

Environmental Assessment of Ethanol
Produced from Corn Starch and used as an
Alternative to Conventional Gasoline for Car Driving

By Per H. Nielsen and Henrik Wenzel

June 2005

**The Institute for Product Development
Technical University of Denmark**

Content

Executive Summary.....	3
1 Introduction.....	9
1.1 Study commissioner and motivation	9
1.2 Objectives.....	9
1.3 Decision support and system delimitation	10
2 Method	13
2.1 System analysis.....	13
2.2 Methodology for environmental impact assessment.....	13
2.3 Assessment criteria	14
2.4 Reference unit and functional unit	14
3 Production of ethanol from corn starch and application as fuel.....	15
3.1 Production of corn	16
3.2 Transport of corn to ethanol factory	19
3.3 Production of ethanol from corn	19
3.4 Transport, storage and distribution of ethanol	23
3.5 Use of ethanol as fuel for car driving.....	24
4 Results of the baseline scenario	26
4.1 Energy balance	26
4.2 Environmental impact assessment of car driving.....	27
5 Sensitivity analysis of results from the baseline scenario	31
5.1 Sensitivity to assumption on displacement of animal feed by DDGS.....	31
5.2 Sensitivity to assumption on efficiency of ethanol as fuel for car driving.....	33
5.3 Sensitivity to geographical variation of corn production	33
6 Extensions of the baseline scenario	36
6.1 Scenario of using stovers as feed or energy sources.....	36
6.2 Scenario including the opportunity cost of extra land use.....	41
6.3 Scenario of petrochemical ethanol	42
7 Comparison with other studies	43
8 Interpretation and conclusion	47
9 References	50
Appendix 1: Conversion factors.....	53
Appendix 2: Inventory	54
Appendix 2: Normalisation.....	68

Executive Summary

Introduction:

This report presents an environmental assessment of ethanol produced from corn starch and used as an alternative to conventional gasoline for car driving – involving the use of the enzymes Termamyl SC and Spirizyme Fuel from the company Novozymes A/S. The study addresses the case where bioethanol is used as the main constituent of the fuel as well as the case where ethanol is added in a smaller percentage.

The study has been carried out by Per H. Nielsen and Henrik Wenzel, The Institute for Product Development, Technical University of Denmark during November and December 2004 and final version of the report has been made in June 2005.

Methodology:

The study is based on the Life Cycle Assessment (LCA) method, which is a generally accepted method for assessing the environmental impact of different processes throughout the product chain. An LCA provides the basis for choosing the environmentally most attractive process from a number of alternative processes providing the same service. The current assessment is in agreement with the ISO 14040 requirements and is based on the principles described by Wenzel et al. (1997). The modelling has been facilitated in SimaPro 6.0 LCA software.

Goal and scope:

The overall objective of the study is to evaluate the environmental impact of substituting conventional gasoline for car driving with ethanol produced from corn starch. More specifically there are 2 overall objectives:

- a) to compare conventional gasoline with E10 gasoline (10% ethanol instead of MTBE) in a conventional gasoline vehicle
- b) to compare conventional gasoline with E85 gasoline (85% ethanol and 15% gasoline) in a flexible fuel vehicle

The *functional unit* serving as basis for the comparison is *driving one mile* in both cases.

Geographical scope: The majority of corn based ethanol is currently produced in the US, where the advantages and disadvantages are subject to comprehensive discussion. Thus, the study refers to US conditions and most data is derived from recognised US institutions. A comparison with central US studies is also included.

Technological and temporal scope: The bioethanol technology has developed significantly in recent years and continues to do so. The most recent data for ethanol production in the United States have been used. The study includes an assessment of the environmental consequences of some not yet realized options, namely as use of corn stovers for animal feed or fuel for combined heat and power production (CHP).

The study addresses use of agricultural land for corn growing and is, as a first scenario, based on an assumption that unlimited land for biomass production is available. The study shall, however, look ahead, as it has to cover the period of amortisation of any investments related to bioethanol production. As the situation for biomass availability may change, due to potential future changes in demand, e.g. for CO₂-neutral fuels, it is uncertain if biomass continues to be of unlimited availability. Therefore, an alternative scenario is included in which biomass becomes limited, implying that any use of it will have an opportunity cost of depriving any better uses of it.

Scope of impact assessment: Following environmental impact categories, for which standardised impact assessment methods exist, have been considered:

- Global warming potential (kg CO₂-equivalents)
- Acidification potential (g SO₂-equivalents)
- Eutrophication potential (g PO₄-equivalents)
- Photochemical ozone creation potential (g ethylene-equivalents) (summer smog)

Following resource indicators have been considered:

- Energy consumption (MJ fossil energy carrier)
- Use of agricultural land (m²·year)

Key assumptions:

- One scenario assuming unlimited availability of biomass, and one alternative scenario assuming limited availability
- Production of ethanol is based on dry milled corn
- Data on ethanol production represent a modern plant with high energy efficiency
- Displacement of animal feed as a result of Distillers Dried Grain with Solubles (DDGS) production is included in the study
- Fuel efficiency is similar for conventional gasoline and E10 (9.5 km/litre) whereas fuel efficiency for flexible fuel vehicle (E85) is 9.9 km/litre
- The marginal source of electricity is natural gas

Results:

Based on the first assumption, that the availability of biomass is unlimited, the results are as shown in the table below. The table indicates the total environmental load from driving one mile on conventional, E10 and E85 fuel, respectively. Changes refer to impact from displacing conventional gasoline with either of the two alternatives. Positive changes are favourable to corn ethanol, whereas negative changes are disadvantageous.

Total changes of environmental impact potential per one mile driving, assuming unlimited availability of biomass:

Impact category	Conventional gasoline	E10 gasoline		E85 gasoline	
			Change		Change
Global warming (kg CO ₂ -equivalents)	0.53	0.51	0.017	0.36	0.17
Photochemical smog (g ethylene equivalents)	0.57	0.55	0.023	0.21	0.36
Acidification (g SO ₂ -equivalents)	1.1	1.2	-0.11	2.0	-0.87
Nutrient enrichment (g PO ₄ -equivalents)	0.09	0.27	- 0.18	1.7	-1.6
Fossil energy consumption (MJ)	6.8	6.5	0.25	4.0	2.8
Use of agricultural land (m ² in one year)	-	0.038	-0.038	0.34	-0.34

The table shows that use of corn ethanol as fuel for car driving under this assumption is favourable in terms contributions to global warming and photochemical smog formation and in terms of fossil energy consumption but disadvantageous in terms of contributions to acidification and nutrient enrichment.

If biomass becomes a priority resource, e.g. as a CO₂-neutral fuel, and of limited availability due to increased demand for it, any use of it will deprive society of other potentially better uses of it. This may be the situation in e.g. Denmark in the future covered by the study (which is the amortisation period for any investments in bioethanol production) due to demand for CO₂-neutral fuels and scarcity of oil and gas. The probability that such a situation arises in USA in the near future is not known, but with increasing world interest in CO₂ reductions, the probability is there. It has been outside the scope of this study to conduct a probability analysis on how the future situation will be on biomass availability, and in the absence of a probability analysis, the two future scenarios should be interpreted with equal probability until further qualification on this issue is provided.

The scenario of limited biomass availability has, however, not been given equal weight in terms of underlying work and qualification of data background, and it is included here as a quite rough illustration of the environmental implications of producing bioethanol under the boundary conditions of limited biomass availability. The scenario assumes an alternative use of the corn and corn stovers for combined heat and power production, and this use is compared to the use for bioethanol production. Moreover, it is assumed that the biomass can substitute fossil fuels for both heat and power production on a 1:1 basis (1 MJ : 1MJ). This is, for comparison, more or less the case with the use of biomass on the Danish energy sector. There is some uncertainty related to this scenario, the biggest uncertainty being that biomass for energy purposes would probably not be corn and corn stovers in the first place, but a more energy efficient biomass crop. The two uses of corn and corn stovers are thus compared only as a rough illustration of the environmental implication of choosing to use these specific crops for bioethanol instead of heat and power under general boundary conditions of limited biomass availability. For the sake of simplicity, only contribution to impacts on global warming has been addressed.

The results indicate, that there is a higher global warming reduction by using the biomass for heat and power than for corn ethanol for car driving. Using the same amount of corn and corn stovers for CHP as for bio-ethanol production gives approximately 50% higher CO₂ reduction. If a future situation is, that society wants to get the highest CO₂ reduction for the available biomass, use of corn for bio-ethanol for car driving will, therefore, result in an increased CO₂ emission.

Breakdown of results:

To explain the results and ease interpretation, a breakdown on contributions to the results is done within the scenario of unlimited biomass availability, see the table below.

The main contributions to the environmental impacts from producing bioethanol within the scenario of unlimited biomass availability

	Fossil energy	Global warming potential	Smog formation	Acidification potential	Nutrient enrichment potential	Agricultural land use
Corn production incl. fertilizer	21%	45%	37%	82%	96%	100
Transport of corn and ethanol	5%	4%	26%	6%	-	-
Heat and electricity consumption at ethanol plant	72%	49%	36%	10%	-	-

Main sources of impact are agriculture and heat consumption of the ethanol plant. It is worth noticing that transport only contributes very little to the energy load of bioethanol production.

Comparison with similar studies:

Much discussion has been going on in the US about the energy balance of producing ethanol from starch. As a consequence it has become important to compare the current study with other studies.

The three most important differences between this study and most other studies are:

1. This study addresses the environmental impact from driving one mile. Most other studies build on thermal energy balances and ignore the fuel efficiency of ethanol.
2. In addition to energy this study includes a comparative evaluation of the impact in terms of global warming, acidification, smog formation, nutrient enrichment and land use.
3. This study addresses a potential future opportunity cost of using biomass for bio-ethanol. No other of the identified studies does that.

In addition to these overall scope related differences, the actual data used for the calculations have been compared. The current study has aimed at data representing state of the art level for farming and bioethanol production and thus builds on data which in some cases are in the high end compared to older studies. The table below roughly illustrates the data of the current study in comparison with the studies by Pimentel (1991,2001, 2003), Keeney and de Luca (1992), Marland and Turhollow (1990), Lorenz and Morris (1995), Wand et al. (1999), Agri Food Canada (1999), Shapouri et al. (2002, 2004). The table shows that for all parameters the data for this study are within the overall range represented by these studies. The relatively high corn yield has been addressed in sensitivity analyses (see below).

	This study	Maximum	Minimum
Corn yield	139 Bu/acre	139 Bu/acre Shapouri 2004	110 Bu/acre Pimentel 1991
N-fertilizer application rate	134 lb/acre	136 lb/acre Pimentel 1991	125 lb/acre Shapouri et al 1995
N- fertilizer production	24,400 Btu/lb	37,551Btu/lb Pimentel 1991	18,392 Btu/lb Shapouri 2002
Corn ethanol conversion rate	2.64 Gal/bu	2.69 Gal/bu Agri and Agr Food Canada 1999	2.50 Gal/bu Pimentel 1991,2001,2003
Ethanol conversion process	56,000 Btu/gal	75,117 Btu/gal Pimentel 2001	40,850 Btu/gal Wang 1999
Total energy use	84,700 Btu/gal	131,067 Btu/gal Pimentel 1991	68,450 Btu/gal Wang et al 1999
Co-products energy credit	7,500 Btu/gal	27,579 Btu/gal Lorenz and Morris 1995	6,728 Btu/gal Pimentel 2003

Sensitivity analyses – robustness of results:

In order to evaluate the robustness of the results, sensitivity analyses have been performed on a number of parameters which are expected to influence the result significantly and where uncertainties/variations of data input exist. Sensitivity analyses have been carried out on a) corn production – including yield and agricultural practises b) fuel efficiency of ethanol and c) use of DDGS for animal feed. All sensitivity analyses have been carried out within the scenario of unlimited biomass availability.

The agricultural data of the current study are based on a weighted average of data from nine states. The sensitivity analysis shows a significant impact of the geographical variation of corn yield and agricultural practises (5% less or 35% more depending on impact category) and emphasises the need for evaluation of areas most suited for corn production.

The data for efficiency of ethanol as fuel for E85 cars has been selected in the middle of the range of data published. The extreme values of fuel efficiency represent adjustments of the current data on fossil energy consumption in the range from 10% more to 5% less depending on impact category.

The current study includes replacement value of the DDGS as feed for pigs. If the DDGS product was used for cattle instead, where it mainly substitutes soybean meal the energy credit provided becomes significantly less, resulting in an increase of 10% of the total energy for ethanol production.

The sensitivity analyses show how great changes are if critical data are adjusted in a downward or upward direction. The selected parameters have a notable influence on the result, and the analyses indicate that other reasonable assumptions on critical parameters may provide somewhat different results in favour as well as disfavour of corn ethanol.

Interpretation and conclusion:

The results show that there is no simple conclusion regarding the environmental benefits of substituting fossil based gasoline with bioethanol. First of all, the assumptions on the future availability of biomass and the judgement of the probability, that there will be an opportunity cost related to the use of biomass, are crucial. Secondly, within the assumption of unlimited availability of biomass, the conclusion is not unambiguous either: For the fossil fuel consumption and the environmental impacts of global warming and smog formation, bioethanol is favourable whereas for the aspects of acidification, nutrient enrichment and land use, conventional gasoline is preferable.

Such a situation calls for a deeper analysis, especially a probability analysis of the future availability of biomass, and a more detailed investigation of the individual impact potentials and a weighting of these. Particularly nutrient enrichment induced by agriculture should be studied more carefully. First and foremost, the data on emissions from farmland are very uncertain. Secondly the actual impact of emissions depends very much on local conditions. An emission which causes severe damage to the environment in certain areas may have very limited impact in other areas. Similarly, the aspect of land use needs to be given specific attention whenever farming expands to new areas or agriculture changes from food to non-food production.

For an overall comparison of the various alternatives it should also be mentioned that this study has only addressed toxicity aspects qualitatively. This means that the potential toxicity impacts from e.g. pesticides applied during corn growing and the potential displacements of toxicity due to cleaner exhaust gas emissions while driving have not been quantified.

MTBE is widely used as anti-knocking agent in gasoline and has got much attention over the past years because it is recalcitrant in the environment and can pollute groundwater seriously when gasoline is spilled. Ethanol can displace MTBE in gasoline and is not associated with the same concern because it is readily degradable in environment. A comparison of ethanol produced from corn and ethanol produced from mineral oil indicates that corn-ethanol has advantages with respect fossil fuel consumption and to a some degree contributions to global warming whereas contributions to acidification and nutrient enrichment appears to be in favour of mineral oil based ethanol.

The advantages and disadvantages of producing ethanol from corn are subject to debate in The United States these years. This study contributes to this debate by

- calling attention to the importance of ethanol fuel efficiency for a proper evaluation of bioethanol for driving
- showing that the fossil energy consumption from driving is less on bioethanol than on conventional gasoline if biomass is of unlimited availability
- showing also, however, that use of biomass for combined heat and power production will be more environmentally efficient than using it for ethanol production for car driving, implying that using it for bioethanol at the cost of using it for heat and power production will increase overall global warming contribution from society.

1 Introduction

Growing concern on global warming and oil supply from unstable regions of the world has increased interest in application of ethanol produced from biomass as alternative to conventional gasoline in the United States during the past years.

Ethanol can be produced in large scale from corn starch and used as fuel for cars, and is considered a promising mean to meet the concerns by governmental organisations such as the National Biomass Initiative¹ (an initiative by the United States Department of Agriculture and U.S. Department of Energy) and US Environmental Protection Agency², and several NGOs/ stakeholder organisations such as The American Coalition for Ethanol³, Journey to Forever⁴ National Corn Growers Association⁵ and The Institute for Local Self-Reliance⁶.

The present study is a holistic environmental assessment, a so-called life cycle assessment, of the environmental consequences of producing ethanol from corn starch and using the ethanol as an alternative to conventional gasoline. It is, thus a comparative study, and it comprises all consequences from the growing of the corn/extraction of the oil to and including driving the car. Among other issues, the study includes a total energy balance of substituting gasoline by ethanol, and it contributes, thus, to the debate about the overall energy balance and environmental implications of replacing conventional gasoline with ethanol which has been raised by e.g. Patzek (2004), Hodge (2002) and David Pimentel/Andrew Ferguson (see National Biomass initiative (2004)).

1.1 Study commissioner and motivation

The study is financed by the Danish company Novozymes A/S and the applied environmental model is delivered to Novozymes together with the present report.

Novozymes is producing enzymes for conversion of starch to sugars for fermentation into ethanol and is interested in a deeper understanding of ethanol production and application from an environmental point of view in order to participate in the discussion in the United States about the environmental issues related to production and use of corn based ethanol.

1.2 Objectives

The aim of the study is therefore to analyse the environmental consequences of using bio-ethanol produced from corn in car fuels in the United States. As part of the environmental assessment, an overall energy balance of substituting gasoline with bio-ethanol has been made.

This objective is met by an assessment of the consequential energy balance, environmental impacts and resource use induced by application of ethanol produced from corn to

¹ See National Biomass Initiative (2004).

² www.epa.gov, see <http://www.epa.gov/otaq/consumer/fuels/altfuels/altfuels.htm>

³ www.ethanol.org

⁴ www.journeytoforever.org

⁵ www.ncga.com

⁶ www.ilsr.org

conventional gasoline for car driving in 1) a 10% mixture and 2) an 85% mixture of ethanol with conventional gasoline.

Moreover, it is the objective to assess the essential system boundary conditions for the results and conclusions and to do sensitivity analyses and comparisons with key US publications on these.

As discussed in the following section, it is compulsory to match the system delimitation and boundary conditions to the decision that the assessment is meant to support – and the other way round, it is bidding to acknowledge the constraints on the interpretation of results implied by the chosen system boundaries.

1.3 Decision support and system delimitation

Life Cycle Assessment (LCA) is by nature a tool to support decisions, and the decision to be supported by the LCA is, therefore, central to defining the objective and the methodological issues like boundary conditions, system delimitation and choice of assessment criteria. The overall criterion for the methodological choices is that the results of the LCA shall, as well as possible, reflect the environmental consequences of the decision to be supported by the LCA. Any decision maker reading the LCA shall, therefore, pay attention to the delimitations made and the match between these and the taken decision. Likewise should the initiator and the conductor of the LCA be well aware and very transparent about the decisions that are actually supported by the study.

An LCA on bio-ethanol for car fuel is a good example of the importance of matching system boundaries to the decision making. For the sake of transparency and explanation of the delimitation of the study and constraints on the decisions supported by this study, this is further explained. The explanation is supported by the illustration in Figure 1.

In most systems studied by LCA, the resources entering the system are considered unlimited, and using them implies no opportunity cost. Alternative uses of resources may exist, but using them for one purpose does not restrain any use of them for any other purpose society may choose. Moreover, systems governed by a free market economy, will themselves by the free generation of market prices identify the priority uses of the resources.

Market prices, however, do not take account for the costs of externalities like e.g. environmental impacts, and striving to minimise societal costs and optimise societal benefits in cases where externalities are important, one has to base decision and priority setting on analyses instead of market forces. Moreover, many systems (e.g. in agriculture) are characterised by public regulations through quotas and subsidies and not free markets price generation. Furthermore, some systems may imply competitive uses of resources that are of limited availability. In such cases of limited resource availability, society may have opportunity costs of using (and subsidising) one use of resources over alternative uses that would have had less costs or higher benefits. Or in other words, using resources of limited availability for one purpose deprive society the opportunity of using them for other purposes.

Optimising a system using resources of unlimited availability follows a conventional 'demand driven' decision path, i.e. competitive products and technical solutions are compared, and no opportunity cost of using the resources are included in the analysis. Optimising a system using resources of limited availability, however, requires a 'supply driven' decision pathway, in which competitive uses of the resources are compared.

The LCA methodology is in principle developed to take account for any opportunity costs deriving from sub-optimal uses of limited resources. As explained in the subsequent section, any LCA is by nature an analysis of decision consequences – the environmental LCA being an analysis of the environmental consequences of the decision supported by the LCA. For the study of bio-ethanol in question, LCA methodology is quite clear. If the use of biomass for ethanol production in reality will deprive society a better use, both environmentally and in terms of societal economy, the consequence of such use of biomass will be an extra environmental impact compared to the better resource use. And this extra impact should be ascribed to ethanol production.

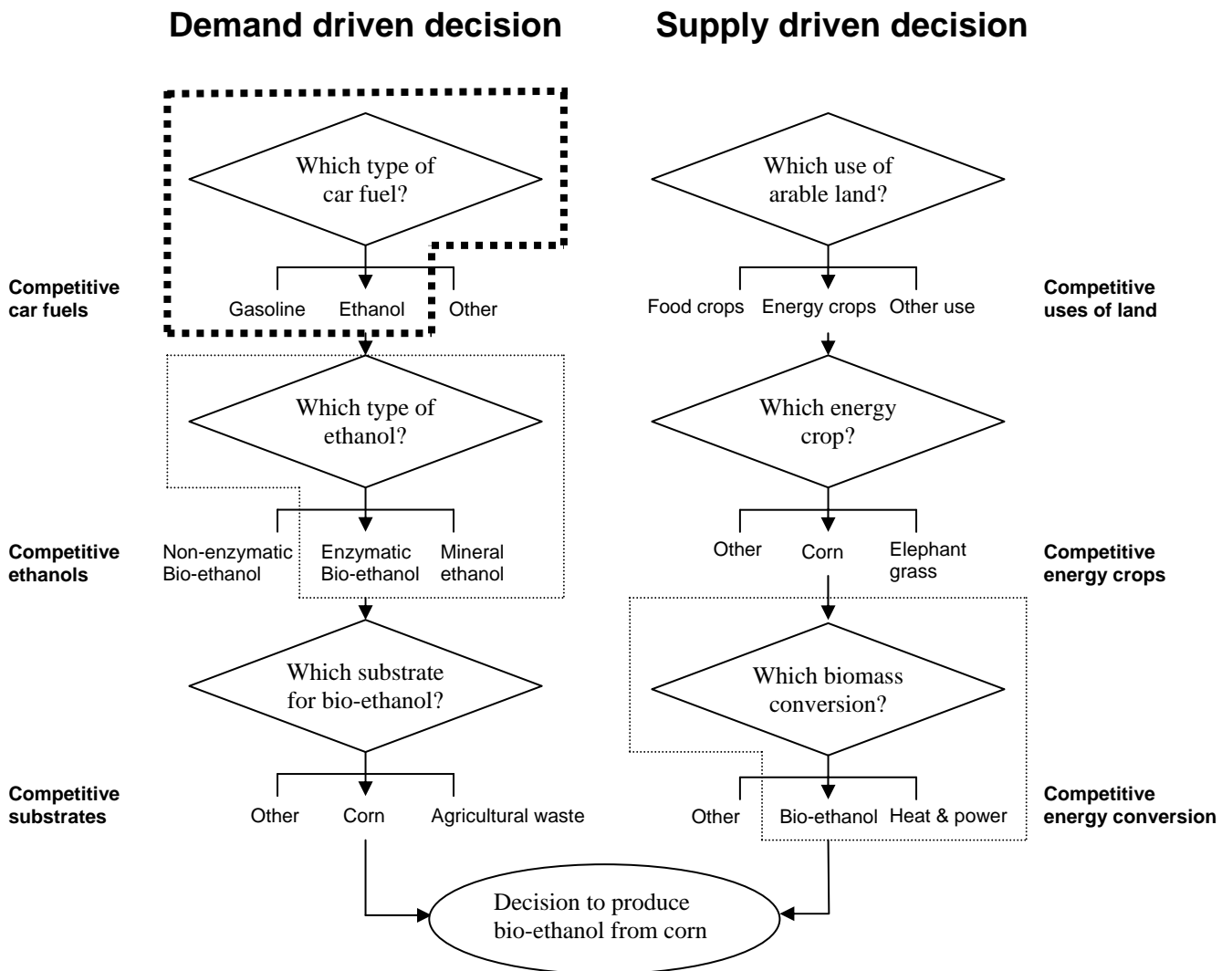


Figure 1. Decision paths leading to the decision of producing ethanol from corn. Left hand side is a demand driven decision path, whereas right hand side is a supply driven decision path. Bold dotted line is the decision intended to be supported by the base study of the present report, whereas thin dotted lines indicate decisions supported by a sensitivity analysis within the study

To further acknowledge the point, one can look at the actual situation in Denmark versus USA. In Denmark, the use of biomass as a CO₂-neutral fuel in the energy sector is one of the prioritised means of meeting the commitments of CO₂ reduction within the frames of the Kyoto

protocol. Biomass for this purpose does, however, come somewhat short, and Denmark will need a number of other means to meet the goals, and there will, thus, probably be an opportunity cost of establishing bio-ethanol production from Danish biomass in terms of lost opportunity of using it for heat and power production (Heding, 2005). Using biomass for bioethanol production would in this case not mean taking the biomass from agriculture or forestry, but taking it out of the heat and power plants implying an increased need for fossil fuel there. Such an increased need for fossil fuel would be a consequence of society's use of biomass for ethanol and thus a direct and simple system extension following normal LCA methodology.

In USA, on the other hand, the energy sector does not at present have the capacity to take anything near the excess biomass from agriculture and forestry. The LCA methodology in this case is, therefore, not a simple case of system extension in order to account for actual consequences of depriving the energy sector its bio-fuel. But doing an LCA on bio-ethanol implies looking around 30 years into the future, this time period being the supposed amortisation time of investments in bio-ethanol factories. In case, therefore, that biomass is of limited availability compared to potential attractive future uses of it, and that using it as fuel for heat and power production is of economic priority to society compared to bio-ethanol production, there will be a future opportunity cost of using it for bio-ethanol. As the opportunity cost is not there today, LCA practice will be to include such an opportunity cost in one scenario for the future, and then discuss the probability of such a scenario in the interpretation of the LCA. The analysis of such a probability may well prove the scenario to have a high probability, and therefore influence the overall interpretation in the direction of the conclusions from such a scenario.

The concept of 'limited resource availability' should be understood as a state, at which an economically attractive use of a resource exists, but the supply side is governing the extent of its use, i.e. the market for the resource is 'supply driven'.

The present LCA is a study of bio-ethanol produced from corn in USA and used as car fuel in mixtures with gasoline. The basic study is conducted to support a conventional demand driven decision of choosing to mix bio-ethanol into conventional gasoline. But the study acknowledges that the market for biomass for energy purposes in the future may be supply driven, and that more attractive uses of the biomass may exist. Therefore, the study includes a scenario in which the biomass is used for combined heat and power production, in order to assess the environmental difference between using it for ethanol and for combined heat and power and thus any opportunity cost related to bio-ethanol production.

The study does not include an assessment of possible alternative uses of agricultural land for other energy crops than corn. If the decision was in fact to use the land for energy crops for CHP production, more efficient crops for this purpose than corn might exist. The inclusion of a scenario in which corn is used for CHP is, therefore, to be seen only as an indication of the opportunity cost there may be in depriving society the opportunity of using biomass for CHP.

Moreover, the study includes a scenario in which the ethanol is produced from petrochemical sources, in order to compare this to the bio-ethanol production pathway.

2 Method

The environmental assessment is based on principles described by Wenzel et al. (1997) which are in agreement with ISO 14040. Moreover, it is conducted according to the principles of the consequential LCA, which is today's best scientific practice. It implies that the LCA is comparative and dedicated to identify the environmental consequence of choosing one alternative over the other, see further explanation of comparative and consequential LCA in Wenzel (1999) and Weidema and Ekvall (2004).

2.1 System analysis

The study addresses production of ethanol and application hereof in the transportation sector where ethanol is mixed with conventional gasoline for private car driving, and it covers all environmentally important processes in the systems which are either induced by ethanol production or displaced.

The geographic scope of the study is fixed to United States of America with respect to production and application of ethanol and to Denmark with respect to production of enzymes. The time and technology perspective is fixed to the presently best available production conditions with respect to corn growing and ethanol production. The study, thus, refers to modern corn and ethanol production in the United States, and the results are considered very dependant of the geographical location and the applied technology. Since the technology is furthermore developing fast in the considered field, the results are only considered valid in the United States for a limited period of time.

The inventory part of the study is a matter of collecting data on inputs and outputs from the processes included in the study taking into account processes induced or displaced by eventual co-products. The resulting procedure of associating environmental inputs from and outputs to environment with ethanol production is, then an algorithm summarizing inputs and outputs (Q_i) from all production processes (p) influenced (induced or displaced) by ethanol production

$$Q_{i, \text{Ethanol}} = \sum Q_{i,p}$$

The results are summarised in an inventory of resource uses, emissions to air, water and soil (solid waste) induced and displaced per litre of ethanol both at the ethanol factory's gate and per distance driven in a car.

Inventory data derived from the US literature are provided with American units. Conversion factors to SI units are provided in Appendix 1.

2.2 Methodology for environmental impact assessment

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

When calculating the potential environmental impacts ($EP(j)_{i, \text{Ethanol}}$) associated with specific substance emissions (i) induced or avoided as a result of choosing corn based bio-ethanol in

car fuels, the algorithm is a simple multiplication of total emissions of substances ($Q_{i, \text{Ethanol}}$) with specific equivalency factors ($EF(j)_i$) for specific impacts categories (j):

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

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

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

Equivalency factors ($EF(j)_i$) are derived from Eco-indicator 95 V2.1⁷ and calculations of environmental impacts have been facilitated by modeling in SimaPro 6.0⁸ LCA software package.

2.3 Assessment criteria

The considered environmental impact categories include

- Global warming (kg CO₂ equivalents)
- Acidification (g SO₂ equivalents)
- Nutrient enrichment (g NO₃ equivalents)
- Photochemical ozone formation (g ethylene equivalents)

The considered environmental impact categories are judged to cover some of the environmentally essential issues, but not all. Contributions to stratospheric ozone depletion are considered insignificant in the considered system and no indicators have been included in the assessment. Toxicity induced by application of pesticides during corn farming and changes in emission patterns of toxic substances induced by application of ethanol as fuel could give good reason for including toxicity assessment in the study. Data on toxicity have, however, not been readily available and hence left to qualitative judgements in the discussion. Gains in terms of avoided groundwater pollution due to displacement of MTBE with ethanol have likewise not been considered quantitatively.

Among resources, use of agricultural land (m²·year) and energy consumption (MJ fossil energy carriers (primary, LHV⁹)) have been considered.

2.4 Reference unit and functional unit

The study addresses comparison of environmental impacts and energy consumptions induced by driving a person car with conventional gasoline and gasoline mixed with 10% or 85% ethanol for which the functional unit is driving 1.6 km (one mile) in a selected 'standard' person car under standardised conditions.

⁷ Pre consultants (www.pre.nl) update of Eco-indicator 95 to SimaPro 6.0 with minor adjustments and corrections.

⁸ www.pre.nl

⁹ Low Heat Value.

3 Production of ethanol from corn starch and application as fuel

The study addresses ethanol production based on dry milling of corn and the main processes influenced by ethanol production from corn and application of ethanol for car driving are shown in Figure 2. Red boxes and arrows refer to induced processes and material streams, green boxes and arrows refer to displaced processes and material streams. Black boxes refer to processes which are considered independent of ethanol production and blue arrows refer to material streams which are changed by application of ethanol as fuel. Yeast production (in a dotted box) is not included due to lack of data.

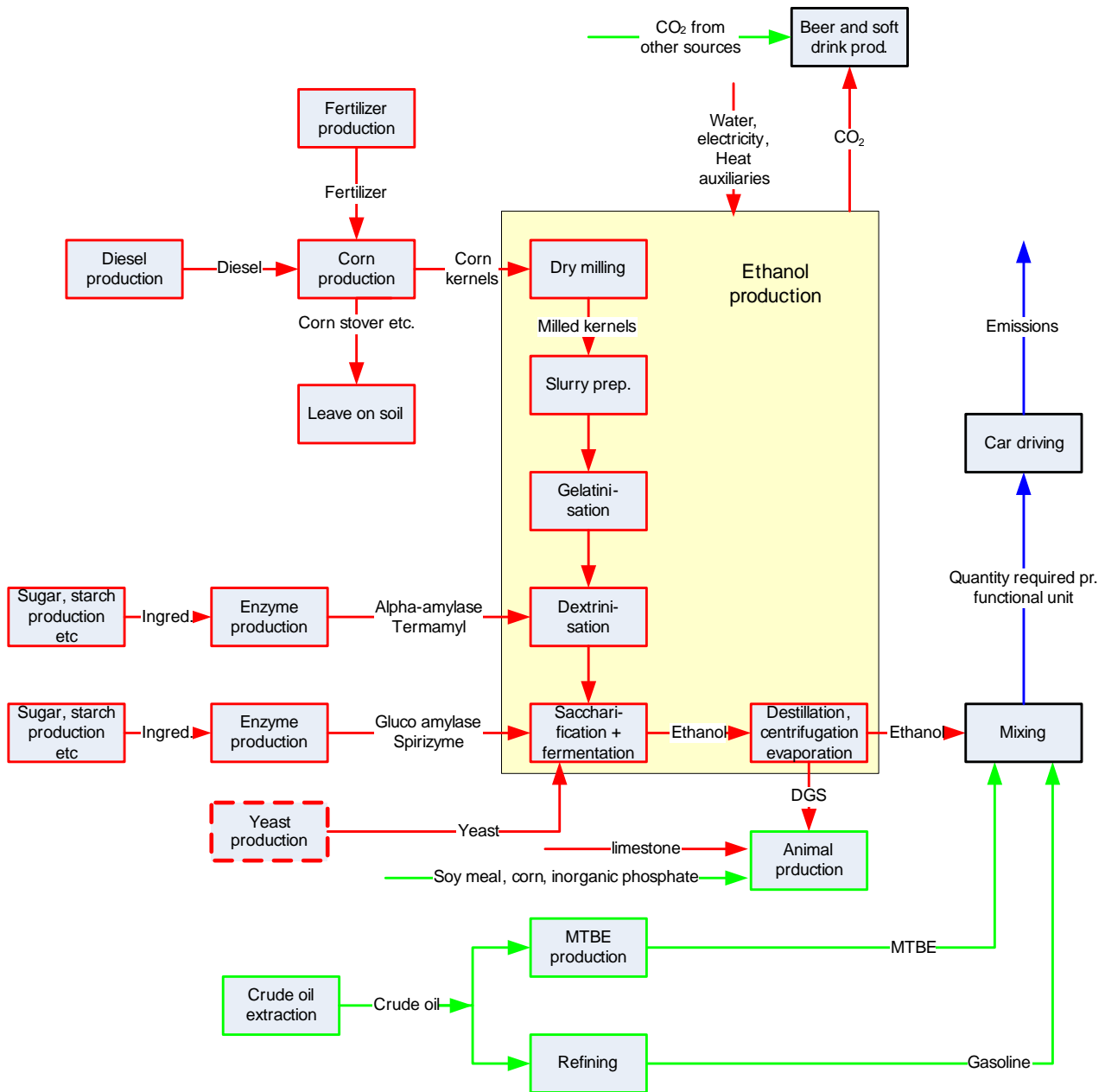


Figure 2: Main processes considered in the analysis of corn based ethanol from corn and application as fuel for car driving as alternative to conventional gasoline.

The following sections address main processes in the considered system.

3.1 Production of corn

Inputs and outputs associated with corn production in United States have been addressed by many authors during the past decade (see e.g. review by Shapouri et al. 2002) and data for the present study are derived from some of the most recent and comprehensive reports. See Table 1.

Table 1: Inputs and outputs associated with corn production.

	Substance	Original data		SI Units		Source
		Unit	Quantity	Unit	Quantity	
Products¹⁰	Corn	Bushels	139	kg	3531	Shapouri et al. (2004)
	Corn stovers	ton	1.4	ton	1.4	Sokhansanj (2002)
Resources	Water	m ³	330	m ³	330	Patzek (2004)
	Agr. land	Acre year ¹¹	1	m ² year	4047	Shapouri et al. (2004)
	Seed	kernels ¹²	29000	kg	10	Shapouri et al. (2004)
Fertilizer	Nitrogen	Pounds	134	kg	61	Shapouri et al. (2004)
	Potash	Pounds	88	kg	40	Shapouri et al. (2004)
	Phosphate	Pounds	57	kg	26	Shapouri et al. (2004)
	Lime	Pounds	16	kg	7.3	Shapouri et al. (2004)
Pesticides	Herbicides	gram	1300	g	1300	Wang (1999)
	Insecticides	gram	94.5	g	95	Wang (1999)
Energy	Diesel	Gallons	6.9	kg	22.0 ¹³	Shapouri et al. (2004)
	Gasoline	Gallons	1.7	kg	4.8	Shapouri et al. (2004)
	LPG	Gallons	3.4	kg	6.5	Shapouri et al. (2004)
	Electricity	kWh	33.6	kWh	34	Shapouri et al. (2004)
	Natural gas	Cubic feet	246	m ³	7.0	Shapouri et al. (2004)
Air emissions from farmland	N ₂ O	Pounds	5.1	kg	2.3	Wang (1999)
	CO ₂	kg	54	kg	54	Wang (1999)
	NH ₃	kg	6.4	kg	6.4	Ecoinvent database
Emissions to water from farmland	NO ₃	kg	130	kg	130	Ecoinvent database
	PO ₄	kg	1.1	kg	1.1	Ecoinvent database

Most data on corn production are derived from a recent source from National Corn Growers Association (NCGA¹⁴) (Shapouri et al. 2004). Data represent weighted averages of inputs and outputs during three years (2000-2002) in nine states: IL, IN IA, MN, NE, OH, MI, SD and WI.

¹⁰ Water content of corn and stoves has not been reported and it is assumed that water content is the same when the products leave the farm (present table) and when applied in ethanol factory (Table 3).

¹¹ One crop per year.

¹² 900-1800 kernels/lb (= 2000 - 4000 kernels per kg ~ 3000 kernels per kg on average)

¹³ Average densities: diesel: 0.85 kg/l, gasoline: 0.75 kg/l, LPG: 0.51 kg/l (www.statoil.dk).

¹⁴ <http://www.ncga.com>

Many other data are derived from Wang (1999) (Transportation Technology R&D Center, ANL¹⁵) who collected data from numerous studies in order to develop "Greet 1.5 – Transportation Fuel-Cycle Model". No data on emissions of nutrients to aquatic recipients from soil have been found in the American literature and data related to corn production in Europe (Ecoinvent database) have been applied as the best alternative. Data on inputs and outputs associated with corn production vary from source to source and the applied data for the environmental assessment will be compared with other sources in the following discussion of the applied data.

Corn yields: Shapouri et al. (2002) reviewed nine studies performed from late 80ties to present and found that estimates of corn yields ranging from 90 to 125 bushels/acre. This is quite low compared with 139 bushels/acre applied in this study but can supposedly to a large extent be explained by a significant development in corn yields over the past years, as also discussed by Wang (1999).

Corn stover yields: Corn stovers are usually left on the ground after harvest, but they can also be used for animal feed or as energy source (see Section 6.1). The yield in terms of stovers has a wide range because more or less of the stovers can be collected respectively left on the ground after harvest. Data on corn stovers in Table 1 are on the low side compared with Anderson (2004) who suggested 6000 pounds/acre (= 2.7 ton/acre).

Water consumption: Data on water consumption for irrigation are derived from Patzek (2004), who estimated an average water usage of 8.1 cm with references to United States Department of Agriculture (USDA). Water consumption has not been addressed by Shapouri et al. (2004) or Wang (1999), but average data on water consumption are considerable lower than specific data reported for Nebraska (8 to 15 inches (= 20 to 38 cm)) by Benham (1998). Nebraska has relatively high energy consumption for corn growing (supposedly due to a large extent for irrigation (Shapouri et al. 2004)) and the observed differences can probably be explained by variations in irrigation needs due to geographic variation as also discussed by Shapouri et al. (2002).

Seeds: Data on seeds are provided in kernels by Shapouri et al. (2004) who also suggests that 4.7 times more energy is required to produce seed kernels than corn¹⁶. It is not clear what parts of energy consumption is included in this estimate, and for simplicity, it has been assumed that one kg seed kernels induce environmental impacts corresponding to 4.7 kg corn. This is in not in agreement with Ecoinvent database where total energy (direct and indirect energy traced back to raw material extraction for all inputs) is only 20 percent higher for corn seeds than corn.

Fertilizer: The exact types of fertilizers applied for corn farming are not reported by Shapouri et al. (2004)¹⁷ and it has been assumed that N-fertiliser is provided as N-equivalents and N-fertilizers are assumed to be calcium ammonium nitrate (CAN). It is furthermore assumed that phosphate use is provided as P₂O₅-equivalents and that potash fertiliser is provided as K₂O equivalents and the applied fertilizers are triple super phosphate respectively potassium chloride. Fertilizer consumption has also been addressed by Wang (1999). Details in terms of exact fertilisers applied have, however, not been reported and the data can be difficult to compare. Assuming, however, that both sources use the same terminology, it seems that N fertiliser consumption is the same order of magnitude in the two studies, whereas Wang (1999) report somewhat higher consumptions of P and K fertilizer. Total energy consumption for fertilizer used during corn production is estimated from numerous observations to 23500

¹⁵ Argonne National Laboratory, Illinois

¹⁶ This is in contrast to Shapouri et al. (2002) where the energy value for growing is assumed to be equal to 150% of the energy required to grow corn.

¹⁷ The author has been contacted to obtain more clarity, but no reply has been provided yet.

BTU/Bushel (=806 kJ/kg corn) by Shapouri et al. (2004) this is somewhat lower than total energy consumption calculated for CAN (990 kJ /kg corn¹⁸) in SimaPro based on Ecoinvent data which has been applied in the present study¹⁹. Energy required to produce phosphate fertilizer is estimated to 1631 BTU/Bushel (= 56 kJ/kg corn) by Shapouri et al. (2004) which is a factor four lower than calculated in SimaPro for triple super phosphate (200 kJ/kg corn) and applied in the present study. Energy required to produce potash fertilizer is estimated to 1899 BTU/Bushel (= 65 kJ/kg corn) by Shapouri et al. (2004) which is somewhat lower than calculated (Ecoinvent data) for K₂O (93 kJ/kg corn) and applied in the present study.

Energy: Energy consumed during corn production as reported by Shapouri et al. (2004) is difficult to compare at a detailed level with previous observations in a review by Wang (1999) (18990 BTU/bushel (=20130 kJ/bushel = 630 kJ/kg corn)) because energy uses are provided in different ways which are not always completely clear. However, total energy use induced by corn farming seems to be of same order of magnitude in Shapouri et al. (2004) and in Wang (1999). It is assumed in the environmental model that electricity for corn production is purchased from the power grid, which is continuously supplied by a variety of power stations. The sources of electricity vary during the day and over the year, and the exact fuel and emissions related to given kWh of electricity cannot be identified. However, changes in demand for electricity induced by corn farming influences the marginal electricity production technology, whereas other production technologies remain unchanged. The marginal electricity production technology is assumed to be natural gas fired power plants²⁰ and data on electricity production are derived from natural gas based electricity (ETH, 1996).

Pesticides: Herbicide and insecticide production have been modelled with average data on pesticide production (Ecoinvent database). Toxic effects of herbicide and insecticide application are not covered by the assessment. Energy use for herbicide and insecticide manufacture has been reviewed by Wang (1999) and it has been reported that energy inputs range between 80 and 120 Btu/pound (= 187 to 280 MJ/kg). Energy consumption (primary energy, LHV) for production of unspecified pesticide based on Ecoinvent data are 190 MJ/kg, i.e. the low end of the interval reported by Wang (1999).

Emissions from farmland: Emissions of N₂O from farmland due to reduction of nitrate in soil under anoxic conditions and emissions of CO₂ due to net degradation of soil organic matter have been considered by Wang (1999). His data, which are based on a series of pretty rough assumptions, have been applied in the present study. Emissions of N₂O from the farmland have also been considered in Ecoinvent database with reference to European corn production. Here the output of N₂O from the farmland is estimated to 2.4 kg/kg 3531 kg corn, same level as suggested by Wang (1999)²¹. No data for verification of CO₂ and NH₃ emissions to air and NO₃ and PO₄ emissions to water from the farmland have been found, and it should be noted that data on emissions from farmland are very uncertain and results related to this part of the assessment should be interpreted with care.

¹⁸ Primary energy (low heat value) including all steps in the entire product chain.

¹⁹ Energy consumption for N-fertilizer production has been reviewed by Shapouri et al. (2002). Average data for modern production is in the order of 20 BTU/kg (=45 MJ/kg) which is somewhat lower than calculated for CAN using Ecoinvent data: total energy consumption in the entire product chain = 57 MJ (LHV)/kg CAN (as N).

²⁰ The US electricity market has been growing slightly over the past few years and is expected to increase further in the short term. Natural gas-fired power generation has greatly increased its share of the U.S. power mix over the past few years, from 9% in 1988 to 18% in 2002. Coal-fired power generation generally has been less attractive than natural gas in recent years due to relatively high capital costs and longer construction periods. As a result, coal's share in the U.S. power mix has fallen from 57% in 1988 to 51% in 2003. The share of nuclear power generation in the U.S. power mix has remained relatively unchanged over the past 15 years or so, increasing slightly from 19% in 1988 to 20% in 2003. Oil's share has fallen from 5% in 1988 to 3% in 2003. Thus, natural gas fired power plants appear to be a likely marginal sources of electricity at least on a short term. United States Country Analysis Brief (2004).

²¹ It should be noted that estimate of N₂O emissions would be about 2 times higher if they were evaluated per are of land used instead of corn output, because yields reported in Ecoinvent database are about two times higher per area of land used.

3.2 Transport of corn to ethanol factory

Transport of corn from corn field to ethanol factory has been addressed by Wang (1999) and Tampier (2004). The transportation scenario suggested by Wang (1999) has been applied in the study, see Table 2.

Table 2: Transportation scenario suggested by Wang (1999).

From / to	Type of transportation	Roundtrip distance	
From corn field to collection stacks	Class 6 truck	20 miles	32 km
From stacks to ethanol plant	Class 8a truck	80 miles	128 km

Properties of the two suggested trucks are unknown and transportation work was initially modelled as 160 kg·km transportation in a 16 ton truck (40% efficiency), (ETH, 1996) per kg of corn used in the ethanol plant. This resulted in a primary energy consumption of 530 kJ per kg corn – three times more than estimated by Wang (1999) (4081 BTU/Bushel corn = 170 kJ/kg corn). Data were therefore adjusted to 55 kg·km (one third of 160 kg·km) in a 28 ton truck, resulting in energy consumption in the order of 180 kJ per kg corn which was more in balance with pure energy calculations by Wang (1999) but still about 50% higher than suggested in a review by Tampier (2004) (15500 BTU/million BTU contained in ethanol ~ 120 kJ/ kg corn).

3.3 Production of ethanol from corn

Ethanol is produced by fermentation of saccharified corn starch. The corn starch can either be prepared by dry milling (a simple grinding process) or wet milling (an advanced corn refining process where starch, oil and proteins are separated in a variety of fractions). Both milling processes are widespread in United States (45% of corn used in ethanol production is produced by dry milling and about 55% is produced by wet milling, Shapouri (2002)).

Ethanol production is expanding in the US, and the present study seeks to address the technology which is most likely to deliver the majority of this expansion (the marginal technology).

Dry-mill plants are designed exclusively for ethanol production (Wang 1999) and it appears that expansion of ethanol production will be in favour of this process because it requires less capital to build, less staff to run and tends to receive tax advantages due to smaller capacity (see McAloon et al. (2000) and Shapouri (1998)). Ethanol production at dry mills is therefore regarded as the most likely marginal technology (see Figure 3) and is considered in the present study

Data on ethanol production (see Table 3) are delivered by Novozymes (based on Olsen (2004), BBI (2001) supplied with information delivered by a producer of corn based ethanol²²) and include all processes from reception and storage of corn to delivery of ethanol and Distillers Dried Grain with Solubles (DDGS) at the factory's gate. Data represent a modern plant with high degree of energy efficiency.

²² Name of ethanol producer is confidential but known by the authors.

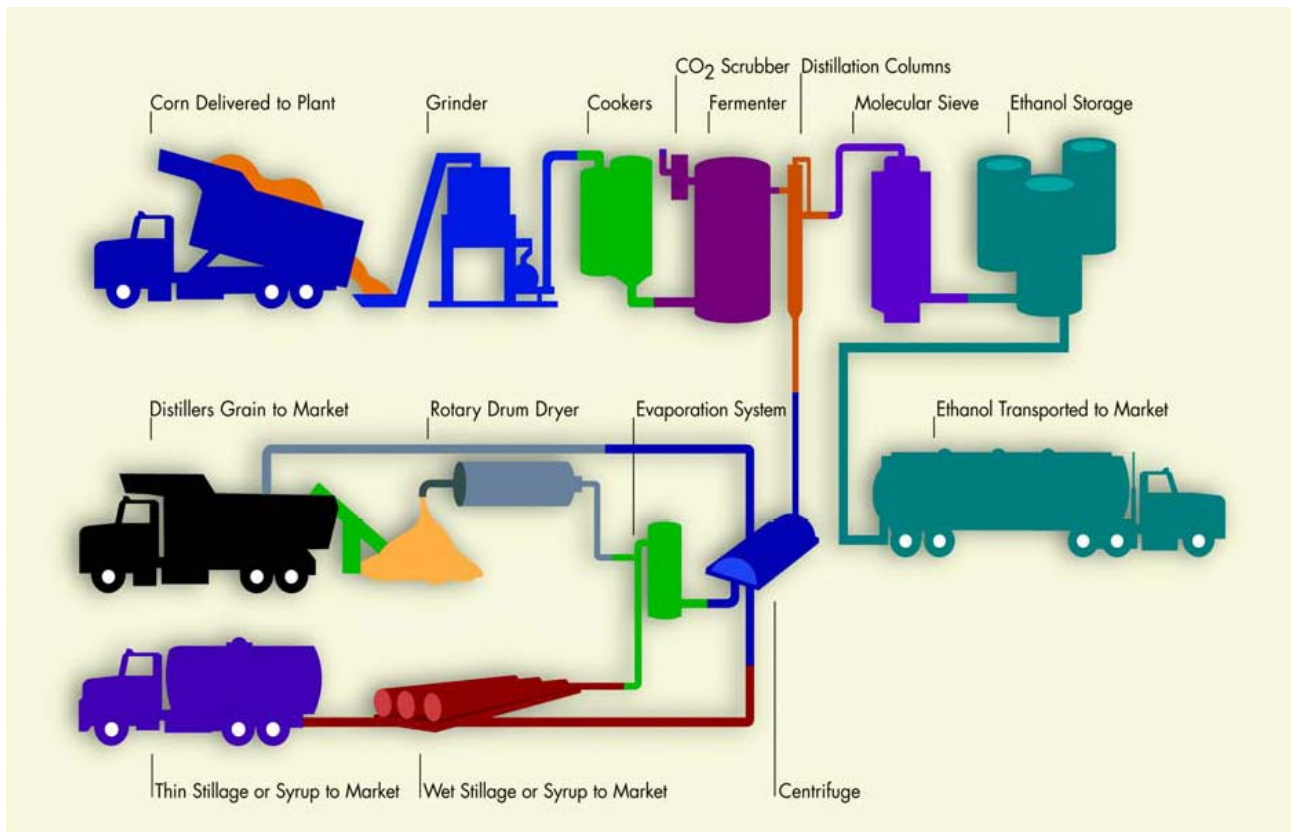


Figure 3: Main processes in ethanol production from corn with dry milling of corn (from Woolf (2003) with permission).

Corn consumption per quantity of ethanol produced is in agreement with recent studies reviewed by Shapouri et al. (2002) (2.5 to 2.7 gallons/bushel (= 3.0 to 3.2 kg corn/litre ethanol))²³.

Quantitative data on enzyme application for ethanol production have not been found in the literature, and no verification has been made. Spirizyme Fuel[®] and Termamyl SC DS[®] are represented by Spirizyme plus FG and Termamyl 120 L from Nielsen (2004). Assessments of the two enzymes is very detailed and cover more than 95% (W/W) of ingredients applied for enzyme production and include all significant energy consumptions.

Electricity consumption is slightly lower than suggested by Shapouri et al. (2004): 1.09 kWh/gallon (= 0.29 kWh/l). Heat consumption on the other hand is slightly higher than suggested by Shapouri et al. (2004): 34700 Btu/gallon (= 9.72 MJ/kg). Energy consumption for ethanol production has been addressed by several authors (see e.g. review by Shapouri et al. 2002) but since energy data are provided as totals of electricity and thermal energy they can only provide rough indications of similarities and differences.

²³ density of corn = 0.845 kg/l.

Table 3: Inputs and outputs associated with ethanol production.

	Raw materials and helping agents etc	Unit	Quantity
Inputs	Corn ²⁴	kg	3.17
	Spirizyme Fuel	g	1.91
	Termamyl SC DS	g	0.48
	Water	l	1.96
	Yeast ²⁵	g	10.58
	Electricity	kWh	0.21
	Heat	MJ	10.6
Outputs	Products		
	Ethanol ²⁶	litre	1.00
	DDGS	kg	0.96
	CO ₂ (to be sold)	kg	1.02
	Air emissions²⁷		
	Ethanol	g	?
	Others	g	?

From the data in Table 3, the primary energy consumption for ethanol production can be calculated to around 16 MJ/litre ethanol, a bit higher than the majority of observations (about 50.000 BTU/gallon = 14 MJ/litre ethanol and much lower than a single high observation (75118 BTU/gallon = 21.0 MJ/litre ethanol). Energy consumption for ethanol production has also been addressed in a "Feature article" from National Biomass Initiative (2004). Here the energy consumption for ethanol production based on dry milling is estimated to 47116 BTU/gallon (= 13 MJ/litre). Energy consumption for ethanol production has decreased during the past decades (Wang 1999) and it has been estimated that total energy use for ethanol production based on dry milling will decrease from 41400 BTU/gallon (=11.6 MJ/litre) to 36900 BTU/gallon (=10.3 MJ/litre) in the near future (2005). Details on the distribution of the expected decrease on electricity and heat have not been provided. Wang (1999) expects that most dry milling plants are fuelled by natural gas, and heat produced from natural gas (ETH 1999) has been applied in the study.

About one third of heat applied for ethanol production is used for drying DDGS, and it can be discussed whether the ethanol plant producing DDGS or the farmer using DDGS drives the processing of suspended matter from fermentation process into a useful product for animal feeding. It is assumed that DDGS has to be processed into a dry product due to legal regulations and heat consumption is therefore allocated to the ethanol factory. This is to some extent compensated for because avoided processing of the alternative feed that DDGS displaces is also allocated to the ethanol production, see below.

Many dry milling plants purchase electricity from the power grid (Wang 1999) for which the marginal fuel is assumed to be natural gas (see Section 3.1). Data on electricity production based on natural gas are derived from ETH (1996).

²⁴ Water content of corn has not been reported and it is assumed that water content is the same when the products leave the farm (Table 1) and when applied in ethanol factory.

²⁵ no data have been found on yeast and yeast input is not included in the study.

²⁶ 100% undenatured ethanol.

²⁷ No data on air emissions from ethanol factory have been found, explaining that the table is empty at this point.

The applied estimate of DDGS production is slightly higher than an estimate provided by Wang (1999): 6.09 lb/gal (= 0.729 kg/l). The explanation can be differences in composition and water content as data from Wang (1999) refer to "bone-dry" Distillers Grains and Solubles (DGS).

DDGS contains protein, fat, fibres, digestible phosphorus, hydrocarbons etc. and is used as feed ingredient for animal production (swine, poultry, dairy cows and meat cattle²⁸). Nutritional value of DDGS varies and displacements of other feed types induced by DDGS production based on "rule of thumb" for swine production is provided in Table 4. These data are used to represent displacement value of DDGS in the model.

Table 4: Induced and displaced swine feed ingredients (Thaler 2002). "+" indicates that the substance is added when DDGS is applied and "-" indicates, that the substance is displaced when DDGS is applied.

	Original data		SI units	
	Unit	Quantity	Unit	Quantity
Limestone	lb/200 lb DDGS	+ 3	g/kg DDGS	+ 15
Dicalcium phosphate	lb/200 lb DDGS	- 6	g/kg DDGS	- 30
Corn	lb/200 lb DDGS	- 178	g/kg DDGS	- 890
Soy bean meal	lb/200 lb DDGS	- 19	g/kg DDGS	- 95

Displacement ratios suggested by Wang (1999) do not include limestone usage and dicalcium phosphate displacement and soy meal displacement is almost a factor 10 higher. Displacement of corn is at the same level²⁹.

Carbon dioxide produced during the fermentation process is to some extent captured and sold to beer and soft-drink producers. Since the captured CO₂ is released to atmosphere when the drinks are consumed, no CO₂ credits are considered and the captured CO₂ is considered as any other CO₂ of non-fossil origin (i.e. no net contribution to global warming). Carbon dioxide capture is driven by the demand in beer and soft drink industry and environmental impacts induced by the capture process should correctly be disregarded in the assessment of ethanol production. Energy consumption and emissions to environment per captured quantity of CO₂ are, however, considered insignificant and thus ignored.

A range of VOCs are emitted from ethanol plants during ethanol production. These include for instance: acetaldehyde, acrolein, ethanol, formaldehyde, 2-furaldehyde, methanol, acetic acid and lactic acid (Woolf 2003). No quantitative data on VOC emissions have been found in the literature and VOC emissions from the ethanol plant have, thus, been disregarded in the study.

Wastewater and solid waste generation during ethanol production are considered insignificant and thus ignored.

²⁸ See <http://www.ddgs.umn.edu/>

²⁹ In the model, limestone, dicalcium phosphate and soybean meal are all processed products ready for feeding animals, whereas corn applied in the model is simply the product coming directly from the field because processing between field and animal is unknown. This adds slightly to the uncertainty of the assessment and probably leads to a small underestimation of impacts induced by the displaced alternative to DDGS, i.e. a small overestimation of impacts associated with ethanol production.

3.4 Transport, storage and distribution of ethanol

Transport, storage and distribution of ethanol use energy and a part of the product is lost due to evaporation on the way from ethanol plant to fuel station.

Evaporation of fuel (about 2.3% of the product, Wang 1999) is ignored because it is assumed to be independent of the fuel applied for car driving and hence unchanged by the replacement of conventional gasoline.

Table 5 shows assumptions about the distribution network, transportation distances and types and calculations of transportation work based on Shapouri et al. (2002). Transportation of ethanol from ethanol plants to "collection terminals" and from "collection terminals" to "fuel distribution terminals" are included in the model because it is assumed that they are added to the fuel supply system when ethanol is used as alternative fuel to gasoline. Transportation from "fuel distribution terminals" to "distribution terminals" and from "distribution terminals" to refuelling stations are not included in the model because the transportation processes are assumed to be independent of the fuel used for car driving. Modelling of transportation processes is based on data from ETH (1996).

Table 5: Calculation of transportation work induced by collection and distribution of one litre³⁰ ethanol from ethanol plant to refuelling stations based on assumptions by Shapouri et al. (2002).

From	To	Distance		Transport type	Transportation work, kg·km	Included in model
		Miles	km			
Ethanol plants	Collection terminals	80	130	Truck	100	yes
Collection terminals	Fuel distribution terminals	520	830	Barge	650	yes
Fuel distribution terminals	Distribution Terminals	800	1280	Rail	1000	no
Distribution Terminals	Refuelling stations	25	40	Truck	30	no

Calculations in SimaPro based on the above assumptions resulted in a primary energy consumption of 0.59 MJ/litre, same level as estimated by Shapouri et al. (2002) and Biomass and Research & Development Initiative (2004) (~ 1500 BTU/gallon (= 0.42 MJ/litre) for the entire system.

It is hard to know what transportation processes are added to the system when ethanol displaces gasoline and thus to estimate the transportation work induced. The results at this particular point should therefore be interpreted with care.

³⁰ Density of ethanol = 0.789 kg/l (www.chemfinder.com)

3.5 Use of ethanol as fuel for car driving

3.5.1 Fuels

Ethanol is usually mixed with gasoline when applied as fuel for car driving and Table 6 shows some of the most commonly applied mixes. Due to its content of oxygen, ethanol can increase octane number of gasoline and hereby replace for instance MTBE.

The present study addresses E10 and E85. For E10 it is assumed that MTBE content of conventional gasoline is 8% and hence that 100 g ethanol replaces 80 g MTBE and 20 g gasoline per kg conventional gasoline. For E85, no information about oxygenates has been found and it is assumed that E85 consists of ethanol and gasoline only. Data on gasoline and MTBE production are derived from Ecoinvent database.

Table 6: Characteristics of three types of fuel mixes of gasoline and ethanol.

Type of fuel	Ethanol content	Gasoline content
E10	10%	90%
E85	85%	15%
E90	90%	10%

3.5.2 Fuel efficiency and air emissions

Fuel efficiency and air emissions from car driving can vary with fuel composition, and this has to be considered when environmental impacts from driving with conventional gasoline and E10/E85 are compared.

Fuel efficiency and air emissions varies, however, also with numerous other factors than fuel³¹ and comparisons of fuel efficiencies and emissions from conventional gasoline driven cars and ethanol/gasoline driving cars often lead to different results.

The most comprehensive and uniform study found in the literature on air-emissions from driving with different types of fuels in different types of cars under standardised conditions in United States has been made by "ANL Transportation Technology R&D Center (see Wang, 1999a, b and c). A baseline conventional gasoline vehicle, a gasoline vehicle fuelled with E10 and a Flexible Fuel Vehicle fuelled with E85 have thus been selected from this source for the comparison. See Table 7.

Table 7: Main characteristics of the three considered types of fuels and cars (Wang 1999).

	Baseline conventional gasoline vehicle	Gasoline Vehicle: E10	Flexible Fuel Vehicle (FFV): E85
Type of car	Passenger car	Passenger car	Passenger car
Technology	Near term	Near term	Near term
Fuel efficiency	22.4 miles per gallon (=9.5 km/l)	22.4 miles per gallon (=9.5 km/l)	23.5 miles per gallon (=9.9 km/l)
Fuel	Conventional gasoline ³²	Gasoline mixed with 10% ethanol from corn ³³	Ethanol from corn mixed with 15% gasoline

³¹ For instance speed of driving, air humidity, altitude, driving mode, road steepness, type of engine, conditions of engine, load of vehicle and presence and efficiency of exhaust gas cleaning equipment.

³² The content of MTBE is not reported and it has been assumed that MTBE content is 8% (Ecoinvent database).

Emissions to air from the three considered cars per distance driven are summarised in Table 8. Emissions have been measured under controlled conditions with focus on understanding emission differences between "Alternative Fuel Vehicles" and comparable "Gasoline Vehicles" (Wang 1999). It is noted by the author that several caveats are associated with the applied methods. For example the fact that trade-offs between emissions and fuel economy exists and individual vehicle models can be designed for different intended trade-offs; either maximizing performance or minimizing emissions.

Table 8: Emissions per distance driven for the three considered cars/fuels (Wang 1999 b, c).

	Baseline conventional gasoline vehicle		Gasoline vehicle E10		Flexible fuel vehicle E85	
	grams/mile	g/km	grams/mile	g/km	grams/mile	g/km
VOC: total	0.21	0.13	0.23	0.15	0.18	0.11
CO	5.5	3.4	3.5	2.2	3.3	2.1
NO _x	0.28	0.17	0.275	0.17	0.25	0.16
PM ₁₀ : exhaust	0.012	0.0075	0.012	0.0075	0.005	0.0031
SO _x	0.050	0.031	0.046	0.029	0.010	0.0063
CH ₄	0.084	0.053	0.084	0.053	0.13	0.081
N ₂ O	0.028	0.018	0.028	0.018	0.028	0.018
CO ₂ (fossil)	390	243	364	228	58 ³⁴	36

Volatile organic compounds (VOC) represent a total of exhaust emissions and evaporative emissions from fuelling the car. Emissions of VOC are a bit higher for E10 cars because evaporation is higher for the E10 gasoline due to a higher Reid Vapour Pressure (RVP) Wang (1999).

PM₁₀ includes exhaust emissions but not emissions from the brakes.

Data on fossil CO₂ emissions have been verified through stoichiometric calculations and a perfect match has been found for E10 whereas data for conventional gasoline vehicle deviate by 2%. The latter can probably be explained by differences in assumptions about additives. The results from stoichiometric calculations match perfectly with data sheets provided for car buyers by Toyota Denmark³⁵.

Data on CO₂ are in balance with Danish emission factors (NERI³⁶) whereas other data are significantly lower. This can supposedly be explained by variations in emission standards and technical and physical variations as explained above.

³³ Information about other additives than ethanol is not reported and it is assumed that MTBE is completely displaced by ethanol and no further additives are applied.

³⁴ Determined by stoichiometric calculations. In agreement with CO₂ emissions from driving one mile in baseline conventional gasoline vehicle after multiplication by 15% (corresponding to gasoline content). Data in Wang (1999): 83 g CO₂/mile.

³⁵ www.toyota.dk

³⁶ www.dmu.dk

4 Results of the baseline scenario

The results of the base study, i.e. the assessment of bio-ethanol versus conventional gasoline, are addressed in terms of an energy balance (see Section 4.1) and in terms of an environmental impact assessment of ethanol when used in mixtures with gasoline for car driving (see Section 4.2). An inventory of total inputs and outputs associated with ethanol production is provided in Appendix 2.

4.1 Energy balance

Modelling of ethanol production based on data and assumptions explained in the previous sections reveals a total amount energy used to manufacture one litre of ethanol from growing the corn to and including transport of the ethanol to the fuel station of 21.6 MJ fossil primary energy (LHV)/litre (see Figure 4). The main sources of energy consumption appear to be 1) heat consumption at the ethanol plant, 2) production of corn (including energy consumption induced by fertiliser application etc.) and 3) electricity consumption at the ethanol factory. This ranking of main sources of energy consumption is in agreement with Tampier (2004) and Shapouri et al. (2002) and results for specific main processes are in pretty good agreement with Shapouri et al. (2002). Further comparison with results provided by Tampier (2004) is difficult because records of energy consumptions are somewhat unclear³⁷. Figure 4 shows furthermore that the DDGS is an important co-product from ethanol production, and that the energy from displacement of corn for feed, contributes significantly to the overall energy profile of ethanol as also discussed by e.g. Shapouri et al. (2002) and Wang (1999).

In driving the car, ethanol will substitute gasoline as a fuel. The car runs around 9.9 km/litre ethanol, whereas it runs 9.5 km/litre gasoline (see Table 7). Expressed per functional unit (one mile driven), the car will use 0.16 litres of ethanol where it uses 0.17 litres of gasoline. The fossil energy used to manufacture gasoline – from the oil extraction throughout to the fuel station – is 40.1 MJ (LHV)/litre including feedstock. The fossil energy balance – or the ratio between induced and avoided fossil energy consumption when substituting gasoline with bio-ethanol, can thus be elaborated as follows:

Fuel substitution ratio: 0.16 litre bio-ethanol/0.17 litre gasoline
Fossil fuel consumption for bio-ethanol: 21.6 MJ (LHV)/litre
Fossil fuel consumption for gasoline: 40.1 MJ (LHV)/litre
Fossil fuel substitution ratio: 3.45 MJ/6.82 MJ ~ 1:1.9

A comparison between the fossil energy used to produce the bio-ethanol and its heat value is a topic often given attention in literature and interpreted as an energy balance. As the lower heat value (LHV) of ethanol is 21.3 MJ/litre (76000 BTU/gal, Tampier et al. 2004), it is seen that the ratio of fossil fuel used/ethanol LHV is 21.3 MJ/21.6 MJ or about 1:1. This apparent paradox, that the fossil energy it takes to manufacture the ethanol, is about equal to its lower heat value, has by many been seen as an 'energy balance' and interpreted as a sign that this 'energy balance' itself proves making bio-ethanol to be a bad idea. The paradox is, however, only apparent, and the ratio of fossil fuel used/LHV is irrelevant. The ethanol is intended as a fuel for use in explosion motors, and the fossil fuels used to produce the ethanol cannot be used to run an explosion motor. Likewise, the heat value of the ethanol does not say anything about its performance in an explosion motor. Therefore, the energy balance of bio-ethanol should be judged, not by the fossil fuel consumption for its production versus its LHV, but by the fossil fuel consumption for ethanol production versus the fossil fuel consumption of the fuel

³⁷ data are recorded per million BTU contained in ethanol without explaining whether low heat or high heat values has been used and it is not clear whether all energy inputs in the entire product chain are included

substituted by the ethanol in the explosion motor. And this is the ratio of around 1:1.9 as shown above.

Figure 2 shows that the DDGS is an important co-product from ethanol production, and that the energy from displacement of corn for feed, contributes significantly to the overall energy profile of ethanol as also discussed by e.g. Shapouri et al. (2002) and Wang (1999).

4.2 Environmental impact assessment of car driving

The environmental impact assessment of using ethanol as fuel for private car driving has, as also stated in the objectives, been addressed in two scenarios: 1) driving 1.6 km (one mile) in a gasoline vehicle using fuel with a 10% mixture of ethanol with gasoline and 2) driving one mile in a flexible fuel vehicle using a fuel with a 85% mixture of ethanol with gasoline. Both scenarios are compared with driving 1.6 km in a baseline conventional gasoline vehicle. Details of the considered scenarios can be found in Section 3.5 and results of the assessment are shown in Figure 5.

The results indicate that environmental gains in terms of global warming, photochemical ozone formation and fossil energy carriers can be achieved by using corn based ethanol as alternative to conventional gasoline. The benefits in terms of global warming and fossil energy carrier consumption is explained by the fact that less fossil fuel is required pr. mile driven, cf. the fossil energy ratio of around 1:1.9 between the induced ethanol and the substituted gasoline. The benefits on photochemical ozone formation is explained by the fact that the E85 Flexible fuel Vehicle is less polluting with VOCs (see Table 8) than the conventional gasoline vehicle.

On the other hand it should also be noted that when the results are considered from other environmental perspectives (nutrient enrichment and acidification) and other resource perspectives (use of agricultural land) the use of ethanol as alternative to gasoline appears to be disadvantageous. This is explained 1) by the fact that corn production for ethanol requires land and 2) the assumptions that nutrients (N and P) are lost to aquatic recipients during corn production and 3) the assumption that NH_3 evaporates to the air from the cornfield (see Table 1). The latter is opposite to conventional gasoline which has no use of agricultural land during production and only relatively small emissions of nutrients (NO_x) and acidifying substances (NO_x and SO_x) during production and use in the car (see Table 8). It should be noted that estimates of emissions to water and soil from cornfields in the present study were based on uncertain data (see Section 3.1), and the exact figures on acidification and nutrient enrichment should be interpreted with care.

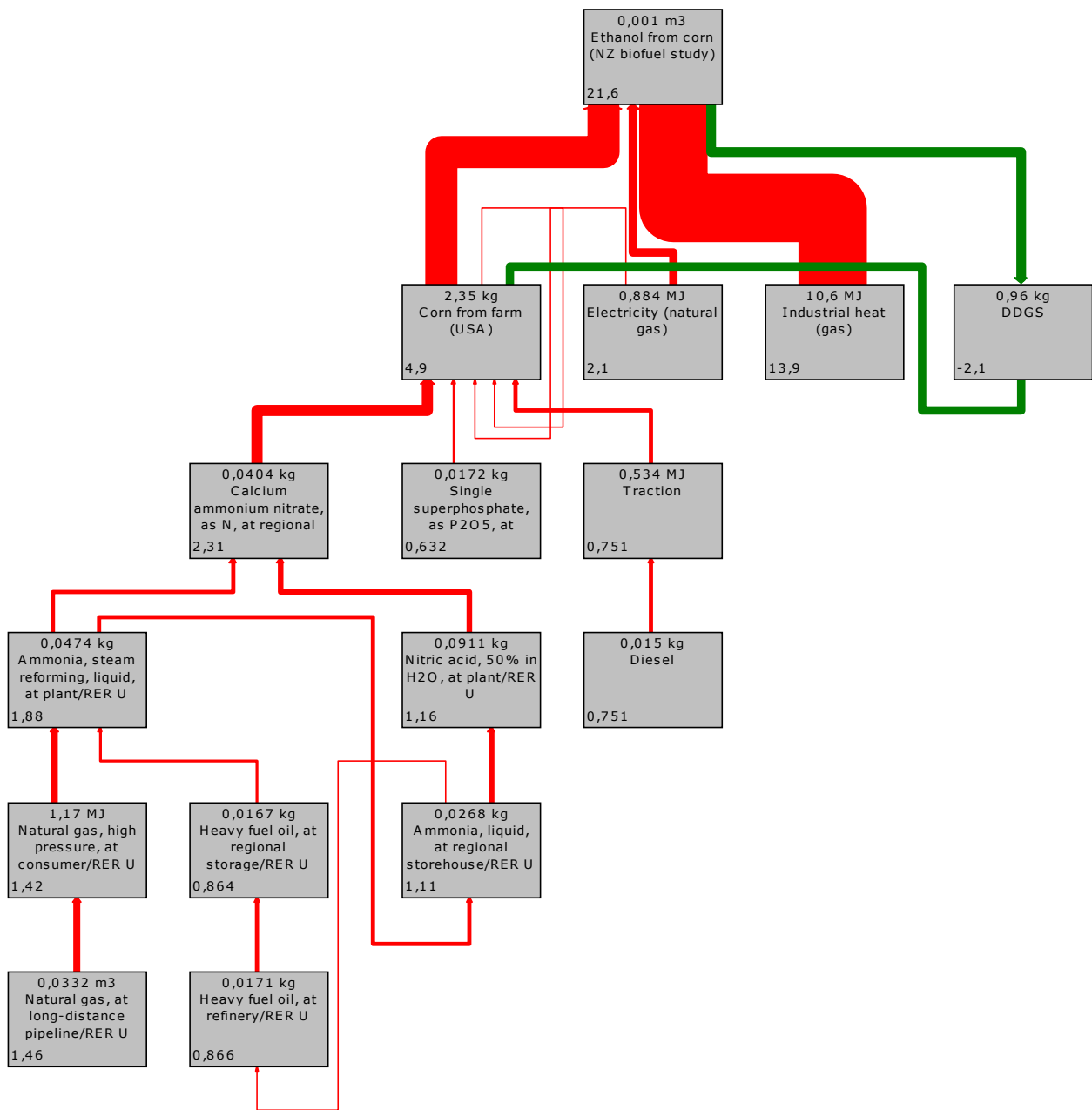


Figure 4: Sources of fossil energy consumption during ethanol production. Red arrows refer to induced energy streams and green arrows refer to displaced energy streams. Thickness of arrows indicates magnitude of energy stream. Processes contributing less than 3.0% are ignored (i.e. "Cut off" = 3.0%).

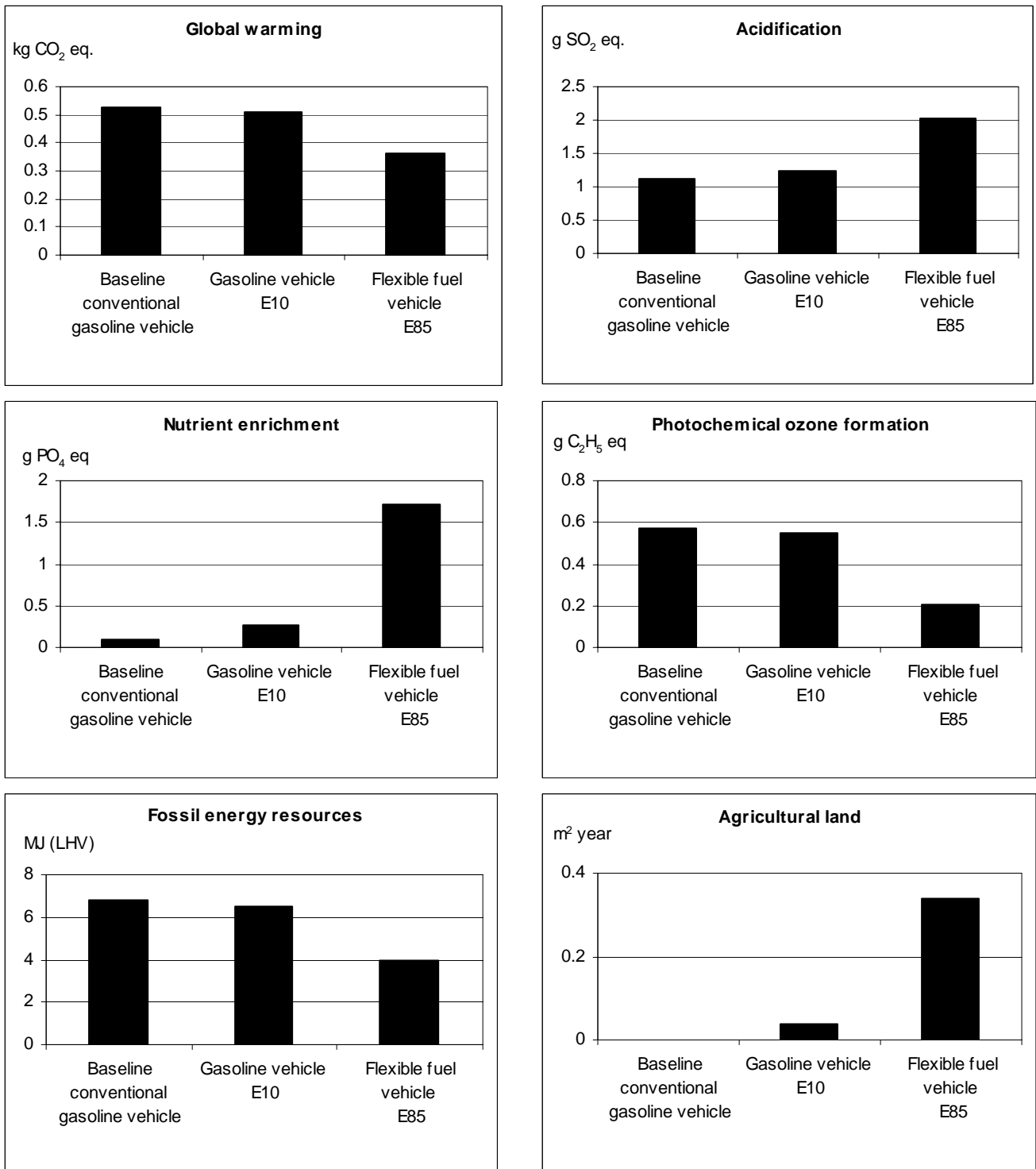


Figure 5: Contributions to global warming, acidification, nutrient enrichment, photochemical ozone formation and use of fossil energy resources(primary, LHV) and agricultural land for driving 1.6 km (one mile) in cars fuelled with gasoline mixed with 0, 10 and 85% ethanol produced from corn starch.

The observed change in fossil energy consumption when E85 is used as fuel as alternative to conventional gasoline is in agreement with observations by Wang (1999) who found about 40% reduction. Other observations by Wang relate to changes in emissions and the results cannot be compared directly.

Other studies in the considered American literature mostly deal with energy balance of ethanol production, and results in terms of environmental impact and agricultural land use recorded in this study cannot be compared with these observations.

The observed trade-off between contributions to global warming and nutrient enrichment and acidification is in agreement with numerous observations on various bio fuels in a comprehensive European study by Calzoni et al. (2000).

It would be desirable to address the relative magnitude of contributions to environmental impacts reported in Figure 5 by normalising all data with the annual contributions by an average US citizen. Such normalisation data are, however, not available and normalisation has been performed for an average Dane/European instead (see Appendix 3). Results are supposedly not representative the US situation, but they indicate that the relative contribution to acidification from corn ethanol may be limited, while the relative contribution to nutrient enrichment may be considerable.

The observed trade-off in terms of extra land use relates to the opportunity cost addressed in Section 1.3. If land and biomass from land were of unlimited availability, there would be no lost opportunity of the extra land use by the bio-ethanol scenarios. If, however, the competitive uses of land and of biomass from the land proved to be more attractive, and land and/or biomass proved to be of limited availability in the future, the extra land use represents a lost opportunity of using the biomass from it for something else. Among other things, the extra land in question could have been used for CO₂ neutral bio-fuels for heat and power production, and there is, therefore, a direct relation between the global warming advantages and the land use disadvantages of the bio-ethanol scenario. The environmental pro's and con's of this relation is addressed in Section 6.

5 Sensitivity analysis of results from the baseline scenario

5.1 Sensitivity to assumption on displacement of animal feed by DDGS

It has been assumed that DDGS generated during ethanol production is used for feeding pigs and that it replaces a mixture of corn and soy, see Table 4. DDGS can, however, be used as feed for a variety of other animals and the feed replacements that DDGS induces depend on the species considered, the growth stadium of the animal, feed prices etc. (see e.g. Thaler 2002, Tjardes and Wright 2002 and Garcia and Taylor 2002). Replacement of corn and soy as suggested by Thaler (2002) for swine feed production resulted in a notable credit to DDGS, and the present section will address the sensitivity of the assumption that DDGS was used for pigs.

It has therefore been assumed that DDGS has been used for beef cattle production instead, and following "rules of thumb" by Tjardes and Wright (2002), 2.7 lb DDGS replaces one lb soybean meal. The result is shown in Figure 6.

Figure 6 shows that the energy credit obtained by DDGS when the product displaces corn (see Figure 4) now disappears and turns into a slight contribution to ethanol's fossil energy consumption (see the thin red line between "Ethanol from corn" box and "DDGS used for beef cattle"). The explanation is 1) that soy is produced without N-fertiliser input (see Nielsen 2003) and therefore has a significantly lower total energy input than corn (as also discussed by Pimentel 2003) and 2) that reduced production of soy meal will lead to a reduced production of soy oil (co-product of soy meal) which in turn will induce production of rape seed oil which has an N-fertiliser consumption at the same magnitude per produced unit as corn³⁸.

The example shows that "displacement credits" for DDGS can vary significantly depending on what type of feed is assumed to be displaced, and more focus should be addressed to identifying the marginal displacement induced by DDGS, i.e. the feed type which is influenced by a marginal change in output of DDGS from corn ethanol production.

Energy credits induced by DDGS when used as swine feed was about 10% of total energy consumption for producing ethanol (see Figure 4) and the zero energy credit (approximately) as observed when the product is used to replace soy meal in cattle feed will change ethanol's energy profile accordingly.

³⁸ The fact that rape seed oil has co-product of rape seed meal which displaces soy meal has been accounted for, but the effects on fossil energy consumption is too small to be visible in Figure 6. The principle of infinite circular displacement is explained and justified by Weidema (2003).

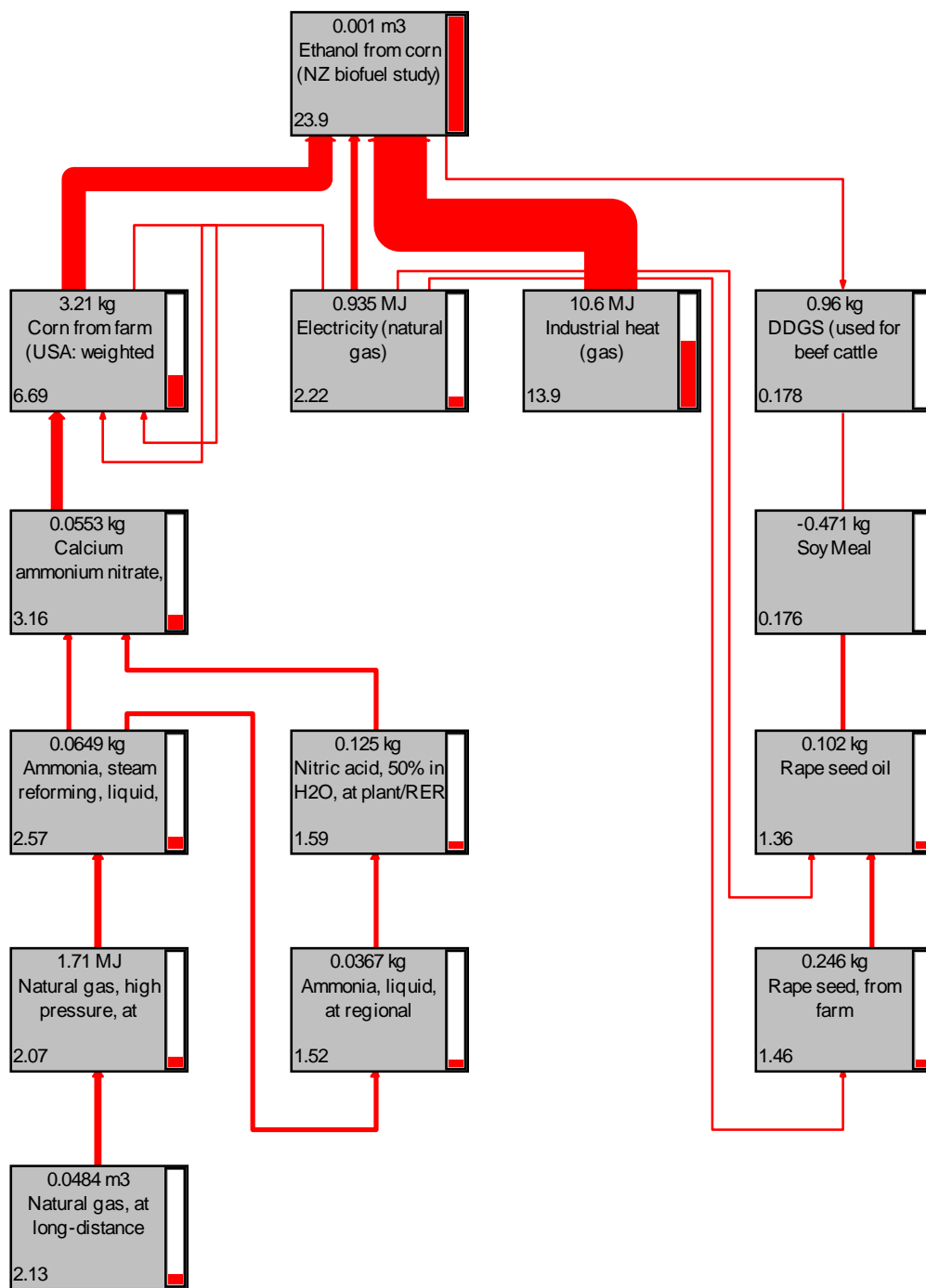


Figure 6: Sources of fossil energy consumption during ethanol production where DDGS is used as feed for beef cattle. Red arrows refer to induced energy streams. Thickness of arrows indicates magnitude of energy stream. Processes contributing less than 5.8% are ignored (i.e. "Cut off" = 5.8%)

5.2 Sensitivity to assumption on efficiency of ethanol as fuel for car driving

The baseline scenario on car driving with ethanol as fuel as alternative to conventional gasoline is based on fuel efficiencies recorded in one study for three particular cars. Since efficiency of cars fuelled with ethanol varies with brand and model and probably also test conditions, the results might come out differently if data from other cars and other testshad been applied. Thus, in order to address the sensitivity of the fuel efficiency assumption, changes in fuel efficiency by use of E85 Flexible-fuel vehicles as alternative to conventional gasoline reported in various studies for different vehicle models are summarised in Table 9.

Table 9: Changes in fuel efficiency by use of E85 Flexible-fuel vehicles as reported in various studies for different vehicle models. Values are relative to conventional gasoline vehicles using conventional gasoline. From Wang (1999).

Vehicle model	Fuel efficiency change, %
1992 GM 3.1-L Lumina	+3.3
1994 Ford 3.0-L Taurus	-4.7
1993 Chrysler 2.5-L Acclaim	+0.5
1993 Chevrolet 3.1-L Lumina ³⁹	-0.2
1998 Ford 3.0-L Taurus	+10

The E85 flexible fuel vehicle which has been addressed in the present study has 4.9% better fuel efficiency than the conventional alternative (see Table 7), corresponding to +4.9 in Table 9. This is in the better end of the interval in Table 9 (seen from an ethanol fuel perspective), and indicates that the environmental assessment of car driving with E85 in a flexible fuel vehicle would have come out differently if other cars had been considered. Fossil fuel consumption for E85 driving (see Figure 5) would for instance⁴⁰ have been about 10%⁴¹ higher if the Ford 3.0-L Taurus from 1994 had been considered instead, or about 5% less if Ford 3.0-L Taurus from 1998 had been considered.

5.3 Sensitivity to geographical variation of corn production

Weighted average data on corn production have been applied for the base case environmental assessment (see Section 3.1). Acknowledging, however, that the geographical variation on energy consumption can be significant (see Shapouri et al. 2004) a sensitivity analysis of the geographical variation has been performed.

Average data in Table 1 provided by Shapouri et al. (2004) have been supplemented with state specific data for Nebraska, Iowa and South Dakota representing a broad spectrum of yields and energy consumptions. Examples of the most important differences taken into account in the assessment are provided in Table 9.

³⁹ Comparison relates to "California Phase 2 reformulated gasoline" not conventional gasoline

⁴⁰ Other indicators in Figure 4 have not been considered here because data basis on changes of emissions from the cars considered in Table 9 are too incomplete to justify more detailed comparisons.

⁴¹ 4.9%- (-4.7%) ~ 10%.

Table 9: Overview of the most important differences between inputs and outputs associated with corn production in three states and the weighted average of nine states applied as base case in the study. All data are provided per 4047 m² farm land (= one acre).

	Unit	Iowa	Nebraska	South Dakota	Weighted average of nine states
Corn yield	Kg	3860	3400	2700	3530
Nitrogen fertilizer	Kg	57	60	50	61
Diesel	Litres	17	47	17	26
Electricity	kWh	17	150	27	34
Natural gas	m ³	0	27	27	7

Results of the comparison are shown in Figure 7.

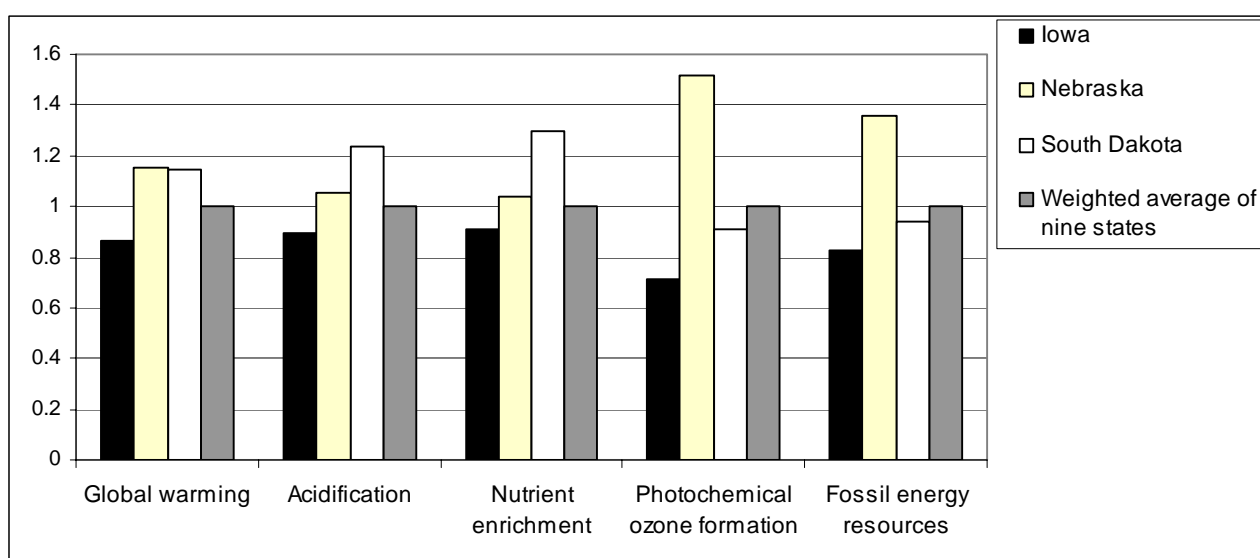


Figure 7: Relative environmental impacts associated with corn production in three specific states and the weighted average of nine states. The weighted average of nine states serves as normalisation reference, and is hence 1.0 in any case

Contributions to acidification are to a large extent driven by the farming process (emissions to air and water from the soil) and are therefore to a large extent determined by the corn yield. The highest contributions to these impacts are therefore observed for South Dakota, see Table 9.

Consumption of fossil energy resources are to a large extent driven by diesel, electricity and natural gas consumption and Nebraska which has high consumption of diesel and electricity comes out with the highest score in this category. Contributions to global warming are partly driven by energy consumption due to CO₂ emissions from combustion process and partly emissions of N₂O and CO₂ from the field, and the large energy consumption for Nebraska is to some extent compensate for by a relatively high yield.

Photochemical ozone formation is to a large extent driven by diesel consumption during corn production and to some extent use of N fertiliser, and Nebraska which has an extraordinarily

high diesel consumption compared with the weighted average and the other states, comes out with a relatively high contribution to photochemical ozone formation.

When driving an E85 person car with ethanol produced from, corn production is responsible for

- about one fourth of fossil energy resources consumption
- about half of global warming
- about one third of photochemical ozone formation
- almost all of contributions to nutrient enrichment and acidification
- and all of agricultural land use (data not shown).

and impacts associated car driving is influenced accordingly, when corn from different states is applied for the ethanol production.

The observed geographical variation in environmental impacts associated with corn production among states stresses that more emphasis should be addressed to analysing which states will be main drivers of an eventual growth of corn production for ethanol in the future.

It should be noted that state averages supposedly cover significant internal variation, which has not been considered here.

6 Extensions of the baseline scenario

The baseline scenario is based on a system delimitation and a set of assumptions that is judged to represent realistic conditions for bio-ethanol in the USA today. As described in Section 1.3, however, the set of assumptions may not represent the optimal system conditions. Especially alternative uses of the biological resources may exist that, in a holistic assessment such as the one performed in this study, prove to be more attractive. In order to serve as a proper decision support, therefore, any study of the use of biomass should address and compare alternative uses of biomass.

The baseline scenario is, therefore, supplemented by two extensions, namely:

- A scenario in which the corn is still used for bio-ethanol production, but stovers are not just left on the ground, but used, either for animal feed or for energy production
- A scenario in which corn and corn + stovers, is used for energy production

6.1 Scenario of using stovers as feed or energy sources

Ethanol is presently produced from corn produced at fields where stovers are left on the ground after harvest, and based on observations of the importance of co-product application for DDGS (Section 4.1) it could be interesting to address environmental improvements of corn-based ethanol if stovers were utilized.

Since the stovers hold a potential value as animal feed (see e.g. Adams 1998) or as energy source⁴², two hypothetical scenarios for ethanol production have been considered.

1. Ethanol is produced from corn which comes from a farm where the stovers are used as animal feed as alternative to hay. Stovers displace a similar quantity of hay on a mass basis (Adams 1998). Data on hay are derived from Ecoinvent database⁴³.
2. Ethanol is produced from corn which comes from a farm, where the stovers are used for combined heat and power production by combustion as alternative to heat produced from oil and electricity produced from natural gas. No specific data on corn stover application for CHP have been found in the literature and it has been assumed that stovers resemble straw produced and applied in Denmark for CHP. Data are derived from the LCA Food Database⁴⁴ (Nielsen et al., 2003).

Both scenarios are intended for pretty rough assessments, just to provide an idea about the potential environmental value of the stovers, and aspects such as collection and transportation have been disregarded for simplicity.

Results of the assessment in terms of energy consumption are provided in Table 10.

⁴² For instance as fuel for combustion in Combined Heat and Power (CHP) plants, as feedstock to biogas production (see e.g. Anderson 2004) or as feedstock for ethanol production (see e.g. Sheehan et al. 2004).

⁴³ The inventories include the cultivation of hay on a permanent meadow. Included steps are harvest, transport to the farm and the storage in the barn during 12 months. Drying occurs only on the meadow. Production process refers geographically to the Swiss plateau (lowlands <700 m) under extensive conditions.

⁴⁴ <http://www.lcafood.dk/processes/energyconversion/heatandpowerfromstraw.htm>

Table 10: Fossil energy consumption induced by production of ethanol in three different stover use scenarios. All data refer to primary energy (LHV).

Scenario	MJ/litre
Stovers are left on the ground (Section 4.1)	21.6
Stovers are used as animal feed	20.9
Stovers are used as fuel for combined heat and power production	5.68

Table 10 shows that the use of stovers as feed for animals or as fuel for combined heat and power production reduces the total fossil fuel consumption associated with ethanol production. This is explained by the fact that application of stovers displaces other production processes which are thus subtracted. The energy value of displacing animal feed with corn stovers (see Figure 8) is quite limited because only little energy is used to produce the alternative of hay, resulting only in a slight decrease of total energy costs to produce ethanol. Use of stovers for combined heat and power production (see Figure 9), on the other hand, displaces quite significant quantities of conventional fuels (here exemplified with oil), and results in a significant reduction of the energy costs associated with ethanol production.

Contributions to global warming from driving 1.6 km in a person car decrease considerably (same pattern as for energy, Table 10) when the stovers are utilised because additional CO₂ emissions are saved due to avoided hay growing or oil combustion for heat and power production. Contributions to nutrient enrichment and acidification from driving 1.6 km in a person car on the other hand are almost independent of the stover use because the considered alternatives' contributions to these impacts are small in comparison. Land use from driving 1.6 km in a person car fuelled partly with ethanol is addressed in Table 11.

Table 11: Land use induced by driving 1.6 km (one mile) with E10/E85 fuel with ethanol production referring to three different stover use scenarios. Agricultural land is used for corn and soy production⁴⁵ and meadow is used for hay production. All data are provided in m²year.

Stover use scenario	E10		E85	
	Agr. land	Meadow	Agr. land	Meadow
Stovers are left on the ground	0.038	0	0.34	0
Stovers are used as animal feed	0.038	-0.052	0.34	-0.457
Stovers are used as fuel for CHP	0.038	0	0.34	0

Table 11 indicates that use of agricultural land is independent of the stover use scenario but that a significant area of extensively grown meadow can potentially be saved if the stovers are used for feeding animals. In fact, the area of meadow saved is larger than the area of agricultural land used because the stover yield in the considered scenario is higher than the hay yield from meadow.

⁴⁵ Soy saved as a result of DDGS application for animal feed.

Data on stover collection are quite conservative as discussed in Section 3.1 and the potential of utilizing the stovers can possibly be about the double if more of the stovers are utilized. This raises the consideration whether loss of organic matter from the corn field will result in a reduction of the content of nutrients or organic matter in the soil and eventually increase soil erosion. This question has not been considered in the present study and needs to be addressed in detail before application of stovers from cornfields eventually can be recommended from an environmental point of view⁴⁶.

⁴⁶ Anderson (2004) has discussed the subject and argues that "soil tilth (health) and percentage of soil organic matter (which continues to decline with tillage) is determined more by what takes place 3-12 inches deep in the soil than by the amount of residue on the surface".

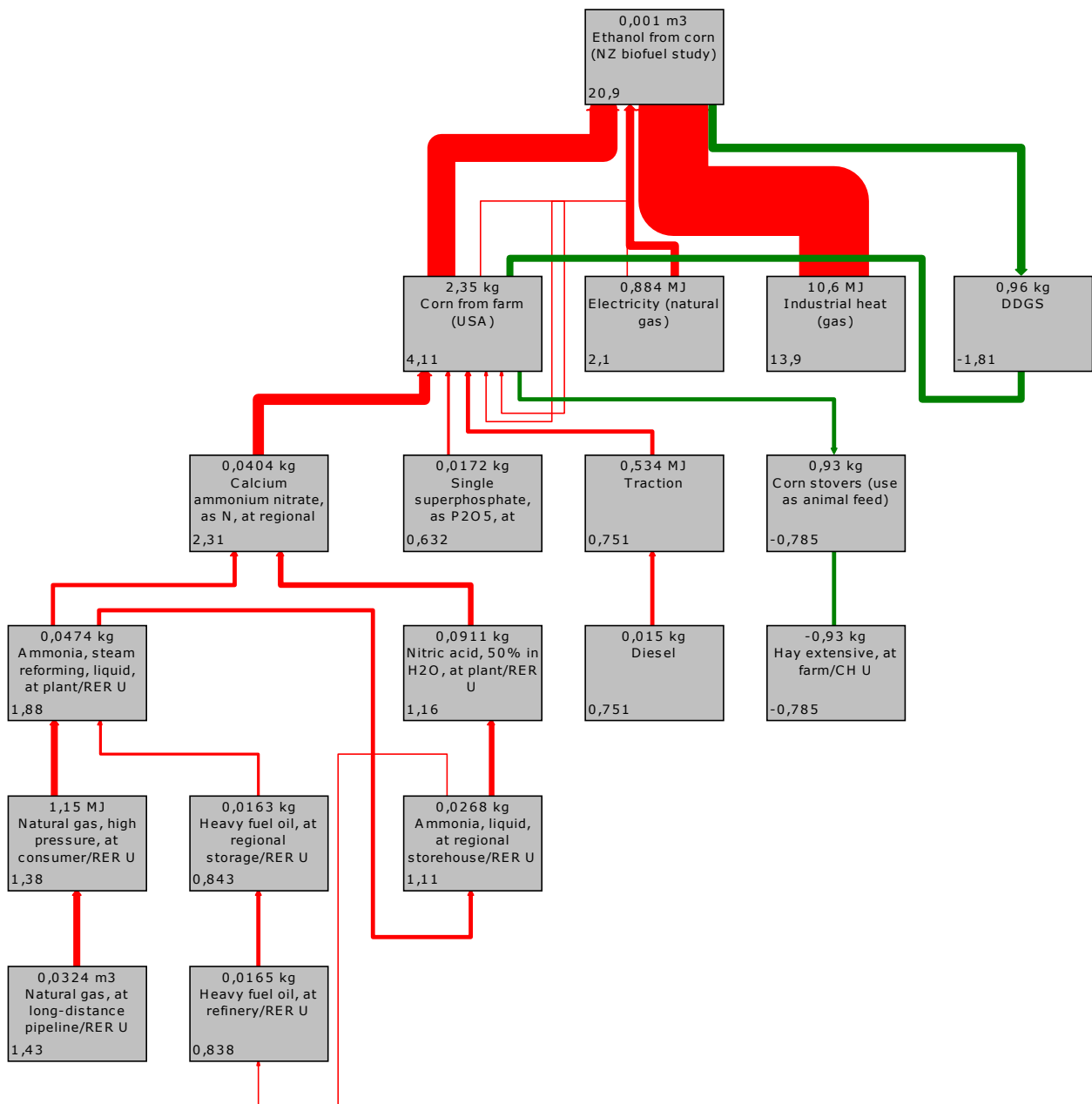


Figure 8: Sources of fossil energy consumption (primary, LHV) for ethanol production when stovers are used as animal feed (Cut off = 2.9%).

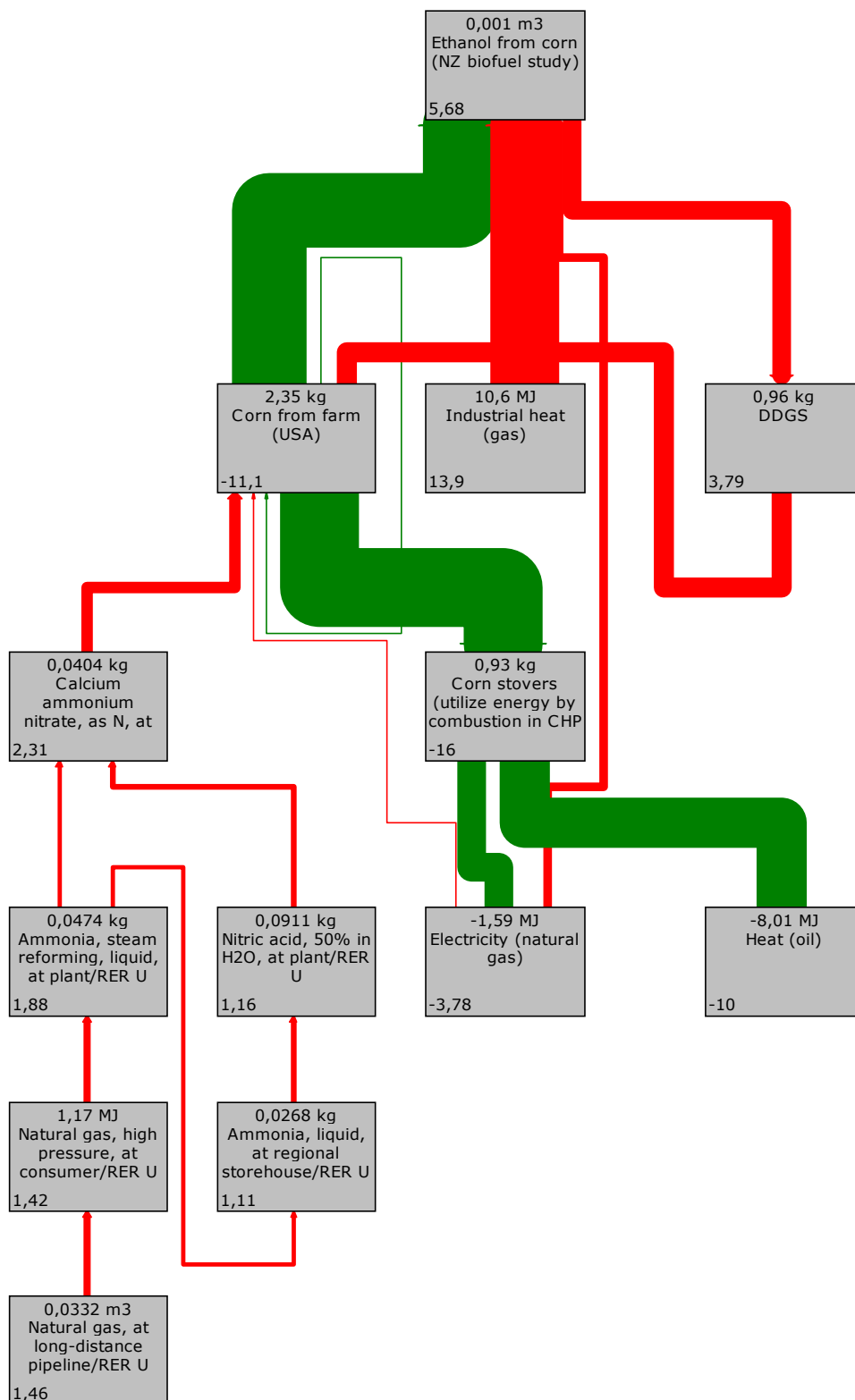


Figure 9: Sources of fossil energy consumption (primary, LHV) for ethanol production when stovers are used as fuel for combined heat and power production (Cut off = 5.8%).

6.2 Scenario including the opportunity cost of extra land use

In order to assess the proportions of any opportunity cost of using biomass for bio-ethanol production, a rough assessment of alternative energy use of the corn for combined heat and power (CHP) production has been made. In case the objective is to grow biomass for CHP production, corn might not be the optimal choice of crop, but an assessment of using the corn for CHP will, anyhow, give an impression of the environmental difference between this application of the corn and the application as substrate for ethanol production.

A rough calculation was made in which A) corn and B) corn and corn stovers are used for CHP. Calculation of CHP produced from corn is based on full scale CHP production from straw in Denmark (Nielsen et al. 2003) because no data on CHP production from corn in the United States were readily available.

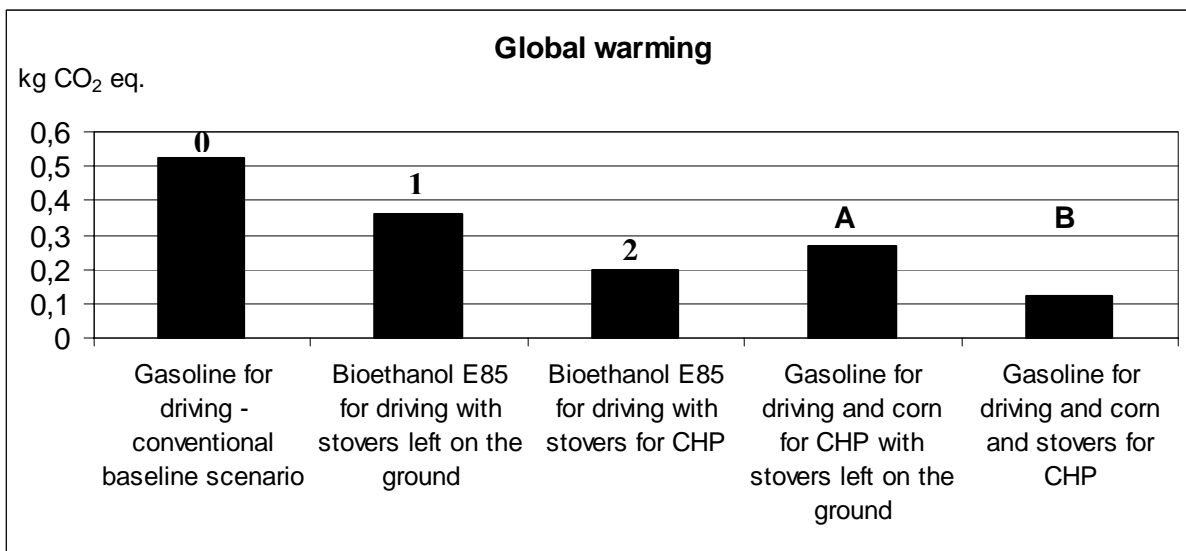


Figure 10: A scenario of using corn (A) and corn & stovers (B) for CHP production compared to using it for bio-ethanol in car fuel. All data are provided per functional unit, i.e. per one mile driven in a car.

Figure 10 indicates that using the corn for CHP gives a 50% higher reduction of greenhouse gas emissions than using it for ethanol production for car fuel. In scenario A, the car is run on conventional gasoline, and the corn used for bio-ethanol production in the E85 scenario is used for CHP instead. In scenario B, the car is likewise run on conventional gasoline, and both the corn and the stovers are used for CHP. The results indicate that it is much more efficient, in terms of reducing greenhouse gas emission, to use biomass for CHP and fossil fuel for driving cars than vice versa. The reason is that energy efficiency of CHP production is much higher (> 90 %) than for ethanol fermentation implying that the substitution of fossil fuels by using biomass directly in the energy sector (CHP) is much more efficient than by converting it to bio-ethanol for substituting fossil fuel in the transportation sector. If, then, one of the limiting factors for fossil fuel substitution is the availability of useable biomass, the difference between CO₂ reduction through bio-ethanol and through direct use for CHP becomes a true opportunity cost of using the biomass for ethanol production. In this case, the comparison between conventional gasoline and bio-ethanol is not a comparison between the baseline scenario (scenario 0 in Figure 10) and the E85 scenarios 1 and 2 in Figure 10, but a comparison of Scenarios 1 and 2 with Scenarios A and B respectively.

6.3 Scenario of petrochemical ethanol

Ethanol can be produced from corn as explained above, but it can also be synthesised by hydrating ethylene derived from mineral oil ($C_2H_4 + H_2O \rightarrow C_2H_5OH$, Kirk-Othmer, 1980)) and the environmental competitiveness of the two ethanol products has been addressed in this section.

Data on synthesising ethanol from ethylene have not been found in available databases or literature. Thus, mineral oil based ethanol has been simulated with mineral oil based ethylene acknowledging that this simplification supposedly underestimates impacts of mineral oil based ethanol⁴⁷. Quantities of ethylene applied per litre of ethanol produced are determined by stoichiometric calculations and data on ethylene are derived from Ecoinvent database. Transportation of mineral oil based ethanol has been disregarded because no significant changes compared with the existing distribution system are expected.

Modelling of corn based ethanol refers to the base case: Corn production is based on average data from nine states (see Section 3.1), corn stovers are left on the ground after harvest and ethanol is produced with present technology as explained in Section 3.3 .

The comparison of corn based ethanol and mineral oil based ethanol refer to combustion of one litre of ethanol. Emissions of fossil CO_2 from combustion of mineral based ethanol and emissions of non-fossil CO_2 from combustion of corn based ethanol are included, because they do respectively do not contribute to global warming. Other emissions from the combustion process are disregarded because they are similar. The results are shown in Figure 11.

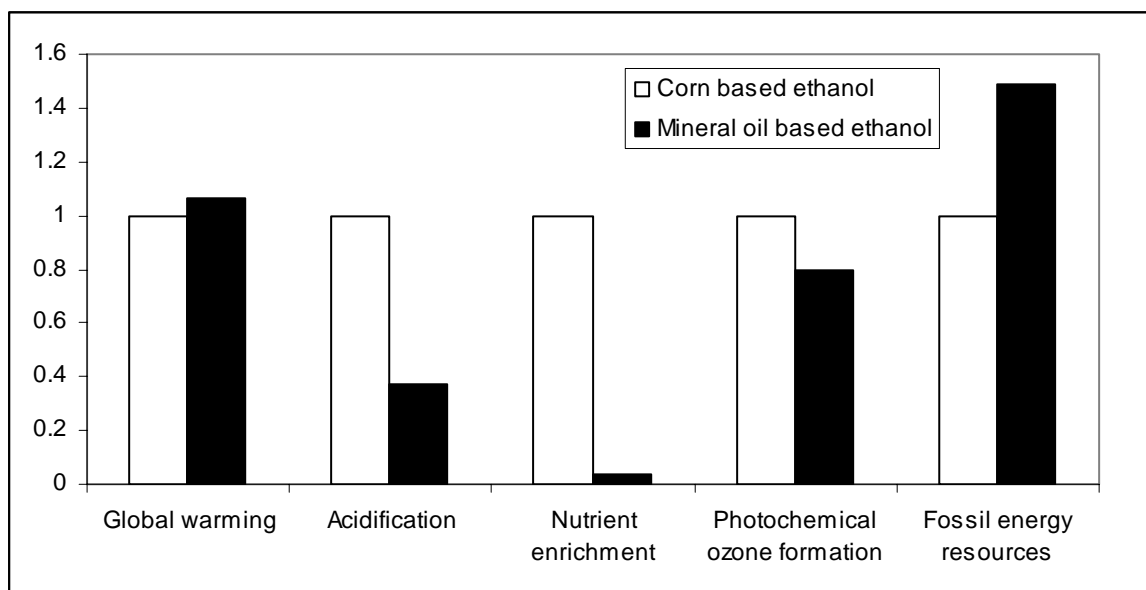


Figure 11: Relative contributions to various environmental impacts from combustion of corn based ethanol and mineral oil based ethanol. Combustion of corn based ethanol serves as normalisation reference and is hence 1.0 in any case.

Data on mineral oil based ethanol are supposedly somewhat underestimated because the final hydration of ethylene to form ethanol is disregarded and the results in Figure 11 do only

⁴⁷ The reaction between ethylene and water takes place at elevated temperature (250 to 300°C) and encounters a number of purification steps (Kirk-Othmer 1980) and a certain amount of heat and electricity is presumably used for the synthesis.

provide a pretty rough indication of the two products relative contributions to the considered impacts.

It is, however, obvious that contributions to global warming from the two ethanol products are in the same order of magnitude although apparently in favour of corn based ethanol. It is also obvious that in terms of acidification, nutrient enrichment and to some extent photochemical ozone formation, mineral oil based ethanol appears to be favourable. The relatively high contribution from corn based ethanol to these impact categories is explained by emissions of acidifying substances and nutrients from the farmland during corn production and emissions of VOCs from traction processes as discussed earlier. The quite significant difference between corn based ethanol and mineral oil based ethanol in terms of fossil energy resources consumption in favour of corn based ethanol is explained by the feedstock input of crude oil to mineral oil based ethanol production. The magnitude of the difference when fossil energy resources are considered is not reflected in contributions to global warming because other emissions than CO₂ from the combustion of ethanol contribute to global warming in the production of corn-ethanol, namely emissions of N₂O and CO₂ from the cornfield, see Table 1. Data on emissions of N₂O and CO₂ from the cornfield are very uncertain (see Section 3.1) and exact figures on global warming from corn based ethanol should be interpreted with care.

7 Comparison with other studies

Quite a number of assessments of corn based ethanol have been performed during the past decade and some of the main approaches from the most recent reports are summarised in Table 12.

The table shows that the present study uses the same basic approach as Wang (1999), with respect to "basis for comparison" and that the indicators considered relate to the same environmental concerns⁴⁸ except that use of agricultural land has not been given attention by Wang (1999).

Shapouri et al. (2003), Patzek (2004) and Pimentel (2003) use "energy balances" as basis for comparison and the present study has included this indicator to make comparison of energy results possible even though the results are considered irrelevant in the context of using ethanol for car driving as discussed above.

"Displacement method", "Replacement value method" and "System expansion method" refer to the same principle when handling of co-products is considered, and all studies except Patzek (2004) apply the same principle⁴⁹ that environmental impacts from the products that co-products of corn ethanol displace are subtracted. Patzek (2004) sees co-products from ethanol factory as waste and gives zero credit to the co-products.

With respect to conclusions, the present study is in agreement with Wang (1999) at points where the results are comparable, namely use of fossil fuels and apparently also global warming. Other indicators cannot be compared directly because Wang (1999) provide results as emissions of selected substances and the present study apply recalculation of a broader spectrum of emissions into environmental impact potentials.

Fossil energy input determined in the present study is about the same level as thermal energy content of ethanol, and the results of the present study in terms of energy balance study ends

⁴⁸ Emissions considered by Wang (1999) all contribute to the environmental impact categories considered in this study.

⁴⁹ as recommended in the ISO standards for LCA

up between Shapouri et al. (2003) who find a positive energy balance and those who find a negative energy balance (Patzek (2004) and Pimentel (2003)).

Essential inputs and outputs in corn ethanol's product chain in terms of energy have been addressed in a review by Shapouri (2002) for a number of studies from the past decade. The results are repeated in Table 13 and supplemented with same type of information from the present study and a recent study by Pimentel (2003).

The table addresses a range of parameters of varying importance for the overall result of energy assessments. An impression of each parameter's importance can be found in Figure 4.

The table shows that "corn yield" and "N fertiliser application rate" applied in the present study is quite high compared with most other studies. This is not surprising since yield of corn has grown steadily in the US in the past decades (FAOSTAT 2004) and the present study uses the most recent data. Data on yields are in agreement with statistics from FAOSTAT (2004) and it is likely that the increasing yield is linked with the increasing fertiliser application.

N-fertiliser is supplied by the fertiliser industry in many different forms and it can be produced with a range of different energy inputs depending on the applied technology and the level of energy management in the considered factories (see Patyk and Reinhardt 1997). Together with the fact that energy consumption per produced unit of N-fertiliser has decreased quite significantly during the past decades⁵⁰ this probably explains some of the variation between studies. The present study refers to European N-fertiliser production technology and the applied energy data are at the same level as the energy data used by in the most recent studies, except Pimentel (2003) who used significantly higher energy input data.

Corn ethanol conversion rate has increased gradually over the past decade and it is not surprising that the conversion rate applied in the present study is among the highest because the most recent and efficient technology intentionally has been applied. It is more surprising that energy input per produced unit of ethanol recorded in the present study is quite high compared to most other studies. Explanations can be different calculation principles, different background data and many other things and cannot be revealed without digging deep into each study.

The total energy use calculated for corn ethanol production in the present study is at the same level as in most other studies considered in Table 13 except those reported by Pimentel (2003), which are much higher than all others.

Significant variation exists between different studies when it comes to co-product energy credits. This can be explained by application of different assessment principles in different studies, ranging from various allocation principles to differences in system expansion basis. In the present study, application of DDGS as replacement for corn in swine diet has been used as basis for system expansion and energy credit comes out in the lower end of the interval reported in the literature. Sensitivity analyses where DDGS displaces soy meal in cattle's diet indicate, however, that energy credit can vary significantly depending on the specie considered and the suggested energy credit can in fact be overestimated significantly.

⁵⁰ European Fertilizer Manufacturers Association (www.efma.org)

Table 12: Main approaches and conclusions from the most recent reports.

Study	Quantitatively considered indicators	Basis for comparison ⁵¹	Handling of co-products.	Conclusions
Wang (1999)	Fossil energy consumption, CO ₂ and GHG ⁵² emissions, VOC emissions, CO emissions, NO _x emissions and more.	Driving in a variety of conventional vehicles and alternative vehicles with a broad spectrum of conventional and alternative fuels	Displacement method	Corn ethanol is favourable to conventional gasoline in terms of fossil fuel consumption, CO ₂ and GHG emissions and in favour/disfavour in terms of VOC, CO and NO _x emissions.
Shapouri et al. (2003)	Energy	Net energy value ⁵³ (NEV)	Replacement value method	Energy value of corn ethanol exceeds the energy required to producing it (HHV) and NEV is positive
Patzek (2004)	Energy	Calorific value	Zero credit p. 29	More fossil energy is used to produce ethanol from corn than the ethanol's calorific value
Pimentel (2003)	Energy	Energy balance	Displacement method	The total energy input to produce corn ethanol is higher than the energy value of ethanol (LHV) p. 128.
This study	Fossil energy Consumption Global warming Acidification Nutrient enrichment Photochemical ozone formation and use of agricultural land.	Energy balance Driving one mile in personal car with conventional gasoline, E85 and E10 as fuel. Comparison of corn based ethanol and mineral oil based ethanol.	System expansion method	Primary energy input associated with corn ethanol production is same order of magnitude as the low heat value of ethanol. The ratio between used and displaced fossil fuel is about 1:1.9. Corn ethanol is favourable to conventional gasoline in terms of fossil fuel consumption, global warming and photochemical ozone formation but not in terms of acidification, nutrient enrichment and agricultural land use. If biomass becomes a priority resource of limited availability, e.g. due to increased demand for CO ₂ neutral fuels for heat and power production, corn ethanol is likely to be unfavourable from a fossil fuel consumption and global warming point.

⁵¹ All energy balances refer to thermal energy value of ethanol.

⁵² Greenhouse gas

⁵³ Energy content of ethanol minus total energy used to produce it when energy credits from co-products are subtracted.

Table 13: Comparison with essential energy input and output data in other studies as done by Shapouri et al. 2002. Data on study 1-10 are taken directly from Shapouri et al. (2002) whereas data on study 11 and 12 are determined in the present context.

Study no. and year		Corn yield	Nitrogen fertilizer application rate	Nitrogen fertilizer production	Corn ethanol conversion rate	Ethanol conversion process	Total energy use	Co-product energy credits
		<i>Bu/acre</i>	<i>lb/acre</i>	<i>Btu/lb</i>	<i>Gal/bu</i>	<i>Btu/gal</i>	<i>Btu/gal</i>	<i>Btu/gal</i>
1	Pimentel (1991)	110	136	37,551	2.50	73,687	131,017 (LHV)	21,500
2	Pimentel (2001)	127	129	33,547	2.50	75,118	131,062 (LHV)	21,500
3	Keeney and DeLuca (1992)	119	135	37,958	2.56	48,470	91,196 (LHV)	8,078
4	Marland and Turhollow (1990)	119	127	31,135	2.50	50,105	73,934 (HHV)	8,127
5	Lorenz and Morris (1995)	120	123	27,605	2.55	53,956	81,090 (HHV)	27,579
6	Ho (1989)	90	NA ⁵⁴	NA	NA	57,000	90,000 (LHV)	10,500
7	Wang et al. (1999)	125	131	21,092	2.55	40,850	68,450 (LHV)	14,950
8	Agri. and Agri-Food Canada (1999)	116	125	NA	2.69	50,415	68,450 (LHV)	14,055
9	Shapouri et al. (1995)	122	125	22,159	2.53	53,277	82,824 (HHV)	15,056
10	Shapouri et al. (2002)	125	129	18,392	2.66	51,779	77,228 (HHV)	14,372
11	Pimentel (2003)	113 ⁵⁵	132 ⁵⁶	33,500 ⁵⁷	2.5 ⁵⁸	57,000 ⁵⁹	104,300 ⁶⁰	6,728 ⁶¹
12	This study	139 ⁶²	134 ⁶³	24,400 ⁶⁴	2.64 ⁶⁵	56,000 ⁶⁶	84,700 ⁶⁷ (LHV)	7,500 ⁶⁸

⁵⁴ Not available.

⁵⁵ 8590 kg/ha. 8590 kg/ha / 0.845 kg/l / 36.4 l/bushel / 10,000 m²/ha · 4047 m²/acre = 113 Bu/acre (p. 128).

⁵⁶ 148 kg/ha. 148 kg/ha / 0.453 kg/pound / 10,000 m²/ha · 4047 m²/acre = 132 pound/acre. See Table 1.

⁵⁷ 10,952,000 Btu/ha. 148 kg/ha = 326,7 pound/ha . 10,952,000 Btu/ha / 326.7 pound/ha = 326= 33,500 Btu/pound. See Table 1.

⁵⁸ See p. 128

⁵⁹ 54,200 Btu/gal 95% ethanol = 57,000 Btu/gal 100% ethanol. See Table 2 ("corn" and "transport of corn" has been excluded).

⁶⁰ 99,100 Btu/gal 95% ethanol = 104,300 Btu/gal 100% ethanol. See Table 2

⁶¹ See p. 130.

⁶² See Table 1.

⁶³ See Table 1.

⁶⁴ 25.9 MJ · 1000/1.06 KJ/Btu = 24,400Btu/lb (See process tree from SimaPro).

⁶⁵ (3.17 kg corn/l ethanol / 0.845 kg/l (density, see p. 13) / 36.4 l/Bushel = 0.10 Bushel. 1 l ethanol / 3.785 l/gal = 0.264 gal. 0.264 gal / 0.1 Bushel = 2.64 gal/Bushel. See Table 3.

⁶⁶ (6.78 (electricity) + 52.7 MJ (heat)) · 1000/1.06 KJ/Btu = 56,000 Btu/gal (See process tree from SimaPro).

⁶⁷ (81.9 + 7.92 MJ/gal) · 1000/1.06 KJ/Btu = 84,700 Btu/gal (See process tree from SimaPro).

⁶⁸ (7.92 MJ/gal · 1000)/1.06 KJ/Btu = 7500 Btu/gal (See process tree from SimaPro).

8 Interpretation and conclusion

Energy analyses in the present study indicate that thermal energy content of ethanol produced from corn with present technology is at the same level as the input of fossil fuel used to produce it. This could be taken as an indication that ethanol production from corn is inefficient and it probably explains some of the discussion which has been going on in the American literature in the past years – whether corn based ethanol is advantageous for from an energy point of view or not.

The environmental implications of producing ethanol from corn can, however, not be determined from thermal energy balances, when application of the product as fuel for car driving is considered. Cars are equipped with explosion motors, which are driven by the explosion power of the fuel and not the heat output. Moreover, the energy balance of using bio-ethanol in car fuels, is not a 'balance' between thermal energy used for the production of the ethanol versus the heat value of the ethanol. The balance shall be the balance of induced consumption of fossil fuel for the ethanol production versus avoided consumption of fossil fuel for the gasoline or the MTBE substituted by the ethanol. And for gasoline substitution, that balance is around 1:1.9 in favour of the ethanol – provided that biomass for ethanol production is of unlimited availability, see below.

In addition to energy, the present study addresses four environmental impact indicators: global warming, acidification, nutrient enrichment and photochemical ozone formation and one additional resource indicator: use of agricultural land. Furthermore, the study includes application of ethanol as alternative to conventional gasoline and as alternative to ethanol produced from mineral oil.

Use of this broader approach reveals a more differentiated picture. In a baseline scenario, in which biomass is anticipated to be of unlimited availability, corn ethanol appears to be competitive with its alternatives (conventional gasoline and mineral oil based ethanol) when energy resources and contributions to global warming and photochemical ozone formation are considered. The mineral oil based alternatives appear, however, to be favourable when use of agricultural land and contributions to acidification and nutrient enrichment are considered. The exact figures behind acidification and nutrient enrichment are associated with much uncertainty because of uncertain data on emissions from corn production, but the general picture is in agreement with a comprehensive European study by Calzoni et al (2000). Thus, a weighting and comparison of the observed trade-offs, i.e. the advantages and disadvantages, associated with replacing conventional fuels with corn based ethanol appears to be necessary.

The trade-off between use of agricultural land on the one side and fossil fuel consumption and global warming on the other side is dealt with in the present study. The point is that land use, fossil fuel consumption and global warming to some extent are linked, implying that they can be measured on the same scale.

The apparent advantages of bio-ethanol in the baseline scenario are, therefore, only real and leading to reduced consumption of fossil fuel and reduced global warming if land and biomass from the land is of unlimited availability, and there is no opportunity cost of using it. If, however, biomass is or becomes a resource of economic priority to reduce society's contribution to global warming, and at the same time a resource of limited availability, the opportunity cost of using it for bio-ethanol will turn the balance and imply that using bio-ethanol for car fuel will in fact increase society's contribution to global warming and fossil fuel consumption.

A quantified probability analysis of the future demand-supply situation for biomass in the US has not been made within the scope of the present study. It is known, however, that the situation in Denmark is at present already such that a large proportion of heat and power plants have been rebuilt to use biomass in parallel with fossil fuels. As Denmark has far from enough biomass to meet the goals of Kyoto-protocol by means of biomass alone, it means that Denmark will probably have an opportunity cost of using biomass for less efficient purposes. Comparing Europe's CO₂ reduction targets with the non-utilised production capacity of European agriculture and forestry also points to the fact that biomass may come short on the European scale (see Frees et al. 2004). It is, therefore, recommended that the possible opportunity costs of using biomass for bio-ethanol be taken seriously.

Toxicity issues have not been quantified and dealt with in the present study because of data and constraints. Emissions of toxic substances occur, however, in all steps of the product chain of corn based ethanol and its alternatives⁶⁹ and it is unknown how toxicity would add to our view of the environmental implications of corn based ethanol. It should, however, be noted 1) that use of ethanol as alternative to gasoline can possibly provide important contributions to reductions of toxicity due to reduced emissions of carbon monoxide, PM₁₀, and SO_x from car's exhaust gasses (see Table 8) and 2) that use of ethanol as oxygenation agent in gasoline can displace carcinogenic aromatic compounds in the gasoline and hence in the exhaust gas. These improvements are characteristic for both corn based and mineral oil based ethanol and can be particularly important where exposure of humans is direct, for instance in major cities.

The analytical method applied in the present study has been compared with analytical methods applied in other studies addressing the same subject. Most existing studies address energy balances at the gate of the ethanol factory whereas the present study addresses a broad spectrum of environmental indicators in a more complete perspective where ethanol's environmental properties as fuel for car driving and displacement of conventional alternatives are included. This broader view provides new and more nuanced insight into corn ethanol's interactions with our surroundings, which should be taken into account in the further debate about fuel ethanol.

Handling of the DDGS in environmental assessments has been subject to many considerations in the past year's literature, and many different expressions have been used to explain what has been done. The comparison of methods indicates that the same principle, "system expansion" (according to ISO terminology) lies behind the different wordings and that the method applied in the present study are in agreement with methods applied in most of the other considered studies. It is, however, also clear that the principle can be used in many different ways, leading to quite different conclusions with respect to the value of DDGS in environmental terms.

Basic data on corn yield, fertiliser application, ethanol yield, DDGS application etc. are important for the final result of the study, and energy data applied in the present study have been compared with energy data reported in the literature. The comparison indicates that data behind the present study are in the same order of magnitude as the majority of other recent studies, though the applied data belong to the high end in some cases (e.g. corn yield and fertiliser application rate in agriculture and ethanol yield at the ethanol factory) and the low end in other cases (e.g. energy value of DDGS). Use of relatively high corn yields, high fertilisation rates and ethanol yields are justified by the fact that these parameters have increased over the past years and that the present study is among the most recent.

⁶⁹ For instance pesticides from farming, VOC emissions from the ethanol plant, VOC emissions from fuel extraction and refining, carbon monoxide, VOC and particulate emissions from all combustion processes.

Some of the most important assumptions applied in the study have been subject to sensitivity analyses. These sensitivity analyses have revealed that location of corn production, efficiency of ethanol fuelled cars, and use of DDGS are all quite important for the final result of the study and that other reasonable assumptions may provide slightly different results in favour as well as disfavour of corn ethanol.

9 References

- Adams RS (1998): Corn stovers as feed for cattle. PENpages College of Agricultural Sciences. News service: 8/5/88. Document no. 28902108.
www.penpages.psu.edu/penpages_reference/28902/28902108.HTML
- Anderson (1994): Anaerobic digestion of corn stover and swine manure. IOWA Energy Centre.
www.energy.iastate.edu/renewable/biomass/cs-anerobic.html
- BBI (2001): Ethanol Plant Development Handbook: Fourth Edition. BBI International.
www.bb ethanol.com
- Benham BL (1998): Irrigating corn. Institute of agriculture and natural resources, University of Nebraska. Lincoln.
- Calzoni J, Caspersen N, Dercas N, Gaillard G, Gosse G, Hanegraaf M, Heinzer L, Jungk N, Kool A, Korsuize G, Lechner M, Leviel B, Neumayr R, Nielsen AM, Nielsen PH, Nikolaou A, Panoutsou C, Panvini A, Patyk A, Rathbauer J, Reinhardt GA, Riva G, Smedile E, Stettler C, Weidema BP, Wörgetter M, Zeijts H van. (2000) Bioenergy for Europe: Which ones fit best? A comparative analysis for the community. The European Commission in the framework of the FAIR V Programme. Contract CT 98 3832.
- DOE (1999): Ethanol for sustainable transportation. Separating fact from fiction. US Department of Energy. National Renewable Energy Laboratory. DOE/GO-10099-736.
www.pugetsoundcleancities.org/pdfs/ethanol_facts_fiction.pdf
- Ecoinvent Database (2004): Version 1.01. www.ecoinvent.com
- Ekvall T and Weidema B P (2004): System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. Int. J. LCA 9 (3) 161-171 (2004)
- ETH (1996): Ökoinventare für Energisysteme (Teil I-VII), ETH. ETH Zurich. www.eth.ch.
- FAOSTAT (2004): <http://faostat.fao.org>
- Frees N, Hansen M S, Ottosen L M, Tønning K and Wenzel H (2004): Up-date of the knowledgebase on the environmental aspects of paper and cardboard recycling. Environmental Project xxx, Danish Environmental Protection Agency, 2004 (accepted for publication). (In Danish, summary in English).
- Garcia A and Taylor G (2002): Economics of feeding Distillers grains to Dairy cows. Extra (ExEx 4025) College of agriculture biological sciences – South Dakota State University.
<http://www.ddgs.umn.edu/articles-dairy/ExEx4025.pdf>
- Hodge C. (2002): Ethanol in US gasoline should be banned, not expanded. Oil and gas Journal. Sept. 9: 20-28.
- Kirk-Othmer (1980): Encyclopedia of chemical technology. Third edition. Vol. 9. John Wiley & Sons.

McAloon A, Taylor F, Yee W, Ibsen K, Wooley R (2000): Determining the cost of producing ethanol from corn starch and lignocellulosic feedstocks. National Renewable Energy Laboratory, NREL.

National Biomass Initiative (2004). Feature article. www.bioproducts-bioenergy.gov/news/displayRecentArticle.asp?idarticle=150.

NREL: Ford Taurus – Ethanol fueled sedan. Fact sheet, National Renewable Energy Laboratory. NREL/FS-540-26578.

Nielsen PH, Nielsen AM, Weidema BP, Dalgaard R and Halberg N (2003). LCA Food Database. www.lcafood.dk.

Nielsen PH (2004): Cradle to gate Environmental assessment of enzymes produced by Novozymes – Improvement of data basis, full assessment of six selected enzymes and development of a simplified tool. The Institute for Product Development, October 2004

Nielsen PH and Wenzel H (2004). Integrated environmental assessment of Ronozyme® phytase application as an alternative to phosphate supplementation to pig feed. Draft report by The Institute for Product Development, Technical University of Denmark.

Patyk A and Reinhardt G (1997). Düngemittel- Energie- und Stoffstromsbilanzen. Friedr. Vieweg & Sohn Publishers. Braunschweig/Wiesbaden, Germany. ISBN: 3-528-06885-X.

Olsen HS (2004): "Using Enzymes in Ethanol Production" by Hans Sejr Olsen. Published by Novozymes A/S. 2004-13388-01.

Patzek TW (2004) Sustainability of the corn-ethanol biofuel cycle. Submitted to critical Reviews of plant Science. Manuscript 416Patzek5-9-04. College of Engineering, Berkeley CA University of California.

Pimentel D (2003): Ethanol fuels: Energy balance, economics, and environmental impacts are negative. Natural resources Research. 12(2) p. 127-134.

Heding N (2005): Research Centre Forest and Landscape, Denmark, personal communication.

Shapouri H, Duffield J and Wang M (2002): The energy balance of corn ethanol: an update. United States Department of Agriculture. Office of Energy Policy and New Uses. Agricultural Economic Report number 814.

Shapouri H, Duffield J and Wang M (2004): The 2001 net energy balance of corn-ethanol. United States Department of Agriculture. Report no. 814. www.bioproducts-bioenergy.gov/pdfs/net%20energy%20balance.pdf

Shapouri H, Gallagher P, Graboski MS (1998): US Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses. Agricultural Economic Report Number 808.

Sheehan J, Aden A, Paustian K, Killian K, Brenner J, Walsh M and Nelson R (2004): Energy and environmental aspects of using corn stovers for fuel ethanol. Journal of Industrial Ecology. Vol. 7 p. 117-146.

Sokhansaj S, Turhollow A and Perlack R (2002): Stochastic modelling of costs of corn stover costs delivered to an intermediate storage facility. 2002 ASAE Annual International Meeting/CIGR XVth World Congress. Chicago, Illinois, USA July 28-31. Paper no. 024190.

Stranddorf HK, Hoffmann L and Schmidt A (2001): Normalisation and weighting – update of selected impact categories. Report in press Danish EPA (www.mst.dk).

Tampier M, Smith D, Bibeau E and Beauchemin PA (2004): Identifying environmentally preferable uses for biomass resources. Stage 1 report: Identification of Feedstock-to-threads and Stage 2 report: Life-cycle GHG emission reduction benefits of selected feedstock-to-product threads. EnvironChem Services Inc.

Thaler B (2002): Use of distillers dried grains with solubles (DDGS) in swine diets. Extension Extra (ExEx 2035) College of agriculture biological sciences – South Dakota State University. <http://www.ddgs.umn.edu/articles-swine/ExEx2035.pdf>

Tjardes K and Wright C (2002): Feeding corn distiller's co-products to beef cattle. Extension Extra (ExEx 2036) College of agriculture biological sciences – South Dakota State University. <http://www.ddgs.umn.edu/articles-beef/ExEx2036.pdf>

United States Country Analysis Brief (2004). www.eia.doe.gov/emeu/cabs/usa.html

Wang MQ (1999a): Greet 1.5 – Transportation fuel-cycle model. Volume 1: Methodology, development, use and results. Argonne National Laboratory. ANL/ESD-39, Vol. 1. www.transportation.anl.gov/software/GREET/publications.html#reports

Wang MQ (1999b): Greet 1.5 – Transportation fuel-cycle model. Volume 2: Appendices of data and results. Argonne National Laboratory. ANL/ESD-39, Vol. 2. www.transportation.anl.gov/software/GREET/publications.html#reports

Wang MQ (1999c): Greet 1.5 Spreadsheet model
www.transportation.anl.gov/software/GREET/downloads/greet1.5a-rev.zip

Weidema B (2003). Market information in life cycle assessments. Technical report, Danish Environmental Protection Agency ([Environmental Project no. 863](#)). www.mst.dk.

Wenzel H, Hauschild M and Alting L (1997): Environmental assessment of products. Volume 1. Methodology, tools and case studies in product development. Chapman and Hall.

Wenzel H (1998): Application Dependency of LCA Methodology – Key Variables and Their Mode of Influencing the Method. Int. J. LCA 3 (5) 281 – 288, Ecomed Publishers, Landsberg, Germany.

Wolf M (2003): Airquality and ethanol production - Nebraska's experience. Nebraska Department of Environmental Quality.

Yacobucci BD and Womach (2003) Fuel ethanol: Background and public policy issues. Congressional Research Service (CRS) Report for the congress. Order code RL30369. www.ncseonline.org/nle/crsreports/03Aug/RL30369.pdf

Appendix 1: Conversion factors

1 gallon (US) = 3.785 l

1 mile = 1.6 km

1 bushel = 36.4 l

1 BTU⁷⁰ = 1.06 kJ

1 pound = 0.453 kg

1 acre = 4047 m²

1 cubic feet = 28.3 l

1 inch = 2.54 cm

1 miles/gallon = 0.423 km/l

1 g/mile = 0.625 g/km

1 BTU/gallon = 0.280 KJ/l

1 BTU/bushel = 0.029 KJ/l

1 BTU/pound = 2.34 kJ/kg

1 pound/gallon = 0.120 kg/l

1 bushel/gallon = 9.62 l/l

1 gallon/bushel = 0.104 l/l

1 pound /acre = 1.12 10⁻⁴ kg/m²

⁷⁰ British Thermal Unit

Appendix 2: Inventory

The table below provides a list of total inputs and outputs induced by production of one litre corn based ethanol.

No	Substance	Compartment	Unit	Quantity
1	Aluminium, 24% in bauxite, 11% in crude ore, in ground	Raw	mg	109
2	Anhydrite, in ground	Raw	µg	1.19
3	Barite, 15% in crude ore, in ground	Raw	mg	199
4	Baryte, in ground	Raw	mg	839
5	Basalt, in Boden	Raw	mg	77.1
6	Bauxite, in ground	Raw	mg	204
7	Borax, in ground	Raw	µg	63.8
8	Calcite, in ground	Raw	g	59.6
9	Carbon dioxide, in air	Raw	g	1.26
10	Chromium, 25.5 in chromite, 11.6% in crude ore, in ground	Raw	mg	217
11	Chromium, in ground	Raw	mg	8.84
12	Chrysotile, in ground	Raw	µg	3.01
13	Cinnabar, in ground	Raw	ng	260
14	Clay, bentonite, in ground	Raw	mg	166
15	Clay, unspecified, in ground	Raw	g	2.86
16	Coal, 18 MJ per kg, in ground	Raw	g	13.4
17	Coal, brown, 8 MJ per kg, in ground	Raw	g	12.7
18	Coal, brown, in ground	Raw	g	12.2
19	Coal, hard, unspecified, in ground	Raw	g	7.97
20	Cobalt, in ground	Raw	ng	444
21	Colemanite, in ground	Raw	µg	67.2
22	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	Raw	mg	75.6
23	Copper, in ground	Raw	mg	61.2
24	Diatomite, in ground	Raw	ng	23.3
25	Dolomite, in ground	Raw	mg	7.49
26	Energy, from coal	Raw	kJ	26
27	Energy, from coal, brown	Raw	J	856
28	Energy, from gas, natural	Raw	kJ	142
29	Energy, from hydro power	Raw	J	914
30	Energy, from oil	Raw	kJ	24.8
31	Energy, from uranium	Raw	kJ	2.43
32	Energy, gross calorific value, in biomass	Raw	kJ	14.1
33	Energy, kinetic, flow, in wind	Raw	kJ	8.93
34	Energy, potential, stock, in barrage water	Raw	kJ	130
35	Energy, solar	Raw	J	126
36	Feldspar, in ground	Raw	ng	6.16
37	Fluorine, 4.5% in apatite, 1% in crude ore, in ground	Raw	g	-1.71
38	Fluorine, 4.5% in apatite, 3% in crude ore, in ground	Raw	g	1.28
39	Fluorspar, 92%, in ground	Raw	mg	41.4
40	Gas, mine, off-gas, process, coal mining/kg	Raw	mg	99.7
41	Gas, natural, 35 MJ per m ³ , in ground	Raw	l	446
42	Gas, natural, in ground	Raw	l	40

No	Substance	Compartment	Unit	Quantity
43	Gas, petroleum, 35 MJ per m ³ , in ground	Raw	l	3.05
44	Granite, in ground	Raw	µg	66.4
45	Gravel, in ground	Raw	g	130
46	Gypsum, in ground	Raw	µg	751
47	Iron, 46% in ore, 25% in crude ore, in ground	Raw	g	3.15
48	Iron, in ground	Raw	g	4.8
49	Kaolinite, 24% in crude ore, in ground	Raw	µg	572
50	Kieserite, 25% in crude ore, in ground	Raw	µg	4.25
51	Kiselgur	Raw	mg	37.5
52	Land use II-III	Raw	cm ² a	47.7
53	Land use II-III, sea floor	Raw	cm ² a	137
54	Land use II-IV	Raw	cm ² a	18.2
55	Land use II-IV, sea floor	Raw	cm ² a	14.1
56	Land use III-IV	Raw	cm ² a	40.7
57	Land use IV-IV	Raw	mm ² a	8.83
58	Lead, in ground	Raw	mg	48.6
59	Magnesite, 60% in crude ore, in ground	Raw	mg	46.3
60	Magnesium, 0.13% in water	Raw	ng	260
61	Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	Raw	mg	14.9
62	Manganese, in ground	Raw	mg	2.76
63	Marl, in ground	Raw	g	-15.6
64	Molybdenum, 0.11% in sulfide, Mo 0.41% and Cu 0.36% in crude ore, in ground	Raw	mg	1.94
65	Molybdenum, in ground	Raw	ng	39.6
66	Nickel, 1.13% in sulfides, 0.76% in crude ore, in ground	Raw	mg	14.2
67	Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	Raw	mg	367
68	Nickel, in ground	Raw	mg	5.39
69	Occupation, arable	Raw	m ² a	2.9
70	Occupation, arable, non-irrigated	Raw	cm ² a	56
71	Occupation, construction site	Raw	cm ² a	-72
72	Occupation, dump site	Raw	mm ² a	426
73	Occupation, dump site, benthos	Raw	mm ² a	21
74	Occupation, forest, intensive	Raw	mm ² a	31.2
75	Occupation, forest, intensive, normal	Raw	cm ² a	25.2
76	Occupation, industrial area	Raw	mm ² a	156
77	Occupation, industrial area, benthos	Raw	mm ² a	0.183
78	Occupation, industrial area, built up	Raw	mm ² a	669
79	Occupation, industrial area, vegetation	Raw	mm ² a	119
80	Occupation, mineral extraction site	Raw	mm ² a	-146
81	Occupation, pasture and meadow, extensive	Raw	mm ² a	1.71
82	Occupation, permanent crop, fruit, intensive	Raw	mm ² a	0.37
83	Occupation, shrub land, sclerophyllous	Raw	mm ² a	41.2
84	Occupation, traffic area, rail embankment	Raw	mm ² a	89.4
85	Occupation, traffic area, rail network	Raw	mm ² a	98.9
86	Occupation, traffic area, road embankment	Raw	mm ² a	49.8
87	Occupation, traffic area, road network	Raw	cm ² a	20.4
88	Occupation, urban, discontinuously built	Raw	mm ² a	5.45
89	Occupation, water bodies, artificial	Raw	mm ² a	162
90	Occupation, water courses, artificial	Raw	cm ² a	32.4
91	Oil, crude, 42.6 MJ per kg, in ground	Raw	g	44.6
92	Oil, crude, in ground	Raw	g	32.2

No	Substance	Compartment	Unit	Quantity
93	Olivine, in ground	Raw	ng	578
94	Palladium, in ground	Raw	ng	66.7
95	Peat, in ground	Raw	µg	310
96	Perlite	Raw	mg	486
97	PGM, 4.7E-4% Pt, 3.1E-4% Pd, 0.2E-4% Rh, in crude ore, in ground	Raw	pg	303
98	Phosphate ore, in ground	Raw	mg	-962
99	Phosphorus, 18% in apatite, 12% in crude ore, in ground	Raw	g	5.11
100	Phosphorus, 18% in apatite, 4% in crude ore, in ground	Raw	g	-6.86
101	Platinum, in ground	Raw	ng	76.4
102	Rhenium, in crude ore, in ground	Raw	pg	849
103	Rhenium, in ground	Raw	ng	56.5
104	Rhodium, in ground	Raw	ng	71.1
105	Rutile, in ground	Raw	ng	5.74
106	Sand, unspecified, in ground	Raw	g	10.8
107	Shale, in ground	Raw	µg	3.37
108	Silver, 0.01% in crude ore, in ground	Raw	ng	51.3
109	Silver, in ground	Raw	µg	148
110	Sodium chloride, in ground	Raw	g	1.08
111	Sodium sulphate, various forms, in ground	Raw	mg	13.4
112	Stibnite, in ground	Raw	ng	2.43
113	Sulfur, in ground	Raw	mg	-63.8
114	Sylvite, 25 % in sylvinite, in ground	Raw	g	50.3
115	Talc, in ground	Raw	µg	36.3
116	Tin, 79% in cassiterite, 0.1% in crude ore, in ground	Raw	µg	306
117	Tin, in ground	Raw	µg	82.1
118	TiO2, 45-60% in Ilmenite, in ground	Raw	mg	41.1
119	Transformation, from arable	Raw	mm2	0.0509
120	Transformation, from arable, non-irrigated	Raw	cm2	46.7
121	Transformation, from arable, non-irrigated, fallow	Raw	mm2	0.00699
122	Transformation, from dump site, inert material landfill	Raw	mm2	0.278
123	Transformation, from dump site, residual material landfill	Raw	mm2	7.94
124	Transformation, from dump site, sanitary landfill	Raw	mm2	0.00908
125	Transformation, from dump site, slag compartment	Raw	mm2	0.00175
126	Transformation, from forest	Raw	mm2	42.6
127	Transformation, from forest, extensive	Raw	mm2	20.5
128	Transformation, from industrial area	Raw	mm2	0.265
129	Transformation, from industrial area, benthos	Raw	mm2	0.00125
130	Transformation, from industrial area, built up	Raw	mm2	-2.45
131	Transformation, from industrial area, vegetation	Raw	mm2	-4.18
132	Transformation, from mineral extraction site	Raw	mm2	-11.2
133	Transformation, from pasture and meadow	Raw	mm2	7.16
134	Transformation, from pasture and meadow, intensive	Raw	mm2	7.43
135	Transformation, from sea and ocean	Raw	mm2	21
136	Transformation, from shrub land, sclerophyllous	Raw	mm2	8.52
137	Transformation, from unknown	Raw	mm2	71.8
138	Transformation, to arable	Raw	mm2	2.58
139	Transformation, to arable, non-irrigated	Raw	cm2	46.8
140	Transformation, to arable, non-irrigated, fallow	Raw	mm2	0.0161
141	Transformation, to dump site	Raw	mm2	1.46
142	Transformation, to dump site, benthos	Raw	mm2	21
143	Transformation, to dump site, inert material landfill	Raw	mm2	0.278

No	Substance	Compartment	Unit	Quantity
144	Transformation, to dump site, residual material landfill	Raw	mm2	7.94
145	Transformation, to dump site, sanitary landfill	Raw	mm2	0.00908
146	Transformation, to dump site, slag compartment	Raw	mm2	0.00175
147	Transformation, to forest	Raw	mm2	8.98
148	Transformation, to forest, intensive	Raw	mm2	0.208
149	Transformation, to forest, intensive, normal	Raw	mm2	20.1
150	Transformation, to heterogeneous, agricultural	Raw	mm2	2.44
151	Transformation, to industrial area	Raw	mm2	1.19
152	Transformation, to industrial area, benthos	Raw	mm2	0.0219
153	Transformation, to industrial area, built up	Raw	mm2	2.26
154	Transformation, to industrial area, vegetation	Raw	mm2	0.274
155	Transformation, to mineral extraction site	Raw	mm2	43.5
156	Transformation, to pasture and meadow	Raw	mm2	-12.8
157	Transformation, to permanent crop, fruit, intensive	Raw	mm2	0.00363
158	Transformation, to sea and ocean	Raw	mm2	0.00125
159	Transformation, to shrub land, sclerophyllous	Raw	mm2	8.23
160	Transformation, to traffic area, rail embankment	Raw	mm2	0.208
161	Transformation, to traffic area, rail network	Raw	mm2	0.229
162	Transformation, to traffic area, road embankment	Raw	mm2	0.263
163	Transformation, to traffic area, road network	Raw	mm2	18.5
164	Transformation, to unknown	Raw	mm2	-4.64
165	Transformation, to urban, discontinuously built	Raw	mm2	0.109
166	Transformation, to water bodies, artificial	Raw	mm2	4.03
167	Transformation, to water courses, artificial	Raw	mm2	27.7
168	Ulexite, in ground	Raw	µg	4.33
169	Uranium, 560 GJ per kg, in ground	Raw	µg	868
170	Uranium, in ground	Raw	µg	665
171	Volume occupied, final repository for low-active radioactive waste	Raw	mm3	1.37
172	Volume occupied, final repository for radioactive waste	Raw	mm3	0.341
173	Volume occupied, reservoir	Raw	l*day	816
174	Volume occupied, underground deposit	Raw	mm3	2.94
175	water (in ground)	Raw	ml	56.4
176	Water, cooling, unspecified natural origin/m3	Raw	l	1.31
177	Water, lake	Raw	ml	1.6
178	Water, river	Raw	ml	402
179	Water, salt, ocean	Raw	ml	79.5
180	Water, salt, sole	Raw	ml	25.1
181	Water, turbine use, unspecified natural origin	Raw	l	791
182	Water, unspecified natural origin/kg	Raw	kg	4.6
183	Water, unspecified natural origin/m3	Raw	ml	999
184	Water, well, in ground	Raw	l	1.56
185	Wood, dry matter	Raw	mg	514
186	Wood, hard, standing	Raw	mm3	215
187	Wood, soft, standing	Raw	ml	1.18
188	Wood, unspecified, standing/m3	Raw	mm3	0.0496
189	Zinc 9%, Lead 5%, in sulfide, in ground	Raw	mg	110
190	Zinc, in ground	Raw	µg	755
191	Acetaldehyde	Air	µg	140
192	Acetic acid	Air	mg	2.88
193	Acetone	Air	µg	135
194	Acrolein	Air	µg	3.57

No	Substance	Compartment	Unit	Quantity
195	Actinides, radioactive, unspecified	Air	nBq	14.4
196	Aerosols, radioactive, unspecified	Air	µBq	1.06
197	Aldehydes, unspecified	Air	µg	1.81
198	Aluminum	Air	mg	4.34
199	Americium-241	Air	µBq	6.68
200	Ammonia	Air	g	4.9
201	Ammonium carbonate	Air	ng	26.5
202	Antimony	Air	µg	3.3
203	Antimony-124	Air	nBq	101
204	Antimony-125	Air	nBq	38.3
205	Argon-41	Air	Bq	1.07
206	Arsenic	Air	µg	47.7
207	Barium	Air	µg	12.1
208	Barium-140	Air	µBq	3.06
209	Benzaldehyde	Air	µg	1.23
210	Benzene	Air	mg	8.2
211	Benzene, ethyl-	Air	µg	177
212	Benzene, hexachloro-	Air	ng	31.4
213	Benzene, pentachloro-	Air	ng	2.53
214	Benzo(a)pyrene	Air	µg	1.78
215	Beryllium	Air	ng	103
216	Boron	Air	µg	851
217	Bromine	Air	µg	70.7
218	Butadiene	Air	pg	10.6
219	Butane	Air	mg	22.1
220	Butene	Air	µg	571
221	Cadmium	Air	µg	33.6
222	Calcium	Air	mg	1
223	Carbon-14	Air	Bq	1.73
224	Carbon dioxide	Air	kg	1.13
225	Carbon dioxide, biogenic	Air	g	1.35
226	Carbon dioxide, fossil	Air	g	178
227	Carbon disulfide	Air	µg	926
228	Carbon monoxide	Air	mg	837
229	Carbon monoxide, biogenic	Air	mg	3.42
230	Carbon monoxide, fossil	Air	mg	233
231	Cerium-141	Air	nBq	431
232	Cerium-144	Air	µBq	71
233	Cesium-134	Air	µBq	254
234	Cesium-137	Air	µBq	490
235	Chlorine	Air	µg	53.7
236	Chloroform	Air	ng	527
237	Chromium	Air	µg	514
238	Chromium-51	Air	µBq	1.28
239	Chromium VI	Air	µg	12.4
240	Cobalt	Air	µg	54.2
241	Cobalt-57	Air	nBq	0.613
242	Cobalt-58	Air	µBq	10.2
243	Cobalt-60	Air	µBq	15.4
244	Copper	Air	µg	191
245	Cumene	Air	µg	14.1

No	Substance	Compartment	Unit	Quantity
246	Curium-242	Air	nBq	0.0351
247	Curium-244	Air	nBq	0.319
248	Curium alpha	Air	µBq	10.6
249	Cyanide	Air	µg	10.1
250	Dinitrogen monoxide	Air	g	2.29
251	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Air	ng	26
252	Ethane	Air	mg	88
253	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	µg	35.6
254	Ethane, 1,2-dichloro-	Air	µg	-67.4
255	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	µg	7.53
256	Ethane, dichloro-	Air	µg	19.4
257	Ethane, hexafluoro-, HFC-116	Air	µg	3.19
258	Ethanol	Air	µg	240
259	Ethene	Air	mg	14.8
260	Ethene, chloro-	Air	µg	6.92
261	Ethylene diamine	Air	pg	80.5
262	Ethylene oxide	Air	ng	87.4
263	Ethyne	Air	µg	-4.96
264	Fluorine	Air	µg	5.45
265	Fluosilicic acid	Air	µg	1.14
266	Formaldehyde	Air	mg	3.71
267	Halogenated hydrocarbons, chlorinated	Air	µg	3.03
268	Heat, waste	Air	MJ	22
269	Helium	Air	mg	3.15
270	Heptane	Air	mg	1.23
271	Hexane	Air	mg	45.5
272	Hydrocarbons, aliphatic, alkanes, cyclic	Air	ng	160
273	Hydrocarbons, aliphatic, alkanes, unspecified	Air	mg	2.7
274	Hydrocarbons, aliphatic, alkenes, unspecified	Air	µg	64.5
275	Hydrocarbons, aliphatic, unsaturated	Air	µg	82.7
276	Hydrocarbons, aromatic	Air	µg	446
277	Hydrogen	Air	mg	1.32
278	Hydrogen-3, Tritium	Air	Bq	11.6
279	Hydrogen chloride	Air	mg	11.2
280	Hydrogen fluoride	Air	mg	-1.83
281	Hydrogen sulfide	Air	mg	7.28
282	Iodine	Air	µg	34.6
283	Iodine-129	Air	mBq	3.09
284	Iodine-131	Air	mBq	12.4
285	Iodine-133	Air	µBq	120
286	Iodine-135	Air	µBq	177
287	Iron	Air	g	1.53
288	Iron-59	Air	nBq	13.9
289	Isocyanic acid	Air	µg	5.75
290	Krypton-85	Air	kBq	32.9
291	Krypton-85m	Air	mBq	86.1
292	Krypton-87	Air	mBq	34.8
293	Krypton-88	Air	Bq	1.57
294	Krypton-89	Air	mBq	19.4
295	Lanthanum	Air	ng	247
296	Lanthanum-140	Air	µBq	1.03

No	Substance	Compartment	Unit	Quantity
297	Lead	Air	µg	365
298	Lead-210	Air	mBq	8.2
299	m-Xylene	Air	ng	593
300	Magnesium	Air	µg	195
301	Manganese	Air	µg	230
302	Manganese-54	Air	nBq	377
303	Mercury	Air	µg	13.8
304	Methane	Air	g	2.43
305	Methane, biogenic	Air	mg	-1.01
306	Methane, bromochlorodifluoro-, Halon 1211	Air	µg	2.01
307	Methane, bromotrifluoro-, Halon 1301	Air	µg	18.4
308	Methane, chlorodifluoro-, HCFC-22	Air	µg	7.36
309	Methane, chlorotrifluoro-, CFC-13	Air	ng	37.1
310	Methane, dichloro-, HCC-30	Air	ng	127
311	Methane, dichlorodifluoro-, CFC-12	Air	ng	88.7
312	Methane, dichlorofluoro-, HCFC-21	Air	µg	126
313	Methane, fossil	Air	mg	194
314	Methane, monochloro-, R-40	Air	pg	2.81
315	Methane, tetrachloro-, CFC-10	Air	µg	4.68
316	Methane, tetrafluoro-, FC-14	Air	µg	28.7
317	Methane, trichlorofluoro-, CFC-11	Air	ng	275
318	Methane, trifluoro-, HFC-23	Air	pg	4.97
319	Methanol	Air	mg	1.95
320	Molybdenum	Air	µg	11.5
321	Monoethanolamine	Air	µg	1.49
322	Neptunium-237	Air	nBq	0.35
323	Nickel	Air	µg	499
324	Niobium-95	Air	nBq	65.8
325	Nitrate	Air	ng	175
326	Nitrogen	Air	mg	124
327	Nitrogen oxides	Air	g	3.37
328	NMVOC, non-methane volatile organic compounds, unspecified origin	Air	mg	816
329	Noble gases, radioactive, unspecified	Air	kBq	11.4
330	Ozone	Air	µg	363
331	PAH, polycyclic aromatic hydrocarbons	Air	µg	175
332	Paraffins	Air	pg	292
333	Particulates	Air	mg	11.4
334	Particulates, < 10 µm (mobile)	Air	mg	16.8
335	Particulates, < 10 µm (stationary)	Air	mg	33.1
336	Particulates, < 2.5 µm	Air	mg	125
337	Particulates, > 10 µm	Air	mg	557
338	Particulates, > 10 µm (process)	Air	mg	-115
339	Particulates, > 2.5 µm, and < 10µm	Air	mg	481
340	Particulates, diesel soot	Air	mg	37.9
341	Particulates, unspecified	Air	µg	13.1
342	Pentane	Air	mg	26.9
343	Phenol	Air	µg	17.8
344	Phenol, pentachloro-	Air	ng	408
345	Phosphorus	Air	µg	2.08
346	Phosphorus, total	Air	µg	-2.97
347	Platinum	Air	ng	143

No	Substance	Compartment	Unit	Quantity
348	Plutonium-238	Air	nBq	0.954
349	Plutonium-241	Air	μBq	583
350	Plutonium-alpha	Air	μBq	21.2
351	Polonium-210	Air	mBq	9.2
352	Polychlorinated biphenyls	Air	ng	51.6
353	Potassium	Air	mg	1
354	Potassium-40	Air	mBq	1.09
355	Promethium-147	Air	μBq	180
356	Propanal	Air	ng	21.2
357	Propane	Air	mg	30.7
358	Propene	Air	μg	330
359	Propionic acid	Air	μg	317
360	Propylene oxide	Air	μg	1.96
361	Protactinium-234	Air	μBq	374
362	Radioactive species, other beta emitters	Air	mBq	37.4
363	Radium-226	Air	mBq	-3.76
364	Radium-228	Air	μBq	843
365	Radon-220	Air	mBq	42.1
366	Radon-222	Air	kBq	69.2
367	Ruthenium-103	Air	nBq	4
368	Ruthenium-106	Air	mBq	2.12
369	Scandium	Air	ng	86.8
370	Selenium	Air	μg	30.5
371	Silicates, unspecified	Air	μg	396
372	Silicon	Air	mg	1.72
373	Silicon tetrafluoride	Air	mg	-5.24
374	Silver	Air	ng	2.18
375	Silver-110	Air	nBq	362
376	Sodium	Air	μg	529
377	Sodium chlorate	Air	ng	545
378	Sodium dichromate	Air	ng	150
379	Sodium formate	Air	ng	3.94
380	Strontium	Air	μg	10.2
381	Strontium-89	Air	nBq	636
382	Strontium-90	Air	μBq	350
383	Styrene	Air	ng	5.18
384	Sulfate	Air	mg	-72.8
385	Sulfur dioxide	Air	mg	249
386	Sulfur hexafluoride	Air	μg	5.66
387	Sulfur oxides	Air	mg	438
388	t-Butyl methyl ether	Air	μg	2.54
389	Technetium-99	Air	nBq	14.9
390	Tellurium-123m	Air	μBq	1.6
391	Thallium	Air	ng	115
392	Thorium	Air	ng	159
393	Thorium-228	Air	μBq	343
394	Thorium-230	Air	mBq	-10.7
395	Thorium-232	Air	μBq	-89.2
396	Thorium-234	Air	μBq	374
397	Tin	Air	μg	6.47
398	Titanium	Air	μg	23.5

No	Substance	Compartment	Unit	Quantity
399	Toluene	Air	mg	4.21
400	Uranium	Air	ng	180
401	Uranium-234	Air	mBq	-9.26
402	Uranium-235	Air	µBq	215
403	Uranium-238	Air	mBq	-8.5
404	Uranium alpha	Air	mBq	16.5
405	Vanadium	Air	mg	1.62
406	VOC, volatile organic compounds	Air	mg	3.57
407	Water	Air	mg	5.94
408	Xenon-131m	Air	mBq	160
409	Xenon-133	Air	Bq	27.3
410	Xenon-133m	Air	mBq	23.9
411	Xenon-135	Air	Bq	5.1
412	Xenon-135m	Air	mBq	930
413	Xenon-137	Air	mBq	25.2
414	Xenon-138	Air	mBq	208
415	Xylene	Air	mg	1.51
416	Zinc	Air	mg	1.92
417	Zinc-65	Air	µBq	1.64
418	Zirconium	Air	ng	82.1
419	Zirconium-95	Air	nBq	86.9
420	Acenaphthene	Water	ng	12.7
421	Acenaphthylene	Water	µg	182
422	Acetic acid	Water	µg	2.75
423	Acidity, unspecified	Water	µg	9.32
424	Acids, unspecified	Water	µg	19
425	Actinides, radioactive, unspecified	Water	mBq	1.92
426	Aluminum	Water	mg	64.5
427	Americium-241	Water	µBq	880
428	Ammonia, as N	Water	mg	3.55
429	Ammonium, ion	Water	mg	39.1
430	Antimony	Water	µg	153
431	Antimony-122	Water	µBq	5.82
432	Antimony-124	Water	µBq	952
433	Antimony-125	Water	µBq	313
434	AOX, Adsorbable Organic Halogen as Cl	Water	µg	10.8
435	Arsenic, ion	Water	µg	-204
436	Barite	Water	mg	184
437	Barium	Water	mg	9.92
438	Barium-140	Water	µBq	9.11
439	Benzene	Water	µg	528
440	Benzene, chloro-	Water	pg	133
441	Benzene, ethyl-	Water	µg	102
442	Beryllium	Water	µg	4.45
443	BOD5, Biological Oxygen Demand	Water	mg	429
444	Boron	Water	µg	943
445	Bromate	Water	µg	15.1
446	Bromine	Water	mg	1.63
447	Butene	Water	ng	409
448	Cadmium-109	Water	nBq	28
449	Cadmium, ion	Water	µg	6.4

No	Substance	Compartment	Unit	Quantity
450	Calcium, ion	Water	g	-6.9
451	Carbon-14	Water	mBq	44.5
452	Carbonate	Water	µg	160
453	Carboxylic acids, unspecified	Water	mg	8.83
454	Cerium-141	Water	µBq	2.43
455	Cerium-144	Water	mBq	20.2
456	Cesium	Water	µg	4.26
457	Cesium-134	Water	mBq	45.3
458	Cesium-136	Water	nBq	329
459	Cesium-137	Water	mBq	636
460	Chlorate	Water	µg	148
461	Chloride	Water	g	67.5
462	Chlorinated solvents, unspecified	Water	µg	1.93
463	Chlorine	Water	µg	5.92
464	Chloroform	Water	µg	6.1
465	Chromium	Water	µg	70.3
466	Chromium-51	Water	µBq	534
467	Chromium VI	Water	mg	1.27
468	Chromium, ion	Water	µg	569
469	Cobalt	Water	µg	661
470	Cobalt-57	Water	µBq	14.6
471	Cobalt-58	Water	mBq	6.79
472	Cobalt-60	Water	mBq	197
473	COD, Chemical Oxygen Demand	Water	mg	478
474	Copper, ion	Water	mg	2.78
475	Cumene	Water	µg	33.9
476	Curium alpha	Water	mBq	1.17
477	Cyanide	Water	µg	292
478	Dichromate	Water	ng	514
479	DOC, Dissolved Organic Carbon	Water	mg	158
480	Ethane, 1,1,1-trichloro-, HCFC-140	Water	ng	52.3
481	Ethane, 1,2-dichloro-	Water	µg	-167
482	Ethane, dichloro-	Water	µg	10
483	Ethane, hexachloro-	Water	pg	222
484	Ethene	Water	µg	7.53
485	Ethene, chloro-	Water	ng	88.1
486	Ethene, tetrachloro-	Water	ng	26.4
487	Ethene, trichloro-	Water	µg	1.66
488	Ethylene diamine	Water	pg	195
489	Ethylene oxide	Water	ng	2.19
490	Fatty acids as C	Water	mg	12.7
491	Fluoride	Water	mg	-71.4
492	Fluosilicic acid	Water	µg	2.05
493	Formaldehyde	Water	µg	2.38
494	Glutaraldehyde	Water	µg	22.7
495	Heat, waste	Water	kJ	71.5
496	Hydrocarbons, aliphatic, alkanes, unspecified	Water	µg	621
497	Hydrocarbons, aliphatic, alkenes, unspecified	Water	µg	32.9
498	Hydrocarbons, aliphatic, unsaturated	Water	µg	24.3
499	Hydrocarbons, aromatic	Water	mg	3.03
500	Hydrocarbons, unspecified	Water	µg	326

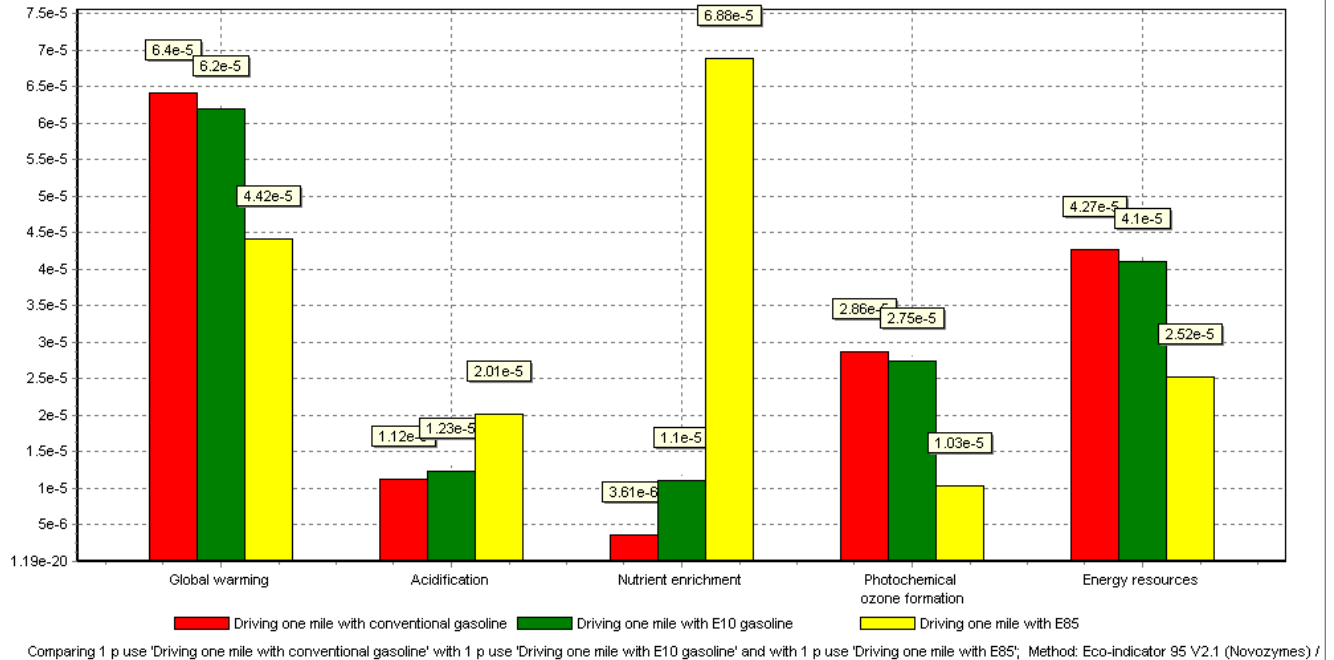
No	Substance	Compartment	Unit	Quantity
501	Hydrogen-3, Tritium	Water	kBq	1.82
502	Hydrogen peroxide	Water	µg	2.89
503	Hydrogen sulfide	Water	µg	82.8
504	Hydroxide	Water	ng	917
505	Hypochlorite	Water	µg	174
506	Hypochlorous acid	Water	µg	141
507	Iodide	Water	µg	427
508	Iodine-129	Water	mBq	127
509	Iodine-131	Water	µBq	145
510	Iodine-133	Water	µBq	24.9
511	Iron	Water	mg	30
512	Iron-59	Water	nBq	822
513	Iron, ion	Water	mg	48.6
514	Lanthanum-140	Water	µBq	5.55
515	Lead	Water	µg	829
516	Lead-210	Water	Bq	-19.4
517	Magnesium	Water	g	1.04
518	Manganese	Water	µg	895
519	Manganese-54	Water	mBq	30
520	Mercury	Water	µg	77.8
521	Methane, dichloro-, HCC-30	Water	µg	103
522	Methane, tetrachloro-, CFC-10	Water	ng	40.3
523	Methanol	Water	µg	27.3
524	Molybdenum	Water	µg	107
525	Molybdenum-99	Water	µBq	1.91
526	Neptunium-237	Water	µBq	56.2
527	Nickel, ion	Water	mg	2.87
528	Niobium-95	Water	µBq	22.5
529	Nitrate	Water	g	93.7
530	Nitrite	Water	µg	42.5
531	Nitrogen	Water	mg	17.4
532	Nitrogen, organic bound	Water	mg	1.26
533	Nitrogen, total	Water	mg	4.42
534	Oils, unspecified	Water	mg	373
535	PAH, polycyclic aromatic hydrocarbons	Water	µg	52.7
536	Paraffins	Water	pg	849
537	Phenol	Water	µg	197
538	Phenols, unspecified	Water	µg	364
539	Phosphate	Water	mg	491
540	Phosphorus	Water	µg	-267
541	Phosphorus compounds, unspecified	Water	µg	4.43
542	Phthalate, dioctyl-	Water	ng	1.28
543	Phthalate, p-dibutyl-	Water	ng	18.5
544	Phthalate, p-dimethyl-	Water	ng	116
545	Plutonium-241	Water	mBq	73
546	Plutonium-alpha	Water	mBq	3.5
547	Polonium-210	Water	Bq	-29.7
548	Potassium	Water	mg	18.6
549	Potassium-40	Water	Bq	-2.34
550	Potassium, ion	Water	mg	833
551	Propene	Water	µg	17.2

No	Substance	Compartment	Unit	Quantity
552	Propylene oxide	Water	µg	4.72
553	Protactinium-234	Water	mBq	6.93
554	Radioactive species, alpha emitters	Water	mBq	-30
555	Radioactive species, from fission and activation	Water	mBq	2.62
556	Radioactive species, Nuclides, unspecified	Water	Bq	1.15
557	Radium-224	Water	mBq	213
558	Radium-226	Water	Bq	-3.4
559	Radium-228	Water	mBq	426
560	Rubidium	Water	µg	20.4
561	Ruthenium	Water	µg	22.3
562	Ruthenium-103	Water	µBq	1.95
563	Ruthenium-106	Water	mBq	212
564	Salts, unspecified	Water	mg	45.5
565	Scandium	Water	µg	6.57
566	Selenium	Water	µg	120
567	Silicon	Water	g	1.44
568	Silver	Water	µg	1.64
569	Silver-110	Water	mBq	4.63
570	Silver, ion	Water	µg	2.11
571	Sodium-24	Water	µBq	161
572	Sodium formate	Water	ng	9.46
573	Sodium, ion	Water	g	39.1
574	Solids, inorganic	Water	mg	45.1
575	Solved solids	Water	mg	46.4
576	Solved substances	Water	mg	8.97
577	Strontium	Water	mg	26.4
578	Strontium-89	Water	µBq	48.7
579	Strontium-90	Water	Bq	1.92
580	Sulfate	Water	g	3.91
581	Sulfide	Water	µg	77.5
582	Sulfite	Water	µg	87.5
583	Sulfur	Water	mg	333
584	Sulfur trioxide	Water	µg	138
585	Suspended solids, unspecified	Water	mg	32.7
586	t-Butyl methyl ether	Water	µg	35.7
587	Technetium-99	Water	mBq	22.3
588	Technetium-99m	Water	µBq	38.5
589	Tellurium-123m	Water	µBq	32.1
590	Tellurium-132	Water	nBq	175
591	Thallium	Water	ng	666
592	Thorium-228	Water	mBq	613
593	Thorium-230	Water	Bq	1.03
594	Thorium-232	Water	mBq	1.09
595	Thorium-234	Water	mBq	6.97
596	Tin, ion	Water	µg	17.7
597	Titanium, ion	Water	mg	3.8
598	TOC, Total Organic Carbon	Water	mg	412
599	Toluene	Water	µg	553
600	Tributyltin	Water	µg	-11.8
601	Tributyltin compounds	Water	µg	6.61
602	Triethylene glycol	Water	mg	6.6

No	Substance	Compartment	Unit	Quantity
603	Tungsten	Water	µg	8.14
604	Undissolved substances	Water	mg	531
605	Uranium-234	Water	mBq	8.86
606	Uranium-235	Water	mBq	13.8
607	Uranium-238	Water	Bq	-9.95
608	Uranium alpha	Water	mBq	429
609	Vanadium, ion	Water	µg	376
610	VOC, volatile organic compounds as C	Water	µg	780
611	VOC, volatile organic compounds, unspecified origin	Water	µg	717
612	Xylene	Water	µg	468
613	Yttrium-90	Water	nBq	560
614	Zinc-65	Water	µBq	476
615	Zinc, ion	Water	mg	20.3
616	Zirconium-95	Water	mBq	1.81
617	Mineral waste, from mining	Waste	µg	116
618	Aclonifen	Soil	ng	126
619	Aluminum	Soil	mg	11.9
620	Antimony	Soil	pg	37.5
621	Arsenic	Soil	µg	4.76
622	Atrazine	Soil	µg	302
623	Barium	Soil	µg	551
624	Bentazone	Soil	ng	64.2
625	Boron	Soil	µg	14.5
626	Cadmium	Soil	µg	3.87
627	Calcium	Soil	mg	47.8
628	Carbetamide	Soil	µg	1.52
629	Carbon	Soil	mg	36
630	Chloride	Soil	mg	31.5
631	Chlorothalonil	Soil	ng	121
632	Chromium	Soil	µg	91.1
633	Chromium VI	Soil	µg	19.7
634	Cobalt	Soil	ng	73.8
635	Copper	Soil	µg	42.2
636	Cypermethrin	Soil	ng	76.8
637	Dinoseb	Soil	ng	32.9
638	Fenpiclonil	Soil	ng	9.11
639	Fluoride	Soil	µg	68.5
640	Glyphosate	Soil	mg	6.13
641	Heat, waste	Soil	kJ	22.3
642	Iron	Soil	mg	35.2
643	Lead	Soil	µg	6.06
644	Linuron	Soil	ng	976
645	Magnesium	Soil	µg	904
646	Mancozeb	Soil	ng	157
647	Manganese	Soil	µg	489
648	Mercury	Soil	ng	8.19
649	Metaldehyde	Soil	ng	666
650	Metolachlor	Soil	µg	278
651	Metribuzin	Soil	ng	5.53
652	Molybdenum	Soil	ng	3.53
653	Napropamide	Soil	µg	1.18

No	Substance	Compartment	Unit	Quantity
654	Nickel	Soil	µg	14.6
655	Nitrogen	Soil	µg	2.53
656	Oils, biogenic	Soil	µg	259
657	Oils, unspecified	Soil	mg	110
658	Orbencarb	Soil	ng	29.9
659	Phosphorus	Soil	µg	520
660	Phosphorus, total	Soil	µg	85.2
661	Pirimicarb	Soil	ng	6.09
662	Potassium	Soil	µg	421
663	Silicon	Soil	µg	171
664	Silver	Soil	ng	261
665	Sodium	Soil	mg	2.24
666	Strontium	Soil	µg	11.1
667	Sulfur	Soil	mg	7.14
668	Tebutam	Soil	µg	2.79
669	Teflubenzuron	Soil	pg	369
670	Tin	Soil	ng	4.75
671	Titanium	Soil	ng	902
672	Vanadium	Soil	ng	25.8
673	Zinc	Soil	µg	373
674	Arable land use, soy bean, Brazil	Non mat.	m2a	-0.487
675	Pu241 beta	Non mat.	mBq	13.9

Appendix 2: Normalisation



Normalised contributions to global warming, acidification, nutrient enrichment, photochemical ozone formation and use of primary energy (LHV) for driving 1.6 km (one mile) in cars fuelled gasoline mixed with 0, 10 and 85% ethanol from corn.

Normalised environmental impact potentials, $NEP(j)_{Ethanol}$ are determined by dividing environmental impact potentials $EP(j)_{Ethanol}$ (see Section 2.2) by specific normalisation references $NR(j)$ for each impact category (j).

$$NEP(j)_{Ethanol} = EP(j)_{Ethanol} / NR(j)$$

Normalization references are expressed in terms of an average person's yearly contribution to each impact category and have been derived from Stranddorf et al. (2001) except energy resources (Ecoindicator 95 v. 2.1, Europe). Normalisation of global environmental impact potentials (global warming) refer to an average world citizen, normalization of regional environmental impact potentials (acidification, nutrient enrichment and photochemical ozone formation) refer to an average Dane.