feed consumption for milk production, including recruitment (Emanuelson et al., 2006). As a comparison the admixture of rapeseed products into feed for dairy cows amounts to about 5% today. The total use of rapeseed products in feed in Swedish animal production amounts to between 250,000 and 300,000 tonnes (DM) of which approximately half is imported (Börjesson, 2007). An RME production of around 1-2 TWh per year would thus generate rapeseed meal that can be sold on the Swedish domestic market. In addition, there are other markets beyond of Sweden, for example the EU or on a wider international market, and as replacement for soybean meal, etc.

Today the area available for cultivation of oilseed plants in Sweden amounts to approximately 100,000 hectares, of which a small proportion is used for fuel production. If the production capacity of RME is fully exploited, approximately 180,000 hectares are required, which represents the maximum area for cultivating oilseed plants in Sweden due to crop rotation restrictions (Börjesson, 2007). Theoretically approximately 1 TWh RME could thus be produced from domestic oilseed plant cultivation with an unchanged production of other oilseed plant products. At the same time the production of rapeseed meal (including rapeseed cake) would increase to approximately 140,000 tonnes, which represents approximately 5% of the current total feed consumption in the dairy industry. A summarised assessment is that RME production based on domestic oilseed plant production is limited mainly by the area available for its cultivation and to a lesser extent by the market for rapeseed meal as protein feed (Börjesson, 2007).

When producing RME a certain amount of glycerol is also generated which today is considered to replace 50% fossil-based alternative products and 50% biomass-based products. This market limit and distribution is considered to remain valid also for the next few years (Mårtensson and Svensson, 2009). Historically, the proportion of glycerol from RME production replacing fossil-based glycerol has decreased gradually (Henard, 2007). Now however, new markets for bio-glycerol are being developed on which fossil-based products other than fossil-based glycerol are being replaced (Mårtensson and Svensson, 2009).

Pulp from the production of ethanol from beets is assessed to substitute feed grains for which the market is larger than that for protein feed, i.e. the market for pulp as feed is considered to be less restricted than the market for distillers waste and rapeseed meal as protein feed. If the market for pulp as feed is limited, it can, for example, be used for biogas production. Another limitation is the area available for the cultivation of sugar beets since these require good soil and growing conditions. Today sugar beets are grown mainly on the plains of the southern part of southern Sweden but previously sugar beets were also grown on the plains of the northern part of southern Sweden. Today about 40,000 hectares are cultivated in Sweden which is a decrease since 2005 when almost 50,000 hectares were under cultivation (SBA, 2009). An assessment made by the Swedish Board of Agriculture (2009b) is that the maximum arable area suitable for cultivation of sugar beets amounts to 70,000 hectares. The theoretical production of ethanol from 70,000 hectares of sugar beets is about 2 TWh. The corresponding potential for biogas is about 3.5 TWh (including tops and leaves).

The area available for the cultivation of maize is also considered to be limited as this requires specific growing and climatic conditions. Today the area available for the cultivation of maize as feed is increasing rapidly in Sweden but from a relatively low level (Börjesson, 2007). However, information on the size of the area that could come under maize cultivation in future is lacking.

The market for straw for energy purposes from grain and oilseed crops is in the current situation assessed to be “unlimited”. The potential for straw as an energy raw material is estimated to amount to approximately 6-7 TWh per year (Börjesson, 2007). This can be compared to an estimated increase in demand of solid biofuels for the production of heat and combined heat and power production of between 25-50 TWh per year till 2020, compared to 2006 (Ericsson and Börjesson, 2008). Since the use of straw for energy purposes is currently limited, the procurement of crop residues is not included in the base case for the environmental performance of the biofuels.

When biogas is produced from residues and crops the digestate is assumed to replace mineral fertiliser. The market for digestate as a replacement for mineral fertiliser is considered “unlimited” in the current situation. Table 3 summarises the restrictions assessed to exist in production volumes of the biofuels that generate by-products and when system expansion is applied as the calculation method.

Table 3. Summarising assessment of restrictions in production volumes for biofuel systems which generate by-products and when system expansion is applied, and regarding the potential area for cultivation.

Biomass	**Biofuel**	**Market of by-products**	**Other restrictions**[1]
		TWh / year	*TWh / year*
Crops			
Wheat	Ethanol	Approx. 1-2 TWh –distillers waste as protein feed in Sweden > 2 TWh -when exported	-
Sugar beets	Ethanol	-	Approx. 2.0 -max. 70,000 ha domestic area appropriate for cultivation
	Biogas[2]	-	Approx. 3.5 -max. 70,000 ha domestic area appropriate for cultivation
Rapeseed	RME	Approx. 1-2 TWh –rapeseed meal as protein feed in Sweden > 2 TWh -when exported	Approx. 1 TWh -max. increased domestic area for cultivation because of restrictions in crop rotations
Ley crops	Biogas	-	-
Maize	Biogas	-	? –limited domestic area appropriate for cultivation (estimation lacking)
Wheat	Ethanol & biogas	-	-
Residues			
Househ. waste	Biogas	-	Approx. 0.8 –supply of substrate[3]
Industrial waste	Biogas	-	Approx. 1.1 –supply of substrate[3]
Manure	Biogas	-	Approx. 2.8 –supply of substrate[3]
Import			
Sugar cane	Ethanol	-	-

[1] Does not include general limitations in access to cropland because of competition with food and feed production.

[2] Includes tops & leaves.

[3] Based on Linné et al. (2008).

4.2. Changed land use

There are several factors with an influence on whether the production of biofuels from agricultural crops leads to a change in land use or not. One factor is the proportion of the total cropland used for farming today, and the proportion not being used is, e.g. land lying fallow. Another factor is how the market limits for grains etc. for food and feed purposes varies over time and whether there are large surpluses on the world market or not. A third factor is how current feed production is optimized regarding requirements of within the livestock industry or whether there is a potential to improve the efficiency of the production of animal feed if, for instance, the prices of agricultural crops increase (dynamic effects).

4.2.1. Direct effects

One way to assess whether the current biofuel production results in a change in land use and what direct environmental impacts this may result in, is to study how the use of cropland has changed in Sweden over recent years. Table 4 shows the areas under grain, oilseed plants, sugar beets, ley crops and of fallow land in 2005 and 2009. As the table shows, the areas under grain and oilseed plants have each increased by approximately 20,000 hectares over the past five years while the areas under sugar beets and fallow land have decreased by approximately 10,000 and 170,000 hectares, respectively. A large part of the decrease in the area lying fallow can be linked to the increasing area of ley crop of approximately 100,000 hectares. As comparison, the area needed for grain and oilseed plants for the Swedish-produced ethanol and RME is currently equivalent to approximately 100,000 and 50,000 hectares, respectively, when the existing production capacity is fully utilised (see section above). Since 1990 the total cropland area in Sweden has decreased by 200,000 hectares and the area of grain by approximately 300,000 hectares (SBA, 2009b).

A rough estimate is therefore that a certain proportion of the increased grain cultivation for ethanol production and rapeseed cultivation for RME production may be using former grassland, but that most is taking place on previously open cropland. Based on the reasoning above, the following assumption is therefore made concerning direct land use changes linked to current biofuel production in Sweden: *it is assumed that on average 1/4 of the cultivation of raw material is taking place on previous grassland while 3/4 is assumed not to result in any direct carbon stock changes.* This assumption is considered to overestimate rather than underestimate the possible direct soil effects in the current domestic biofuel production. As described previously, there are uncertainties regarding the size of potential carbon stock changes when cultivation begins on previously grass-covered land, since this largely depends on how long the ground has been grass-covered and whether new equilibriums in the carbon stock have been reached or not. The statistics for the area of ley crop cultivation presented in Table 4 include both hay ley and pasture ley and it is here assessed that pasture ley has longer rotation periods than hay ley which can often be included in crop rotations with annual crops.

Concerning the area of fallow land this can be both grass-covered and open, and in this case the corresponding uncertainty regarding possible carbon stock changes exists when cultivation is taken up again. It is stated in the calculation methodology in the RED of the EU that cropland lying fallow is always to be classified as cropland and not be loaded with biogenic emissions of carbon dioxide, regardless of whether it is overgrown or not. The sensitivity analyses illustrate how the climate benefit changes depending on whether the proportion of grassland used for biofuel production increases or not.

The size of greenhouse gas emissions due to land use change refers to cultivation of mineral soils, which represent more than 90% of Swedish cropland. The proportion of organogenic soils represents approximately 7-8% and in this case the biogenic emissions of carbon dioxide become many times larger with a land use change, as when annual crops replace permanent ley crops (see e.g. Börjesson, 2009). Therefore, in general, cultivation of annual crops on grass-covered organogenic soils should be avoided; regardless of whether they are used for biofuel production or for food production.

Table 4. Changed use of cropland in Sweden between 2005 and 2009.[1]

Crop	**Area 2005**	**Area 2009**	**Change**	
	1000 ha	1000 ha	1000 ha	%
Grain	1030	1050	20	+ 2
Oilseed plants	83	100	17	+ 20
Sugar beets	49	40	9	- 18
Ley crops[2]	1090	1190	100	+ 9
Fallow land	320	150	- 170	- 53

[1] Based on data from SBA, 2009.

[2] Includes both hay ley and pasture ley.

4.2.2. Indirect effects

In this study, the assessment is made that Swedish biofuels of today have not had any significant negative net effects from indirect changes in land use beyond the borders of Sweden through displacement of food production (called ILUC, indirect land use changes). The reason for this is among other things that we do not fully make use of existing cropland, that the intensity of current plant cultivation can increase, and that we can get positive indirect land effects by replacing soybean feed by by-products which can counter possible negative effects. Not even in the case of imported Brazilian sugar cane ethanol are there any confirmed links to ILUC under current situation (Berndes et al, 2010).

Currently the world market prices for grain are down at a level equivalent to those in 2006-2007 and approximately 35% lower than those of 2008 when a sharp peak in price was reached, which indirectly reflects a world market surplus of grain (FAO, 2010). These low prices of grain lead to lower intensity in current crop cultivation, i.e. with increasing prices of grain the yield from the present area under grain cultivation could increase without indirect negative land effects as a consequence. A part of the grain produced in Sweden today can therefore be used for biofuel production without coming into conflict with the need for grain for food and feed production. Approximately 10% of the grain produced in Sweden is used for biofuel production which corresponds approximately to 4% of the cropland. The corresponding global use of cropland for fuel production is about 2%.

As shown by the statistics presented in Table 4 about 94% of Sweden's total cropland is used for cultivation while approximately 6% still lies fallow. The expansion of cultivated area that is the result of increased biofuel production has thus been possible within the existing cultivated area, partly through a certain redistribution of plant cultivation with more cultivation of ley crops on fallow land, which in turn is being replaced by grain cultivation. The arable area chosen to lie fallow has often the lowest production capacity and is therefore more suitable for the cultivation of ley crops than for annual crops. The direct land use effects this assumed redistribution is considered to have resulted in are included in this analysis (see Section 4.2.1).

In the future, the risk of potential indirect land effects beyond of Sweden may increase when the Swedish production capacity of plant cultivation starts to be fully exploited, i.e. when all economically feasible cropland is being cultivated and potential increases of yields are utilised by an increased intensity of cultivation. However, there are still the dynamic effects in the current agricultural production that counteract this risk. In a study by the Swedish Board of Agriculture (2009b), an assessment is made of how much land could be released for energy production in the future without diminishing the current domestic food and feed production. The result shows that between 300,000-650,000 hectares could be made available for energy production through different measures. One measure is an amended distribution of crops through which, above all, feed is produced much more efficiently than today since we have a large surplus of cultivation of ley crop that is not necessary to meet the domestic need for coarse fodder. This potential is assessed to be the equivalent of 200,000 to 500,000 hectares. Through changed intensity and improved methods of production another approximately 100,000 hectares can be released. In addition to this there are about 100,000 hectares of former cropland that can be used for energy cultivation. An increased production of biofuels on this “surplus area”, for instance, may to some extent lead to direct land effects, such as when an increasing proportion of ley crops cultivation is turned into cultivation of annual crops. In other words, the size of the direct biogenic emissions of soil carbon may need to be adjusted as the production of biofuels from annual crops increases.

However, it is not reasonable to assume that all of this potential surplus area can be used in a cost-effective way for the cultivation of annual crops in the future. A relatively large proportion of this potential cropland is probably more suitable for the cultivation of perennial energy crops such as coppice and energy forest of various kinds (see e.g. SOU, 2007). In addition, the proportion of organogenic soils may possibly be slightly over-represented in this surplus area, which from a greenhouse gas perspective are less appropriate for the cultivation of annual crops compared to perennial crops. A very rough estimate in this study is that up to one third of this surplus land can potentially be used for cultivation of annual energy crops in the future, which represents over 7% of current cropland, i.e.

approximately 200,000 hectares. In addition, biofuels based on ley crops, such as biogas, can be produced without negative, direct land effects.

The risk of future indirect land-use effects and displacement of food and feed production also depends on the increase in production of biofuels from traditional crops, and how large the production volumes will be. With a very rapid and extensive expansion of, for instance, wheat-based ethanol the risks of displacement effects increase, while the risks can be minimised by a well-balanced expansion rate and adjusted production volumes which are restricted by the current and available base of raw material (Börjesson et al, 2008, Berndes et al., 2010). By adjusting the rate of expansion, there is enough time for the dynamic effects discussed above to be realised. For example, the global production of wheat has increased by approximately 3 times over 30 years while the global cultivation area of wheat has decreased by approximately 10% (Ensus, 2008).

In the RED of the EU there is a debate as to whether indirect effects should be included when the climate benefit of biofuels is considered. In this context, various studies have been made to develop basic information. One example is a study by IFPRI (2010) that analyses the impacts of the EU target of 10% renewable fuels by 2020 in global agricultural production. The results of this futurological study show that the global area of cropland could come to increase by approximately 0.07% and that the negative indirect land effects (ILUC) reduce the climate benefit of biofuels compared with fossil fuels by an average of just under 30%. Concerning specific crops, sugar cane-based ethanol from Brazil gives the lowest negative ILUC, equivalent to approximately 20% of the climate load of fossil fuels while grain-based biofuels give a larger negative ILUC. Including these indirect land effects the climate benefit of biofuels is assessed to amount, on average, to approximately 55% compared to fossil fuels. This model is a development of previous simulation models of global agriculture (see e.g. Searchinger, 2008) where parameters such as substitution of different types of energy, division of energy crops and input material, sale of by-products as animal feed, amended intensity of fertilisation and substitution of different soil types have been developed and refined.

Another study that analyses possible modes of procedure to include possible indirect effects in the LCA of biofuels shows that previous global modelling of ILUC vary greatly (Cornelissen and Dehue, 2009). For example, IIASA (2009) estimate a negative ILUC corresponding to 35% of the climate load of fossil fuels while Searchinger (2008) arrives at a result significantly higher than all other studies, corresponding to 120% of the climate load of fossil fuels (based on an expansion of American maize ethanol by 2020). An important parameter is if, and in that case how, by-products that can be used as protein feed are to be considered, such as distillers waste from grain-based ethanol production and rapeseed meal from RME production. If the corresponding approach concerning marginal effects in the form of ILUC is applied for these feed by-products as is applied for biofuels, studies show that the climate benefit of grain-based ethanol and biodiesel from rapeseed can exceed 100% (Lywood, 2009). The reason for this is that the positive ILUC obtained when soybean cultivation is reduced on the margin is much larger than the negative ILUC obtained when grain cultivation is increasing on the margin. The expansion of soybean cultivation on the margin is considered to be taking place, among other places, in the Amazon where this cultivation leads to extensive biogenic greenhouse gas emissions from soil and vegetation, while the corresponding expansion of grain cultivation on the margin is considered to be taking place on grass-covered land and unused land in temperate regions which results in much lower biogenic greenhouse gas emissions (Lywood, 2009).

An expansion of biofuel production can also lead to an initiation of cultivation on an increased area of so-called marginal soils with low carbon content which also gives a positive ILUC (see e.g. Ravindranath et al, 2009, Bustamante et al, 2009). Concerning sugar cane ethanol estimates have been made showing that the expansion in recent years has occurred largely on low-productive pastureland with low carbon content (Macedo and Seabra, 2008). This loss of low-productive pasture has been compensated by a slightly increased intensity on more productive pasture, which has made possible a somewhat greater number of grazing animals per hectare. The net effect of these changes in land use may be a slightly increased binding of carbon in soil and vegetation, i.e. a positive ILUC. However, it is not possible today to make any definite links between an expansion of Brazilian sugar cane ethanol and ILUC, irrespective of whether this is negative or positive (Berndes et al, 2010).

The conclusion and the recommendations given by Cornelissen and Dehue (2009), for example, are that ILUC cannot be quantified in the LCA of biofuels due to the large uncertainties existing in both data and calculation methods. Possible, indirect land-use effects must be managed with other tools, such as risk analyses that focus on minimising the risks of negative ILUC. In addition, the potential positive ILUC must also be considered in the corresponding way that the potential negative ILUC is considered.

4.3. Emissions of greenhouse gases

4.3.1. Results of the calculations

Figures 3 and 4 show the climate performance of different biofuels, expressed in terms of GWP per unit of energy. As shown in Figure 3, the climate benefit of biofuels varies greatly depending on the calculation methodology used and the type of land being used as reference. Table 5 summarises the climate benefit of biofuels compared to fossil fuels when system expansion is applied and crop residues are excluded. Table 6 shows the climate benefit when energy allocation of by-products (excluding crop residues) is used as base. “No allocation” means that all emissions are assigned to the biofuel and none to the by-products.

As is clear in Tables 5 and 6 the choice of land use taken as reference is of great importance for the climate performance of biofuels. In previous LCAs of biofuels the biogenic emissions of carbon dioxide have most often not been included, but only biogenic emissions of nitrous oxide. The tables also present the results of this traditional calculation method in which carbon stock changes are excluded. One criticism that can be levelled at the calculations made in this study, where grain cultivation is used as reference, is that biogenic emissions of nitrous oxide are "excluded" but that these are affected by the application of nitrogen fertiliser, at least in the long perspective. Field surveys show that emissions of nitrous oxide from cropland have little connection with current nitrogen ration in the short perspective, i.e., emissions of nitrous oxide may be as large from unfertilised as from fertilised fields (Klemedtsson, 2009). For this, the calculations performed in this study regarding grain production as reference can be regarded as relevant in the short term (a few years), but in a longer perspective the emissions of nitrous oxide may be underestimated, as a differently sized nitrogen pool is built up in the soil, depending on the size of the nitrogen ration.

In this study current IPCC methodology is used to calculate biogenic emissions of nitrous oxide (direct and indirect). This method is also expected to be the one mainly used in the RED of the EU at an early stage until improved methods have been developed. One disadvantage of the IPCC methodology is, among other things, that it is based on the nitrogen applied (gross supply) and does not take into account how much nitrogen is removed through the harvested crop (net supply). From a nitrous oxide perspective, it is the net input of nitrous oxide that is relevant. A system with high rations of fertiliser, but which has efficient nitrogen utilisation and a large removal of nitrogen can result in a lower net input than systems with lower rations of fertiliser but with low nitrogen efficiency and removal. Another shortcoming with the IPCC methodology is that it does not take local conditions into account, such as climate, the carbon/nitrogen ratio of the soil, soil water conditions, etc., which have proved to have significant relevance for the risk of the formation of nitrous oxide (Klemedtsson, 2009). Therefore, new methods of calculation need to be developed, which, among other things, take into account the total nitrogen balance of the cultivation system, local soil conditions, etc. In Sweden a development of more site-specific calculation methods for nitrous oxide is currently taking place, in which parameters other than the ration of nitrogen fertilisation are included (Klemedtsson, 2009). In the future these are expected to replace the IPCC methodology to give more reliable estimates of the size of the biogenic emissions of nitrous oxide.

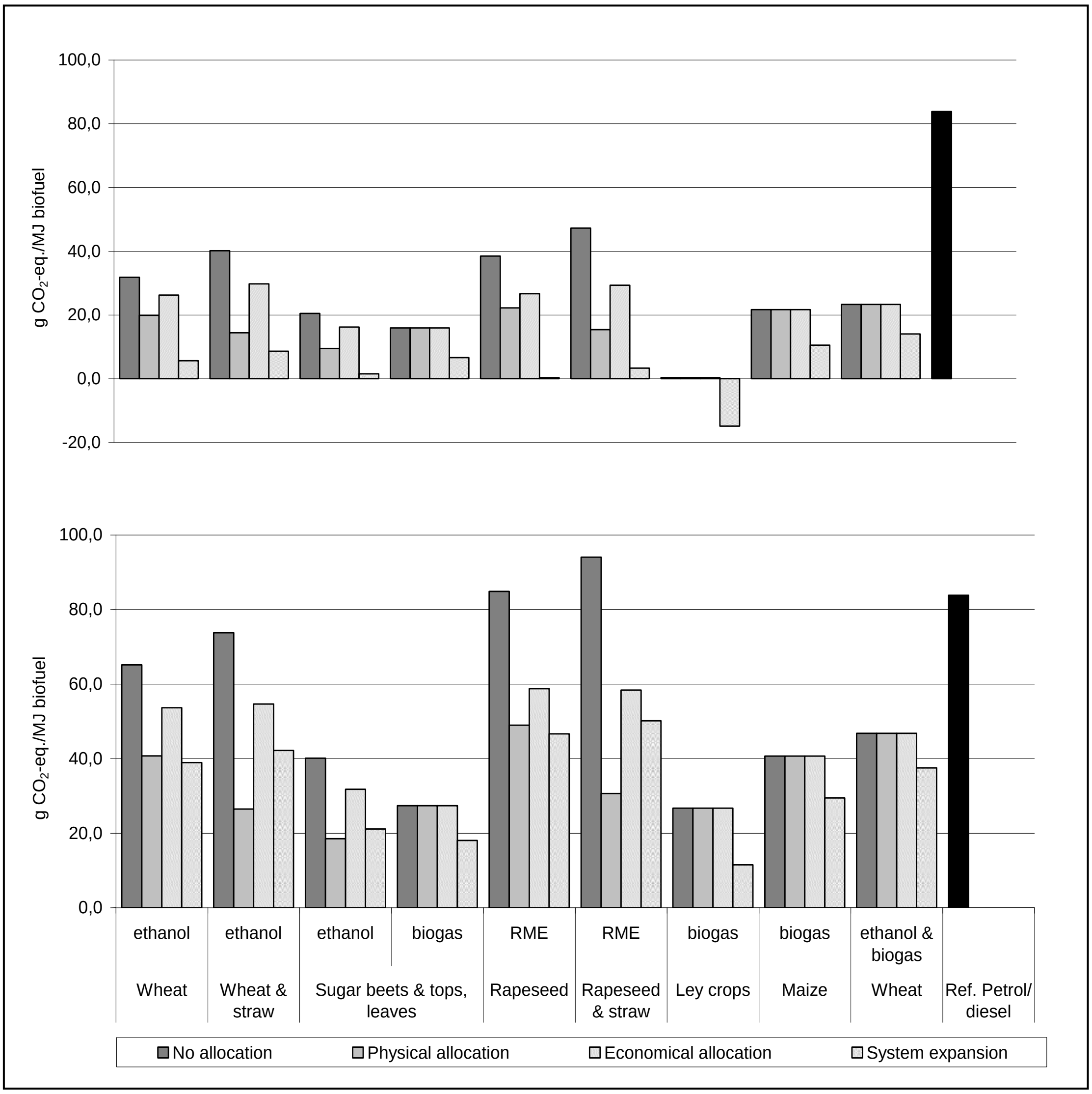

Figure 3. Greenhouse gas emissions for different biofuels based on crops, expressed as g of CO_2-equivalents per MJ fuel. The upper diagram refers to cultivation of grain as reference land use and the lower to unfertilised grassland.

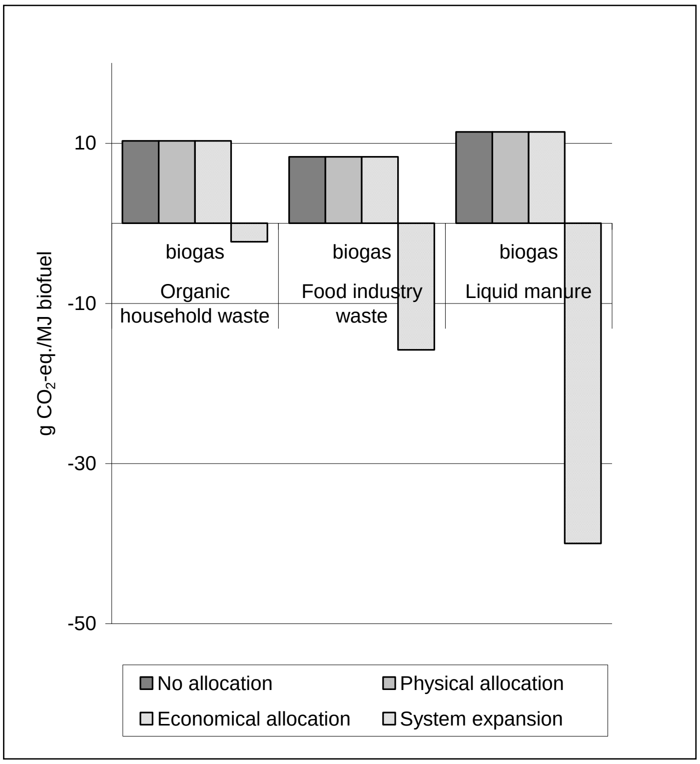

Figure 4. Emissions of greenhouse gases for biogas based on residues, expressed as g CO_2-equivalents per MJ fuel.

Table 5. The reduction of greenhouse gas emissions of biofuels in percent compared to fossil fuels based on system expansion, excluding crop residues in the cultivation.

Biomass	**Biofuel**	**Reduction of greenhouse gases (%)**[1]			
		Unfertilised grassland as land-use reference	*Cultivation of grain as land-use reference*	*Avera-ge*	*Incl. biogenic emissions of nitrous oxide but excl. biogenic flows of carbon dioxide*[2]
Crops					
Wheat	Ethanol	54	93	-	77
Sugar beets	Ethanol	69	94	-	83
	Biogas[3]	78	92	-	87
Rapeseed	RME	44	99	-	76
Ley crops	Biogas	86	118	-	86
Maize	Biogas	65	87	-	78
Wheat	Ethanol & biogas	55	83		71
Residues					
Househ. waste	Biogas	-	-	103	-
Ind. waste	Biogas	-	-	119	-
Manure	Biogas	-	-	148	-
Import					
Sugar cane	Ethanol	-	-	79	-

[1] Emissions of greenhouse gases from fossil fuels are assumed to be 83.8 g per MJ.

[2] Traditional way to calculate climate performance and when alternative land-use reference is not defined, i.e. including biogenic emissions of nitrous oxide but excluding carbon stock changes.

[3] Including tops and leaves.

Table 6. The reduction of greenhouse gases of biofuels expressed in percent compared to fossil fuels based on energy allocation, excluding crop residues in the cultivation.

Biomass	**Biofuel**	**Reduction of greenhouse gases (%)**[1]			
		Unfertilised grassland as land-use reference	*Cultivation of grain as land-use reference*	*Average*	*Incl. biogenic emissions of nitrous oxide but excl. biogenic flows of carbon dioxide*[2]
Crops					
Wheat	Ethanol	51	76	-	67
Sugar beets	Ethanol	69	84	-	76
	Biogas[3]	67	81	-	76
Rapeseed	RME	42	74	-	58
Ley crops	Biogas	68	99	-	68
Maize	Biogas	51	74	-	65
Wheat	Ethanol & biogas	44	72		60
Residues					
Household waste	Biogas	-	-	88	-
Industrial waste	Biogas	-	-	90	-
Manure	Biogas	-	-	86	-
Import					
Sugar cane	Ethanol	-	-	77	-

[1] Emissions of greenhouse gases from fossil fuels are assumed to be 83.8 g per MJ.

[2] Traditional way to calculate climate performance and when alternative land-use reference is not defined, i.e. including biogenic emissions of nitrous oxide but excluding carbon stock changes.

[3] Including tops and leaves.

4.3.2. Assessed climate benefit, including changed land use

The results presented above concerning greenhouse gas emissions with grain cultivation as reference land-use should be used with caution, and above all be regarded as an illustration of the importance of how biogenic emissions of nitrous oxide are calculated and the time perspective being referred to. Until more reliable calculation methods of biogenic nitrous oxide emissions have been developed, existing calculation methods can be used despite their shortcomings, such as the fact that they are based on gross input of nitrogen, which can imply an overestimation of the nitrous oxide emissions for some cultivation systems. Table 7 gives a summarised assessment of the climate performance of Swedish biofuels of today, i.e., when an average of 1/4 of the cultivation of raw material is assumed to take place on previously grass-covered cropland, while 3/4 is assumed not to bring about any direct changes in soil carbon content.

Table 7. Summarised assessment of the climate benefit of biofuels based on current conditions. For fuels produced from crops in Sweden carbon stock changes are included in the equivalent of 1/4 of the cultivated area (i.e. unfertilised and grass-covered cropland).[1]

Biomass	**Biofuel**	**System expansion**[2]		**Energy allocation**[2]		**End-use in vehicles** g CO_2-eq. / MJ	
		g CO_2-eq. / MJ	Reduction in %	g CO_2-eq. / MJ	Reduction in %	*Light duty vehicles*	*Heavy duty vehicles*[3]
Crops							
Wheat	Ethanol	24.4	71	30.9	63	-	(3.2)
Sugar beets	Ethanol	16.9	80	21.6	74	-	(3.2)
	Biogas[4]	12.5	85	21.8	74	0.9	0.9
Rapeseed	RME	26.4	68	39.4	53	-	-
Ley crops	Biogas	11.5	86	26.7	68	0.9	0.9
Maize	Biogas	21.2	75	32.4	61	0.9	0.9
Wheat	Ethanol & biogas	27.3	67	36.6	56	- / 0.9	(3.2) / 0.9
Residues							
Household waste	Biogas	-2.3	103	10.3	88	0.9	0.9
Industrial waste	Biogas	-15.8	119	8.3	90	0.9	0.9
Manure	Biogas	-40.4	148	11.4	86	0.9	0.9
Import							
Sugar cane	Ethanol	17.6	79	18.9	77	-	(3.2)

[1] Emissions of greenhouse gases from fossil fuels are assumed to be 83.8 g per MJ.

[2] System expansion and energy allocation excluding crop residues.

[3] Values in brackets refer to ignition additive in ethanol (ED95).

[4] Including tops and leaves.

4.4. Emissions of compounds contributing to eutrophication

4.4.1. Results of the calculations

Figures 5 and 6 show the impact on eutrophication by the different biofuels, expressed as PO_4^{3-}-equivalents per unit of energy. As shown in Figure 5 the contribution to eutrophication varies largely depending on the calculation methodology used and the land-use reference assumed. Table 8 summarises the contribution to eutrophication of biofuels when system expansion and energy allocation, excluding crop residues, are applied and also depending on alternative land-use reference.

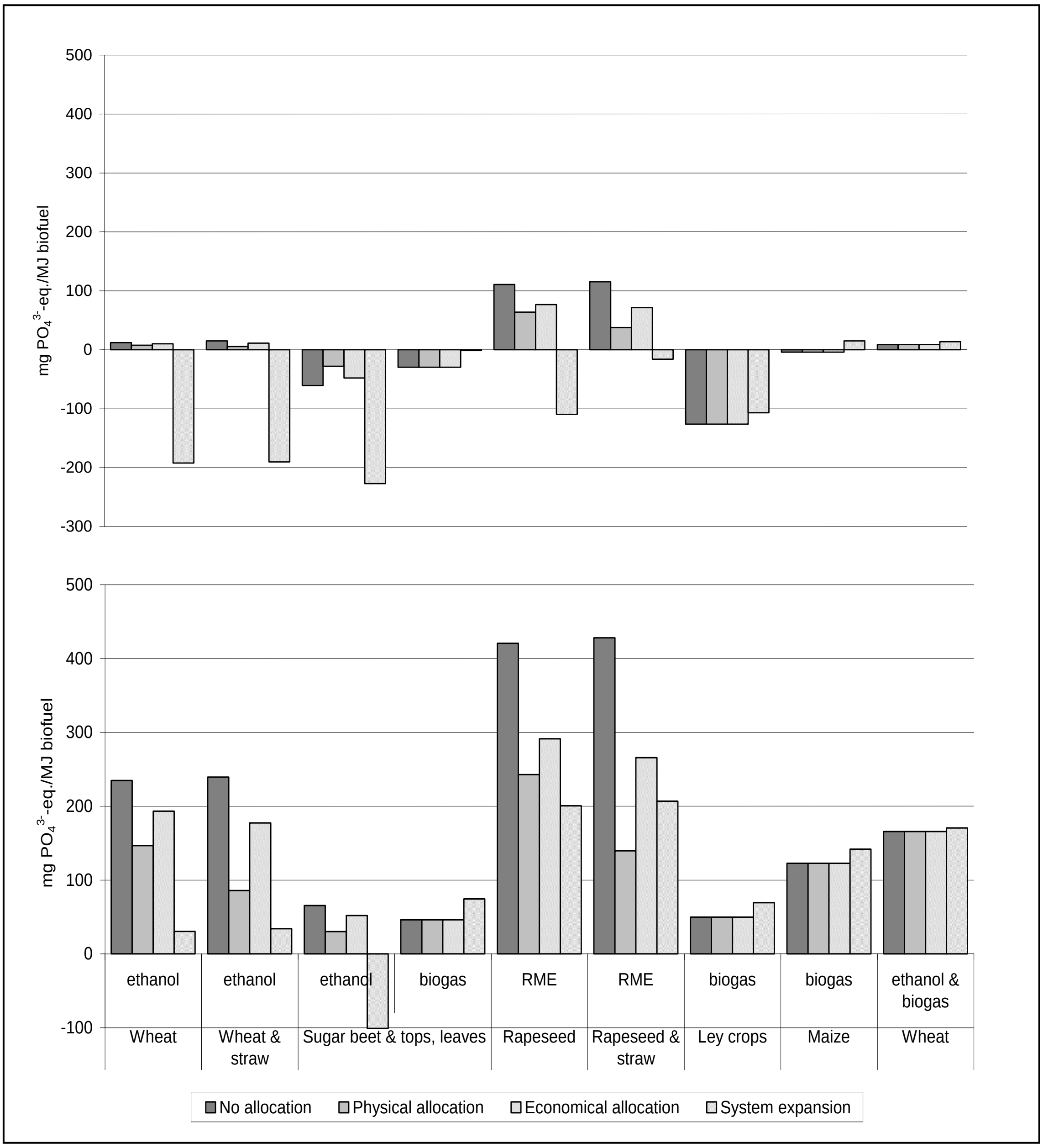

Figure 5. Emissions of compounds contributing to eutrophication from different biofuels based on crops, expressed as mg PO_4^{3-}-equivalents per MJ biofuel. The upper diagram refers to cultivation of grain as reference land-use and the lower to unfertilised grassland.

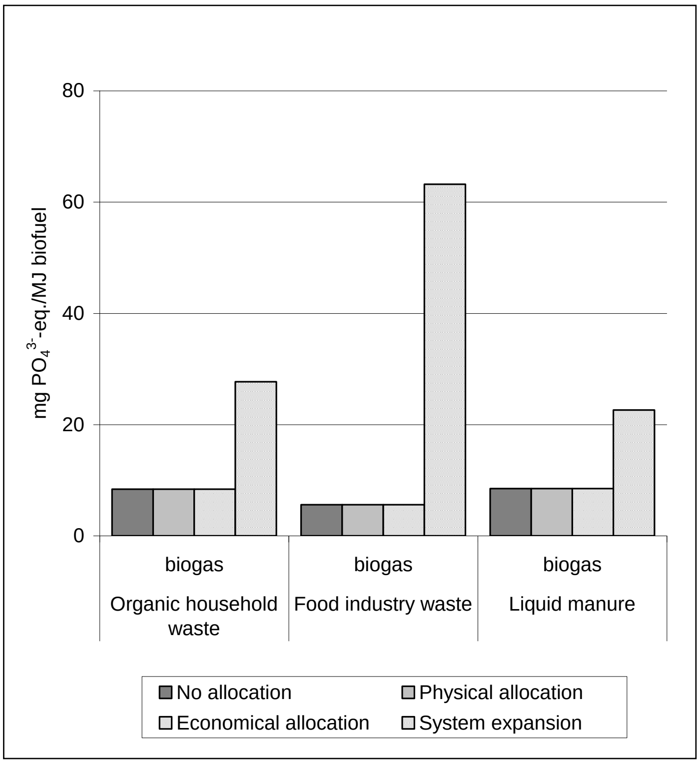

Figure 6. Emissions of compounds contributing to eutrophication from biogas based on residues, expressed as mg PO_4^{3-}-equivalents per MJ fuel.

Table 8. Emissions of compounds contributing to eutrophication from biofuels (mg PO_4^{3-}-eq. / MJ) when system expansion and energy allocation are applied and when different land-use references are used (excluding crop residues).

Biomass	**Biofuel**	**System expansion**		**Energy allocation**	
		Unfertilised grassland as land-use reference	*Cultivation of grain as land-use reference*	*Unfertilised grassland as land-use reference*	*Cultivation of grain as land-use reference*
Crops					
Wheat	Ethanol	30	-195	147	8
Sugar beets	Ethanol	-56	-195	69	-16
	Biogas[1]	74	-1	46	-30
Rapeseed	RME	200	-113	243	64
Ley crops	Biogas	69	-107	50	-126
Maize	Biogas	142	15	123	-4
Wheat	Ethanol & biogas	170	13	166	9
Residues					
Household waste	Biogas	28		8	
Industrial waste	Biogas	63		6	
Manure	Biogas	23		9	
Import					
Sugar cane	Ethanol	68		62	

[1] Including tops & leaves.

4.4.2. Assessed contribution to eutrophication including changed land use

One criticism that can be levelled at the calculations made in this study regarding nitrogen leakage where grain production is used as a reference, like the criticism discussed earlier regarding biogenic nitrous oxide emissions, is that the nitrogen leakage is largely influenced by the amount of applied nitrogen fertiliser (net). In the short perspective (one year), the estimates made in this study regarding grain production as a reference can be seen as relevant, but in the longer perspective the nutrient leakage may be underestimated by this calculation method. When assessing the climate impact of biofuels, including land-use change, biogenic nitrous oxide emissions are included in all biofuel systems based on crops, to avoid an underestimation of the climate impact. Analogous with this approach and to avoid that an underestimation of the contribution of biofuels to the eutrophication is occurring, unfertilised grass-covered cropland is used as reference land here, see Table 9. In this way the differences in the amount of nitrogen applied in each cultivation system are taken into account as well as intrinsic differences in the form of annual or perennial systems.

Table 9. Summarising assessment of emissions of compounds contributing to eutrophication from biofuels (mg PO_4^{3-}-eq. / MJ) based on current conditions.

Biomass	**Biofuel**	**System expansion**[1]	**Energy allocation**[1]	**End-use in vehicles**	
Crops				*Light duty vehicles*	*Heavy duty vehicles*[2]
Wheat	Ethanol	30	147	1.0	39 (40)
Sugar beets	Ethanol	-56	69	1.0	39 (40)
	Biogas[3]	74	46	1.0	26
Rapeseed	RME	200	243	72	91
Ley crops	Biogas	69	50	1.0	26
Maize	Biogas	142	123	1.0	26
Wheat	Ethanol & biogas	170	166	1.0	39 (40) / 26
Residues					
Househ. waste	Biogas	28	8	1.0	26
Ind. waste	Biogas	63	6	1.0	26
Manure	Biogas	23	9	1.0	26
Import					
Sugar cane	Ethanol	68	62	1.0	39 (40)

[1] System expansion and energy allocation, excluding crop residues.

[2] Values in brackets include ignition additive in ethanol (ED95).

[3] Including tops and leaves.

4.5. Emissions of compounds contributing to acidification

4.5.1. Results of the calculations

Figures 7 and 8 show the impacts on acidification by different biofuels, expressed as SO_2-equivalents per energy unit. As is clear in the figures the contribution to acidification varies largely depending on the calculation methodology used.

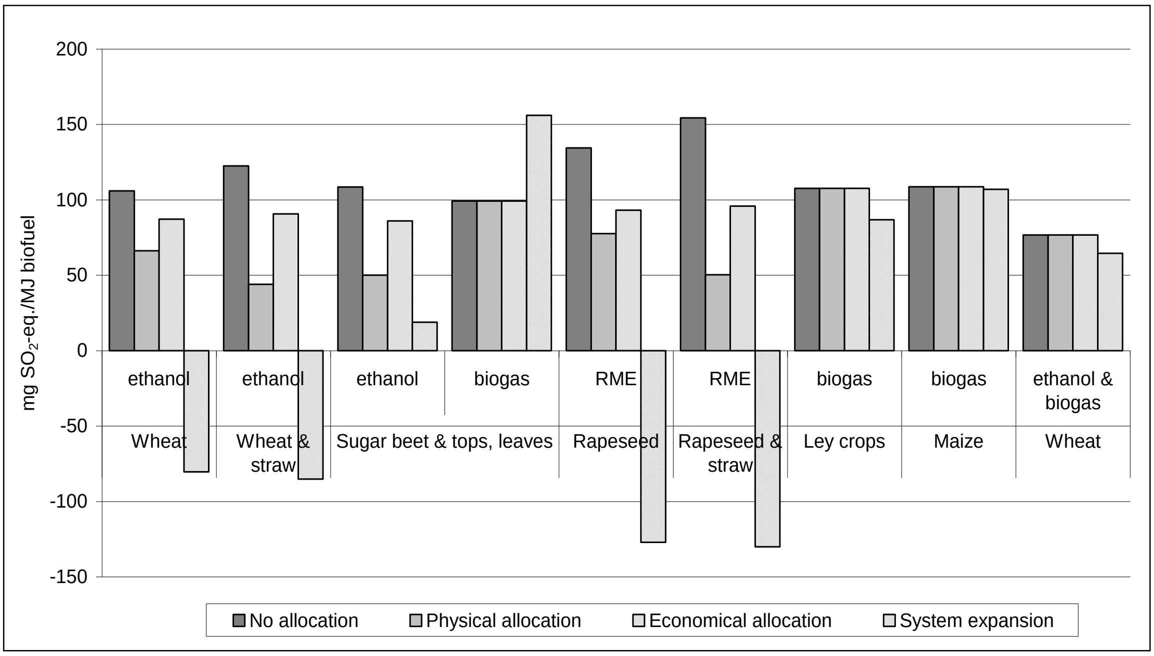

Figure 7. Emissions of compounds contributing to acidification from different biofuels, expressed as mg SO_2-equivalents per MJ fuel.

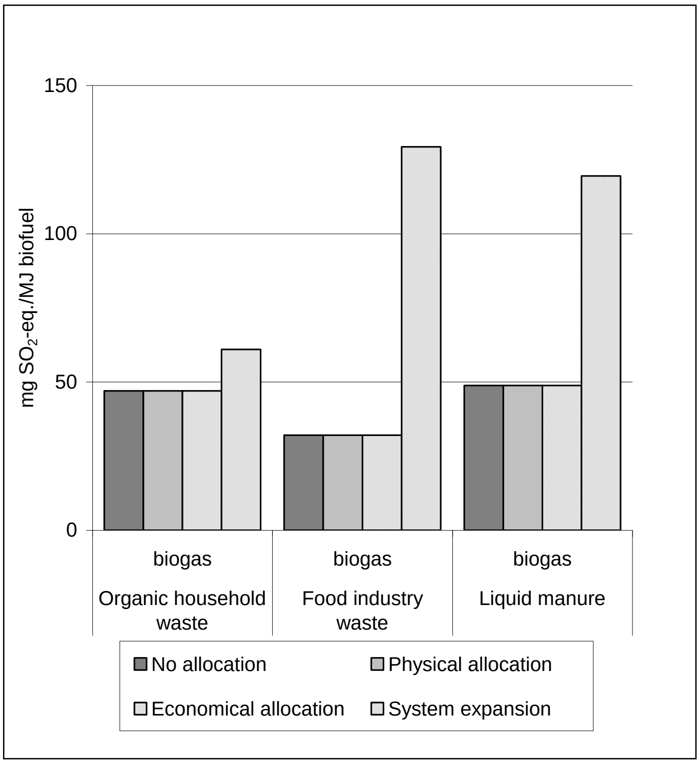

Figure 8. Emissions of compounds contributing to acidification from biogas from residues, expressed as mg SO_2-equivalents per MJ fuel.

4.5.2. Assessed contribution to acidification

Table 10 summarises the assessment of the size of the contribution to the acidification of current biofuels in Sweden, assuming that system expansion and energy allocation, excluding crop residues, are being applied. The large contribution from sugar cane ethanol is primarily due to emissions from the transport by boat from Brazil to Sweden for which oil containing sulphur is assumed to be the fuel used.

Table 10. Summarising assessment of emissions of compounds contributing to acidification from biofuels (mg SO_2-eq. / MJ) based on current conditions.

Biomass	**Biofuel**	**System expansion**[1]	**Energy allocation**[1]	**End-use in vehicles**	
Crops				*Light vehicles*	*Heavy duty vehicles*[2]
Wheat	Ethanol	-80	66	7.0	210 (240)
Sugar beets	Ethanol	18	67	7.0	210 (240)
	Biogas[3]	156	99	7.0	140
Rapeseed	RME	-127	78	385	490
Ley crops	Biogas	87	108	7.0	140
Maize	Biogas	107	109	7.0	140
Wheat	Ethanol & biogas	65	77	7.0	210 (240) / 140
Residues					
Household waste	Biogas	61	47	7.0	140
Industrial waste	Biogas	129	32	7.0	140
Manure	Biogas	120	49	7.0	140
Import					
Sugar cane	Ethanol	241	229	7.0	210 (240)

[1] System expansion and energy allocation, excluding crop residues.

[2] Values in brackets include ignition additive in ethanol (ED95).

[3] Including tops & leaves.

4.6. Emissions of compounds contributing to the formation of photochemical ozone

4.6.1. Results of the calculations

Figures 8 and 9 show the impact on the formation of photochemical oxidants (photochemical ozone) of different biofuels, expressed as C_2H_2-equivalents per energy unit. As is clear from the figures the contribution of compounds that can form photochemical ozone vary, largely depending on the calculation methodology applied.

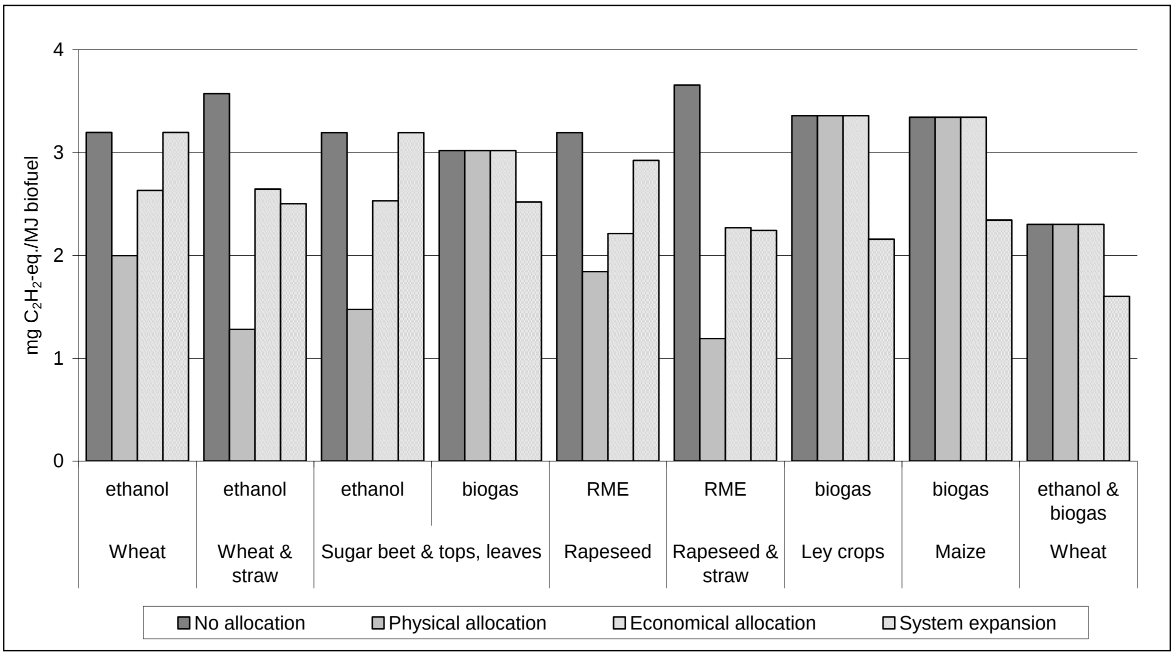

Figure 8. Emissions of compounds contributing to the formation of photochemical ozone from different biofuels, expressed as mg C_2H_2-equivalents per MJ fuel.

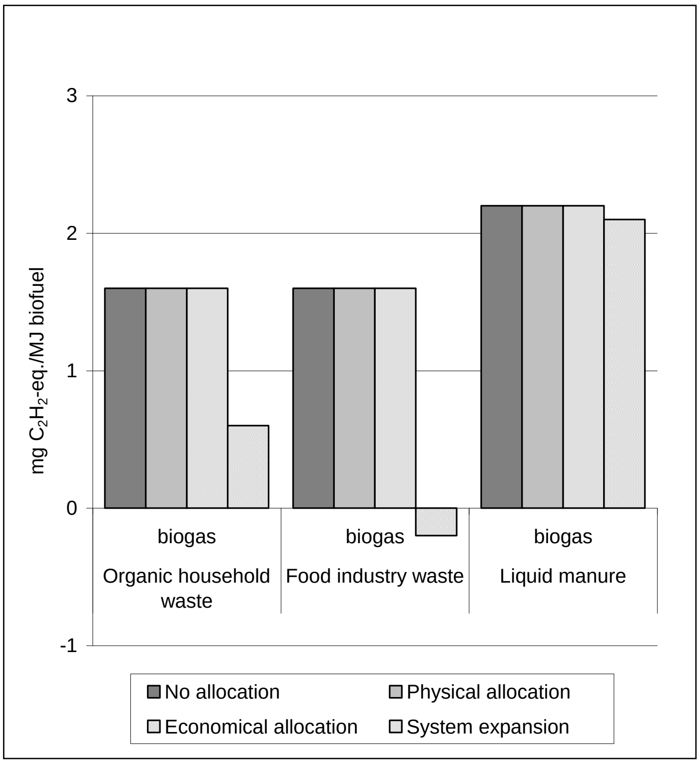

Figure 9. Emissions of compounds contributing to the formation of photochemical ozone from biogas based on residues, expressed as mg C_2H_2-equivalents per MJ fuel.

4.6.2. Assessed contribution to the formation of photochemical ozone

Table 11 summarises the assessment of the size of the contribution to the formation of photochemical ozone of current biofuels in Sweden, assuming that system expansion and energy allocation, excluding crop residues, are applied. The large contribution from sugar cane ethanol is primarily due to emissions from the transport by boat from Brazil to Sweden.

Table 11. Summarising assessment of emissions of compounds from biofuels forming photochemical oxidants (mg C_2H_2-eq. / MJ) based on current conditions.

Biomass	**Biofuel**	**System expansion**[1]	**Energy allocation**[1]	**End-use in vehicles**	
Crops				*Light duty vehicles*	*Heavy duty vehicles*[2]
Wheat	Ethanol	3.2	2.0	15	6.0 (12)
Sugar beets	Ethanol	3.2	2.0	15	6.0 (12)
	Biogas[3]	2.5	3.0	15	2.0
Rapeseed	RME	2.9	1.8	12	2.0
Ley crops	Biogas	2.2	3.4	15	2.0
Maize	Biogas	2.3	3.3	15	2.0
Wheat	Ethanol & biogas	1.6	2.3	15	6.0 (12) / 2.0
Residues					
Household waste	Biogas	0.6	1.6	15	2.0
Industrial waste	Biogas	-0.2	1.6	15	2.0
Manure	Biogas	2.1	2.2	15	2.0
Import					
Sugar cane	Ethanol	26	24	15	6.0 (12)

[1] System expansion and energy allocation, excluding crop residues.

[2] Values in brackets include ignition additive in ethanol (ED95).

[3] Including tops and leaves.

4.7. Emissions of particles

4.7.1. Results of the calculations

Figures 10 and 11 show the emissions of particles from different biofuels, expressed per energy unit. As is clear from the figures the emissions of particles vary largely depending on the calculation methodology used.

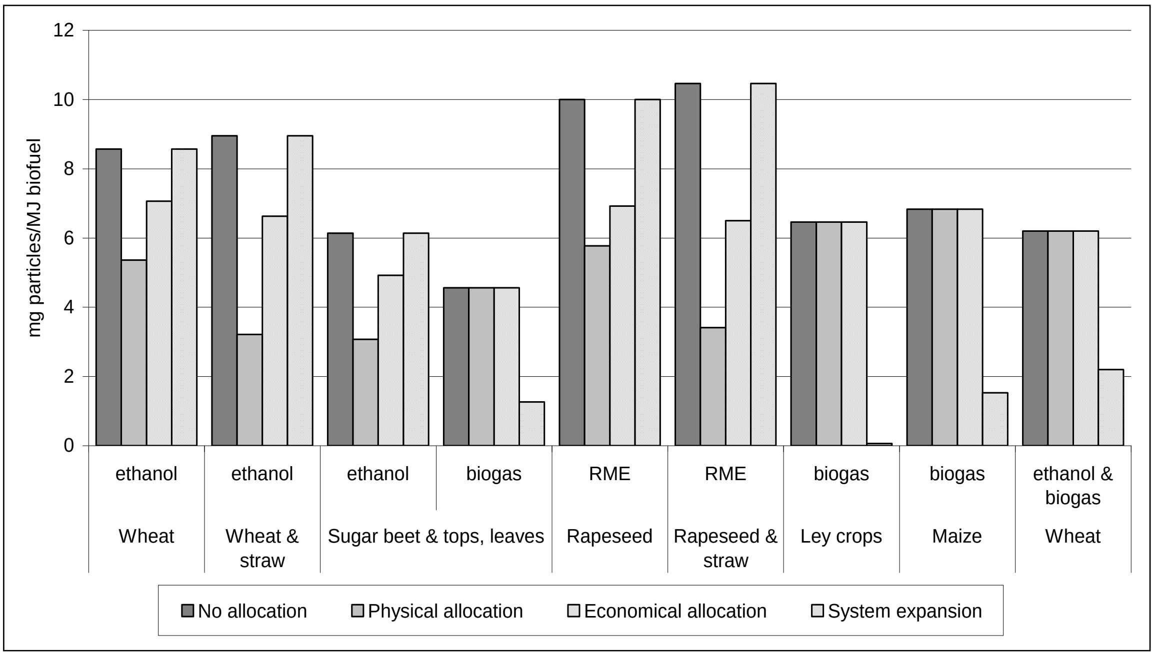

Figure 10. Emissions of particles from different biofuels from crops, expressed as mg per MJ fuel.

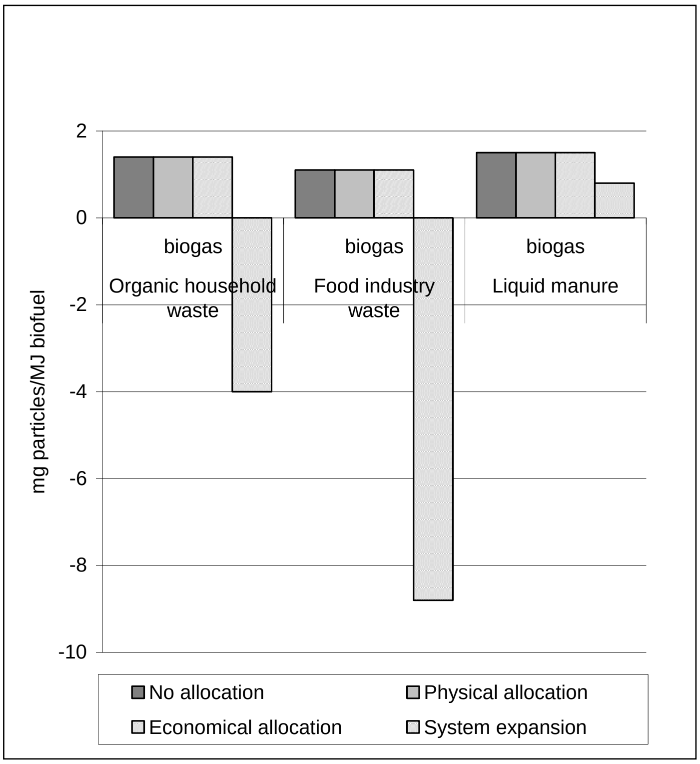

Figure 11. Emissions of particles from biogas based on residues, expressed as mg per MJ fuel.

4.5.2. Assessed emission of particles

Table 12 summarises the assessment of the amount of particles emitted from current biofuels in Sweden when system expansion and energy allocation, excluding crop residues, are applied.

Table 12. Summarised assessment of the emissions of particles (mg / MJ) from biofuels based on current conditions.

Biomass	**Biofuel**	**System expansion**[1]	**Energy allocation**[1]	**End-use in vehicles**	
Crops				*Light duty vehicles*	*Heavy duty vehicles*[2]
Wheat	Ethanol	8.6	5.4	1.0	1.0 (2.3)
Sugar beets	Ethanol	6.6	3.7	1.0	1.0 (2.3)
	Biogas[3]	1.3	3.1	0.5	0.5
Rapeseed	RME	10	5.8	10	3.0
Ley crops	Biogas	0.1	6.5	0.5	0.5
Maize	Biogas	1.5	6.8	0.5	0.5
Wheat	Ethanol & biogas	2.2	6.2	1.0 / 0.5	1.0 (2.3)
Residues					
Household waste	Biogas	-4.0	1.4	0.5	0.5
Industrial waste	Biogas	-8.8	1.1	0.5	0.5
Manure	Biogas	0.8	1.5	0.5	0.5
Import					
Sugar cane	Ethanol	9.0	8.7	1.0	1.0 (2.3)

[1] System expansion and energy allocation, excluding crop residues.

[2] Values in brackets include ignition additive in ethanol (ED95).

[3] Including tops and leaves.

4.8. Energy balance

Table 13 summarises the energy balance for each biofuel according to the calculation method and whether or not crop residues are included in the calculations.

Table 13. Energy balance for each biofuel system, expressed as the quotient between the yield of biofuel and the input energy expressed as primary energy.

Biomass	**Fuel**	**No allocation**	**Energy allocation**	**Economic allocation**	**System expansion**
Crops					
Wheat	Ethanol	1.29	2.07	1.57	1.87
	Biogas	2.38	2.38	2.38	2.79
Wheat & straw	Ethanol	1.24	3.46	1.68	1.93
	Biogas	2.25	2.25	2.25	2.90
Sugar beets	Ethanol	1.65	2.64	2.00	2.00
	Biogas	2.40	2.40	2.40	2.56
Sugar beets, tops & leaves	Ethanol	1.61	3.48	2.03	2.02
	Biogas[1]	2.51	2.51	2.51	2.65
Rapeseed	RME	2.18	3.77	3.14	6.11
Rapeseed & straw	RME	2.02	6.19	3.25	6.48
Ley crops	Biogas	2.63	2.63	2.63	2.87
Maize	Biogas	2.46	2.46	2.46	2.78
Wheat	Ethanol & biogas	2.15	2.15	2.15	2.44
Residues					
Household waste	Biogas	3.53	3.53	3.53	4.56
Industrial waste	Biogas	3.61	3.61	3.61	5.69
Manure	Biogas	2.55	2.55	2.55	2.84
Import					
Sugar cane	Ethanol	4.7	5.4	-	5.1

[1] Including digestion of tops and leaves.

4.9. Area efficiency

Figure 12 summarises the energy output and energy input for each biofuel system based on crops, expressed per hectare and year. Next, figure 13 shows the climate benefit per hectare and year based on the assessed greenhouse gas reduction of this study, i.e. when carbon stock changes are estimated to take place on approximately 25% of the cultivated area and when system expansion and energy allocation (excluding crop residues) are applied.

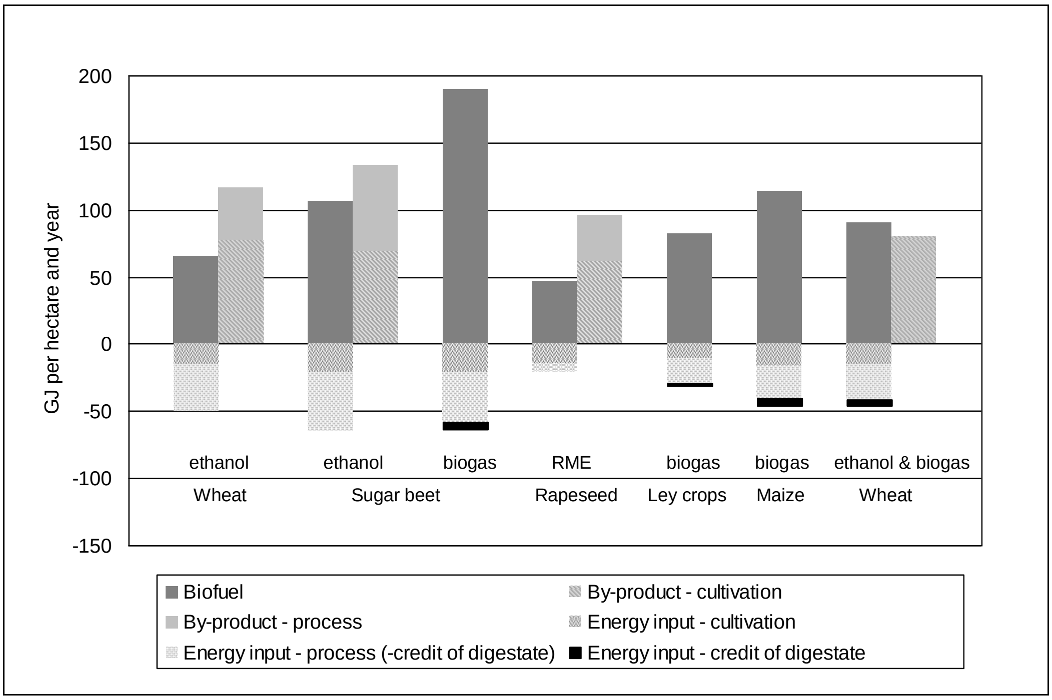

Figure 12. Yield of biofuel and by-products per hectare and year, and input of external energy in the cultivation and transformation of each biofuel based on crops. The energy saving when digestate replaces mineral fertiliser in the production of biogas is also shown.

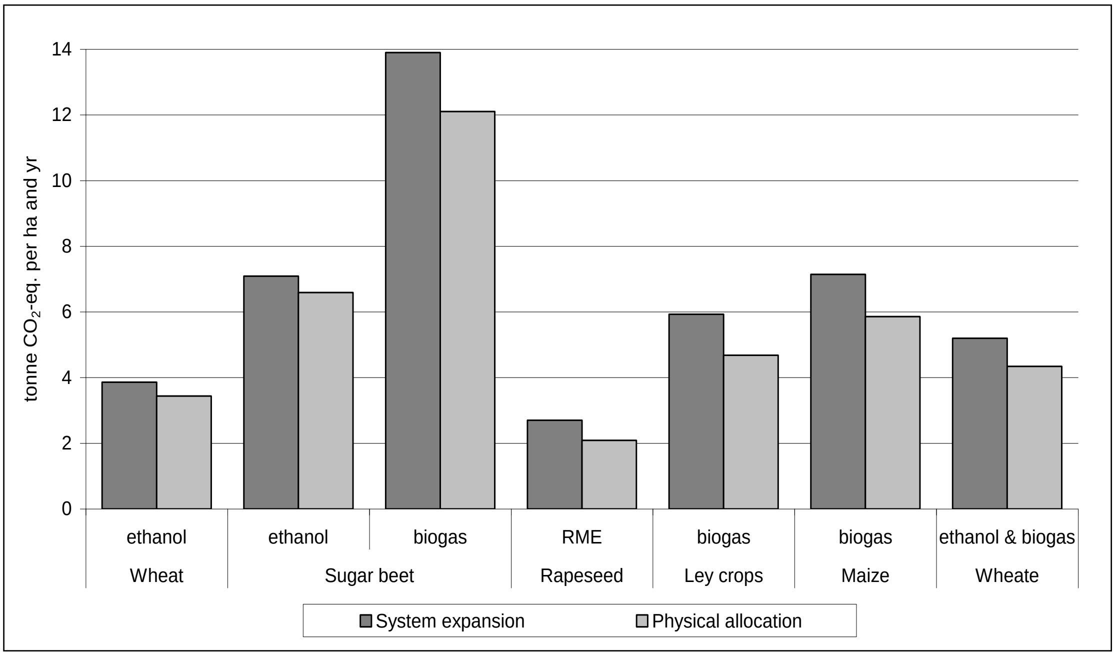

Figure 13. Greenhouse gas savings per hectare and year for each biofuel based on crops when system expansion and energy allocation (excluding crop residues) are applied. Direct carbon stock changes are estimated to take place on 25% of the cultivated area. When producing biogas from sugar beets tops & leaves are included.

5. Sensitivity analysis

5.1 Choice of land-use reference

The choice of land-use reference may have great importance for the climate impact as well as the contribution of biofuels to eutrophication, as is illustrated in the figures of the previous section. Concerning biogenic emissions of nitrous oxide and nitrogen leaching, conservative estimates are made in this analysis so as not to underestimate these emissions, i.e., the land-use reference is unfertilised, grass-covered cropland. Concerning biogenic emissions of carbon dioxide from the soil it is here assumed that direct land-use changes are taking place on a quarter of the cropland used for biofuel production (grass-covered cropland), based on current conditions, and to avoid underestimations. An assessment of the proportion of cultivated areas, which leads to direct land-use changes, should be undertaken on an ongoing basis, because this measure is of great importance for the climate performance of biofuels. This is illustrated in Figure 14.

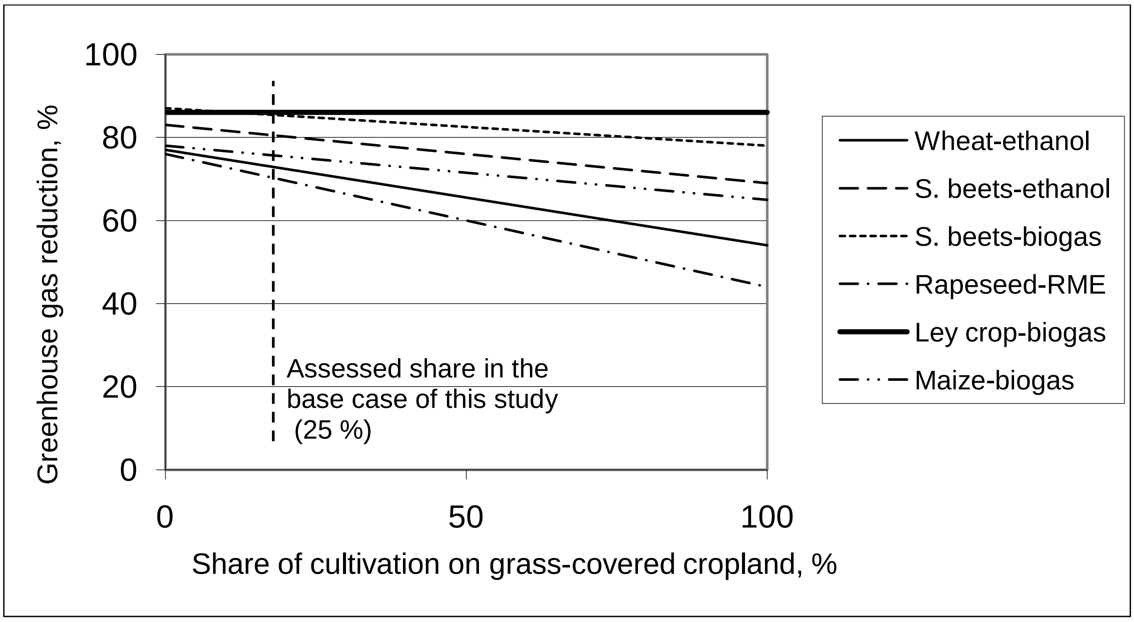

Figure 14. Reduction of greenhouse gases for each biofuel compared to fossil fuels depending on the proportion of the cultivation taking place on grass-covered cropland and when system expansion is applied. The remaining cultivation is assumed to take place on previously open cropland.

5.2 Choice of allocation method

As is clear from the presentation of the results, the choice of allocation method has a very large impact on the results. The calculation method considered to best reflect the current environmental performance for each biofuel is system expansion. In the assessments of current environmental performance the results are also presented based on energy allocation, excluding crop residues (which is applied in the Renewable Energy Directive of the EU). The results of these two calculation methods do, however, often differ, sometimes significantly.

5.3 The quality of feed by-products when applying system expansion

For the biofuel systems that generate by-products in the form of protein feed, especially grain ethanol and RME, the indirect environmental benefits that these feed by-products entail have a significant impact on the result. The reason is that the alternative protein feed these are replacing is soybean meal, which in turn implies a significant environmental impact during production (here relating to average existing soybean cultivation). The share of soybean meal that distillers waste and rapeseed meal are assessed to replace is based, among other things, on the protein quality of each type of feed which may vary. Table 14 shows how the climate benefit of grain ethanol and RME changes when it is assumed that a smaller or larger proportion of soybean meal could be replaced by distillers waste and rapeseed meal. These results clearly show the importance of producing distillers waste and rapeseed meal of high quality to maximise the climate benefit of these feed by-products.

Table 14. Reduction of greenhouse gases for ethanol and RME in percent compared to fossil fuels when the share of soybean meal and barley that is replaced by distillers waste and rapeseed meal varies with a system expansion.

Bio-mass	**Bio-fuel**	**Alternative System expansion**[1]	**Reduction of greenhouse gases (%)**[2]	
			Grassland as land-use reference	*Cultivation of grain as land-use reference*
Wheat	Ethanol	*Alt. 1* 0.6 soybean meal & 0.4 barley	58	97
		Base case 0.4 soybean meal & 0.6 barley	54	93
		Alt. 2 0.2 soybean meal & 0.8 barley	49	89
Rapeseed	RME	*Alt. 1* 0.85 soybean meal & 0.15 barley	48	103
		Base case 0.7 soybean meal & 0.3 barley	44	100
		Alt. 2 0.5 soybean meal & 0.5 barley	40	95

[1] Kg (dry matter) soybean meal and barley that is replaced by 1 kg (dry matter) distillers waste in ethanol production and by rapeseed meal in RME production.

[2] Emissions of greenhouse gases from fossil fuels are assumed to be 83.8 g per MJ.

5.4 Fossil-based electricity and process energy

One factor of great importance for the climate performance of biofuels is the types of electricity and process energy used in the biofuel production. In the base case for biofuels produced in Sweden it is assumed that the Swedish electricity mix and biomass-based process heat (and steam) are used in the fuel plants. If instead natural gas-based or coal-based electricity and process heat (and steam) are used, the emissions of greenhouse gases increase significantly, as is illustrated in Figure 15.

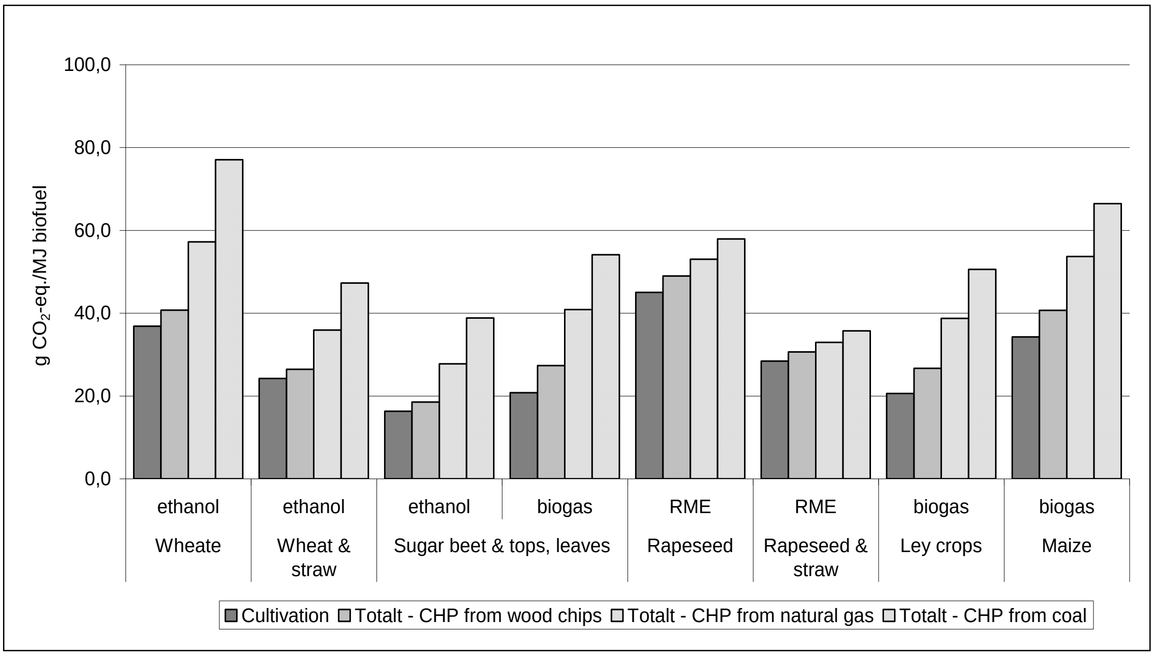

Figure 15. Emissions of greenhouse gases from different biofuels based on crops, expressed as g CO_2-equivalents per MJ fuel, depending on whether the process energy in the fuel plants is based on biomass, natural gas or coal. The diagram applies to unfertilised, grass-covered cropland as land-use reference and energy allocation of by-products.

5.5 Reduced emissions of nitrous oxide when producing fertiliser

The emissions of nitrous oxide from the production of mineral nitrogen fertiliser decrease rapidly thanks to the installation of catalytic nitrous oxide cleaning equipment in an increasing number of fertiliser plants. In the current situation it is estimated that just under half of the plants in Western Europe have nitrous oxide cleaning, which is calculated to give an average emission of 9 g N_2O/kg N (Jenssen and Kongshaug, 2003; Snaprud, 2008). Approximately 60% of the nitrogen fertiliser currently used in Sweden is assessed to come from these facilities, while about 40% is imported from countries outside of Western Europe (Eriksson, 2010). These facilities are assumed to lack nitrous oxide cleaning, which means a nitrous oxide emission of 15 g N_2O/kg N. The nitrous oxide emissions from mineral nitrogen fertiliser used in Sweden today are therefore assessed to amount to an average of 11.5 g N_2O/kg N. When all nitrogen fertiliser production is using catalytic nitrous oxide cleaning the emissions are estimated to be on average approximately 3 g N_2O/kg N (Jenssen and Kongshaug, 2003). Table 15 shows how this affects the total greenhouse gas emissions for each biofuel based on crops (the emissions refer to no allocation).

Table 15. Total emissions of greenhouse gases (g CO_2-eq. /MJ biofuel), excluding allocation, of different emissions of nitrous oxide in the production of nitrogen fertiliser.

Biomass	**Biofuel**	***Unfertilised grassland as reference land use***		***Cultivation of grain as reference land use***	
		Base case[1]	Red. nitrous oxide[2]	Base case[1]	Red. nitrous oxide[2]
Wheat	Ethanol	65	59	32	26
Sugar beets	Ethanol	42	39	22	19
	Biogas[3]	27	26	16	14
Rapeseed	RME	85	77	38	31
Ley crops	Biogas	27	25	0	-2
Maize	Biogas	41	38	22	19

[1] The current level of emissions which is assumed to be on average 11.5 g N_2O/kg N.

[2] Future level of emissions which is assumed to be on average 3 g N_2O/kg N.

[3] Including digestion of tops and leaves.

5.6 Increased leakage of methane in the production of biogas

In previous LCAs of biogas, methane emissions during digestion and upgrading have been pointed out as a very important factor for the climate performance of biogas (Börjesson and Berglund, 2006). In the base case of this study it is assumed that methane leakage amounts to an equivalent of 0.5% of the biogas produced, which assumes the current best technology. In some older biogas systems, however, these leakages may be higher (Lantz et al, 2009). Table 16 shows how the total greenhouse gas emissions are affected if the methane leakage increases to 1.5% of the biogas produced.

Earlier analyses of Börjesson and Berglund (2007) show that if the leakage of methane amounts to approximately 15%, 20% and 30% from upgraded biogas from ley crops, household waste and liquid manure, no climate benefit results compared to petrol as fuel in light duty vehicles.

Table 16. Total emissions of greenhouse gases (g CO_2-eq. /MJ biofuel), excluding allocation, with different levels of methane leakage in the production of biogas.

Biomass	**Biofuel**	***Unfertilised grassland as land-use reference***		***Cultivation of grain as land-use reference***	
		Base case[1]	Incr. methane leak.[2]	Base case[1]	Incr. methane leak.[2]
Sugar beets	Biogas[3]	27	32	16	21
Ley crops	Biogas	27	31	0	5
Maize	Biogas	41	45	22	26

[1] Methane leakage equivalent of 0.5% of the biogas produced.

[2] Methane leakage equivalent of 1.5% of the biogas produced.

[3] Including digestion of tops and leaves.

5.7 Change in methane leakage in the conventional storage of manure

A major indirect gain of biogas production from liquid manure is that a large part of the spontaneous methane emissions which occur when manure is stored conventionally is avoided. In addition, the spontaneous emissions of nitrous oxide are also assessed to decrease. The size of these reduced emissions of greenhouse gases depends, however, on several factors and therefore the uncertainty is large (see Lantz et al, 2009). In addition, the number of studies in which actual and periodic measurements are made over long periods of time are currently limited. In the future, better input data are therefore required in order to be able to make more accurate estimates of the sizes of methane and nitrous oxide emissions from liquid manure storage.

The methane emission is expressed in terms of MCF (Methane Conversion Factor) and is given as a percentage of the maximum methane production per kg VS (Volatile Solids) of the liquid manure. The calculations in the base case of this study correspond to an MCF of 6.5%. This level is lower than that normally calculated for Swedish conditions by the Environmental Protection Agency (2006) (10%), which in turn is based on a calculation methodology developed by the IPCC (2006b). Danish calculations show that the conversion factor may be even higher, around 12% (Sommer et al., 2001). Former Swedish environmental systems studies of manure-based biogas use a conversion factor of around 9-10% (see Börjesson and Berglund, 2007; Lantz et al., 2009). The reason the MCF has been reduced in this study compared to previous Swedish studies is that new Swedish measurements in central and southern Sweden over a season of storage indicate significantly lower spontaneous methane leakages from the storage of cattle manure with and without coverage, equivalent to an MCF of around 3% (Rodhe et al., 2008). Previous analyses show that when semi-permeable covers are used, about 30-40% of the methane formed can be oxidized when it passes the membrane (Sommer et al, 2000). At the same time, coverage of the liquid manure container may mean a temporary reduction of methane emissions of about 70-85% during the storage period, but the methane gas formed and stored as gas bubbles in the liquid manure during the storage period is normally released when the liquid manure is stirred and spread (Nicholson et al., 2002). To get a complete picture of the size of the total spontaneous methane leakage from manure storage, measurements are therefore also necessary from the stirring and spreading, and not only from the storage itself.

When the storage temperature is lowered the risk of spontaneous methane leakages is reduced. One experiment shows for instance 40% lower methane emissions from cattle manure when the storage temperature was lowered from 20 to 11 degrees C (Clemens et al., 2006). The emission level calculated in the base case of this study applies above all to the southern Sweden, i.e. Götaland, where about 70% of the Swedish biogas potential from manure is assessed to exist (Börjesson, 2007; Linné et al., 2008). The spontaneous methane leakages from conventional manure storage, and thus the indirect gain of manure digestion, is therefore estimated to be slightly lower in central Sweden, Svealand, (where just over 20% of the biogas potential from manure is) and especially in northern Sweden, Norrland, (where just under 10% of the potential can be found). The mean temperature during the half year of winter season is on average approximately 5 and 10 degrees lower in central Sweden and northern Sweden, respectively, compared to southern Sweden. Rodhe et al. (2008) show by a measurement over one year that the average storage temperature for liquid manure in Halland (southern Sweden) was about 10 °C, in Uppland (central Sweden) about 8 °C and in Jämtland (northern Sweden) 5-6 °C.

Table 17 shows how the total greenhouse gas emissions from manure-based biogas change when the indirect gain in terms of reduced methane emissions from conventional manure storage is 50% higher (MCF approximately 10%) and 50% lower (MFC approximately 3%) respectively. Emissions of nitrous oxide from the storage of liquid manure are in the base case assumed to be half the size of the levels obtained when using the methodology of IPCC (IPCC, 2006b), based on results of Rodhe et al. (2008) which indicate significantly lower nitrous oxide emissions. In the sensitivity analysis these are also assumed to vary +/- 50%.

Table 17. Total emissions of greenhouse gases (g CO_2-eq. /MJ biofuel) from manure-based biogas, including system expansion, at different levels of methane leakage with conventional manure storage.[1]

Bio-mass	**Biofuel**	***Base case***[2]	***50% higher methane leakage with conventional manure storage***	***50% lower methane leakage with conventional manure storage***
Manu-re	Biogas	-40	-63	-17
		Total reduction in % compared to fossil fuels		
		148	176	120

[1] Including nitrous oxide leakage.

[2] Spontaneous gross leakage of methane with conventional manure storage equivalent to 1.1 kg CH_4 / tonne liquid manure and a leakage of nitrous oxide of 20 g N_2O / tonne liquid manure.

5.8 Energy input in infrastructure – local biogas grids

This study does not include the distribution of biofuels from production plants to filling stations, which is often carried out by truck. The reason is that there are large uncertainties in transport distances depending on the location of the plant, its size, whether or not the biofuel is distributed by mixing in a small amount in petrol and diesel etc. Previous studies also show that distribution of fuel normally has a small impact on the energy balance and environmental effects when the distances are limited (some hundreds of kilometres) (Börjesson and Gustavsson, 1996). A local/regional development of biogas as vehicle fuel is expected to lead to an increased need for local gas grids by which production facilities are connected and the gas is transported to a common upgrading facility. In order to investigate whether this type of infrastructure construction has a significant influence on the energy and environmental performances of the biogas, a summarised calculation is made here.

An example of a local/regional gas grid is the project “Biogas Brålanda” being planned in Västergötland (Eriksson, 2010). In total, a 55 km-long, dual gas pipeline will be built for the transport of raw gas and upgraded vehicle fuel, to which 10 to 15 biogas plants will be connected with upgrading facilities and filling stations. The pipelines are made of polyethylene and have an outer diameter of between 63 and 160 mm adapted for a gas pressure of 4 bar but which can be increased to 10 bar. The pipes are buried by means of excavators. Table 18 shows calculations of the energy input and climate impact this gas grid results in compared to the biogas that will be distributed. The conclusion is that both from an energy and a climate point-of-view, this local gas grid has little importance as the energy input is assessed to equal approximately

1.2% of the energy content of the distributed gas, and the climate impact amounts to the equivalent of approximately 0.85 g CO_2-eq. per MJ of biogas when the depreciation period for the gas grid is assumed to be 20 years (i.e. approximately 1% of the emissions of fossil fuels). With a longer depreciation period the impact of the gas grid is reduced further.

Table 18. Calculations of energy and climate performance of local gas grids based on project ”Biogas Brålanda”.[1]

	Length	**Energy input**	**Greenhouse gas emissions**	**Energy balance**	**Climate impact**
		GJ	ton CO_2-eq.	Energy input / distributed amount of gas - %[5]	g CO_2-eq./MJ distributed gas [5]
Gas pipeline	55 km – Raw gas	23,800[2]			
	55 km Vehicle gas	7,710[2]			
	In total	31,500	2.250[4]		
Excavation	55 km	1,960-2,350[3]	164-197		
Sum		33,500-33,900	2.410-2.450	1,16-1,17	0,83-0,85

[1] Data from Eriksson (2010) if not otherwise indicated.

[2] The outer diameter of the raw gas pipeline and the vehicle fuel pipeline vary between 63-160 mm and 63-90 mm, respectively, and have a total weight of 315 tonnes and 102 tonnes, respectively (Onninen, 2009). The energy input per kg HDPE-plastic (expressed as primary energy) is estimated to be 75 MJ, including energy input in the raw material (Boustead, 2005).

[3] Excavation is carried out by 2 excavators á 25-30 litres of diesel per hour and by tractors á 5-6 litres of diesel per hour. The burial capacity is assessed to be on average 25 metres per hour.

[4] Life cycle emissions of greenhouse gases per kg HDPE plastic are assumed to be 1.9 kg CO_2-eq. regarding production, and 5.4 kg CO_2-eq. (Boustead, 2005).

[5] The amount of raw gas and vehicle gas distributed each year is assumed to amount to 3.2 and 2.0 millions Nm^3 respectively. In energy terms this is equivalent in total to 144,000 GJ. The depreciation period for the gas grid is set to 20 years.

5.9 Improved efficiency through plant breeding and process development

In the future, the environmental performance of biofuels may be improved generally through higher yields per hectare, thanks to, among other things, plant breeding, and through more efficient use of fertilisers. In addition, there is a potential to improve the efficiency in the transformation of biomass into biofuel, both regarding fuel yield and the need for process energy. As is presented in the Appendix there is a spread in the input data regarding the size of the fuel yield and the need for process energy within each production system and which in some cases illustrates the improvement potentials. To concretely exemplify different improvement potentials, results from previous studies of the cultivation of energy crops (Börjesson, 2007a), of wheat-based ethanol (Börjesson, 2007b, 2009), of RME (Mårtensson and Svensson, 2009), and of biogas from manure and residues (Lantz et al, 2009) are used here. Similar improvement potentials usually exist in general for all the fuel systems presented.

Today traditional varieties of wheat are used in the cultivation of ethanol wheat, but breeding is in progress to develop special varieties of "energy wheat" which is especially suitable for ethanol production. The breeding potential of these "energy varieties" is considered greater compared to traditional bread wheat since fewer properties need to be taken into account in the breeding. There are, above all, three properties to maximise: high yield, high content of starch and good hardiness properties. Within a 10- to 15-year period the increased yield of "wheat ethanol" is assessed to be equivalent of about 2 percentage units per year compared to about 1 percentage unit per year for traditional bread wheat (Börjesson, 2007a). Today the starch content is often about 70% of the total dry matter content, but with new ethanol wheat varieties this could be increased towards 75% (Granstedt, 2007). An assessment is therefore that the ethanol yield per kg dry matter grain could by increased from the current 55% up to approximately 58%. This is assessed to simultaneously lead to a slightly lower yield of distillers waste and thus slightly reduced indirect environmental benefits of this feed by-product.

Sugar beets as energy raw material for ethanol or biogas can also be refined to produce greater yields when these are not to be optimised to produce white sugar. By developing a winter beet which is sown in autumn and harvested in the autumn of the following year, a yield up to 25% higher is obtained (Börjesson, 2007a). However, this requires that flowering is "turned off" through genetic engineering as well as making varieties more tolerant to frost and resistant to plant diseases.

Traditional ley crops can also be developed when these are used for biogas production instead of for feed. One example is breeding towards an increased energy yield instead of protein yield. This can also be achieved through changes in the point of time for harvesting and in the composition of grass species, which are jointly estimated to give possibly 10-20% higher yields (Börjesson, 2007a). Depending on the mixture of substrates used in biogas production, it may in some cases be justified to optimise ley crop harvests with regard to high protein yield in order to maximise the biogas yield.

Maize is a relatively new crop in Sweden and is currently used solely as animal feed. Based on the experience in Germany, where maize is the dominating biogas crop, breeding and adapted cultivation systems can give increased harvests in the future when these are dedicated to biogas production. When cultivating maize for animal feed, it is important that there is enough time for the cobs to develop and produce as energy-rich a feed as possible, while this is not required when maize is used as biogas raw material, which makes higher biomass yields possible (Börjesson, 2007a).

A general change from traditional food and feed crops to crops better adapted for energy crops, where an increased biomass yield becomes more important than protein yield etc., for instance, at the same time implies that the need for nitrogen fertilisation can decrease per harvested amount of biomass. This in turn leads to energy savings, reduced greenhouse gases and a lower risk of eutrophication (Börjesson, 2007a).

The ethanol plants of today are not fully optimised from an energy point-of-view. For example, a better adapted integration of a cogeneration plant and an ethanol plant is assessed to give energy savings via the utilisation of more optimal steam pressures for each process and electricity generation, improved heat exchange and recovery of waste heat, and also integration of drying processes etc. In addition, the local conditions can determine the amount of "waste heat" that can be disposed of in, for example, district heating systems. How big the improved efficiency potential is of new ethanol combine plants is difficult to say in general since more detailed technical analyses and descriptions of the local conditions of the site in question (e.g. regarding potential for disposing of heat in district heating systems) are needed in this area. Based on previous theoretical studies of energy combines of different varieties, a conservative estimate is that it should be possible to decrease the energy consumption in a fully developed ethanol plant by 15% compared to the facilities currently in use. For example, if the conditions to utilise "waste heat" are very good (up to 70% of low-grade waste heat), the energy savings are likely to be higher. In the ethanol plant of today the production of "waste heat" is equivalent of approximately 22% of the ethanol production on an energy basis (Granstedt, 2007).

An improved process integration is also possible in RME and biogas plants, which leads to efficiency gains. Examples are improved heat exchange and heat recovery etc. Another measure which leads to greater climate benefits in the production of biogas is to replace biogas with wood chips as fuel in the biogas plant. This may increase the climate benefit by over 5 percentage units compared to fossil fuels (Lantz et al, 2009). An equivalent measure in RME production is to use bio-based instead of fossil-based methanol. In this case as well, the climate benefit can increase by about 5 percentage units compared to fossil fuels (Mårtensson and Svensson, 2009). When producing biogas, the energy and climate benefit is additionally enhanced by complementary post-digestion chambers allowing extra gas collection. The climate benefit of this measure can amount to approximately 3-4 percentage units (Lantz et al, 2009).

The total climate benefit of all the measures described above for grain-based ethanol is assessed to be equivalent to approximately 15 percentage units compared to fossil fuels (Börjesson, 2009). At the same time the energy balance is assessed to improve by approximately 40% (excluding allocation) (Börjesson, 2007b). For other biofuels it is assessed that the equivalent overall climate benefit of different measures is substantial as well, but it varies slightly from one biofuel system to another.

6. Discussion

This study analyses biofuels produced and used in Sweden today, for which our specific conditions have been taken into account. This means that the results may differ from previous and more general studies which have a different geographic resolution, namely, the average for Europe or the global average, and also have a different time perspective, for instance, one or a few decades into the future. An important conclusion of previous life-cycle assessments of biofuels is that it is impossible to generalise over how good or bad ethanol, RME or biogas are from an environmental point-of-view, but this depends entirely on the type of production system and the aspects being considered (see e.g. Börjesson and Berglund, 2007; Börjesson, 2009; Börjesson and Tufvesson, 2010). The purpose of this study is therefore to describe the current environmental performance of Swedish biofuels in the most relevant and transparent manner possible.

A general conclusion which can be drawn from this study is that environmental systems analyses of biofuels are very complex and that there are a large number of parameters to be considered, both concerning the handling of input data and the calculation methodology. Therefore, it is more or less impossible to achieve perfectly fair and “real” assessments. All systems studies and life cycle assessments allow for different types of interpretations, which is also the case for this study. One aim of this study is, however, to be as transparent as possible and clearly point out the factors that have a major impact on the results and on the environmental performance of different biofuels. This knowledge is very important, among other things, for the development of standards and certification of biofuels, as these can focus on the most critical factors. In this way this development of the more sustainable systems can be guaranteed and the development of the less sustainable ones can be avoided.

This knowledge is also important for individual biofuel producers in connection with strategic decisions and priorities of measures to improve environmental performance. This is also becoming increasingly important from a market perspective, when new standardisation and certification systems are developed, such as the RED within the EU and internationally through the ISO standardisation. From a consumer perspective an in-depth knowledge about the environmental performance of biofuels, and about the factors which have a major impact, is also increasingly important. In this way, transport companies and other purchasers and distributors of biofuels, can propose relevant and effective requirements on producers and suppliers to guarantee that increasingly sustainable fuels are supplied.

Another conclusion to be drawn from the present study is that different biofuels have their advantages and disadvantages and that one should not be limited to study solely climate performance, which is in focus today. There are also different types of constraints in production volumes for the various biofuels, which means that there is room for all the systems included in this study in a future biofuel mix. Domestic biofuels based on agricultural raw material can in the future only replace a limited share of the fossil fuels used today. Future focus should thus be on how different biofuels can best cooperate, both in production and in use, to maximise their environmental benefit as well as the proportion of fossil fuel that can be replaced.

7. References

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Appendix 1 – Input data

Table A1. Characterisation indicators used when aggregating emission data for each environmental effect category.

Emissions	Environmental effect category			
	GHG effect (GWP)[1]	Eutrophication (EP)[2]	Acidification (AP)[3]	Photochemical oxidants (POCP)[4]
Carbon dioxide, CO_2	1			
Carbon oxide, CO				0.032
Nitrogen oxides, NO_x		0.13	0.7	
Sulphur dioxide, SO_2			1	
Hydrocarbons, HC				0.42
Methane, CH_4	23			0.007
Nitrous oxide, N_2O	296			
Ammonia, NH_3		0.35	1.88	
Nitrate, NO_3^-		0.10		
Phosphate, PO_4^{3-}		1		
Particles				

[1] Global Warming Potential, expressed as carbon dioxide equivalents.

[2] Eutrophication Potential, expressed as phosphate equivalents.

[3] Acidification Potential, expressed as sulphur dioxide equivalents.

[4] Photochemical Oxidant Creation Potential, expressed as ethylene equivalents (C_2H_2).

Table A2. Crop yield and energy input in the cultivation of energy crops as raw material for biofuel.

Crop	DM-cont.	Yield [1]		Energy input[2] GJ / hectare and year				Energy balance
	%	Ton DM /hectare ,year	GJ / hectare, year	Diesel[3]	Fertil -iser[4]	Others [5]	In total	Energy yield / energy input
Wheat	86	6.4	120	3.9	7.4	3.9	15.2	7.7
Wheat & straw[6]	86 / 85	10.7	200	5.6	7.4	4.2	17.2	11.3
Sugar beets	24	11.0	190	12.8	6.1	1.9	20.8	9.3
Sugar beets & tops & leaves[6]	24 / 14	14.5	260	14.3	6.1	2.1	22.5	11.3
Rapeseed	91	2.8	80	4.4	7.2	2.8	14.4	5.4
R.seed & straw[6]	91/85	6.1	140	5.9	7.2	3.0	16.1	8.7
Ley crop[7]	32	7.5	130	5.2	4.0	1.5	10.7	12.3
Maize[8]	32	9.5	170	5.9	7.8	1.9	15.6	10.7

[1] Crop yields are based on official statistics of yields assembled in Börjesson (2007) and refer to cultivation in Southern Sweden on good cropland. Crop yields for straw and tops & leaves are based on calculations in Börjesson (2007) and the update based on Linné (2010). The higher heating value, expressed as GJ/ton DM, is for wheat 18.4; sugar beets 17.6; rapeseed 27.7; ley crops and maize 17.6; straw (wheat and rapeseed) 17.9 and for tops & leaves 17.6.

[2] Expressed as primary energy.

[3] Diesel use for cultivation and biomass transport (50 km by truck to fuel plant) based on Börjesson (1996) including an improved energy efficiency reached in the past decade of 15% based on Cederberg and Flysjö (2008), Schmidt (2008) and Törner (2008). One litre diesel is equivalent to 42.6 MJ primary energy (Berglund and Börjesson, 2006).

[4] Energy input in fertiliser production for N, P and K is, expressed as MJ/kg, 45, 25 and 5 respectively, based on processed data from Börjesson (1996); Davis and Haglund (1999) and Jenssen and Kongshaug (2003). The fertiliser ration, expressed as kg N-P-K per hectare and year is for wheat 150-25-10; sugar beets 120-20-40; rapeseed 145-25-10 (including preceding crop value of 25 kg N, based on Cederberg and Flysjö, 2008); ley crop 70-30-40 and for maize 140-25-180. Based on processed data from Börjesson (1996); Johnsson and Mårtensson, (2002) and SCB (2004).

[5] Energy input in the form of seeds, pesticides and machinery, based on Börjesson (1996), including an improved energy efficiency of 15% (see above). Energy input in the drying of wheat and rapeseed, based on Mårtensson and Svensson (2009).

[6] It is assumed to be possible to harvest approximately 60% of the biological straw yield in the cultivation of wheat and rapeseed, and a corresponding 50% of the biological tops & leaves yield in the cultivation of sugar beets, based on ecological restrictions and practical aspects (losses in yield) (Börjesson, 2007). In the tops & leaves yield, the upper part of the beet is included which represents between 3-7% of the beet yield (Eriksson, 2010).

[7] Clover-grass ley.

[8] Whole-crop harvest.

Table A3. Energy input in the collection and transportation of residues for biogas[1].

Biomass	DM-content	Collection	Transport			In total	Biogas-yield	In total
	%	MJ/ton	MJ/ ton*km	Km[3]	MJ/ton	MJ/ton	GJ/ ton	MJ/ GJ
Household waste	30	260[2]	2.4	20	48	310	4.2	74
Food industry waste	8	-	1.1	30	33	33	1.3	25
Manure	8	-	1.1	10	11	11	0.56	20

[1] Based on Berglund and Börjesson (2006), Börjesson and Berglund (2006) and Carlsson and Uldal (2009).

[2] Average for collection in densely populated areas (120 MJ/ton), residential districts and country areas (330 MJ/ton).

[3] Estimated average transport distances under current conditions.

Table A4. Emissions from tractor operations and road transport by truck (mg/MJ diesel)[1]

	Emissions					
	CO_2	CO	NO_x	SO_2	HC	Particles
Ploughing	76,000	85	900	2	17	11
Harrowing & sowing	76,000	50	800	2	20	11
Spreading of fertiliser	76,000	70	700	2	27	11
Harvest	76,000	50	800	2	17	11
Pressing of straw	76,000	100	850	2	30	11
Loading	76,000	200	700	2	40	11
Field transport	76,000	120	900	2	28	11
Road transport	76,000	11	720	2	11	11

[1] Based on processed data in Börjesson and Berglund (2006) from original data from Hansson et al. (1998).

Table A5. Emissions in the production of mineral fertiliser[1]

	Emissions							
	CO_2	CO	NO_x	SO_2	HC	Particles	CH_4	N_2O
Nitrogen fertiliser (g/kg N)	3,200	0.36	8.0	4.6	0.18	0.82	3.1	11.5
Phosphorus fertiliser (g/kg P)	2,900	4.6	18	39	3.9	9.5	7.2	0.29
Potassium fertiliser (g/kg K)	440	0.7	2.7	5.9	0.58	1.4	1.1	0.002

[1] Based on processed data in Börjesson and Berglund (2006) from original data in Davis and Haglund (1999). Updates concerning improved efficiency and nitrous oxide emissions (N_2O) from nitrogen fertiliser production are based on Jenssen and Kongshaug (2003) and Snaprud (2008). Here it is assumed that half of the current nitrogen fertiliser production in the Yara facilities is taking place using nitrous oxide cleaning. This plant has currently approximately 60% of the Swedish market (Eriksson, 2010). The remaining share of nitrogen fertiliser is imported from producers outside of Europe, where plants are assumed to lack nitrous oxide cleaning today. Without nitrous oxide cleaning the emissions are assumed to be on average 15 g N_2O/kg N and with nitrous oxide cleaning on average 3 g N_2O/kg N.

Table A6. Emissions in the production of agricultural machinery and in the drying of cereal and rapeseed (mg / MJ energy input)

	Emissions						
	CO_2	CO	NO_x	SO_2	HC	Particles	CH_4
Prod. of machinery[1] (mg/MJ)	85,000	25	90	150	4.0	8.0	0.5
Drying of cereal and rapeseed[2] (mg/MJ)	50,000	13	80	27	5.0	3.3	0.3

[1] Refers to average emissions based on processed data from Börjesson and Berglund (2006). The division between coal, oil and natural gas as primary fuel is assumed to be 23%, 42% and 35%, respectively (Börjesson, 1996b).

[2] Refers to average emissions based on processed data from Mårtensson and Svensson (2009). The division between electricity and heat, which is here based on fuel oil, is assumed to be 34% and 66%, respectively.

Table A7. Nutrient leakage in the cultivation of energy crops as raw material for biofuel[1]

Crop	In total (gross)		Net[2] (Unfertilised grassland as reference)		Net (Grain cultivation as reference)	
	Nitrogen	Phosphorus	Nitrogen	Phosphorus	Nitrogen	Phosphorus
	Kg N / hectare,year	Kg P / hectare,year	Kg N / hectare,year	Kg P / hectare,year	Kg N / hectare,year	Kg P / hectare,year
Wheat	40	0.5	30	0.4	0	0
Wheat & straw	40	0.5	30	0.4	0	0
Sugar beets	30	0.5	20	0.4	-10	0
Sugar beets, tops & leaves	20	0.5	10	0.4	-20	0
Rapeseed	50	0.5	40	0.4	10	0
Rapeseed & straw	50	0.5	40	0.4	10	0
Ley crops	15	0.3	5	0.2	-25	-0.2
Maize	35	0.5	25	0.4	-5	0

[1] Based on processed data from Börjesson and Berglund (2007), Johnsson and Mårtensson (2002) and Flysjö et al. (2008). Refers to average leakage from cropland in Southern Sweden.

[2] Gross leakage of nitrogen and phosphorus from unfertilised, grass-covered cropland is assumed to be 10 and 0.1 kg per hectare and year, respectively.

Table A8. Biogenic emissions of nitrous oxide in the cultivation of energy crops as raw material for biofuels[1]

Crop	Biomass yield	Net (Unfertilised grassland as reference)		Net (Grain cultivation as reference)	
	GJ/ha and year (excluding crop residues)	Kg N_2O / ha and year	g N_2O / GJ harvested biomass (excl. crop res.)	Kg N_2O / ha and year	g N_2O / GJ harvested biomass (excl. crop res.)
Wheat	120	3.1	26	0	0
Wheat & straw		2.5	21	- 0.6	- 3
Sugar beets	190	2.5	13	- 0.6	- 3
Sugar beets, tops & leaves		1.6	8.5	- 1.5	- 8
Rapeseed	80	2.6	33	- 0.5	- 6
Rapes.& straw		2.3	29	- 0.8	- 10
Ley crops	130	2.0	15	- 1.1	- 8
Maize	170	3.2	19	0.1	- 0.6

[1] Based on the calculation method according to IPCC (2006), which includes direct emissions from nitrogen fertilisation and from crop residues that mineralise, as well as indirect emissions through emissions of ammonia and nitrogen leakage. Background emissions from grass-covered, unfertilised cropland are assumed to be on average 0.5 kg N_2O / ha and year (Alhgren et al., 2009).

Table A9. Carbon stock changes in the cultivation of energy crops as raw material for biofuel[1]

Crops	Biomass yield	Net (Unfertilised grassland as reference)		Net (Grain cultivation as reference)	
	GJ/ha and year (excluding crop residues)	Kg C / ha and year	Kg CO_2 / GJ harvested biomass (excluding crop residues)	Kg C / ha and year	Kg CO_2 / GJ harvested biomass (excluding crop residues)
Wheat	120	- 350	- 11	0	0
Wheat & straw		- 500	- 15	- 150	- 2.8
Sugar beets	190	- 350	- 6.5	0	0
Sugar beets, tops & leaves		- 400	- 7.4	- 50	- 1.8
Rapeseed	80	- 350	- 16	0	0
Rapeseed & straw		- 450	- 21	- 100	- 2.6
Ley crops	130	0	0	350	9.5
Maize	170	- 350	- 7.5	0	0

[1] Based on processed data from Börjesson (1999). Carbon stock changes decrease with time and a new steady state is reached after approximately 30 to 50 years.

Table A10. Summary of emissions of greenhouse gases from the cultivation of energy crops as raw material for biofuel, expressed as kg CO_2-equivalents per GJ harvested biomass (excluding crop residues)[1]

Crops	Biomass yield	CO_2-fossil fuels	N_2O-production of fertiliser[2]	Unfertilised grassland as reference		Grain cultivation as reference		In total	
	GJ/ha and year (excl. crop res.)			N_2O-bio-genic	CO_2-bio-genic	N_2O-bio-genic	CO_2-bio-genic	Ref. Unfert. grassl.	Ref. Grain cult.
Wheat	120	9.7	4.4 (1.1)	7.7	11	0	0	33	14
Wheat & straw		11		6.2	15	-0.9	2.8	37	17
Sugar beets	190	8.2	2.1 (0.6)	3.7	6.5	-1.0	0	21	9.3
Sugar beets, tops & leaves		8.8		2.5	7.4	-1.8	0.8	21	9.9
Rapeseed	80	14	6.4 (1.7)	10	16	-1.6	0	46	19
Rapeseed & straw		16		9.0	21	-1.5	2.6	52	24
Ley crops	130	6.4	2.1 (0.5)	4.6	0	-2.3	-9.5	13	-3.3
Maize	170	7.2	2.9 (0.7)	5.8	7.5	0.3	0	23	10

[1] Based on data from the tables above.

[2] Values in brackets refer to emissions when all nitrogen fertiliser factories have installed catalytic nitrous oxide cleaning.

Table A11. Summary of emissions contributing to eutrophication when cultivating energy crops as raw material for biofuels, expressed as PO_4^{3-}eq. per GJ harvested biomass (excluding crop residues)[1]

Crop	Biomass yield	NO_x-fossil fuels	NO_3-leakage		PO_4^{3-}-leakage		In total	
	GJ/ha,year (excl. crop res.)		Ref. Unfert. grassl.	Ref. Grain cult.	Ref. Unfert. grassl.	Ref. Grain cult.	Ref. Unfert. grassl.	Ref. Grain cult.
Wheat	120	5.7	110	0	10	0	130	5.7
Wheat & straw		7.2	110	0	10	0	130	7.2
Sugar beets	190	8.0	46	-23	6.3	0	60	-15
Sugar beets, tops & leaves		8.8	23	-46	6.3	0	38	-37
Rapeseed	80	9.1	230	57	16	0	260	66
Rapes. & straw		11.1	230	57	16	0	260	68
Ley crops	130	5.4	17	-83	4.6	-5	27	-83
Maize	170	5.4	66	-13	7.3	0	79	-7.6

[1] Based on data from the tables above.

Table A12. Estimated average efficiency when biomass is converted into biofuel and the need for external energy in each process respectively.[1]

Biomass	Biofuel	Conversion efficiency [2]		Need for external energy [3]	
		Energy content in biofuel / energy content in biomass, expressed as %		External energy / energy cont. in biofuel, expr. as % (of which electricity is in brackets)	
		Chosen value	Interval	Chosen value	Interval
Wheat (kernel)	Ethanol[4]	55	52-55	54 (13)	49-61
Sugar beets	Ethanol[6]	55	53-55	41 (10)	36-53
	Biogas[6]	75	70-79	28 (20)	25-30
Rapeseed (seed)	RME[7]	60	41-64	15 (6)	8-22
Ley crops	Biogas[8]	62	46-72	25 (18)	20-33
Maize	Biogas[8]	68	52-78	27 (20)	25-38
Manure	Biogas[9]	40	32-50	30 (18)	22-36
Waste-Household	Biogas[9]	60	48-68	20 (15)	15-25
Waste-Industrial	Biogas[9]	60	48-68	22 (15)	15-27

[1] Based on a data compilation of Börjesson (2007) which has been updated and complemented here.

[2] Based on how much energy is contained in the biofuel in relation to the energy contained in the original biomass (excluding crop residues).

[3] Based on how much external energy in the form of heat, steam and electricity (converted into primary energy) is needed to drive the processes, in relation to the energy content in the biofuel produced. This also includes other possible material input needed in the processes as well as upgrading and pressurization of the biogas and transportation and distribution of digestate, expressed as primary energy (energy input in the handling of digestate contributes on average 3 % of the energy content of the biogas). The primary energy factor for forest fuel and biogas-based heat/steam is assumed to be 1.17 (Börjesson and Berglund, 2007) and for the Swedish electricity mix 1.14 incl. losses in distribution but excl. the heat losses in nuclear power production (Lantz et al., 2009).

[4] Based on data from Mårtensson and Svensson (2009), Paulsson (2007), JRC (2006), Bernesson et al. (2006), Fredriksson et al. (2006) and Börjesson (2004). Including the drying of distillers waste and the use of additive.

[5] Based on data from Börjesson (2004) and Edström and Nordberg (2001).

[6] Based on data from Linné et al. (2005), Björnsson (2006), JRC (2006), Mårtensson and Svensson (2009) and Carlsson and Uldal (2009). Including the drying of pulp in the production of ethanol and the use of additive. The biogas yield from beets is based on an average when both beets and tops and leaves are digested (with a specific conversion efficiency of approximately 79% and 58%, respectively).

[7] Based on data from Mårtensson and Svensson (2009), Cederberg and Flysjö (2008), Bernesson et al (2004), Fredriksson et al. (2006) and JRC (2006). Including the addition of methanol and use of other additives.

[8] Based on data from Berglund and Börjesson (2006), Börjesson (2004), Fredriksson et al (2006), Karpenstein Machan (2005) and Carlsson and Uldal (2009).

[9] Based on data from Berglund and Börjesson (2006) and Börjesson and Berglund (2007) which have been updated using data from Lantz et al. (2009) and Carlsson and Uldal (2009).

Table A13. Fuel cycle emissions, expressed as MJ, for the energy carriers used in the manufacturing processes of each biofuel.

	Emissions						
	CO_2	CO	NO_x	SO_2	HC	Particles	CH_4
	g	mg	mg	mg	mg	mg	mg
Swedish average electricity[1]	10	20	20	10	3	3	50
Wood chips[2]	3.3	310	100	40	25	3	5
Natural gas[2]	60	30	80	2	4	3	14
Coal[3]	94	40	45	70	2	25	1100
Biogas – *end-use*[4]	0	20	60	1	1	1	100

[1] Based on updated data applying to current Swedish average electricity, compiled in Lantz et al. (2009) and Mårtensson and Svensson (2009). One MJ electricity is equivalent to 1.14 MJ primary energy including losses in distribution (excl. heat losses in nuclear power production).

[2] Based on processed data in Börjesson and Berglund (2007) from original data from Uppenberg et al (2001) and Brännström-Nordberg et al (2001).

[3] Based on data assembled by Mårtensson and Svensson (2009).

[4] Refers only to ”end-use”-emissions. Based on data from Börjesson and Berglund (2006). Emissions of methane from the biogas process and upgrading are assumed to be the equivalent of 0.5 % of the produced biogas based on the current best technology (Linné, 2009).

Table A14. Assumed efficiencies, expressed as % of the original energy content of the biomass, in the transformation of different fuels to electricity and heat.[1]

	Heat	Combined heat and power generation			Electricity (condensation)
		Heat	Electricity	In total	
Wood chips	90	55	30	85	-
Biogas	95	45	40	85	-
Natural gas	95	45	40	85	58
Coal	90	55	30	85	45

[1] Based on data from Börjesson and Berglund (2007) and Mårtensson and Svensson (2009).

Table A15. Emissions in the transportation and distribution of digestate, expressed as gram per ton digestate[1]

	Emissions					
	CO_2	CO	NO_x	SO_2	HC	Particles
Transportation	1200	0.21	10	0.36	0.60	0.17
Distribution	1900	1.7	15	0.30	0.53	0.23

[1] Based on processed data from Börjesson and Berglund (2006) where the energy input for transportation (10 km) and distribution of the digestate is calculated to be 16 and 25 MJ, respectively, per tonne digestate. The digestate ration per hectare is assumed to be 30 tonnes (approximately 8% DM). One tonne substrate is assumed to generate 1 tonne digestate (see discussion in Berglund and Börjesson, 2006).

Table A16. Emissions contributing to the greenhouse effect and eutrophication from biofuel plants.[1]

Biomass	Biofuel	CO_2-emissions	CH_4-emissions	In total – GHG	NO_x-emissions
		kg / GJ	kg CO_2-eq/GJ	kg CO_2-eq/GJ	g PO_4^{3-}eq/GJ
Wheat (kernel)	Ethanol	5.6	0.6	6.2	1.7
	Biogas[2]	3.5	2.3	5.8	6.2
Sugar beets	Ethanol	4.3	0.5	4.8	1.4
	Biogas[2]	4.3	2.3	6.6	7.6
Rapeseed (seed)	RME[3]	6.7	0.2	6.8	1.0
Ley crops	Biogas[2]	3.8	2.3	6.1	6.8
Maize	Biogas[2]	4.1	2.3	6.4	7.3

[1] Based on forest fuel-based or, alternatively, biogas-based heat/fuel and the Swedish electricity mix (see tables above).

[2] Emissions of methane from the biogas process and upgrading are assumed to be equivalent to 0.5% of the produced biogas based on the current best technology (Linné, 2009). Emissions from transportation and distribution of digestate are also included.

[3] Including emissions of fossil carbon dioxide from natural gas-based methanol used in the process equivalent to 4.8 kg per GJ (Bernesson et al., 2004; Mårtensson and Svensson, 2009).

Table A17. Emissions contributing to the greenhouse effect and eutrophication from biogas systems based on residues.[1]

Biomass	Biofuel	CO_2-emissions	CH_4-emissions[2]	In total – GHG	NO_x-emissions
		kg / GJ	kg CO_2-eq/GJ	kg CO_2-eq/GJ	g PO_4^{3-}eq/GJ
Household waste	Biogas	8.7	2.5	11.2	9.4
Industrial waste	Biogas	5.8	2.5	8.3	5.6
Manure	Biogas	8.9	2.5	11.4	8.5

[1] Includes collection and transportation of substrate, production of upgraded biogas and transportation and distribution of digestate. Production based on biogas-based heat/steam and the Swedish electricity mix (see tables above).

[2] Emissions of methane from the biogas process and upgrading are assumed to be equivalent to 0.5% of the produced biogas based on the current best technology (Linné, 2009).

Table A18. Data for the energy yield of biofuel and by-products as well as allocation with regard to energy content and economic value, respectively.[1]

Crop	Products	Energy yield[2]	Energy allocation	Economic allocation[2]	
				Chosen value	Interval (biofuel)
		GJ/ha, yr	%	%	%
Wheat	Ethanol/distillers waste	65/42	61/39	81/19	74-87
	Ethanol/distillers w./straw	65/42/77	35/23/42	73/17/1	63-80
	Biogas/straw	80/77	51/49	84/16	80-86
Sugar	Ethanol/pulp	105/57	65/35	84/16	75-88
	Ethanol/pulp/tops &	105/57/62	47/25/28	81/15/4	72-85
Rapeseed	RME/rapeseed	47/28/2	61/36/3	72/25/3	56-74
	RME/rapeseed meal/glycerol/straw	47/28/2/59	35/21/1/43	65/23/3/9	44-67

[1] Based on data from Börjesson (2007), updated and complemented, based on Mårtensson and Svensson (2009), Cederberg and Flysjö (2008), Flysjö et al (2008) and Lantz et al. (2009).

[2] 2.1 kg DM wheat gives 1 l ethanol and 0.8 kg DM distillers waste; 2.2 kg DM sugar beets give 1 l ethanol and 0.68 kg DM pulp; 2.0 kg DM rapeseed seed gives 1 l RME, 1.3 kg DM rapeseed meal and 0.1 kg glycerol.

[3] ”Chosen value” is based on average prices for 2008 and “interval” on estimated price variations for the period 2004-2008. The estimated prices were the following: 0.62 €/l ethanol (0.46-0.69); 0.017 €/MJ upgraded biogas (0.015-0.018); 0.88 €/l RME (0.58-0.93); 0.18 €/kg DM distillers waste (0.13-0.21); 0.17 €/kg DM pulp (0.12-0.19); 0.24 €/kg DM rapeseed meal (0.18-0.26); 0.36 €/kg glycerol (0.18-0.54); 0.06 €/kg DM straw (0.05-0.08); 0.05 €/kg DM tops & leaves from beets. 1 € = 10 SEK.

Table A19. Values used for energy content of energy crops and organic residues, biofuel and by-products.[1]

	Energy content	
	MJ / kg	MJ / litre
Wheat (grain)	18.4	-
Sugar beets	17.6	-
Rapeseed (seed)	27.7	-
Ley crops	17.6	-
Maize	17.6	-
Straw	17.9	-
Tops & leaves	17.6	
Manure	17.3	-
Waste (mixed)	17.8	-
Distillers waste (ethanol – wheat)	17.3	-
Pulp (ethanol – s. beets)	16.8	-
Rapeseed meal	15.3	-
Glycerol	16.2	
Ethanol	26.8	21.3
RME	37.2	33.1
Methane	-	35.3 (/Nm^3)
Petrol	43.2	32.2
Diesel	43.1	35.9
Heating oil	42.0	34.4
Wood chips	18.7	-
Methanol	19.8	15.8

[1] Based on Börjesson (2007), JRC (2006) and Mårtensson and Svensson (2009). Applies to per kg dry matter for biomass and corresponds to higher heating value.

Table A20. Alternative products that are currently assumed to be replaced by the by-products obtained from biofuel systems, when system expansion is applied.

By-product	Replacement product			
	Soybean meal	Barley	Wood chips	Glycerol-replacement
	kg DM	kg DM	kg DM	kg
Distillers waste[1] (1 kg DM)	0.4	0.6	-	-
Pulp[1] (1 kg DM)	-	1.0	-	-
Rapeseed meal[1] (1 kg DM)	0.7	0.3	-	-
Straw[2] (1 kg DM)	-	-	0.9	-
Glycerol[3] (1 kg)	-	-	-	1.0

[1] Compiled and processed data from Bertilsson (2008), Cederberg and Flysjö (2008), Börjesson (2007) and JRC (2006), based on content of meltable protein and energy.

[2] Based on large-scale combustion of straw and wood chips with a furnace efficiency of 85% and 90%, respectively (Börjesson and Berglund, 2007).

[3] Based on Mårtensson and Svensson (2009). This is equivalent to replacing 50% fossil-based products and 50% bio-based, respectively, based on the current situation.

Table A21. Data for system expansion for ethanol and RME.

Product	Environmental impact category				
	Energy input	Greenhouse effect	Eutrophication	Acidification	Photochemical oxidants
	MJ	g CO_2-eq.	g PO_4-eq.	g SO_2-eq.	g C_2H_2-eq.
Soybean meal[1] (per kg DM)	9.3	980	5.8	8.2	- [4]
Barley[1] (per kg DM)	2.9	450	5.2	2.8	- [4]
Wood chips[2] (per MJ)	0.04	3.5	0.01	0.02	0.001
Glycerol-replacement – *net effect*[3] (per kg)	- 40	- 1,800	- 0.15	- 1.4	- 0.09

[1] Based on data from Flysjö et al. (2008).

[2] Based on data from Börjesson and Berglund (2007).

[3] Based on Mårtensson and Svensson (2009). Equivalent of replacing 50% fossil-based products and 50% bio-based, respectively, based on the current situation.

[4] Due to a lack of calculations possible differences between by-products and replacement products regarding contribution to POCP are not taken into account here.

Table A22. Nutrient content of crops used as biogas substrate.[1]

Biomass	Nitrogen	Phosphorus	Potassium
	% per ton DM	% per ton DM	% per ton DM
Wheat (grain)	2.1	0.38	0.5
Sugar beets	0.83	0.17	0.83
+ tops & leaves	1.0	0.19	1.2
Rapeseed (seed)	4.0	0.66	0.88
Ley crops	2.3	0.23	2.5
Maize	1.6	0.28	2.0

[1] Data regarding nutrient content are based on SBA (2006). The share of nutrients accessible to plants which is returned to the soil via the digestate is assumed to be equivalent to 70% for nitrogen and 100% for phosphorus and potassium (Börjesson and Berglund, 2007).

Table A23. Amount of mineral fertiliser being replaced by digestate from biogas production based on residues. [1]

Biomass	Nitrogen	Phosphorus	Potassium
	kg per ton substrate	kg per ton substrate	kg per ton substrate
Household waste [2]	4.2	1.2	3.7
Food industry waste [2]	2.2	0.8	2.5
Manure [3]	0.5	0	0

[1] Based on processed data from Börjesson and Berglund (2007) and Berglund and Börjesson (2003).

[2] Amount of nutrients being replaced is based on 70% and 100% of the nitrogen and the phosphorus, respectively, being available to the plants.

[3] The share of ammonium accessible to plants is assumed to increase from 70% in undigested manure to 85% in digested manure.

Table A24. General and direct impacts when digestate replaces mineral fertiliser.[1]

Environmental impact		
Increased supply of carbon to the soil [2]	kg C / ton manure kg CO_2-eq / ton manure	3.6 13
Increased emissions of ammonia [3]	kg NH_3 / ton manure	0.14
Increased leakage of nitrogen [4]	kg N / ton manure kg NO_3-eq / ton manure	0.08 0.3
Sum of Environmental impacts		
Greenhouse effect (GWP)	kg CO_2-eq / ton manure	- 13
Eutrophication (EP)	kg PO_4-eq / ton manure	+ 0.08
Acidification (AP)	kg SO_2-eq / ton manure	+ 0.26

[1] The average digestate ration is assumed to be 30 ton per hectare and year (Börjesson and Berglund, 2007; Lantz et al, 2009)

[2] Based on data from Lantz et al. (2009) which have been adjusted here, where the share of carbon in the digestate that leads to the building up of soil organic matter is assumed to be equivalent to approx. 18%.

[3] Based on processed data in Lantz et al. (2009) from original data of Karlsson and Rodhe (2002) and Rodhe (2009). Losses of ammonia are assumed to be equivalent to 5% of the content of nitrogen in the digestate, which requires an efficient distribution technology and good weather conditions. The losses of ammonia when distributing mineral fertiliser is assumed to be equivalent to 1% of the nitrogen content.

[4] Based on data processed in Lantz et al. (2009) from original data of Sörenssen and Birkemose (2002). Fertilisation with digestate instead of mineral fertiliser is assumed to increase the nitrogen leakage by 10% on average. The average nitrogen leakage is assumed to be 25 kg N per hectare and year.

Table A25. Indirect effects when liquid manure is digested compared to conventional storage.[1]

Environmental impact		
Reduced emissions of methane [2]	kg CH_4 / ton manure kg CO_2-eq / ton manure	1,1 25
Reduced emissions of nitrous oxide [3]	kg N_2O / ton manure kg CO_2-eq / ton manure	0,02 6
Changed emissions of ammonia [4]	kg NH_3 / ton manure	0
Sum of Environmental impacts		
Greenhouse effect (GWP) [5]	kg CO_2-eq / ton manure	- 26
Eutrophication (EP)	kg PO_4-eq / ton manure	0
Acidification (AP)	kg SO_2-eq / ton manure	0

[1] Adjusted data from Lantz et al., (2009) based on a large compilation from the literature (see sensitivity analysis also).

[2] The estimations of methane leakage from liquid manure storage are weakened by great uncertainty since the extent of the leakage depends on a number of factors, among others temperature, which means methane leakage generally decreases the further north in Sweden manure storage is taking place. Methane Conversion Factor (MCF) is assumed to be 6.5%, which is an average of the current calculation method of the Swedish Environmental Protection Agency (SEPA, 2006) which gives a factor of 10% based on IPCC (2006), and values measured during a storage season at 3 sites in Sweden, which gave a MCF of about 3% (Rodhe et al., 2008).

[3] Includes both direct emissions of nitrous oxide from storage of manure and indirect from emissions of ammonia. Based on IPCC (2006) where calculated values of emissions are reduced by 50% since the measurements of Rodhe et al. (2008) have indicated lower levels of emissions.

[4] The ammonia losses are assumed to be the same from the storage of digested and of undigested manure (Lantz et al., 2009).

[5] Net reduction of emissions of methane and nitrous oxide from digestate storage when the equivalent of 5 kg CO_2-eq. / ton bio-fertiliser have been included (Lantz et al., 2009).

Table A26. Energy balance and emissions of greenhouse gases for sugar-cane ethanol.[1]

	Energy balance			Greenhouse gases	
	MJ / ton sugarcane	GJ / hectare and year [2]		kg CO_2-eq./m^3 ethanol	g CO_2-eq./MJ ethanol
Energy input			*Sugarcane prod.*		
Sugar-cane cultivation [3]	109	9.5	Cultivation	107	4.8
Mineral fertiliser [4]	65	5.7	Mineral fertiliser	47	2.1
Transportation	37	3.2	Transportation	32	1.4
In total cultivation	211	18.4	Burning–crop res. [8]	84	3.8
Ethanol prod.-chemicals	19	1.7	Biogenic emissions of nitrous oxide	146	6.6
Equipment etc.	5	0.4	*In total cultivation*	417	18.7
In total industry [5]	24	2.1	*Ethanol production*		
In total energy input	235	20.5	Chemicals	21	0.9
			Equipment etc.	4	0.2
Energy yield			*Total ethanol prod.*	25	1.1
Ethanol	1930	168	Ethanol distribution [9]	51	2.3
Electricity surplus [6]	96	8.4	*Total emissions*	493	22.1
Bagasse surplus [7]	180	16			
In total energy yield	2200	192	*Credit – by-products*		
			Electricity surplus [10]	-74	- 3.3
Energy balance	9.4	9.4	Bagasse surplus [11]	-15	- 0.7
			Net-greenhouse gases	404	18.1

[1] Refers to average ethanol production from sugarcane in Brazil using current production methods, based on data from Macedo and Seabra (2008).

[2] The average sugar-cane yield is estimated to be 87 ton per hectare.

[3] The diesel consumption per hectare is estimated to be 230 litre on average.

[4] The supply of N, P and K is on average 25, 37 and 60 kg per hectare, respectively. Additionally, the amount of lime supplied is the equivalent of 600 kg per hectare.

[5] This does not include energy input in the form of electricity and steam as the production system is self-sufficient in electricity and steam.

[6] Approximately 10% of the ethanol plants of today have combustion equipment that generates high-pressure steam (65 bar and 480 degrees C) which gives a considerably higher electricity surplus than the 90% of plants which generate low-pressure steam (21 bar and 300 degrees C).

[7] Surplus accessible for energy extraction (not pre-burnt on the field before harvest).

[8] Approximately 69% of the area growing sugarcane is currently pre-burnt before harvest which means a certain reduction of the carbon storage in the soil as well as decreased emissions of methane and nitrous oxide.

[9] Based on transportation by truck and an average transportation distance of 340 km between the ethanol factory and the filling station.

[10] Replacement of natural gas-based electricity produced at an efficiency of 40%.

[11] Adjustment in this study as surplus of bagasse for external heat production is assumed to replace other biomass (and not heating oil as in the original study) to become more comparable with the assumptions made for the Swedish biofuel systems. The accreditation of greenhouse gases has been reduced by 90%.

Table A27. Biogenic emissions of carbon dioxide through changed land use in the sugarcane cultivation for ethanol production.[1]

Reference crop	Changed amount of bound carbon	Emissions	
	ton C per ha	kg CO_2-eq./m^3 ethanol	g CO_2-eq./MJ ethanol
Degraded pasture	10	-302	-13.5
Natural pasture	-5	157	7.0
Cultivated pasture	-1	29	1.3
Soybeans	-2	61	2.7
Maize	11	-317	-14.2
Cotton	13	-384	-17.2
Cerrado	-21	601	27.0
Present average [2]		-118	-5.3

[1] Based on data from Macedo and Seabra (2008). Refers to comparison with sugar-cane cultivation without burning of crop residues.

[2] Based on the following current land reference distribution: 50% pasture (70% degraded and 30% natural) and 50% cropland (65% soybeans and 35% remaining crops). The share of Cerrado is less than 1%.

Table A28. Energy input and emissions of greenhouse gases in the transportation of sugarcane ethanol from Brazil to Sweden.[1]

Transportation work	Energy input	Emissions
	MJ / GJ ethanol	g CO_2-eq./MJ ethanol
Truck – 400 km to harbour[2]	9	0.7
Boat – 10 000 km to Sweden	80	6.4
In total	89	7.1

[1] Based on data from Egeskog and Gustafsson (2007).

[2] Adjusted distance based on data from Edlund (2010).

Table A29. Summarising energy input and emissions of greenhouse gases for sugarcane based ethanol in Sweden.[1]

	Energy input	Emissions
	MJ / GJ ethanol	g CO_2-eq./MJ ethanol
Production (net)	106	15.8[2]
Changed land use	-	-5.3
Transportation (to Sweden)	89	7.1
In total	195	17.6

[1] Based on Table A27-29.

[2] Excluding emissions from distribution from factory to filling stations.

Table A30. Additional environmental impacts for sugarcane based ethanol in Sweden, expressed per MJ ethanol.[1]

Environ-mental impact		Cultiva-tion	Pro-cess	Transp –truck	Transp -boat[2]	In total - excl. system expansion	In total - incl. system expansion[3]
EP	mg PO_4-eq.	50[4]	0.2	1.7	21	73	70
AP	mg SO_2-eq.	48	1.4	9.1	210[5]	270	250
POCP	mg C_2H_2-eq.	18	0.2	0.4	9.7	28	26
Particles	Mg	2.1	0.1	0.2	7.6	10	9

[1] Based on new calculations in this study where data from Table A27-A30 and emission data valid for Swedish conditions have been used, i.e. this implies a certain uncertainty in the results.

[2] Based on emission data from NTM (2010).

[3] 0.05 MJ electricity and 0.09 MJ bagasse per MJ ethanol is assumed to replace natural gas-based electricity and biofuels, respectively, according to Table A27. Emission data according to A13.

[4] The nitrogen leakage from sugar-cane cultivation is assumed to amount on average to 15 kg N/ha and year (Simpson et al., 2009).

[5] The sulphur content of ship fuels is assumed to be 2.6%.

Table A31. Fuel yield and energy input in the conversion process in the co-production of ethanol and biogas from wheat.[1]

Parameter	
Conversion efficiency – energy content in biofuel / energy content in biomass, expressed as % [2]	ethanol 55 & biogas 23
Need for external energy - external energy / energy content in ethanol & biogas, expressed as % total fuel yield (of which electricity is in brackets) [3]	30 (14)
As comparison: need for external energy - external energy / energy content in ethanol, expressed as % of only the ethanol yield (of which electricity is in brackets) [3]	*42 (20)*

[1] Based on input data from Börjesson (2004) which have been processed and updated here with regard to current yield levels, process technology etc., and used in this study.

[2] The yield of ethanol and biogas from distillers waste is assessed to amount to 8.6 and 3.6 GJ per ton raw material (wheat), respectively, based on Börjesson (2004) which has been updated with data from Carlsson and Uldal (2009). The yield of biogas from distillers waste is assumed to amount to, on average 63%, expressed in energy terms.

[3] Energy input in the form of heat/steam is assessed to decrease by approximately 50% per MJ ethanol in ethanol production when distillers waste is being digested instead of being dried into feed (Börjesson, 2004; Runesson, 2010). At the same time the input of heat and electricity increases by approximately 10% and 50% per MJ ethanol, respectively, due to the production, upgrading and pressurisation of the biogas (Börjesson, 2004). The energy input for transportation and distribution of the digestate is also included.

Table A32. Changed environmental impact compared to only ethanol production (excluding allocation or system expansion), expressed per MJ ethanol.[1]

Biomass	Biofuel	GWP	EP
		g CO_2-eq.	mg PO_4^{3-}eq.
Wheat (grain)	Ethanol & biogas[2,3]	1.2	0.2

[1] Based on forest fuel-based or alternatively biogas-based heat/steam and the Swedish electricity-mix (see tables above).

[2] Emissions of methane from the biogas process and upgrading are assumed to be equivalent to 0.5% of the biogas produced, based on the current best technology (Linné, 2009). Also includes emissions from transportation and distribution of the digestate.

Table A33. Emissions and environmental impact, expressed per MJ, in the production of additives in ethanol for heavy duty vehicles. [1]

Emissions	CO_2	CO	NO_x	SO_2	HC	Particles	CH_4
	G	Mg	mg	mg	mg	mg	mg
	3.2	0.7	8.9	5.1	13	1.4	0

Environmental impact	GWP	EP	AP	POCP	Particles
	g CO_2-eq.	mg PO_4-eq.	mg SO_2-eq.	mg C_2H_2-eq.	mg
	3.2	1.2	29	5.7	1.3

[1] Based on data assembled by Mårtensson and Svensson (2009). The amount of additive is estimated to represent approximately 7.8% of the total weight of the fuel. The energy input for the production of additive is estimated to be the equivalent of approximately 10% of the energy content of the ethanol.

Table A34. Compilation of studies that describe emissions in the final combustion of fuels in heavy duty vehicles, expressed per MJ fuel.

	Emissions						
	CO_2 (fossil)	CO	NO_x	HC (excl. CH_4)	Particles	CH_4	N_2O
	g	mg	mg	mg	mg	mg	mg
Heavy duty vehicles[1]							
Diesel (MK 3)	n.s.	53	595	17	8	n.s.	n.s.
Diesel (MK 1)	n.s.	58	500	21	6	n.s.	n.s.
RME	-	43	645	8	3	n.s.	n.s.
Ethanol	-	290	370	35	2	n.s.	n.s.
Heavy duty vehicles[2]							
Diesel	n.s.	132	1340	4.4	19	n.s.	n.s.
RME	-	71	1580	2.2	8.6	n.s.	n.s.
Buses[3]							
Diesel (Euro 1)	74	85	957	20	27	n.s.	n.s.
Diesel (Euro 2)	74	92	780	11	13	n.s.	n.s.
Diesel (Euro 3)	74	52	539	9.2	12	n.s.	n.s.
Diesel (Euro 4)	74	200	396	3.1	6	n.s.	n.s.
Diesel (EEV)	74	176	318	0.8	1.6	n.s.	n.s.
CNG (Euro 2)	56	216	846	356	0.4	314	n.s.
CNG (Euro 3)	56	8.5	461	61	0.5	41	n.s.
CNG (EEV)	56	59	126	48	0.3	38	n.s.
Truck[4]							
Diesel	n.s.	340	750	13	24	n.s.	n.s.
RME	n.s.	190	910	13	11	n.s.	n.s.
Heavy duty vehicles[5]							
Diesel	72	11	720	27	21	n.s.	n.s.
Biogas	-	1.8	170	4.3	1.4	36	n.s.
Heavy duty vehicles[6]							
RME	-	11	830	11	11	n.s.	n.s.
Ethanol	-	11	440	22	2.2	n.s.	n.s.
Biogas	-	1.9	180	46	1.9	n.s.	n.s.
Buses[7]							
Diesel	n.s.	8.3	897	2.2	n.s.	n.s.	n.s.
RME	-	33	1120	1.4	n.s.	n.s.	n.s.
Heavy duty vehicles[8]							
Diesel	n.s.	63	735	79	1.4	n.s.	0.05
Diesel (exhausts recirculat.)	n.s.	5.5	481	15	0.01	n.s.	0.16
Ethanol	-	213	358	55	0.14	n.s.	0.04
Ethanol (catalytic converter)	-	2.1	349	14	0.11	n.s.	0.11
Ethanol (exhausts recirc.)	-	4.2	265	16	0.05	n.s.	0.09
Heavy duty vehicles[9]							
Ethanol (ED95) (Euro IV)	-	1.9	197	6.7	1.1	n.s.	n.s.
Ethanol (EVV)		0	110	3.4	0.5	n.s.	n.s.
Ethanol (Pre Euro)		1.1	247	6.1	1.7	n.s.	n.s.
Buses[10]							
Ethanol	-	7.5	390	23	3.5	n.s.	n.s.
Chosen values[11]							
Ethanol (ED100)	-	50	300	10	1	n.s.	n.s.
RME	-	30	700	3	3	n.s.	n.s.
Biogas	-	2	200	4	0.5	40	n.s.
Diesel *(comparison)*	*74*	*50*	*500*	*10*	6	n.s.	n.s.

[1] Based on data from Bernesson (2004) assembled by Mårtensson and Svensson (2009).

[2] Based on data from Krahl et al. (2006) assembled by Mårtensson and Svensson (2009).

[3] Based on data from Nylund (2007).

[4] Based on data from Nylund (2007). Apply to MAN Euro 3-truck – distribution truck.

[5] Based on data from Blinge et al. (1997) assembled by Börjesson and Berglund (2006; 2007).

[6] Based on data assembled by Uppenberg et al. (2001) with original data from among others Blinge et al. (1997) and other sources of data from the 1990's.

[7] Based on data from Almén (2009). Applies to Scania buses and measurements of their operation in regional bus routes.

[8] Based on data from Rehnlund et al. (2007). Applis to Scania DC904 (diesel) and DSI9E01 (ethanol). The technology of recirculation of the exhaust fumes is known as DNOx.

[9] Based on data from Wästljung (2010).

[10] Based on data from Millbrook Proving Ground Ltd (2006). Applies to Scania buses operating in practice in local traffic.

[11] Estimation based on current fuel quality, vehicle technology and cleaning equipment, i.e. the aim is as fair a comparison as possible for all fuels and with current and new vehicles on the market today.

(n.s: not stated)

Table A35. Compilation of studies that describe emissions in the final combustion of fuels in light duty vehicles, expressed per MJ fuel.

	Emissions						
	CO_2	CO	NO_x	HC (excl. CH_4)	Particles	CH_4	N_2O
	g	Mg	mg	mg	mg	mg	mg
Light duty vehicles[1]							
Diesel	n.s.	132	1340	4.4	19	n.s.	n.s.
RME	-	71	1580	2.2	8.6	n.s.	n.s.
Light duty vehicles[2]							
Petrol	72	190	36	27	3.6	n.s.	n.s.
Biogas	-	36	27	17	1.7	17	n.s.
Light duty vehicles[3]							
RME	-	160	290	21	21	n.s.	n.s.
Ethanol (E85)	-	310	18	21	1.8	n.s.	n.s.
Biogas	-	35	28	18	1.9	450	n.s.
Private car – flexifuel[4]							
Petrol (E5)	n.s.	340	10	22	0.08	3.3	n.s.
Ethanol (E85)	-	210	6.7	22	0.07	3.3	n.s.
Biogas (CBG)	-	210	7.4	26	0.04	19	n.s.
Limiting value – Euro 5 (Otto engine) [5]	n.s.	1500	90	105	7.7	150[6]	n.s.
Limiting value – Euro 5 (diesel engine)	n.s.	1500	550	150	15	n.s.	n.s.
Chosen values[7]							
Ethanol (E100)	-	200	10	20[8]	1	n.s.	n.s.
RME	-	100	550	20	10	n.s.	n.s.
Biogas	-	200	10	20	0.5	40	n.s.
Petrol *(comparison)*	*72*	*350*	*10*	*20*	*2*	n.s.	n.s.

[1] Based on data from Nylund (2007). Applies to Volkswagen Transporter 1.9 TDI – light-duty van.

[2] Based on data from Blinge et al. (1997) assembled by Börjesson and Berglund (2006; 2007).

[3] Based on data assembled by Uppenberg et al (2001) with original data from, among others, Blinge et al. (1997) and other sources of data from the 1990's.

[4] Calculated average values based on data from Westerholm et al. (2008).

[5] Based on limiting values Euro 5 valid as of 2009 (Delphi, 2009). The fuel consumption per km is assumed to be equivalent to 0.65 MJ (0.75 l petrol per 10 km) for Otto engines and 0.33 MJ for diesel engines.

[6] Refers to total emissions of hydrocarbons (non-methane HC and methane).

[7] Estimation based on current fuel quality, vehicle technology and cleaning equipment, i.e. the aim is as fair a comparison as possible for all fuels and with current and new vehicles on the market today. Includes information from Stålhammar (2010).

[8] Including uncombusted ethanol (see e.g. BEST, 2009).

(n.s: not stated)

Table A36. Environmental impacts in the end-use of biofuels in light- and heavy-duty vehicles (per MJ).[1]

Product	Environmental impact category				
	Greenhouse effect (GWP)	Eutrophication (EP)	Acidification (AP)	Photochemical oxidants (POCP)	Particles
	g CO_2-eq.	mg PO_4-eq.	mg SO_2-eq.	mg C_2H_2-eq.	mg particles
Light-duty vehicles					
Ethanol (E100)	0	1.0	7.0	15	1.0
RME	0	72	385	12	10
Biogas	0.9	1.0	7.0	15	0.5
Petrol *(comp.)*	*72*	*1.0*	*7.0*	*20*	*2*
Heavy-duty vehicles					
Ethanol [2]	0 (3.2)	39 (40)	210 (240)	6.0 (12)	1.0 (2.3)
RME	0	91	490	2.0	3.0
Biogas	0.9	26	140	2.0	0.5
Diesel *(comp.)*	*74*	*65*	*350*	*6.0*	*6.0*

[1] Based on particular values chosen from Table A34 and A35.

[2] Refers to ED100 and ED95 in brackets (based on Table A33).

Appendix 2 – Tables of results

Table A37. Compilation of the environmental impact of each fuel when the whole production chain is included (from cultivation/collection to ready to use fuel), expressed per MJ fuel. The first value applies to unfertilised grassland as land reference and the second value to cultivation of crops.

Fuel system	Allocation[1]	Environmental impact				
		GWP	EP	AP	POCP	Particles
		g CO_2-eq.	mg PO_4-eq.	mg SO_2-eq.	mg C_2H_2-eq.	mg
Crops						
Wheat – ethanol	No	65.1 / 31.8	234.7 / 12.0	105.9	3.2	8.57
	Energy	40.7 / 19.9	146.7 / 7.5	66.2	2.0	5.36
	Econ.	53.6 / 26.2	193.3 / 9.9	87.2	2.6	7.06
	Syst. exp.	38.9 / 5.6	30.4 / -192.3	-80.3	3.2	8.57
Wheat & straw – ethanol	No	73.7 / 40.2	239.4 / 14.9	122.5	3.6	8.95
	Energy	26.4 / 14.4	85.8 / 5.3	43.9	1.3	3.21
	Econ.	54.6 / 29.7	177.3 / 11.0	90.7	2.6	6.63
	Syst. exp.	42.2 / 8.6	34.0 / -190.4	-85.2	2.5	8.95
S. beets – ethanol	No	42.0 / 21.7	110.0 / -25.5	107.2	3.2	5.96
	Energy	26.2 / 13.6	68.7 / -15.9	67.0	2.0	3.72
	Econ.	34.8 / 18.0	91.1 / -21.1	88.7	2.6	4.93
	Syst. exp.	25.7 / 5.4	-56.5 / -192.0	17.5	3.2	6.58
S. beets – biogas	No	32.5 / 18.4	83.2 / -11.1	107.6	3.2	4.43
	Energy	32.5 / 18.4	83.2 / -11.1	107.6	3.2	4.43
	Econ.	32.5 / 18.4	83.2 / -11.1	107.6	3.2	4.43
	Syst. exp.	25.1 / 11.0	106.4 / 12.2	158.7	2.7	1.83
S. beets, tops & leaves – ethanol	No	40.1/ 20.5	65.5 / -60.8	108.5	3.2	6.14
	Energy	18.5 / 9.5	30.3 / -28.1	50.1	1.5	3.07
	Econ.	31.8 / 16.2	51.9 / -48.2	86.0	2.5	4.92
	Syst. exp.	21.1 / 1.5	-101.0 / -227.3	18.8	3.2	6.14
S. beets, tops & leaves – biogas	No	27.4 / 15.9	46.0 / -29.7	99.2	3.0	4.56
	Energy	27.4 / 15.9	46.0 / -29.7	99.2	3.0	4.56
	Econ.	27.4 / 15.9	46.0 / -29.7	99.2	3.0	4.56
	Syst. exp.	18.1 / 6.6	74.4 / -1.3	156.0	2.5	1.26
Rapeseed – RME	No	84.8 / 38.4	420.6 / 110.7	134.4	3.2	10.0
	Energy	48.9 /	242.7 / 63.9	77.5	1.8	5.77

		22.2				
	Econ.	58.8 / 26.6	291.4 / 76.7	93.1	2.2	6.92
	Syst. exp.	46.6 / 0.2	200.4 / -109.6	-127.1	2.9	10.0
Rapeseed & straw – RME	No	94.0 / 47.2	428.0 / 115.1	154.4	3.7	10.46
	Energy	30.6 / 15.4	139.5 / 37.5	50.3	1.2	3.41
	Econ.	58.4 / 29.3	265.8 / 71.5	95.9	2.3	6.50
	Syst. exp.	50.1 / 3.3	206.6 / -16.1	-130.0	2.2	10.46
Ley crops – biogas	No	26.7 / 0.3	49.9 / -126.4	107.7	3.4	6.46
	Energy	26.7 / 0.3	49.9 / -126.4	107.7	3.4	6.46
	Econ.	26.7 / 0.3	49.9 / -126.4	107.7	3.4	6.46
	Syst. exp.	11.5 / -14.9	69.3 / -107.0	86.8	2.2	0.06
Maize – biogas	No	40.7 / 21.7	122.8 / -4.1	108.6	3.3	6.83
	Energy	40.7 / 21.7	122.8 / -4.1	108.6	3.3	6.83
	Econ.	40.7 / 21.7	122.8 / -4.1	108.6	3.3	6.83
	Syst. exp.	29.5 / 10.5	141.8 / 14.9	106.9	2.3	1.53
Wheat – ethanol & biogas	No	46.8 / 23.3	165.7 / 8.6	76.7	2.3	6.2
	Energy	46.8 / 23.3	165.7 / 8.6	76.7	2.3	6.2
	Econ.	46.8 / 23.3	165.7 / 8.6	76.7	2.3	6.2
	Syst. exp.	37.5 / 14.0	170.6 / 13.5	64.5	1.6	2.2
Residues						
Organic household waste – biogas	No	10.3	8.4	47.0	1.6	1.4
	Energy	10.3	8.4	47.0	1.6	1.4
	Econ.	10.3	8.4	47.0	1.6	1.4
	Syst. exp.	-2.3	27.7	61.0	0.6	-4.0
Organic food waste – biogas	No	8.3	5.6	32.1	1.6	1.1
	Energy	8.3	5.6	32.1	1.6	1.1
	Econ.	8.3	5.6	32.1	1.6	1.1
	Syst. exp.	-15.8	63.2	129.3	-0.2	-8.8
Liquid manure – biogas	No	11.4	8.5	48.8	2.2	1.5
	Energy	11.4	8.5	48.8	2.2	1.5
	Econ.	11.4	8.5	48.8	2.2	1.5
	Syst. exp.	-40.4	22.6	119.5	2.1	0.8
Sugar cane						
Ethanol (import)	No	21.6	71	262	28	10
	Energy	18.9	62	229	24	8.71
	Econ.	-	-	-	-	-
	Syst. exp.	17.6	68	241	26	9.0

[1] *No allocation* means that all environmental impact is assigned to the biofuel, *energy allocation* that the environmental impact is divided between the fuel and the by-products according to their energy content, *economical allocation* that the division is based on the economic value of the products, and *system expansion* that the indirect environmental effect produced when the by-products replace alternative products is included.

Table A38. Emissions of greenhouse gases in the cultivation of raw material, expressed as g CO_2-eq. per MJ fuel.

		CO_2-fossil	N_20-fert. prod.	N_2O-biogenic		Changes in soil carbon content		In total	
				Unf. grassl	Grain cult.	Unf. grassl	Grain cult.	Unf. grassl	Grain cult.
Wheat	Ethanol	17.7	7.9 (2.1)	14.0	0.0	19.3	0.0	58.9	25.6
Wheat & straw	Ethanol	20.2	8.0 (2.1)	11.4	-2.8	28.0	8.6	67.6	34.0
Sugar beets	Ethanol	14.9	3.9 (1.0)	6.7	-1.8	11.7	0.0	37.2	16.9
	Biogas	10.3	2.7 (0.7)	4.7	-1.2	8.2	0.0	25.9	11.8
Sugar beets, tops & leaves	Ethanol	15.0	3.6 (1.0)	4.2	-4.5	12.5	1.6	35.3	15.7
	Biogas	9.0	2.2 (0.6)	2.5	-2.7	7.5	0.9	21.2	9.4
Rapeseed	RME	23.5	10.7 (2.8)	16.9	-2.6	26.9	0.0	78.0	31.6
Rapeseed & straw	RME	26.4	10.8 (2.8)	15.1	-4.6	34.9	7.8	87.2	40.4
Ley crops	Biogas	10.3	2.9 (0.8)	7.4	-3.7	0.0	-15.3	20.6	-5.8
Maize	Biogas	10.6	4.2 (1.1)	8.5	0.5	11.0	0.0	34.3	15.3
Wheat	Ethanol & Biogas	12.5	5.6 (1.5)	9.8	0.0	13.6	0.0	41.5	18.1

Table A39. GWP per MJ fuel (the whole production chain but without end-use in vehicles) excluding changes in carbon stock but including biogenic emissions of nitrous oxide, i.e. without a defined alternative land-use reference, and also the reduction in comparison with fossil fuels.[1]

		System expansion		Energy allocation	
		g CO_2-eq.	Reduction in %	g CO_2-eq.	Reduction in %
Wheat	Ethanol	19.6	77	27.9	67
Wheat & straw	Ethanol	14.2	83	16.0	81
Sugar beets	Ethanol	14.0	83	19.7	76
	Biogas	16.9	80	24.3	71
Sugar beets, tops & leaves	Ethanol	8.6	90	13.0	84
	Biogas	10.6	87	19.9	76
Rapeseed	RME	19.7	76	35.3	58
Rapeseed & straw	RME	15.2	82	20.7	75
Ley crops	Biogas	11.5	86	26.7	68
Maize	Biogas	18.5	78	29.7	65
Wheat	Ethanol & Biogas	23.9	71	33.2	60

[1] Emissions of greenhouse gases from fossil fuels are assumed to be 83.8 g per MJ, based on the RED of the EU.

Table A40. GWP per MJ fuel (the whole production chain but without the end-use in vehicles) including changes in carbon stock, equivalent to 25 % of the cultivated area for each crop and excluding changes in carbon stock, equivalent to 75 % of the cultivated area based on an assessment of the current conditions, as well as a reduction in comparison with fossil fuels.[1]

		System expansion		Energy allocation	
		g CO_2-eq.	Reduction in %	g CO_2-eq.	Reduction in %
Wheat	Ethanol	24.4	71	30.9	63
Wheat & straw	Ethanol	21.2	75	18.5	78
Sugar beets	Ethanol	16.9	80	21.6	74
	Biogas	18.9	77	26.3	69
Sugar beets & tops, leaves	Ethanol	11.7	86	14.4	83
	Biogas	12.5	85	21.8	74
Rapeseed	RME	26.4	68	39.4	53
Rapeseed & straw	RME	23.9	71	23.7	72
Ley crops	Biogas	11.5	86	26.7	68
Maize	Biogas	21.2	75	32.4	61
Wheat	Ethanol & Biogas	27.3	68	36.6	56

[1] Emissions of greenhouse gases from fossil fuels are assumed to be 83.8 g per MJ, based on the RED of the EU.

Table A41. Emissions of compounds from biofuels contributing to eutrophication (PO_4^{3-}-eq. / MJ) (the whole production chain but without the end-use in vehicles) when system expansion and energy allocation (excluding crop residues) are applied respectively and with different land-use references.

		System expansion		Energy allocation	
		Unfertilised grassland	Cultivation of grain	Unfertilised grassland	Cultivation of grain
Wheat	Ethanol	30	-192	147	8
Wheat & straw	Ethanol	34	-190	86	5
Sugar beets	Ethanol	-56	-192	69	-16
	Biogas	106	12	83	-11
Sugar beets, tops & leaves	Ethanol	-100	-227	30	-28
	Biogas	74	-1	46	-30
Rapeseed	RME	200	-110	243	64
Rapeseed & straw	RME	207	-16	140	38
Ley crops	Biogas	69	-107	50	-126
Maize	Biogas	142	15	123	-4
Wheat	Ethanol Biogas	170	13	166	9

Appendix 3 – Sensitivity analyses

Table A42. Changed contribution to GWP for grain ethanol and RME when system expansion is used where the share of soybean meal being replaced by distillers waste and rapeseed meal, respectively, is altered (g CO_2-equivalents/MJ biofuel) (the whole production chain but without the end-use in vehicles).

		Rapeseed meal					
		0.85 and 0.15 resp.		0.7 and 0.3[1] resp.		0.5 and 0.5 resp.	
		Unfertilis. grassland	Grain cultiv.	Unfertilis. grassland	Grain cultiv.	Unfertilis. grassland	Grain cultiv.
Rapeseed	RME	43.9	-2.5	46.6	0.2	50.3	3.9
Rapes. & straw	RME	47.4	0.5	50.1	3.3	53.8	7.0

		Distillers waste					
		0.6 and 0.4 resp.		0.4 and 0.6[1] resp.		0.2 and 0.8 resp.	
		Unfertilis. grassland	Grain cultiv.	Unfertilis. grassland	Grain cultiv.	Unfertilis. grassland	Grain cultiv.
Wheat	Ethanol	35.4	2.1	38.9	5.6	42.5	9.1
Wheat&straw	Ethanol	38.7	5.1	42.2	8.6	45.7	12.1

[1] Corresponds to the base case in the report.

Table A43. Changed contribution to GWP depending on whether the process energy in the fuel plants is based on biofuels, natural gas or coal (g CO_2-equivalents/MJ biofuel). The results refer to unfertilised grasslands as land-use reference and energy allocation of by-products (the whole chain of production but without end-use in vehicles).

			Total emissions		
		Cultivation	Process – bio[1]	Process – NG	Process – coal
Wheat	Ethanol	36.8	40.7	57.2	77.0
Wheat & straw	Ethanol	24.2	26.4	35.9	47.3
Sugar beets	Ethanol	23.3	26.2	38.7	53.7
	Biogas	25.9	32.5	46.0	59.2
Sugar beets, tops & leaves	Ethanol	16.3	18.5	27.8	38.8
	Biogas[2]	20.8	27.4	40.9	54.1
Rapeseed	RME	45.0	48.9	53.0	57.9
Rapeseed & straw	RME	28.4	30.6	33.0	35.7
Ley crops	Biogas	20.6	26.7	38.8	50.5
Maize	Biogas	34.3	40.7	53.7	66.4

[1] Corresponds to the base case in the report.

[2] Includes digestion of tops and leaves.

Table A44. Total contribution to GWP (g CO_2-eq./MJ biofuel) at different levels of nitrous oxide emissions in the fertiliser production, excluding allocation (the entire chain of production but without end-use in vehicles).

		Unfertilised grassland		Cultivation of grain	
		3 g	11.5 g[1]	3 g	11.5 g[1]
Wheat	Ethanol	59.3	65.1	26.0	31.8
Wheat & straw	Ethanol	67.8	73.7	34.2	40.2
Sugar beets	Ethanol	39.1	42.0	18.9	21.7
	Biogas	30.5	32.5	16.4	18.4
Sugar beets, tops & leaves	Ethanol	37.4	40.1	17.8	20.5
	Biogas[2]	25.8	27.4	14.3	15.9
Rapeseed	RME	76.9	84.8	30.6	38.4
Rapeseed & straw	RME	86.1	94.0	39.3	47.2
Ley crops	Biogas	24.5	26.7	-1.9	0.3
Maize	Biogas	37.5	40.7	18.6	21.7

[1] Corresponds to the base case in the report.

[2] Includes digestion of tops and leaves.

Table A45. Total contribution to GWP (g CO_2-eq./MJ biofuel) at different levels of methane leakage in the process, excluding allocation (the whole chain of production but without end-use in vehicles).

		Unfertilised grassland		Cultivation of grain	
		0.5%[1]	1.5%	0.5%[1]	1.5%
Sugar beets	Biogas	32.5	37.1	18.4	23.0
Sugar beets, tops & leaves	Biogas[2]	27.4	32.0	15.9	20.5
Ley crops	Biogas	26.7	31.3	0.3	4.9
Maize	Biogas	40.7	45.3	21.7	26.3

[1] Corresponds to the base case in the report.

[2] Includes digestion of tops and leaves.

Appendix 4 – Report from the critical review

Reviewers: Lars-Gunnar Lindfors, Linus Hagberg & Andreas Öman, IVL Svenska Miljöinstitutet AB, Box 21060, S-100 31 STOCKHOLM

The mandate

IVL, The Swedish Environmental Institute has on behalf of the Swedish Gas Centre (SGC) conducted a critical review of the study "Life Cycle Assessment of Biofuels in Sweden". The study has been conducted by Pål Börjesson, Linda Tufvesson and Michael Lantz associated with Lund University, Faculty of Engineering at the Department of Technology and Society, Division of Environmental and Energy Systems Studies. The reviewing commission was initiated mainly to ensure that the methodology used in the study under review follows the appropriate standards in this field (SS-ISO 14040:2006 and SS-ISO 14044:2006) and good practice. These standards highlight among other things the importance of transparency, which implies that the methods of calculation used and why and what assumptions have been made, are presented. Apart from the methodological issue in itself, the validity of the conclusions of the study has been examined. It should be emphasised that the mandate does not include examining the quality of the data used other than that regarding the chosen method.

The reviewing process

The review is not the result of an individual reviewing effort after the completion of the study but has been an ongoing process since the study was initiated. The reviewing process began with the examiners participating in a reference group meeting at which the design of the study was discussed. The subsequent procedure was that the authors on a number of occasions sent a draft of the final report, which was commented on in writing and returned. Telephone meetings usually followed each annotated draft of the report. At these meetings, the authors were able to meet the arguments raised, and also receive clarification of comments. Upon receipt of each new draft of the report, the reviewers in charge assessed whether previous comments had been attended to or not.

Results of the review

Within the scope of this study, the authors made life cycle assessments of biofuels available in Sweden today (2010). The study is a full LCA, i.e. the life cycle begins with the cultivation of raw material and ends in the end-use of the biofuel.

An important part of the reviewing process has been to guarantee a transparent study, i.e. that it must be clearly stated how calculations were made and why, the assumptions made, and to show how uncertainties affect the result. With such a transparency the reader of the report is given the conditions necessary to interpret the information as accurately as possible. The reviewers find that the report provides clear descriptions and motivations of the choice of functional unit, system boundaries and assumptions in the majority of cases. Input data underlying the results of the study are clearly shown and the source of the data is clearly stated. An aspect concerning the transparency of the input data is that some of the original data have been complemented, updated, and/or revised. It is not always clear in what way this has taken place, making it more difficult for the reader to take into account how the uncertainty mentioned affects the result.

The results of the study are presented as different environmental impact categories, such as their contribution to the greenhouse effect (Global Warming Potential, GWP) and eutrophication (Eutrophication Potential, EP), that the use of a fuel entails from "cradle" to "gate". These categories have an important pedagogical value as they are used to show what type of environmental impact the life cycle emissions of the product (fuel) give rise to. However, the emission parameters (per fuel) that are the basis of the result are not reported in a uniform manner. This would be of great value for those readers who are interested in specific emission parameters the fuel in question gives rise to during its life cycle, and would increase the usefulness of the study.

The authors show a clear awareness of how different assumptions affect the result, an insight not least apparent in how the results of the study are presented. The inventory part of an LCA is complicated by the fact that the life cycles of different products are linked to each other even though an LCA focuses on a single product at a time. The solution is to apply different kinds of allocation principles. With these principles, the environmental impact of a manufacturing process involving various functions can be attributed to the product being studied. At the same time, the choice of allocation method can have a major impact on the result as is also made clear in the study.

In particular, one of these allocation principles, system expansion, has been the subject of discussion during the reviewing process. In short, system expansion can be said to be a principle in the LCA methodology which is used to credit the product system studied with any possible environmental benefits the by-products of the product system can generate when they replace another product on the market. Here this refers to the by-products generated in the biofuel process.

The criticism of system expansion is that the result is therefore valid only under certain, specified conditions. As users of the data do not always have the opportunity to familiarise themselves with the assumptions implicit in the result there is thus a risk that data are used in contexts where they may be misleading. System expansion can therefore build in a greater uncertainty than is necessary in the result. In this report this is dealt with in a satisfactory manner as the results are presented with various alternative calculation methods (including system expansion). Thus the reader is given the opportunity to understand that the use of system expansion will have a significant impact on the numerical results. It is also emphasised in text that system expansion is valid only under certain conditions.

A general impression of the study is the many pedagogically important features that give the reader the prerequisite insights to understand the uncertainties inherent in the results produced by the LCA methodology. This is clear not least by fact that the result is calculated using different allocation principles, but is also found in many other contexts, not least through an extensive sensitivity analysis. It is, for example, illustrated how different assumptions about land use for growing energy crops on cropland affect the outcome.

The interpretation of the results is also presented clearly and, as mentioned, the necessary sensitivity analyses that capture the uncertainties embedded in the results are included. The result is thus presented in a way worthy of imitation.

The conclusions drawn are also formulated in a balanced manner and fully motivated by the results of the study.

Endnotes

We note that the comments of the reviewers have been addressed in a satisfactory way in the present final version of the report. It would, however, be desirable that the result, together with the summary of environmental impact categories, is also presented divided into each emission parameter.

To sum up, the methodological choices and implementation on the whole can be declared to be of high quality compared to good practice in the field. The study also essentially follows the requirements of SS-ISO 14040:2006 and SS-ISO 14044:2006.

The reviewers also wish to emphasize, as do the authors, that it is of importance that the users of the results familiarise themselves with and understand the conditions underlying the different calculations and what impact they have on the result.

The reviewers would finally like to convey their appreciation of the open and friendly way with which the work of reviewing has been carried out.

Stockholm the 10th of May
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