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Life cycle assessment of rapeseed oil, rape methyl ester and ethanol as fuels – a comparison between large- and smallscale production

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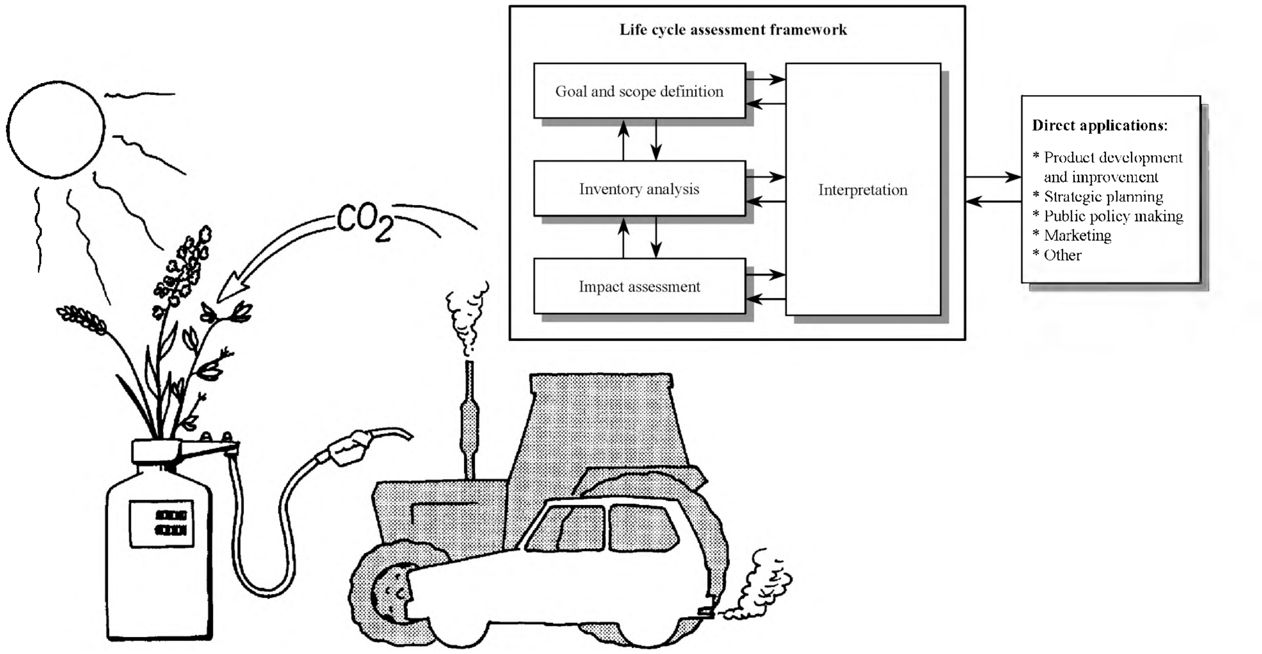
LIFE CYCLE ASSESSMENT OF RAPESEED OIL, RAPE METHYL ESTER AND ETHANOL AS FUELS

- A COMPARISON BETWEEN LARGE- AND SMALL-SCALE PRODUCTION

Sven Bernesson



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SUMMARY

Production of rapeseed oil, rape methyl ester (RME) and ethanol fuel for heavy diesel engines can be carried out with different systems solutions, in which the choice of system is usually related to the scale of the production. The main purpose of this study was to analyse whether the use of a small-scale rapeseed oil, RME and ethanol fuel production system reduced the environmental load in comparison to a medium- and a large-scale system. To fulfil this purpose, a limited LCA, including air-emissions and energy requirements, was carried out for the three fuels and the three plant sizes.

Four different methods to allocate the environmental burden between different products were compared: physical allocation according to the lower heat value in the products [MJ/kg], economic allocation according to the product prices [SEK/kg], no allocation and allocation with a system expansion so that rapemeal and distiller's waste could replace soymeal mixed with soyoil and glycerine could replace glycerine produced from fossil raw material. The functional unit, to which the total environmental load was related, was 1.0 MJ of energy delivered on the engine shaft to the final consumer. Production of raw materials, cultivation, transport, fuel production and use of the fuels produced were included in the systems studied.

The results for small-scale plants (physical allocation) are shown in Table I. It was also shown in the study that the differences in environmental impact and energy requirement between small-, medium- and large-scale systems were small or even negligible in most cases for all three fuels, except for the photochemical ozone creation potential (POCP) during ethanol fuel production. The longer transport distances to a certain degree outweighed the higher oil extraction efficiency, the higher energy efficiency and the more efficient use of machinery and buildings in the large-scale system. The dominating production step was the cultivation, in which production of fertilisers, followed by soil emissions and tractive power, made major contributions to the environmental load.

Table I. Results for small-scale plants with physical allocation

	Global warming potential [g CO_2-eq/MJ_{engine}]	Acidification potential [g SO_2-eq/MJ_{engine}]	Eutrophication potential [mg PO_4^{3-}-eq/MJ_{engine}]	Photochemical ozone creation potential [mg C_2H_4-eq/MJ_{engine}]	Energy requirement [kJ/MJ_{engine}]
Rapeseed oil	121	1.94	343	26.1	692
RME	127	1.98	351	23.2	846
Ethanol	102	1.16	199	99.9	907

The results were, however, largely dependent on the method used for allocation of the environmental burden between the products, *i.e.*: rapeseed oil and meal, RME; meal and glycerine; and ethanol fuel and distiller's waste. The results were also dependent on uncertainty in input data, *e.g.* yield of rapeseed and wheat and use of fertilisers, and on alternative production strategies such as use of catalysts when the fuels produced are consumed, use of an ignition improver of biomass origin during production of ethanol fuel, or use of methanol with biomass origin during production of methanol for transesterification of rapeseed.

The costs for production of the fuels in a small-scale plant from raw products grown on a small farm excl. EU area compensation were: rapeseed oil 0.85 SEK/MJ_{engine}; RME 1.07 SEK/MJ_{engine}; and ethanol fuel 1.29 SEK/MJ_{engine}. The corresponding costs for production of the fuels in a large-scale plant from raw products grown on a large farm incl. EU area compensation were: rapeseed oil 0.33 SEK/MJ_{engine}; RME 0.35 SEK/MJ_{engine}; and ethanol fuel 0.57 SEK/MJ_{engine}.

SAMMANFATTNING

Rapsolja, rapsmetylester (RME) och etanolbränsle avsett för tunga diesel motorer kan framställas i olika produktionssystem, varvid valet av system bl.a. beror av i vilken storleksskala produktionen sker. Huvudsyftet med detta arbete var att göra en analytisk studie för att undersöka om småskalig produktion av rapsolja, RME och etanolbränsle kan minska miljöbelastningen i jämförelse med mellanskalig och storskalig produktion. För att uppfylla detta syfte gjordes en begränsad livscykelanalys (LCA) inkluderande luftföroreningar och energibehov för dessa tre bränslen i tre olika skalor.

Dessutom jämfördes resultaten från fyra olika allokeringsmetoder: fysikalisk allokering med avseende på det effektiva värmevärdet [MJ/kg] hos produkterna, ekonomisk allokering med avseende på produkternas pris [SEK/kg], ingen allokering och allokering med ett utvidgat system så att rapsexpeller/rapsmjöl eller drank ersätter sojamjöl blandat med sojaolja, och glycerin ersätter glycerin producerat från fossila råvaror. Som funktionell enhet, till vilken miljöbelastningen relaterades, valdes 1,0 MJ rörelseenergi mätt på motoraxeln. Produktion av råvaror, odling, transporter, produktion och användning av producerade bränslen ingick i det studerade drivmedelssystemet.

För småskaliga produktionsanläggningar (fysikalisk allokering) erhölls resultaten som redovisas i tabell II. I studien visades också att skillnaderna i miljöbelastning och energibehov mellan små-, mellan- och storskaliga produktionsanläggningar var små eller försumbara för de tre studerade drivmedlen med undantag av fotokemiskt ozonbildande gaser vid produktion av etanol. För storskaliga system uppvägdes de längre transportavstånden till stor del av högre oljeutvinningsgrad, högre energieffektivitet och mer effektivt utnyttjande av maskiner och byggnader. Det mest betydelsefulla produktionssteget var odlingen, där produktionen av gödselmedel, utsläpp av markgaser och behovet av dragkraft, hade störst inflytande på miljöbelastningen.

Tabell II. Resultat för småskaliga anläggningar (fysikalisk allokering)

	Potential för global uppvärmning [g CO_2-ekv/MJ_{motor}]	Potential för försurning [g SO_2-ekv/MJ_{motor}]	Potential för övergödning [mg PO_4^{3-}-ekv/MJ_{motor}]	Potential för foto-kemisk ozonbildning [mg C_2H_4-ekv/MJ_{motor}]	Energibehov [kJ/MJ_{motor}]
Rapsolja	121	1.94	343	26.1	692
RME	127	1.98	351	23.2	846
Etanol	102	1.16	199	99.9	907

Resultaten var beroende av vilken metod som användes för allokering av miljöbelastningen mellan de olika produkterna; rapsolja och rapsexpeller, RME, rapsexpeller och glycerin, samt etanolbränsle och drank. Resultaten var även beroende av osäkerheten i ingående data (t.ex. erhållna skördar av rapsfrö och vete och pålagd mängd gödselmedel) och alternativa produktionsscenarier (t.ex. användning av katalysatorer vid förbränning av de producerade bränslena, användning av biobaserade tändförbättrare vid produktion av etanolbränsle och användning av biobaserad metanol vid omförestring av rapsolja.

Kostnaderna för småskalig produktion av drivmedel på mindre lantbruksenheter, exklusive EU-bidrag, var för rapsolja 0,85 SEK/MJ_{motor}, för RME 1,07 SEK/MJ_{motor} och för etanolbränsle 1,29 SEK/MJ_{motor}. Motsvarande kostnader för storskalig produktion av drivmedel från råvaror odlade på stora lantbruksföretag, inklusive EU-bidrag, var för rapsolja 0,33 SEK/MJ_{motor}, för RME 0,35 SEK/MJ_{motor} och för etanolbränsle 0,57 SEK/MJ_{motor}.

FOREWORD

This report contains background data for the articles:

- Bernesson, S., Nilsson, D., P-.A. Hansson. 2004. A limited LCA comparing large- and small-scale production of rape methyl ester (RME) under Swedish conditions. *Biomass and Bioenergy*, 26(6), 545-559.

- Bernesson, S., Nilsson, D., P-.A. Hansson. 2004. A limited LCA comparing large- and small-scale production of ethanol for heavy engines under Swedish conditions. Manuscript for possible publication in *Biomass and Bioenergy*.

These articles are included in my doctoral thesis 'Farm-scale Production of RME and Ethanol for Heavy Diesel Engines – with Emphasis on Environmental Assessment'.

The report contains comprehensive data and assumptions made in the calculations in accordance with the transparency criterion for public life cycle assessments. For readers only interested in an overview of the study, *i.e.* the problem formulations, the objectives, the system descriptions, the LCA methodology and the most important results, Sections 1, 2, 3.1-3.2, 4.4-4.7, 5 and 6 are recommended. However, for readers interested in all the results, the whole of Section 4, as well as Appendices 1-2, are recommended.

Sections 3.3-3.11 contain detailed descriptions of the assumptions made and the data used in the calculations. The main target group for these sections are people interested in a deeper knowledge of the systems studied and the data used. These sections may also be of value for people involved in LCA studies of similar systems.

I am grateful to my supervisors, Professor Per-Anders Hansson and Researcher Daniel Nilsson, for their involvement and comments throughout the work.

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Sven Bernesson

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1 INTRODUCTION

1.1 Background

Transport is becoming more and more important in society. In Sweden, the use of diesel oil and petrol has increased from 47 TWh in 1970 to 78 TWh in 2000 (STEM, 2001). A changeover to bio-based fuels is therefore an important step towards a more sustainable society. Rapeseed oil, rape methyl ester (RME) and ethanol with ignition improver are possible bio-based fuels that can be used in diesel engines. The production of biodiesel (vegetable oil esters) has increased and was 1.064 million tonnes in the EU in 2002 (EBB, 2003) of which 3 500 tonnes were produced in Sweden (Norup, pers. comm.). The production of fuel ethanol has also increased and in 2001 was 2.2 million cubic metres in the EU, 8 million cubic metres in the USA and 12 million cubic metres in Brazil (Schmitz, 2003). In Sweden, 50 000 cubic metres of ethanol were produced from cereals (mostly wheat) (Agroetanol, 2003) and 13 000 cubic metres of ethanol from wood (Baff, 2003).

Fuels from agricultural crops have become more common as vehicle fuels during recent years. Rapeseed based fuels and ethanol have been used as fuel in tractors, buses and other diesel engined vehicles. Some life cycle assessments (LCAs) and/or energy analyses have been conducted to study the environmental load when these fuels are produced and used as fuels (Johansson *et al.*, 1992; Börjesson, 1994; Ragnarsson, 1994; Almemark, 1996; Blinge, 1998; Hovelius, 1999; Hovelius & Hansson, 1999; Jungk *et al.*, 2000). However, all these studies consider large-scale production. Gärtner & Reinhardt (2001) and Reinhardt & Gärtner (2002) carried out an LCA study for small-scale RME production, but their results are valid for German conditions. Small-scale production of ethanol was studied by Almemark (1996) in the scenario analysis.

Rape is an oil plant (*Brassica napus*) with small dark seeds with an oil content of 40-50%. Wheat (*Triticum aestivum*) is a cereal that normally contains 58-62% of starch (Kaltschmitt & Reinhardt, 1997). The starch can be degraded to glucose monomers that can be fermented to ethanol. There are two variants of both rape and wheat, early autumn-sown types and spring-sown types.

For rape, the oil in the seeds can be extracted mechanically in an oil press or chemically with a solvent. Normally 65–80% of the oil can be extracted in an oil press (Widmann, 1988; Norén, 1990; Bernesson, 1993; Bernesson, 1994; Head *et al.*, 1995; Kaltschmitt & Reinhardt, 1997). Using solvent extraction, approximately 98% of the oil can be extracted (Norén, 1990; Kaltschmitt & Reinhardt, 1997). Solvent extraction is only used in large plants. For wheat, 84-93% of its starch can be converted to ethanol depending on the process used (Kaltschmitt & Reinhardt, 1997; Jacques *et al.*, 1999).

As a fuel, rapeseed oil is more viscous than normal diesel oil, and therefore the engine must be modified to use it straight. The oil can be heated before it is injected into the cylinder (Tickell, 2000) or the engine can be an Elsbett engine (a variant of direct injected diesel engine) (Bernesson, 1993; Bernesson, 1994). The oil consists of triglycerides, which consist of a glycerine molecule connected to three fatty acids (Norén, 1990). During transesterification, three methanol (or ethanol) molecules replace the glycerine molecule; the result is three monoesters (one fatty acid connected to a methanol) with a viscosity similar to normal diesel oil. This fuel can be used in ordinary diesel engines with little or no adjustment. If methanol is used for the transesterification of rapeseed oil the resulting fuel is called rape methyl ester, often shortened to RME.

Ethanol is a fuel with a high octane number that is suitable for use in otto engines but it has bad ignition properties for diesel engines. One way to improve the ignition properties before use in diesel engines is to add an ignition improver to increase the fuel's cetane number (Haupt *et al.*, 1999). The compression ratio is usually also increased to limit the requirement for ignition improver. Spark plugs, glow plugs and two-fuel systems with alcohol and diesel oil can also be used to help improve ignition. The engine must also be modified for a higher fuel flow because of a lower heat value in ethanol compared to diesel oil. Before being sold as a fuel, the ethanol must be denatured to prevent it being used as a drink (Sekab, 2003).

The production of rapeseed oil, RME and ethanol can be carried out on many different system scales. In large-scale systems, process heat can both be produced and used more efficiently (Kaltschmitt & Reinhardt, 1997), while processing technologies for rapeseed also have higher extraction efficiencies (Bernesson, 1993; Head *et al.*, 1995; Kaltschmitt & Reinhardt, 1997), but the transport of raw materials to the processing plant and the transport of residual products back to the farms are long-distance. Small-scale systems have been of great interest in Sweden because of, for example, simple and less expensive process technologies (Norén & Danfors, 1981; Norén, 1990; Norén *et al.*, 1994) and the possibility to increase rural employment (Danielsson & Hektor, 1992). Furthermore, the transport of raw materials and residual products is decreased or eliminated.

During production of ethanol from wheat at different scales the ethanol yield is not expected to vary significantly (Norén & Danfors, 1981; Almemark, 1996; Schmitz, 2003). However, larger plants use the process heat more efficiently and this energy can also be produced more efficiently (Kaltschmitt & Reinhardt, 1997).

1.2 Life cycle assessment (LCA)

A main argument for the production and use of rapeseed oil, RME and ethanol as fuels is their potential to reduce the fossil CO_2-emissions that contribute to global warming. It is therefore important that the choices of production system and scale are made in a way that minimizes the total environmental load. Life cycle assessment (LCA) is a powerful method for such analyses. In an LCA, the total environmental load of a product is studied throughout its life cycle from 'cradle to grave' (Lindfors *et al.*, 1995; Wenzel *et al.*, 1997; Lindahl *et al.*, 2001; Rydh *et al.*, 2002).

When rapeseed oil is produced, the by-product meal is added to the calculation and when RME is produced, the by-product glycerine is added. When ethanol is produced, the by-product distiller's waste is added. The meal and distiller's waste are usually used for animal feeding, and the glycerine can be used as a raw material in many industrial processes. When a production process contributes to several products, the total system environmental load has to be shared between these by allocation. Several methods may be used for allocation in LCA (Lindfors *et al.*, 1995; Wenzel *et al.*, 1997; Lindahl *et al.*, 2001; Rydh *et al.*, 2002), and there are no obvious rules for which method is the most correct to use. The choice of allocation method may impact on the final results considerably, and it is therefore important to bear in mind the effect of allocation on the results of a study.

Life cycle assessment (LCA) could briefly be defined as a process to describe summed resource- and environmental consequences coupled to all activities from cradle to grave needed for a product or service to fulfil its function.

According to ISO 14040 (ISO, 1997) an LCA is characterized by the following key features:

- LCA studies should systematically and adequately address the environmental aspects of product systems, from raw material acquisition to final disposal.
- The depth of detail and time frame of an LCA study may vary to a large extent, depending on definition of goal and scope.
- The scope, assumptions, description of data quality, methodologies and output of LCA studies should be transparent. LCA studies should discuss and document the data sources, and be clearly and appropriately communicated.
- Provision should be made, depending on the intended application of the LCA study, to respect confidentiality and proprietary matters.
- LCA methodology should be amenable to the inclusion of new scientific findings and improvements in the state-of-the-art of the technology.
- Special requirements are applied to LCA studies, which are used to make a comparative assertion that is disclosed to the public.
- There is no scientific basis for reducing LCA results to a single overall score or number, since trade-offs and complexities exist for the systems analysed at different stages of their life cycle.
- There is no single method for conducting LCA studies. Organizations should have flexibility to implement LCA practically as established in this International Standard, based upon the specific application and the requirements of the user.

There are four phases in an LCA-study: 1. Goal and scope definition; 2. Inventory analysis; 3. Impact assessment and 4. Interpretation (Figure 1). During the whole study there are demands for continuous interpretation and updating of data and results.

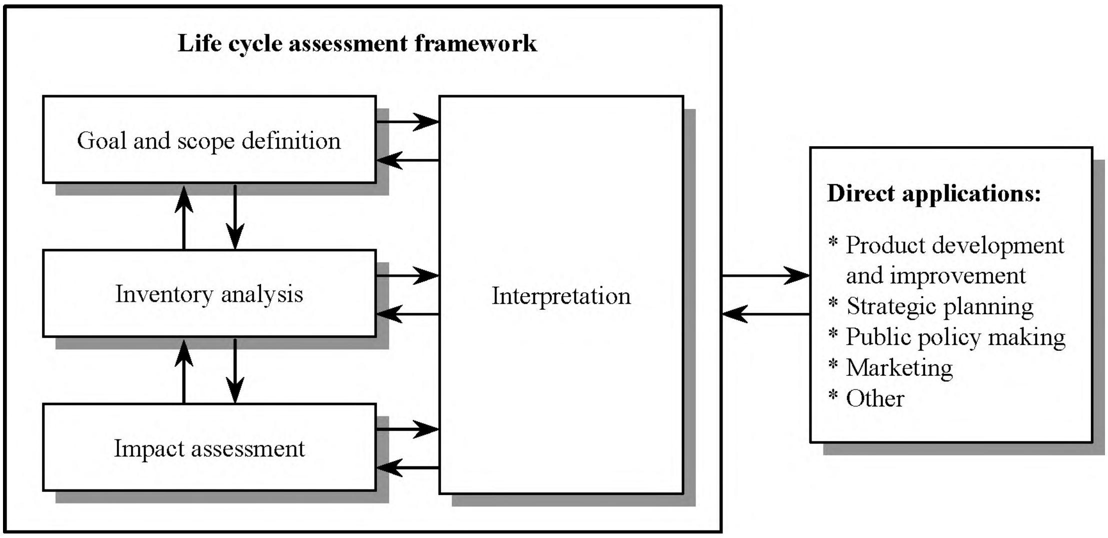

Figure 1. Framework for life cycle assessment (ISO, 1997).

2 OBJECTIVES

The main objective of this work was to analyse whether the small-scale production of rapeseed oil, RME and ethanol reduces the environmental load and costs in comparison to medium- and large-scale production of these fuels. Another objective was to compare the three fuels with each other with regard to environmental load and costs. A final objective was to test the influence of different allocation methods, uncertainty in input data and alternative production strategies on the results.

To fulfil these objectives, limited LCAs, including air-emissions, energy requirements and cost calculations, were carried out for an example of each production plant size and fuel. For all plants, the environmental burdens were allocated by physical allocation after energy content of the products in a basic scenario. Then, three alternative allocation methods were studied for comparison: economic allocation, no allocation and allocation with an expanded system. The study also included sensitivity analyses and Monte Carlo simulations of relevant model parameters, and scenario analyses in which *e.g.* possible future alternatives were evaluated.

3 MATERIALS AND METHODS

3.1 System descriptions and definitions

This study deals with the autumn (winter) variants of rapeseed and wheat. For rapeseed, only mechanical extraction was used in the small- and medium-scale plants, but in the large-scale plants was it followed by solvent extraction. Hexane is usually used for solvent extraction and was therefore chosen in this study. The transesterification was conducted in the same way for all plant sizes and methanol was the alcohol used. For the production of ethanol, the same process was used in all three scales, but the distiller's waste was only dried in the large-scale plant.

The model was created in a spreadsheet format. Sensitivity analyses were made with three different methods: first as traditionally, one value was changed (±20%) at a time for the most important inputs, and the result was observed; second, as a scenario analysis, the influence of some changes to the system was observed; and third the probability for differences between production scales and fuels was calculated using Monte Carlo simulations.

Small-, medium- and large-scale technology for the production of straight rapeseed oil, RME and ethanol as fuels for heavy diesel engines was studied. The model, for each fuel, was built up as a cultivation model followed by three parallel models for each production scale (Figure 2). The small-, medium- and large-scale plants serve areas of 40, 1 000 and 50 000 ha, respectively. The model includes, for production of rapeseed fuels: cultivation of rapeseed, transport of seed to extraction, extraction, hexane for large-scale extraction, transesterification, production of methanol and catalyst for transesterification, transport of methanol and glycerine, transport of rapeseed oil, RME and meal to consumption and consumption of rapeseed oil and RME in heavy-duty diesel engines (Figure 3). The model includes, for production of ethanol: cultivation of wheat, transport of wheat to ethanol plant, ethanol production, transport and production of chemicals used in the ethanol production process, treatment of waste water from ethanol production, drying of distiller's waste in large plants, production and transport of chemicals (ignition improver etc.) used to make ethanol into a fuel for diesel engines, transport of ethanol fuel and distiller's waste to consumption and consumption of ethanol fuel in heavy-duty diesel engines (Figure 4). In the calculations were the seed milling included in the ethanol production.

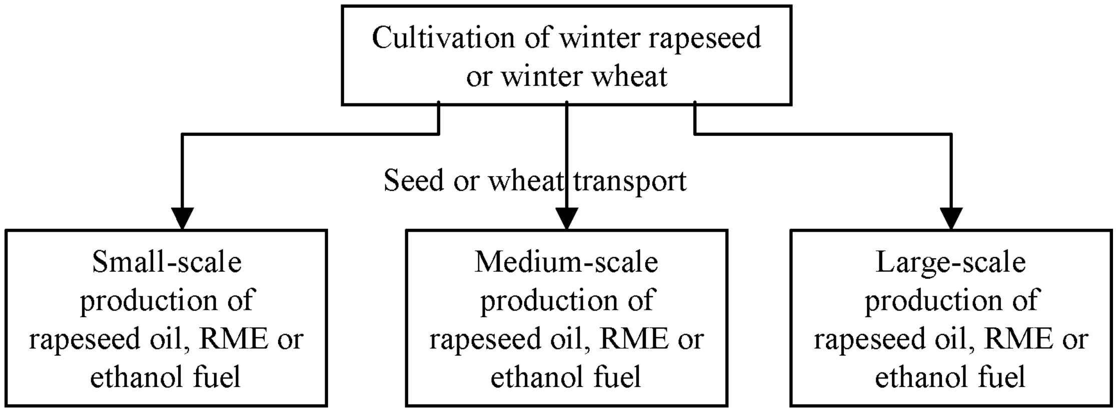

Figure 2. Flow-chart showing how the system was built up with cultivation followed by small-, medium- and large-scale production of the three fuels.

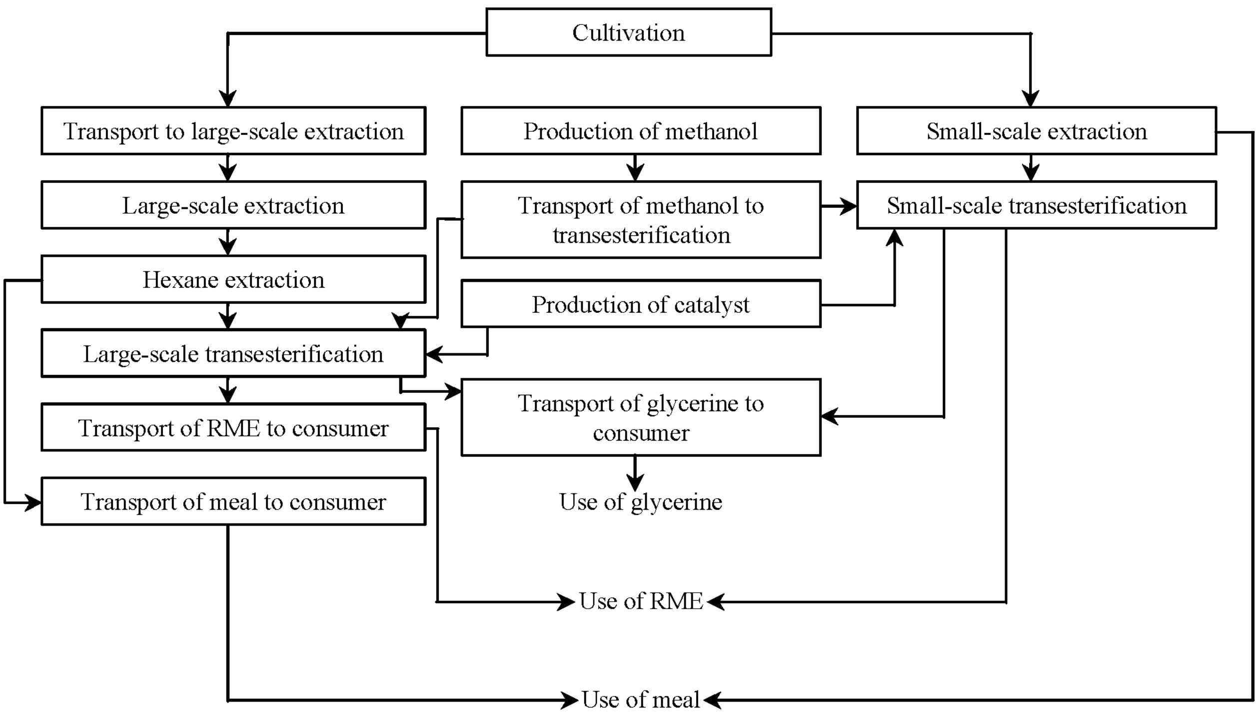

Figure 3. Flow-chart showing the operations (in boxes) that were included for small- and large-scale production of RME. For the medium-scale system, the same operations as for the large-scale were used, with the exception of hexane extraction. The operations 'cultivation', 'production of methanol' and 'production of catalyst' were identical for all scales.

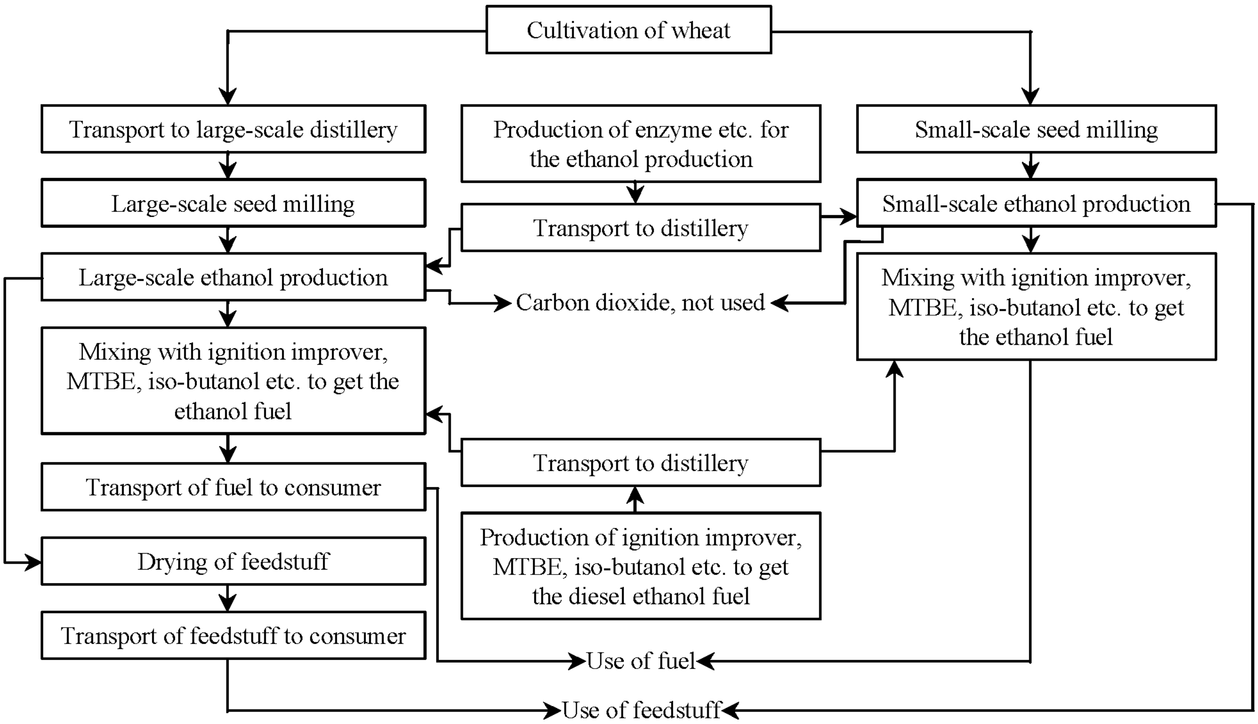

Figure 4. Flow-chart showing the operations (in boxes) that were included for small- and large-scale production of ethanol (distillery). For the medium-scale system, the same operations as for the large-scale were used, with the exception of drying of distiller's waste (feedstuff). The operations 'cultivation', 'production of enzyme etc. for the ethanol production' and 'production of ignition improver, MTBE, isobutanol etc.' were identical for all scales.

Cultivation of rapeseed and wheat, and transport of the seed and wheat from the field to the farm are independent of how the oil is later extracted and transesterified or ethanol produced and is therefore the same for all plant sizes (Figures 3 and 4). Methanol and catalyst were assumed to be produced at a separate site from the extraction and transesterification (Figure 3). The same assumption was made for the chemicals used in the ethanol production and to make the ethanol into a diesel fuel (Figure 4). The distances to the above-mentioned production sites were assumed to be independent of plant size. Therefore these distances were the same, in the model, for all the plant sizes. The consumption of the glycerine was assumed to be at a site separated from the transesterification. The distance to this site was assumed to be independent of plant size. Therefore this distance was also the same, in the model, for all the plant sizes. The by-product carbon dioxide from the production of ethanol was assumed not to be used in this study due to over-production on the market (Gebro, pers. comm.).

The idea with small-scale production of rapeseed oil, RME or ethanol fuel is to produce the fuel at the farm gate. No external transport was required in the small-scale system because extraction and the transesterification or ethanol production were performed in a room adjacent to the farm seed storage and the farm fuel storage. It was assumed that the fuel produced in larger plants (Figures 3 and 4) was transported back to the farm (or an equivalent distance) for consumption. This was so as to make all consumption of fuel produced take place on the same site. This makes the studied system equivalent with the farm as a reference point. Fuels produced in medium-scale and large-scale plants were therefore transported a distance equivalent to the distance back to the farm (Figures 3 and 4). In the same way, and for the same reasons, the meal or distiller's waste from medium-scale and large-scale plants was also transported a distance equivalent to the distance back to the farm (Figures 3 and 4).

Because plants of various sizes were to be compared, the machines for oil extraction, transesterification and ethanol production had to be included in the studied systems. Large-scale plants utilize their machines in a more effective way than small-scale systems. Therefore the machines for the whole production chain were included in the studied systems. This is a difference from most other LCAs on the production of rapeseed oil, RME or ethanol fuels. Unfortunately, there were almost no data on the machine weights and the production of the machines, so this part of the LCA had to be made with some assumptions of machine weights and LCA data on the production of the machines, which made these data uncertain.

The calculations in this study were based on existing data from the literature. No prognoses for the future were made. An uncertainty in the literature was that emission data for the engines running on the three fuels studied were not of the same generation. This was an uncertain factor when the three fuels were compared as regards engine power output.

3.2 Assumptions for the LCA

The functional unit to which the total environmental load was related was 1.0 MJ of energy delivered on the engine shaft to the final consumer, *i.e.* 1.0 MJ_{engine} [g/MJ_{engine} or MJ/MJ_{engine}]. This was because emissions from the same amount of engine work were to be compared. Engines running on ethanol fuel have a slightly better efficiency than engines running on RME, and engines running on RME have a slightly better efficiency than engines running on straight rapeseed oil. During the calculations the functional unit was field area [ha], because it made the calculations easier to perform with the seed yield as start reference. The calculated emission values [g/ha] were summed up for each subject. The unit g/MJ_{engine} was obtained after a final division with total engine work out [MJ_{engine}/ha]. In Appendices 1-2, values are also accounted for with the functional unit 1.0 MJ of energy in the fuel produced delivered to the final consumer *i.e.* 1.0 MJ_{fuel} [g/MJ_{fuel} or MJ/MJ_{fuel}] excl. emissions when driving on the fuel produced.

The LCA was limited to the air emissions: CO_2 (fossil origin), CO, HC (hydrocarbons except for methane), CH_4, NO_x (nitrous oxides), SO_x (sulphur oxides), NH_3, N_2O and HCl. These emissions were classified into the following environmental impact categories: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and photochemical ozone creation potential (POCP). The category indicators used are presented in Table 1. POCP for hydrocarbons (HC) was chosen to be 0.4 g C_2H_4-eq/g (Hauschild & Wenzel, 1998), both for farming and road transport, the main activities for emissions in this study.

The energy required in the operations was also included in the LCA. For all fuels used in the systems, the energy contents were expressed in lower heating values. The electricity used was recalculated to primary energy. PAH (polycyclic aromatic hydrocarbons) and particles were not used in any calculations. The allocation was performed by physical allocation after energy unit [MJ]. Three alternative allocation methods were studied for comparison: no allocation, economic allocation and allocation with an expanded system (soymeal (soybean meal) and soymeal mixed with soyoil (soybean oil) for both rapeseed fuels and ethanol fuel, and fossil glycerine for RME).

When replacement of fossil glycerine with glycerine from the transesterification was not included in the models for physical, economic and no allocation (see Appendix 1), it had to be discussed separately. When fossil carbon atoms from fossil methanol replace the three biomass carbon atoms in the glycerine part of the rapeseed oil molecules, 100% biomass glycerine is produced. In LCAs with physical or economic allocation, it is not obvious how these carbon atoms should be handled. However, they must be discussed or included in the calculations in some way. In this study they are handled on a discussion basis. However, the replacement of fossil glycerine was included in model for allocation with an expanded system. No similar problems were found for the ethanol fuel.

Table 1. Impact category indicators used in this study (Hauschild & Wenzel, 1998)

Emissions to air	$GWP_{100\ years}$ [g CO_2-eq/g]	AP [g SO_2-eq/g]	EP [g PO_4^{3-}-eq/g]	POCP [g C_2H_4-eq/g]
CO_2	1			
SO_2, SO_x		1		
NO_x		0.7	0.13	
NH_3		1.88	0.35	
CO	2			0.04
HCl		0.88		
CH_4	23[a]			0.007
HC				0.4
N_2O	296[a]			

[a] IPCC (2001).

3.3 Assumptions for the economic calculations

The economic calculations were conducted on the same plant sizes for production of rapeseed oil, RME and ethanol fuel as in the LCA. For the cultivation, a 4 times larger production unit was also chosen (300 ha instead of 75 ha). This was because farms in Sweden have to join together to achieve profitability. Data for the cultivation were mainly based on the area calculations made by Agriwise (2003). Machinery data were mainly based on the machine calculations made by Henemo (2002, 2003). A difference from the calculations by Agriwise was that overheads, tenancy costs and seed drying costs were included in this study. The calculations were made both with and without EU area compensation. The EU area compensation was that for oil crops and cereals in the Swedish Region 3 (Jordbruksverket, 2003). EU area compensation is normally included in production calculations for agricultural crops but can easily be changed by political decisions. Calculations were also conducted for purchased rapeseed: 2.00 SEK/kg and for purchased wheat: 0.97 SEK/kg (Agriwise, 2003).

Costs for small- and medium-scale extraction and transesterification were mainly based on calculations made by Norén *et al.* (1993) and Norén *et al.* (1994). Costs for large-scale extraction and transesterification were mainly based on calculations made by Conneman & Fischer (1998) but with relationships between separate parts as in Norén *et al.* (1993) and Norén *et al.* (1994). To calculate the costs for the right plant size from the plants in the literature, the costs were assumed to be proportional to the plant size for plants with similar design and size. To get more current prices, the price level in Norén *et al.* (1993) and Norén *et al.* (1994) was adjusted in comparison to prices given by Ferchau (2000) and Oilpress (2003) especially for oil presses. For other extraction, transesterification equipment and buildings the price trend was assumed to be at the same level.

Costs especially for the larger ethanol production plants were mainly based on calculations made by Schmitz (2003) and the investment costs for Agroetanol's plant in Norrköping (Werling, pers. comm.). The investment costs for smaller plants were estimated with some help from the investment costs between the different plant sizes for rapeseed oil extraction and transesterification. The relationships, in investment cost, between oil extraction and transesterification plants and ethanol production plants were assumed to be the same for the different plant sizes.

The price level in the calculus was that for 2002. The interest calculated for costing purposes was 7%.

3.4 Rapeseed and wheat production

3.4.1 Basic data rapeseed production with fertilisers and pesticides

The farm where the rapeseed (winter rape) was grown was assumed to be in the flatlands of Svealand in Central Sweden and the harvest was assumed to be 2470 kg rapeseed with 8% water and 45% oil (wet weight basis) (estimated after Svenskraps, 2003a; and Engström *et al.*, 2000). Details of the cultivation are given below in Section 3.4. Seed, fertilisers, air emissions during soil cultivation, pesticides, fuels and machinery for cultivation, energy for drying and cleaning of the seed, transport of fertilisers to farm (fuels and lubrication oil with manufacturing) were included in the cultivation part of the model (see Appendix 1, Tables A1-A2).

It was assumed that seed from the previous year was used for sowing. This made the output values from the rapeseed cultivation be used to produce the seed for sowing in a circular process. A seed rate of 8 kg per hectare was used (Agriwise, 2003). The emissions for the seed production were calculated as share of seed of total cultivation emissions: (8 kg seed/ha / 2470 kg rapeseed/ha harvested) * total cultivation emissions [g/ha] (Table A1, Appendix 1). The procedure was repeated in an iterative way until state of equilibrium was obtained. The energy requirement was calculated in a corresponding way.

The rapeseed was fertilised during the autumn with 145 kg/ha calcium ammonium nitrate (Hydro Suprasalpeter N28) and during the spring with 500 kg/ha Hydro NPK Svavel Bor 20-3-5. This is equivalent to 140 kg N/ha, 15 kg P/ha and 25 kg K/ha. Emissions when these two fertilisers were manufactured are given in Table 2. The rapeseed was fertilised according to Jordbruksverket (2001) with fertilisers from the LCI by Davis & Haglund (1999). When the area amounts of each fertiliser were multiplied by the emission values in Table 2 and added, the emission values in Table A1, Appendix 1, were obtained.

Table 2. Emissions from production of fertilisers and pesticides used in rapeseed and wheat production

Factor of production	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	HCl	PAH	Particles	Energy requirement
	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[g/kg]	[MJ/kg]
Manufacturing of fertiliser NPK 20-3-5 S B[a]	749	0.18	0.44	0.75	1.5	2.3	0.15	3.8	0.049	0.000080	0.228	10.3
Manufacturing of fertiliser NPK 21-4-7 S[a]	746	0.21	0.50	0.76	1.6	2.8	0.16	3.5	0.047	0.000076	0.250	10.2
Manufacturing of fertiliser N 28[a]	931	0.11	0.34	0.87	1.5	1.3	0.21	5.6	0.065	0.000107	0.228	12.7
Manufacturing of pesticide active substances[b]	4921	2.66	0.29	0.18	6.9	17.4	0.16	1.5	0.21		0.043	198

[a] Davis & Haglund (1999).
[b] Kaltschmitt & Reinhardt (1997).

As biocides, 2 l/ha of the herbicide Butisan S was used to control the weeds and 0.3 l/ha of the insecticide Sumi-alpha 5 FW was used, 1 time in 2 years, to control blossom beetles (Sonesson, 1993).

The active ingredient in Butisan S is Metazachlor, 500 g/l (Kemikalieinspektionen, 1999). The energy for manufacturing of the active ingredients was calculated as an average of all herbicides according to Green (1987). Kaltschmitt & Reinhardt (1997) have calculated general energy input and emissions for pesticide manufacturing from the figures given by Green (1987). These figures also include packaging and transport, etc. and come to 198.1 MJ/kg active substances. The area need for active substance with requirement of primary energy for production could then be calculated as: 2 l/ha * 0.5 kg active substance/l = 1 kg active substance/ha. One annual treatment gives after multiplying 1.00 kg active substance/ha and 198.1 MJ/ha.

The active ingredient in Sumi-alpha 5 FW is Esfenvalerate, 50 g/l (Kemikalieinspektionen, 1999). The primary energy for manufacturing of the active ingredient was calculated in the same way as for Butisan S, etc. This gives: 0.30 l/ha * 0.05 kg active substance/l = 0.015 kg active substance/ha. The 0.5 annual treatment gives after multiplying: 0.0075 kg active substance/ha and 1.49 MJ/ha.

The total requirement of pesticides is then 1.0075 kg active substance/ha and year, which requires 199.6 MJ/ha to be produced (Table A2, Appendix 1). Emissions and energy requirement for manufacturing of the pesticides are given in Table 2. After multiplication: (active substance [kg/ha] * emissions [g/kg active] substance (Table 2)) the area emission values were obtained (Table A1, Appendix 1).

3.4.2 Basic data on wheat production with fertilisers and pesticides

The farm where the wheat (winter wheat) was grown was assumed to be in the flatlands of Svealand in Central Sweden and the harvest was assumed to be 5900 kg wheat with 14% water (water content at trade price: Agriwise, 2003) and approx. 60% starch (wet weight basis) (estimated after Kaltschmitt & Reinhardt, 1997). Details for the cultivation are given below in Section 3.4. Seed, fertilisers, air emissions during soil cultivation, pesticides, fuels and machinery for cultivation, energy for drying and cleaning of the seed, transport of fertilisers to farm (fuels and lubrication oil with manufacturing) are included in the cultivation part of the model (see Appendix 2, Tables A15-A16).

It was assumed that seed from the previous year was used for sowing. This made the output values from the wheat cultivation be used to produce the seed for sowing in a circular process. A seed rate of 220 kg per hectare was used (Agriwise, 2003). The emissions for the seed production were calculated as share of seed of total cultivation emissions: (220 kg seed/ha / 5900 kg wheat/ha harvested) * total cultivation emissions [g/ha] (Table A15, Appendix 2). The procedure was repeated in an iterative way until state of equilibrium was obtained. The energy requirement was calculated in a corresponding way.

The wheat was fertilised during the autumn with 115 kg/ha calcium ammonium nitrate (Hydro Suprasalpeter N28) and during the spring with 420 kg/ha Hydro NPK Svavel 21-4-7. This is equivalent to 120 kg N/ha, 16.8 kg P/ha and 29.4 kg K/ha. Emissions when these two fertilisers were manufactured are given in Table 2. The wheat was fertilised according to Jordbruksverket (2001) with fertilisers from the LCI by Davis & Haglund (1999). When the area amounts of each fertiliser were multiplied by the emission values in Table 2 and added, the emission values in Table A15, Appendix 2 were obtained.

As biocides: 1.5 kg/ha of the herbicide Express 50 T and 0.6 l/ha of the herbicide Starane 180 were used to control the weeds (Agriwise, 2003); 1.0 l/ha of the fungicide Tilt Top 500 EC was used 0.6 times in 1 year to control fungus attack, giving 0.6 l/ha (Agriwise, 2003); 1.0 l/ha of the fungicide Sportak EW was used 0.4 times in 1 year to control sprouts and 0.3 times in 1 year to control foot rot, giving 0.7 l/ha (Agriwise, 2003); and 0.3 kg/ha of the insecticide Karate 2.5 WG was used 1 time in 2 years to control insects at heading and to control thrips and aphids, giving 0.15 kg/ha (Agriwise, 2003).

The active ingredient in Express 50 T is Tribenuronmethyl, 50 percent by weight and in Starane Fluroxipyr(1-methylheptylester) 180 g/l (Kemikalieinspektionen, 1999). The energy for manufacturing of the active ingredient was calculated as an average of all herbicides according to Green (1987). Kaltschmitt & Reinhardt (1997) have calculated general energy input and emissions for pesticide manufacturing from the figures given by Green (1987). These figures include also packaging and transport, etc. and come to 198.1 MJ/kg active substances. This gives: 1.5 kg/ha * 0.5 kg active substance/kg = 0.75 kg active substance/ha for Express 50 T and 0.6 l/ha * 0.180 kg active substance/l = 0.108 kg active substance/ha for Starane 180, together 0.858 kg active substance/ha. One annual treatment gives after multiplying 0.858 kg active substance/ha and 170.0 MJ/ha.

The active ingredient in Tilt Top 500 EC is Fenpropimorf 375 g/l and Propikonazol 125 g/l (Kemikalieinspektionen, 1999). The energy for manufacturing of the active ingredient was calculated in the same way as for Express 50 T, etc. This gives: 375 g/l + 125 g/l = 0.500 kg active substance/l * 1.0 l/ha = 0.50 kg active substance/ha. The 0.6 annual treatment gives after multiplying 0.30 kg active substance/ha and 59.4 MJ/ha.

The active ingredient in Sportak EW is Perkloraz 450 g/l (Kemikalieinspektionen, 1999). The energy for manufacturing of the active ingredient was calculated in the same way as for Express 50 T, etc. This gives: 0.450 kg active substance/l * 1.0 l/ha = 0.45 kg active substance/ha. The 0.7 annual treatment gives after multiplying 0.315 kg active substance/ha and 62.4 MJ/ha.

The active ingredient in Karate 2.5 WG is Lambda-cyhalotrin 2.5 percentage by weight (Kemikalieinspektionen, 1999). The energy for manufacturing of the active ingredient was calculated in the same way as for Express 50 T, etc. This gives: 2.5 weight-% = 0.025 kg active substance/kg * 0.3 kg/ha = 0.0075 kg active substance/ha. The 0.5 annual treatment gives after multiplying 0.00375 kg active substance/ha and 0.74 MJ/ha.

The total requirement of pesticides is then 1.48 kg active substance/ha and year, which requires 292.5 MJ/ha to be produced (Table A16, Appendix 2). Emissions and energy requirement for manufacturing of the pesticides are given in Table 2. After multiplication: (active substance [kg/ha] * emissions [g/kg active] substance (Table 2)) the area emission values were obtained (Table A15, Appendix 2).

3.4.3 Soil emissions

During the cultivation there were also soil emissions of ammonia and nitrous oxide in the field depending on the supply of nitrogen. Data from Jungk *et al.* (2000) were chosen for this study because that is close to the average from the other authors and were related to how much fertilisers were used. Ammonia emissions were 40 g NH_3/kg fertiliser nitrogen and nitrous oxide emissions were 19.6 g N_2O/kg fertiliser nitrogen.

For rapeseed with a requirement of 140 kg N fertiliser/ha the soil emissions would be 5600 g NH_3/ha and 2740 g N_2O/ha. For wheat with a requirement of 120 kg N fertiliser/ha the soil emissions would be 4800 g NH_3/ha and 2350 g N_2O/ha. See also Tables A1, Appendix 1 and A15, Appendix 2.

3.4.4 Fuel requirement and emissions during crop production

In the basic scenarios, the machines for the agricultural work were run on MK1 (Swedish environmental class 1 diesel oil) fuel, during cultivation of both rapeseed and wheat. In alternative scenarios in the scenario analyses the fuels produced (rapeseed oil, RME and ethanol fuel) were used. Diesel fuel MK3 (Swedish environmental class 3 diesel oil) was used as a reference scenario for help to calculate fuel consumption and emissions for the other fuels used. Catalysts were also used on the vehicles in alternative scenarios.

3.4.4.1 Requirement of fuels and oils

In Tables 3 (rapeseed cultivation) and 4 (wheat cultivation), the use of machines [hours/ha] and fuel consumption are given for each operation. These data also include outwintering. Fuel consumption [l/h] (MK3) for tractors and threshing machines at different working conditions are given in Databok för driftsplanering 1989 (SLU, 1989). Fuel consumption [l/ha] (MK1) for tractors under different working conditions is given in Norén *et al.* (1999) and for threshing machine and transport (tipping trailer) in Hansson & Mattsson (1999). The use of machines [hours in use/ha] was obtained when the fuel consumption [l/ha] was divided by fuel consumption [l/h]. These figures were used when the input of machines was calculated. Outwintering (resowing) of winter rape is about 10% and outwintering of winter wheat is about 5% in Sweden (SCB, 1992) (last year recorded 1990, after that only differences between autumn-sown area and next year area with some errors were available, SCB, 2002). During resowing, seed drilling was followed by one disc harrowing and two harrowings. The small tractor (Tables 3 and 4) was used for seed drilling, rolling, fertiliser spreading and spraying.

Table 3. Calculations for fuel consumption during cultivation of winter rapeseed (Norén et al., 1999; Hansson & Mattsson, 1999; SLU, 1989; Bernesson, 1993)

Field operation		Fuel consumption							
	Use	MK3		MK1		RME		Rapeseed oil	
	[h/ha]	[l/h]	[l/ha]	[l/h]	[l/ha]	[l/h]	[l/ha]	[l/h]	[l/ha]
Tractor, 52 kW[a]	0.98								
Tractor, 66 kW[a]	3.54								
Plough	2.06	11	22.7	11.3	23.4	11.9	24.5	12.3	25.4
Harrow, 2 times[a]	0.54	13	7.0	13.4	7.3	14.0	7.6	14.6	7.9
Seed drill[a]	0.45	8	3.6	8.2	3.7	8.6	3.9	9.0	4.1
Cambridge roller	0.12	12	1.4	12.4	1.4	12.9	1.5	13.4	1.6
Fertiliser spreader, 2 times	0.26	7	1.8	7.2	1.9	7.5	1.9	7.8	2.0
Sprayer, 2 times	0.15	6	0.90	6.2	0.93	6.5	0.97	6.7	1.01
Threshing machine	1.36	11	15.0	11.3	15.5	11.9	16.2	12.3	16.8
Disc harrow, 1 time[a]	0.77	13	10.0	13.4	10.3	14.0	10.8	14.6	11.2
Tipping trailer (field – farm)	0.12	6	0.71	6.2	0.73	6.5	0.77	6.7	0.80
Front-loader	0.05	5	0.25	5.2	0.26	5.4	0.27	5.6	0.28
Sum	5.88		63.4		65.4		68.4		71.1

[a] Machines used for resowing at 10% outwintering.

Table 4. Calculations for fuel consumption during cultivation of winter wheat (Norén et al., 1999; Hansson & Mattsson, 1999; SLU, 1989; Bernesson, 1993)

Field operation	Use	Fuel consumption							
		MK3		MK1		RME		Ethanol fuel	
	[h/ha]	[l/h]	[l/ha]	[l/h]	[l/ha]	[l/h]	[l/ha]	[l/h]	[l/ha]
Tractor, 52 kW[a]	1.02								
Tractor, 66 kW[a]	3.65								
Plough	2.06	11	22.7	11.3	23.4	11.9	24.5	17.1	35.2
Harrow, 2 times[a]	0.52	13	6.7	13.4	6.9	14.0	7.2	20.2	10.4
Seed drill[a]	0.43	8	3.5	8.2	3.6	8.6	3.7	12.4	5.4
Cambridge roller	0.12	12	1.4	12.4	1.4	12.9	1.5	18.6	2.2
Fertiliser spreader, 2 times	0.26	7	1.8	7.2	1.9	7.5	1.9	10.9	2.8
Sprayer, 2.8 times	0.21	6	1.26	6.2	1.30	6.5	1.36	9.3	1.96
Threshing machine	1.36	11	15.0	11.3	15.5	11.9	16.2	17.1	23.3
Disc harrow, 1 time[a]	0.74	13	9.6	13.4	9.8	14.0	10.3	20.2	14.8
Tipping trailer (field – farm)	0.28	6	1.68	6.2	1.74	6.5	1.82	9.3	2.62
Front-loader	0.05	5	0.25	5.2	0.26	5.4	0.27	7.8	0.39
Sum	6.03		63.8		65.8		68.8		99.1

[a] Machines used for resowing at 5% outwintering.

Fertilisers were assumed to be transported to the farm by a tractor with two wagons (rapeseed cultivation Table 5 and wheat cultivation Table 6). The total load of fertilisers was 16 metric tonnes and the transport distance was assumed to be 10 km (one direction). The fuel consumption was 9 litres/h with empty wagons and 12 litres/h with loaded wagons given an average fuel consumption (MK3 diesel oil fuel) of 10.5 litres/h. The average speed was assumed to be 20 km/h. Time for transport with return trip was 1 hour (2*10 km / 20 km/h) and the machine time for unloading with front-loader was assumed to be 0.35 hours with the labour time 0.5 hours. The fuel consumption (MK3 diesel oil fuel) was assumed to be 5 litres/h during loading and unloading. Fuel consumption with MK1 diesel fuel oil, RME, rapeseed oil and ethanol fuel for transportation of fertilisers to the farm, is accounted for in Tables 5 and 6. Transport of fertilisers was separated from field operations because it is not obvious that it should be included there. The calculations and assumptions were made in the same way as for the field operations. Time in use per area [h/ha] was calculated as: (weight fertiliser per hectare / load weight) * time per load.

Table 5. Calculations for tractor transport of fertiliser to the farm during cultivation of rapeseed (Norén et al., 1999; Hansson & Mattsson, 1999; SLU, 1989; Bernesson, 1993)

Field operation		Fuel consumption							
	Use	MK3		MK1		RME		Rapeseed oil	
	[h/ha]	[l/h]	[l/ha]	[l/h]	[l/ha]	[l/h]	[l/ha]	[l/h]	[l/ha]
Tractor, 66 kW	0.054								
Tipping trailer	0.040	10.5	0.423	10.82	0.436	11.32	0.456	11.76	0.474
Front-loader	0.014	5	0.071	5.15	0.073	5.39	0.076	5.60	0.079
Sum	0.054		0.494		0.509		0.532		0.553

Table 6. Calculations for tractor transport of fertiliser to the farm during cultivation of wheat (Norén et al., 1999; Hansson & Mattsson, 1999; SLU, 1989; Bernesson, 1993)

Field operation		Fuel consumption							
	Use	MK3		MK1		RME		Ethanol fuel	
	[h/ha]	[l/h]	[l/ha]	[l/h]	[l/ha]	[l/h]	[l/ha]	[l/h]	[l/ha]
Tractor, 66 kW	0.045								
Tipping trailer	0.033	10.5	0.351	10.82	0.362	11.32	0.378	16.30	0.545
Front-loader	0.012	5	0.059	5.15	0.060	5.39	0.063	7.76	0.091
Sum	0.045		0.410		0.422		0.442		0.636

Consumption of diesel fuel oil MK1, RME, rapeseed oil and ethanol fuel, in Tables 3-6, was calculated from the consumption of diesel fuel oil MK3. The energy outputs from the engines during the field operations were assumed to be the same, independent of the fuel used. In Table 99, Section 3.9, properties are given for all these fuels. In SMP (1993), the engine efficiencies are given for an engine running at its best operating point with MK3, MK1 and RME (Table 99, Section 3.9). In Aakko *et al.* (2000), the efficiency is given for an engine running on MK3 and in Haupt *et al.* (1999) for another engine running on ethanol fuel, both measured according to ECE R49, so the calculated efficiencies could be used to estimate the fuel consumption of ethanol fuel if the fuel consumption of MK3 is known. The volumetric fuel consumption for MK1, RME and ethanol fuel could then be calculated as: volumetric fuel consumption MK3 * ((heat value MK3 * density MK3 * engine efficiency MK3) / (heat value new fuel * density new fuel * engine efficiency new fuel)). For rapeseed oil, the volumetric fuel consumption is approx. 12% higher in Elsbett engines than for diesel oil fuel MK3 in conventional direct injected diesel engines (Bernesson, 1993; Thuneke, 1999).

The quantity of lubrication oil consumed, including oil used for transmissions and hydraulics, was assumed to be 0.7% of the volumetric diesel fuel used (Tables 3-6), for all tractor and threshing operations, based on data (lubrication oil) from ASAE (2000). Furthermore, it was assumed that manufacturing of lubrication oil results in the same amount of emissions and energy requirement for manufacturing of diesel oil (MK1) (Table 13). For the calculations, the density and lower heating value for the lubrication oil was assumed to be as for diesel oil (MK3). Area emissions for production of lubrication oil are accounted for in Tables 14-15.

The consumption of lubrication oil was calculated from some equations in ASAE (2000): Oil consumption is defined as the volume per hour of engine crankcase oil replaced at the manufacturer's recommended change interval. Consumption is in litres/h, where P is the rated engine power in kW. This gives the following equation for diesel engines: 0.00059*P + 0.02169. For the 52 kW and 66 kW tractors and the threshing machine (75 kW) respectively, this gives an oil consumption of 0.052 litres/h, 0.060 litres/h and 0.066 litres/h. If these machines were used for 0.98 h/ha, 3.54 h/ha and 1.36 h/ha the consumption of lubrication oil would be 0.051 litres/ha, 0.215 litres/ha and 0.090 litres/ha respectively. The total consumption of lubrication oil would be 0.356 litres/ha divided by a consumption of 63.4 litres/ha diesel oil MK3 gives the share of lubrication oil to be 0.561%. If use of oil for lubrication of gears, hydraulics and oil slicks etc. is assumed to be an additional 25% of oil, the oil consumption would be: 0.701% of the fuel (MK3) consumption. Therefore the consumption of lubrication and hydraulic oils was assumed to be 0.70% of the fuel consumption in this study (volumetric). This was assumed to be valid independent of the fuel used. The same was also assumed to be valid for the lorries used for transportation (Section 3.7.1).

3.4.4.2 Emissions

Hansson *et al.* (1998) calculated the accounted emissions values, in Table 7, for different field operations, when test bench data were combined with recorded time series for the load at the engine under some field operations. Not all the required field operations for this study were included in Hansson *et al.* (1998). Therefore emission values for harrowing (high engine load) were also used for Cambridge rolling and threshing; baling (low engine load) used for spraying; seed drilling also used for fertilising; and stubble cultivation used for disc harrowing.

Table 7. Regulated emissions for field operations after Hansson et al. (1998)

Field operation	MK3, emissions [g/MJ$_{fuel}$]			MK1, emissions [g/MJ$_{fuel}$]			RME, emissions [g/MJ$_{fuel}$]			Rapeseed oil, emissions[a] [g/MJ$_{fuel}$]		
	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x	HC
Plough	0.085	0.988	0.029	0.091	0.935	0.027	0.078	0.967	0.0119	0.085	1.037	0.0160
Harrow	0.042	0.897	0.016	0.046	0.860	0.016	0.030	0.998	0.0089	0.042	0.942	0.0088
Seed drill	0.108	0.948	0.034	0.114	0.900	0.031	0.097	0.905	0.0129	0.108	0.995	0.0187
Cambridge roller	0.042	0.897	0.016	0.046	0.860	0.016	0.030	0.998	0.0089	0.042	0.942	0.0088
Fertiliser spreader	0.108	0.948	0.034	0.114	0.900	0.031	0.097	0.905	0.0129	0.108	0.995	0.0187
Sprayer	0.228	0.860	0.053	0.226	0.819	0.050	0.192	0.821	0.0200	0.228	0.903	0.0292
Threshing machine	0.042	0.897	0.016	0.046	0.860	0.016	0.030	0.998	0.0089	0.042	0.942	0.0088
Disc harrow	0.076	0.747	0.030	0.083	0.708	0.028	0.062	0.778	0.0120	0.076	0.784	0.0165
Tipping trailer (field – farm)	0.150	0.900	0.037	0.163	0.880	0.036	0.147	0.898	0.0164	0.150	0.945	0.0204
Tipping trailer (fertiliser to farm)	0.100	0.708	0.032	0.106	0.681	0.032	0.081	0.771	0.0140	0.100	0.743	0.0176
Front-loader	0.378	1.194	0.068	0.407	1.227	0.067	0.369	1.009	0.0264	0.378	1.254	0.0374

[a] Emissions for straight rapeseed oil calculated from emissions MK3 (Thuneke, 1999).

For vehicles running on straight rapeseed oil there are poor emission values in the literature. Thuneke (1999) has made a brief summing-up of emissions from engines running on rapeseed oil fuels. In Table 101, Section 3.9, some of these emissions for straight rapeseed oil fuels are given in comparison to European diesel oil fuel, in this study equivalent to diesel oil fuel MK3. The values in Table 101 were used for calculating the emission values for rapeseed oil in Table 7.

There were no emission data for field operations with ethanol fuel in the literature. Therefore emissions for field operations with ethanol fuel were calculated as: emissions field operations MK1 * (engine efficiency ethanol fuel ECE R49 (Haupt *et al.*, 1999) / engine efficiency MK1 fuel ECE R49 (after: Aakko *et al.*, 2000 and SMP, 1993)) * (emission ethanol fuel (Haupt *et al.*, 1999) / emission MK1 fuel (Aakko *et al.*, 2000)). Emissions for field operations with ethanol fuel are accounted for in Table 8. Engine efficiencies are accounted for in Table 99, Section 3.9.

Table 8. Regulated emissions for field operations with ethanol fuel, calculated after Hansson et al. (1998); Aakko et al. (2000); and Haupt et al. (1999)

Field operation	Ethanol fuel, emissions [g/MJ_{fuel}]		
	CO	NO_x	HC
Plough	0.458	0.694	0.046
Harrow	0.231	0.639	0.027
Seed drill	0.573	0.668	0.053
Cambridge roller	0.231	0.639	0.027
Fertiliser spreader	0.573	0.668	0.053
Sprayer	1.136	0.608	0.086
Threshing machine	0.231	0.639	0.027
Disc harrow	0.417	0.526	0.048
Tipping trailer (field – farm)	0.820	0.653	0.062
Tipping trailer (fertiliser to farm)	0.533	0.506	0.055
Front-loader	2.047	0.911	0.115

Emission values on an area basis [g/ha] (cultivation of rapeseed Tables 9 and 10 and cultivation of wheat Tables 11 and 12) were calculated by: emission value [g/MJ_{fuel}] (Tables 7 and 8) * fuel consumption [l/ha] (Tables 3-6) * fuel density [kg/l] (Table 99, Section 3.9) * lower heat value [MJ/kg] (Table 99, Section 3.9). Each fuel was handled separately for growing of each crop. The summed values in Tables 9-12 were used in the LCA (Tables 14-15). The area emissions for CO_2 and particulates could be calculated in the same way from the descriptions of their origin below.

Table 9. Regulated emissions for field operations on an area basis, cultivation of rapeseed, calculated after Hansson et al. (1998)

Field operation	MK3, emissions [g/ha]			MK1, emissions [g/ha]			RME, emissions [g/ha]			Rapeseed oil, emissions [g/ha]		
	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x	HC
Plough	68.2	793	23.3	75.0	770	22.2	65.1	807	9.9	76.2	930	14.3
Harrow, 2 times[a]	10.5	223	4.0	11.7	220	4.1	7.8	258	2.3	11.7	262	2.4
Seed drill[a]	13.9	122	4.4	15.0	119	4.1	12.9	121	1.7	15.5	143	2.7
Cambridge roller	2.1	44	0.79	2.3	44	0.81	1.5	51	0.46	2.3	52	0.49
Fertiliser spreader, 2 times	6.9	60	2.2	7.4	59	2.0	6.4	60	0.9	7.7	71	1.3
Sprayer	7.3	27	1.7	7.4	27	1.6	6.4	27	0.7	8.1	32	1.0
Threshing machine	22.3	476	8.5	25.0	468	8.7	16.5	550	4.9	24.9	558	5.2
Disc harrow, 1 time[a]	26.9	264	10.6	30.1	257	10.2	22.8	286	4.4	30.1	310	6.5
Tipping trailer (field – farm)	3.8	23	0.93	4.2	23	0.93	3.8	23	0.43	4.2	27	0.57
Front-loader	3.3	11	0.60	3.7	11	0.61	3.4	9	0.24	3.7	12	0.37
Sum	165.0	2043	56.9	181.9	1997	55.3	146.7	2194	25.9	184.4	2397	35.0

[a] Machines used for resowing at 10% outwintering.

Table 10. Regulated emissions for transport of fertiliser to the farm on an area basis, cultivation of rapeseed, calculated after Hansson et al. (1998)

Operations, transport of	MK3, emissions [g/ha]			MK1, emissions [g/ha]			RME, emissions [g/ha]			Rapeseed oil, emissions [g/ha]		
fertiliser to the farm	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x	HC
Tipping trailer (fertiliser to farm)	1.50	10.6	0.48	1.63	10.5	0.49	1.26	12.0	0.22	1.67	12.4	0.29
Front-loader	0.94	3.0	0.17	1.04	3.1	0.17	0.96	2.6	0.07	1.05	3.5	0.10
Sum	2.44	13.6	0.65	2.67	13.6	0.66	2.22	14.6	0.29	2.73	15.9	0.40

Table 11. Regulated emissions for field operations on an area basis, cultivation of wheat, calculated after Hansson et al. (1998)

Field operation	MK3, emissions [g/ha]			MK1, emissions [g/ha]			RME, emissions [g/ha]			Ethanol fuel, emissions[a] [g/ha]		
	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x	HC
Plough	68.2	793	23.3	75.0	770	22.2	65.1	807	9.9	336.2	510	34.0
Harrow, 2 times[b]	10.0	213	3.8	11.2	210	3.9	7.4	247	2.2	50.3	139	6.0
Seed drill[b]	13.2	116	4.2	14.3	113	3.9	12.4	115	1.6	64.3	75	6.0
Cambridge roller	2.1	44	0.79	2.3	44	0.81	1.5	51	0.46	10.5	29	1.24
Fertiliser spreader, 2 times	6.9	60	2.2	7.4	59	2.0	6.4	60	0.9	33.4	39	3.1
Sprayer	10.2	38	2.4	10.3	37	2.3	8.9	38	0.9	46.3	25	3.5
Threshing machine	22.3	476	8.5	25.0	468	8.7	16.5	550	4.9	112.3	310	13.3
Disc harrow, 1 time[b]	25.7	252	10.1	28.8	245	9.7	21.8	273	4.2	129.1	163	14.8
Tipping trailer (field – farm)	8.9	54	2.20	10.0	54	2.20	9.1	56	1.02	44.7	36	3.37
Front-loader	3.3	11	0.60	3.7	11	0.61	3.4	9	0.24	16.6	7	0.93
Sum	170.7	2057	58.0	188.1	2011	56.4	152.6	2207	26.4	843.6	1332	86.2

[a] Calculated after Hansson *et al.* (1998), Aakko *et al.* (2000) and Haupt *et al.* (1999).
[b] Machines used for resowing at 5% outwintering.

Table 12. Regulated emissions for transport of fertiliser to the farm on an area basis, cultivation of wheat, calculated after Hansson et al. (1998)

Operations, transport of	MK3, emissions [g/ha]			MK1, emissions [g/ha]			RME, emissions [g/ha]			Ethanol fuel, emissions[a] [g/ha]		
fertiliser to the farm	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x	HC
Tipping trailer (fertiliser to farm)	1.24	8.8	0.40	1.35	8.7	0.41	1.05	10.0	0.18	6.06	5.7	0.62
Front-loader	0.78	2.5	0.14	0.86	2.6	0.14	0.79	2.2	0.06	3.88	1.7	0.22
Sum	2.02	11.3	0.54	2.21	11.3	0.55	1.84	12.1	0.24	9.93	7.5	0.84

[a] Calculated after Hansson *et al.* (1998), Aakko *et al.* (2000) and Haupt *et al.* (1999).

Carbon dioxide emissions could be calculated from the elementary composition of the fuels studied. Carbon dioxide of fossil origin contributes to the global warming. Kaltschmitt & Reinhardt (1997) give average elementary formulae for MK3, RME and rapeseed oil:

- MK3: $C_{15}H_{32}$ gives 72.6 g CO_2/MJ_{fuel} of which all is of fossil origin;
- RME: $C_{19}H_{35}O_2$ gives 73.5 g CO_2/MJ_{fuel} of which 1/19:th, 3.87 g, is of fossil origin if the methanol for the transesterification is of fossil origin. If the methanol is manufactured from products of biomass origin, no CO_2 will be of fossil origin (in this study only for the scenario analysis);
- Rapeseed oil: $C_{57}H_{102}O_6$ gives 74.1 g CO_2/MJ_{fuel} of which nothing is of fossil origin.

Calculations [g CO_2/ MJ_{fuel}]: (number of C * ((12.01 + 2 * 16.00) / (number of C * 12.01 + number of H * 1.008 + number of O * 16.00)) * 1000 g/kg) / (lower heat value); atomic weights: C: 12.01 g/mole; H: 1.008 g/mole; O: 16.00 g/mole. The lower heat values for the fuels are given in Table 99.

Uppenberg *et al.* (2001) state that the emission of fossil carbon dioxide is 73 g/MJ_{fuel} for diesel oil fuel MK1. The carbon dioxide emissions, on an area basis, can then be calculated from the fuel requirement if known.

Ethanol fuel: The carbon dioxide emissions were calculated from the composition of the fuel (Table 100). The ethanol is of biomass origin and Beraid, MTBE and isobutanol is of fossil origin. Calculation of released carbon dioxide during combustion of 1 kg ethanol fuel:

- Ethanol: 843.37 g.
  $C_2H_5OH + 3*O_2$ ---> $2*CO_2 + 3*H_2O$
  Molecular weight C_2H_5OH: 2 * 12.01 + 6* 1.008 + 16.00 = 46.068 g/mole.
  Amount of CO_2 [g]: (2 * 44.01 * 843.37) / (45.068) = 1611.4 g CO_2/kg ethanol fuel (biomass origin).
- Beraid (polyethylene glycol, ignition improver): 70 g.
  $2*(C_2H_4O)_n + 5*n*O_2$ ---> $4*n*CO_2 + 4*n*H_2O$
  Molecular weight $(C_2H_4O)_n$: (2 * 12.01 + 4 * 1.008 + 16.00) * n = 44.052 * n g/mole.
  Amount of CO_2 [g]: (4 * n * 44.01 * 70) / (2 * 44.052 * n) = 139.9 g CO_2/kg ethanol fuel (fossil origin).
- MTBE (methyltertiarybutylether, denaturating agent): 23 g.
  $2*C_5H_{12}O + 15*O_2$ ---> $10*CO_2 + 12*H_2O$
  Molecular weight $C_5H_{12}O$: 5 * 12.01 + 12 * 1.008 + 16.00 = 88.146 g/mole.
  Amount of CO_2 [g]: (10 * 44.01 * 23) / (2 * 88.146) = 57.4 g CO_2/kg ethanol fuel (fossil origin).
- Isobutanol (denaturating agent): 5 g.
  $C_4H_{10}O + 6*O_2$ ---> $4*CO_2 + 5*H_2O$
  Molecular weight $C_4H_{10}O$: 4 * 12.01 + 10 * 1.008 + 16.00 = 74.12 g/mole.
  Amount of CO_2 [g]: (4 * 44.01 * 5) / (74.12) = 11.9 g CO_2/kg ethanol fuel (fossil origin).

Molecular weight CO_2: 12.01 +2 * 16.00 = 44.01 g/mole.

Addition gives total emissions of CO_2 when ethanol fuel is burnt:	1820.5 g/kg ethanol fuel
equivalent to (division with the lower heat value)	72.47 g CO_2/MJ_{fuel},
of which fossil	209.2 g/kg ethanol fuel
equivalent to:	8.326 g CO_2/MJ_{fuel},
of which has biomass origin	1611.4 g/kg ethanol fuel
equivalent to:	64.14 g CO_2/MJ_{fuel}.

Emission of SO_2, which is the main component in SO_x, was calculated from the sulphur content in each fuel. According to Aakko *et al.* (2000), the sulphur content in EN590 (European diesel fuel) is assumed to be equivalent to MK3; MK1; and RME: 403; 10; and 79 ppm respectively. The sulphur content in rapeseed oil was assumed to be the same as for RME when no sulphur is added or subtracted during the transesterification. 1.00 g sulphur gives 2.00 g SO_2 (calculated from the relationship between the mole weights of SO_2 and sulphur: ((32.1 + 2 * 16.00) / 32.1): S 32.1 g/mole; O 16.00 g/mole). The emissions of SO_2 (SO_x) [g/ha] could then be calculated from the fuel consumption for each fuel: (S content [ppm] / 1000000) * 2.00 [g SO_2/g S] * fuel consumption [l/ha] * fuel density [kg/l] (Table 99) * 1000 [g/kg]. Ethanol fuel contains no sulphur (Sekab, 2003) and gives therefore no SO_x emissions.

According to the IVL recommendations particle emissions, on average, are assumed to be 11 mg/MJ_{fuel} for diesel oil fuel MK1 and RME heavy vehicles (Uppenberg *et al.*, 2001). In this study, particle emissions for diesel oil fuel MK3 were assumed to be of the same size as for

MK1. The literature is not unequivocal on whether particle emissions increase or decrease when MK1 and MK3 diesel oil fuels are compared (Aakko *et al.*, 2000; Storey *et al.*, 2000). For rapeseed oil the particle emissions are reduced by 30% in comparison to MK3 (Table 101). According to the IVL recommendations, particle emissions, on average, are assumed to be 2.2 mg/MJ_{fuel} for ethanol fuel used in heavy vehicles (Uppenberg *et al.*, 2001). This value was therefore used in this study when ethanol fuel was used as fuel.

During the scenario analysis, with catalysts in the cultivation machines used, the reduction of emissions was assumed to roughly follow results from Aakko *et al.* (2000) for MK3, MK1, RME and rapeseed oil fuels. Therefore CO- HC- and NO_x-emissions were reduced by 81%; 77.5%; and 6% respectively. Particulate emissions were not influenced. For ethanol fuel, the reduction of emissions, with catalysts in the cultivation machines, was assumed to roughly follow results from Haupt *et al.* (1999). Therefore CO- and HC-emissions were reduced by 93% and 45% respectively. NO_x- and particulate-emissions were not influenced.

Total emissions and energy requirement for cultivation and fertiliser transport were obtained when emissions for production of the fuel used (MK1 in Table 13) and lubrication oil were added with the emissions when the fuel was used (Tables 14-15, A1-A2 and A15-A16). Area emissions and energy requirement for the production of MK1 (Tables 14-15) could be calculated by multiplying: the fuel consumption [l/ha] (Tables 3-6); the fuel density [kg/l] (Table 99); the lower heat value [MJ/kg] (Table 99); and emissions during manufacturing of the fuel [g/MJ_{fuel}] (Table 13). For the scenario analyses, rapeseed oil, RME or ethanol fuel were also used for cultivation and transport depending on the system studied. Values for production of rapeseed oil, RME or ethanol fuel were taken from this study and were different depending on the plant size studied (Tables A3-A14, Appendix 1 and Tables A17-A22, Appendix 2). The calculations were then made in an iterative procedure. In the basic scenario MK1 was used for cultivation and transport.

Table 13. Emissions from production of MK1 diesel oil fuel (Uppenberg et al., 2001)

Factor of production	CO_2	CO	HC	CH_4	NO_x	SO_x	Particles	Input energy
	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[MJ/MJ_{fuel}]
Production of MK1 diesel oil[a]	3.5	0.002	0.033	0.002	0.031	0.019	0.001	0.06

[a] In this study also assumed to be valid for MK3 diesel oil.

Table 14. Total emissions for tractive power and transport of fertiliser during cultivation of rapeseed with MK1 fuel

Production factor	CO_2	CO	HC	CH_4	NO_x	SO_x	N_2O	Particles	Input energy
	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[MJ/ha]
Tractive power:									
Diesel fuel consumption	168032	181.95	55.29		1996.50	1.06		25.32	2301.80
Production of diesel fuel	8056	4.60	75.96	4.60	71.36	43.73	0	2.30	138.11
Production of lubrication oil	57	0.03	0.53	0.03	0.50	0.31	0	0.02	0.97
Total emissions tractive power	176145	186.58	131.78	4.64	2068.36	45.10	0	27.64	2440.88
Transport of fertiliser:									
Diesel fuel consumption	1308	2.67	0.66		13.60	0.01		0.20	17.92
Production of diesel fuel	63	0.036	0.59	0.036	0.56	0.34	0	0.02	1.08
Production of lubrication oil	0.44	0.0003	0.004	0.0003	0.004	0.002	0	0.0001	0.01
Total emissions transport of fertiliser	1371	2.71	1.26	0.036	14.16	0.35	0	0.22	19.00

Table 15. Total emissions for tractive power and transport of fertiliser during cultivation of winter wheat with MK1 fuel

Production factor	CO_2	CO	HC	CH_4	NO_x	SO_x	N_2O	Particles	Input energy
	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[MJ/ha]
Tractive power:									
Diesel fuel consumption	169077	188.08	56.38		2011.26	1.07		25.48	2316.12
Production of diesel fuel	8106	4.63	76.43	4.63	71.80	44.01	0	2.32	138.97
Production of lubrication oil	57	0.03	0.54	0.03	0.50	0.31	0	0.02	0.98
Total emissions tractive power	177240	192.74	133.35	4.66	2083.56	45.38	0	27.81	2456.07
Transport of fertiliser:									
Diesel fuel consumption	1085	2.21	0.55		11.28	0.01		0.16	14.86
Production of diesel fuel	52	0.03	0.49	0.030	0.46	0.28	0	0.01	0.89
Production of lubrication oil	0.4	0.0002	0.003	0.0002	0.003	0.002	0	0.0001	0.01
Total emissions transport of fertiliser	1137	2.24	1.04	0.030	11.74	0.29	0	0.18	15.76

In an alternative scenario (Tables 155-166), ploughing was replaced by three disc harrowings with assumptions according to Hansson *et al.* (1998) and Norén *et al.* (1999) and Hansson & Mattsson (1999) about fuel consumptions and emissions (see Tables 3 and 5). The seed yield was assumed not to be influenced by this operation.

3.4.4.3 Drying of the seed

The rapeseed was dried to 8% and the wheat was dried to 14% water content (wet basis) on the farm. An 8% water content in the rapeseed is the optimum water content for oil extraction (Bernesson, 1993). The trade water content in wheat is 14%. The average harvest water content is approx. 15% for rapeseed and approx. 20% for wheat in the flatlands of Central Sweden (Grimmark, pers. comm.). The energy requirement for drying with heating oil (MK3) is 0.15 litres per kg water removal if the drying is done in a hot-air drier and cereal grain (*e.g.* wheat) is dried (Bernesson, 1993). For drying oil plants the energy requirement is 10-15% lower, which in this study was assumed to be 87.5% of the energy requirement for drying cereal grain.

When the rapeseed harvest was 2470 kg/ha at 8% water, it was equivalent to 2673 kg/ha at 15% water and 203 kg water had to be removed. For this 26.7 litres heating oil (MK3) containing 944 MJ was required. In the same way the wheat harvest was 5900 kg/ha at 14% water, equivalent to 6342.5 kg/ha at 20% water, and 442.5 kg water had to be removed. For this 66.4 litres heating oil (MK3) containing 2347 MJ was required. The energy requirement for drying was assumed to be independent of the liquid fuel used (the lower heat values and the densities for fuels are given in Table 99). The emissions, on a fuel energy basis (Table 16), were also assumed to be independent of the liquid fuel used (excluding SO_x-emissions and fossil CO_2-emissions which depend on the fuel used). For calculation of CO_2- and SO_x-emissions see Section 3.4.4.2 above.

The area emissions (Tables 17-18) were calculated by multiplying the energy requirement for drying [MJ/ha] (see above) by the emissions [g/MJ_{fuel}] (Table 16). In the basic scenario diesel fuel MK1 was used for drying, other fuels were used in the scenario analysis. In the total emissions for drying emissions for manufacturing of the fuel (MK1, Table 13) were also included (Tables 17-18, A1-A2 and A15-A16). In the basic scenario 0.132 litres MK1 (0.15 * 0.875 * ((density MK3 * lower heat value MK3) / (density MK1 * lower heat value MK1))) were required for each litre water removed from the rapeseed and 0.151 litres MK1 (0.15 * ((density MK3 * lower heat value MK3) / (density MK1 * lower heat value MK1))) were required for each litre water removed from the wheat. This means that 26.8 litres MK1/ha was required to dry the rapeseed and 66.7 litres MK1/ha was required to dry the wheat.

Table 16. Emissions, drying of rapeseed and wheat with liquid fuels (Kaltschmitt & Reinhardt, 1997)

Production factor	CO [g/MJ_{fuel}]	HC [g/MJ_{fuel}]	CH_4 [g/MJ_{fuel}]	NO_x [g/MJ_{fuel}]	N_2O [g/MJ_{fuel}]	Particles [g/MJ_{fuel}]
Drying emissions	0.03	0.005	0.007	0.03	0.001	0.001

For drying and cleaning the rapeseed, 0.03 MJ electricity / kg wet product (15% water) was required (Sonesson, 1993). For drying and cleaning the wheat, 0.038 MJ electricity / kg wet product (20% water) was required (Sonesson, 1993: 0.017 MJ electricity / kg wet product to remove 200 kg water from wheat, here 442.5 kg water was removed). Emissions for electricity production are accounted for in Table 49, Section 3.6. The area emissions and energy requirement (Tables 17-18, A1-A2 and A15-A16) were obtained by multiplying; wet seed yield [kg/ha]; electricity requirement [MJ/kg wet seed]; and emissions for electricity production [g/MJ].

Table 17. Total emissions for drying of rapeseed with MK1 fuel

Production factor	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	Particles	Input energy
	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[MJ/ha]
Heat for drying:										
Production of drying fuel	3303	1.89	31.15	1.89	29.26	17.93		0.00	0.94	56.63
Combustion of drying fuel	68900	28.32	4.72	6.61	28.32	0.44		0.94	0.94	943.84
Total emissions heat for drying	72204	30.20	35.87	8.49	57.57	18.37		0.94	1.89	1000.47
Electricity for drying and cleaning of the seed:										
Electricity consumed in rural area	692	1.59	0.26	4.32	1.32	1.15	0.019	0.063	0.22	171.82

Table 18. Total emissions for drying of winter wheat with MK1 fuel

Production factor	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	Particles	Input energy
	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[MJ/ha]
Heat for drying:										
Production of drying fuel	8213	4.69	77.44	4.69	72.74	44.58		0.00	2.35	140.79
Combustion of drying fuel	171298	70.40	11.73	16.43	70.40	1.08		2.35	2.35	2346.54
Total emissions heat for drying	179510	75.09	89.17	21.12	143.14	45.67		2.35	4.69	2487.33
Electricity for drying and cleaning of the seed:										
Electricity consumed in rural area	2079	4.77	0.77	12.99	3.98	3.45	0.058	0.19	0.66	516.32

3.4.5 Economics of rapeseed and wheat production

In Tables 19 and 20, the economic conditions are described for rapeseed and wheat cultivation respectively, in this study. During the economic calculation the same conditions were in principle chosen as during the LCA. In addition to the LCA-study, calculations were also conducted on a larger, more cost-effective farm unit. Another difference was purchased seed for the sowing, the reason for this was that LCA-data were difficult to obtain for purchased seed.

Table 19. Costs in cultivation of rapeseed

Factors of production	Basic scenario, 75 ha farm unit			Larger farm, 300 ha farm unit		
	Quantity […/ha]	Price [SEK/…]	Cost [SEK/ha]	Quantity […/ha]	Price [SEK/…]	Cost [SEK/ha]
Seed [kg][a]	8.8	60	528	8.8	60	528
Fertiliser: Hydro NPK Svavel Bor 20-3-5 [kg]	500	2.60	1302	500	2.60	1302
Fertiliser: Hydro Suprasalpeter, N28 [kg]	145	2.80	405	145	2.80	405
Pesticides, herbicide [kg]	2	380	760	2	380	760
Pesticides, insecticide [kg]	0.15	220	33	0.15	220	33
Fuel, tractive power, etc. [litres][ab]	65.9	5.70	376	65.9	5.70	376
Lubrication oil etc. tractive power, etc.[ac]			56			56
Fuel, heat for seed drying [litres]	26.8	5.70	153	26.8	5.70	153
Electricity for drying and cleaning of the seed [kWh]	22.3	0.719	16	22.3	0.719	16
Crop insurance			28			28
Cultivation charge			84			62
Sum primary costs 1			3741			3719
Machinery maintenance[a]			755			872
Interest circulating capital			246			222
Sum primary costs 2			4742			4813
Machinery depreciation and interest[a]			1713			1125
Tax and insurance, field machines and drier[a]			26			21
Keeping area costs, field machines and drier[a]			185			79
Tenancy (Agriwise, 2003)			934			934
Sum costs (excl. labour)			7600			6972
Total machine operator labour [h][a]	7.54	180	1357	3.88	180	698
Labour work management[d]			136			70
Sum costs (incl. labour)			9092			7740
EU area compensation (subtracted income)[e]			2338			2338
Sum costs with EU area compensation			6754			5402

[a] Including extra requirement of seed, fuel, oil, maintenance, labour, etc. because of outwintering.
[a] Also including threshing machine and fertiliser transport.
[b] Lubrication oil costs was assumed to be 15% of fuel costs (Agriwise, 2002 and 2003).
[c] Assumed to be 10% of machine operator work.
[d] Oil crops in Swedish region 3 (Jordbruksverket, 2003).

Table 20. Costs cultivation of winter wheat

Factors of production	Basic scenario, 75 ha farm unit			Larger farm, 300 ha farm unit		
	Quantity […/ha]	Price [SEK/…]	Cost [SEK/ha]	Quantity […/ha]	Price [SEK/…]	Cost [SEK/ha]
Seed [kg][a]	231	3.39	783	231	3.39	783
Fertiliser: Hydro NPK Svavel 21-4-7 [kg]	420	2.91	1224	420	2.91	1224
Fertiliser: Hydro Suprasalpeter, N28 [kg]	115	2.80	322	115	2.80	322
Pesticides, herbicide [times]	1	287	287	1	287	287
Pesticide, fungicide (Tilt Top 500 EC) [times]	0.6	400	240	0.6	400	240
Pesticide, fungicide (Sportak EW) [times]	0.7	445	312	0.7	445	312
Pesticides, insecticide [times]	0.5	39.9	20	0.5	39.9	20
Fuel, tractive power, etc. [litres][ab]	66.2	5.70	377	66.2	5.70	377
Lubrication oil etc. tractive power, etc.[ac]			57			57
Fuel, heat for seed drying [litres]	66.7	5.70	380	66.7	5.70	380
Electricity for drying and cleaning of the seed [kWh]	66.9	0.719	48	66.9	0.719	48
Crop insurance			28			28
Analysis winter wheat [SEK/10000 kg wet seed]	0.634	145	92	0.634	145	92
Sum primary costs 1			4169			4169
Machinery maintenance[a]			863			933
Interest circulating capital			274			247
Sum primary costs 2			5305			5348
Machinery depreciation and interest[a]			2034			1307
Tax and insurance, field machines and drier[a]			31			23
Keeping area costs, field machines and drier[a]			291			120
Tenancy (Agriwise, 2003)			934			934
Sum costs (excl. labour)			8594			7732
Total machine operator labour [h][a]	8.24	180	1484	4.32	180	778
Labour work management[d]			148			78
Sum costs (incl. labour)			10226			8588
EU area compensation (subtracted income)[e]			2338			2338
Sum costs with EU area compensation			7888			6250

[a] Including extra requirement of seed, fuel, oil, maintenance, labour, etc. because of outwintering.
[b] Also including threshing machine and fertiliser transport.
[c] Lubrication oil costs was assumed to be 15% of fuel costs (Agriwise, 2002 and 2003).
[d] Assumed to be 10% of machine operator work.
[e] Oil crops in Swedish region 3 (Jordbruksverket, 2003).

The prices of fertilisers were calculated from prices of nitrogen, phosphorous and potassium: 10.13 SEK/kg N; 11.70 SEK/kg P; and 4.54 SEK/kg K given by Agriwise (2003). When the composition for each fertiliser was known (20% N, 3% P, 5% K and 4% S for Hydro NPK Svavel Bor 20-3-5; 21% N, 4% P, 7% K and 2.2% S for Hydro NPK Svavel 21-4-7 and 27.6% N for Hydro Suprasalpeter, N28 calcium ammonium nitrate) their prices could be calculated.

The fuel requirement for tractive power, 65.9 litres/ha for rapeseed cultivation and 66.2 litres/ha for wheat cultivation, in this study also includes fuel for threshing machine (see Tables 3 and 4) and transport of fertiliser to the farm (Tables 5 and 6). 26.8 l/ha were used for drying the rapeseed and 66.7 litres/ha for drying the wheat. The fuel used in both these applications was assumed to be MK1 with a price of 5.70 SEK/litre (Henemo, 2002 and 2003). The fuel requirement was not assumed to change in the scenario with the larger farm (Tables 19 and 20).

The labour requirement for tractive power (incl. threshing machine) was assumed to be the same as when the machines were used for each operation with 20% time added as maintenance and wasted time for each operation (Henemo, 2002 and 2003). For transportation of fertiliser, the labour time for loading and unloading was assumed to be 0.5 h each. This makes the total time for loading, unloading and transport 2 hours (1 h loading/unloading + 1 h transport loaded/unloaded, 2*10 km at a speed of 20 km/h). Then, for rapeseed cultivation, the total load was 16 000 kg and 645 kg was required on each hectare, this gives a labour requirement of 0.08 h/ha. In the same way for wheat cultivation, when 535 kg fertiliser was required on each hectare, this gives a labour requirement of 0.07 h/ha. For drying 2.5 tonnes of seed, 0.4 h of labour was required (Agriwise, 2003) and therefore the labour requirement was assumed to be barely 0.40 h/ha for drying the rapeseed. For drying the wheat, the labour requirement was proportionally greater, which with a seed harvest of 5.9 tonnes gives a labour requirement of approx. 0.94 h/ha. The labour cost for work management was assumed to be 10% of machine operator work costs. For the large farm, the labour requirement was assumed to be halved for almost all operations except for transporting the seed from the field to the farm and transportation of fertilisers. These were not assumed to decrease because of longer distances on a bigger farm. The cost for the labour was assumed to be 180 SEK/h, *i.e.* the cost for an experienced machine operator in 2002 (estimated after SCB, 2003; Agriwise, 2003; and Henemo, 2002 and 2003).

The price for the electricity on the farms consisted of: electricity price 0.27 SEK/kWh; tax 0.227 SEK/kWh; grid charge 0.152 SEK/kWh; and fixed grid charge simple tariff 0.07 SEK/kWh together 0.719 SEK/kWh (Vattenfall, 2003 and Brännström, pers. comm.). Value-added tax was not included. The fixed grid charge was assumed to be valid for an 80 Ampere connection with an annual consumption of 75 000 kWh. This gives a grid charge of 5507 SEK/year divided by 75 000 kWh/year = approx. 0.07 SEK/kWh.

The crop insurance was valid for a farm in the flatlands of Central Sweden growing 80% cereal grain and 20% oil crops in 2002 (Agriwise, 2003).

The cultivation charge (only rapeseed) was calculated as 300 SEK/year with an additional charge of 0.022 SEK/kg seed produced (9% water content wet basis, the trade water content for rapeseed). This charge would then be 83.5 SEK/ha if 14% of the area on a 75 ha farm was cropped with rapeseed that yielded 2497 kg/ha (yield at 9% water) (62.1 SEK/ha if 14% of the area of a 300 ha farm was cropped) (Svenskraps, 2003b).

Analysis cost for winter wheat: 145 SEK/10 000 kg not dried seed (Agriwise, 2003) gave approx. 92 SEK/ha (if the yield was 6342 kg wheat/ha with 20% water, wet weight basis).

Outwintering costs were calculated as fuel, labour, maintenance, depreciation and interest (machines and tractors) for one disc harrowing, two harrowings and one seed drilling each 10% of the years for rapeseed and each 5% of the years for wheat. Extra seed was also included in the outwintering costs. In Tables 19 and 20, outwintering costs are included in the appropriate items. The outwintering costs were 105 SEK/ha in the basic scenario and 91 SEK/ha in the scenario with the large farm for rapeseed. The outwintering costs were 65 SEK/ha in the basic scenario and 58 SEK/ha in the scenario with the large farm for wheat.

Interest circulating capital was calculated as: (Sum prime costs 1 + maintenance + labour cost) * factor calculation of demand of circulating capital. The factor calculation of demand of circulating capital is 0.6 for winter crops and 0.3 for spring crops (Agriwise, 2003). The difference to Agriwise (2003) and SLU (1989) in this study is that the maintenance for all machines used was included in the calculations (not just tractors, threshing machine and sprayer). Costs for outwintering were included in interest circulating capital. Labour for work management was not included in interest of circulating capital.

Tax and insurance costs were assumed to be 0.2% of the replacement value for tractors and threshing machines and 0.1% of the replacement value for other machines (Tables 22, 21, 25 and 26), after Henemo (2002). To get the values on an area basis they were multiplied by the use [h/ha] and divided by annual use [h].

Keeping area costs were calculated after Henemo (2002 and 2003). The keeping area is the floor area each machine requires during storage. The demand for floor area is about twice the machine-area. The price for the floor-area was assumed to be 180 SEK/m^2 for tractors and front-loaders and 120 SEK/m^2 for other machines (Tables 21-26), which corresponds to a building tenancy of 90 and 60 SEK/m^2 respectively. These figures could be valid for a mixture between new and old storage houses. To get the values on an area basis they were multiplied by the use [h/ha] divided by annual use [h].

Maintenance and capital costs (depreciation and interest) (Tables 21-26) were mainly calculated after Henemo (2002 and 2003). These values are dependent on how much each machine is used on each hectare and how much it is used annually. Maintenance costs [SEK/ha] were calculated as: maintenance costs [SEK/h and 1000 SEK replacement value] * replacement value [1000 SEK] * use [h/ha].

Table 21. Basic economic data for cultivation machines, rapeseed and wheat cultivation

Machine, use on 75 ha farm in the flatlands of Central Sweden	Repl. value [SEK] (A)[a]	Residual value[b]	Maintenance cost (B)[c]	Length of life [years] (C)	Annual use [hours] (D)	Keeping area [m^2]
Tractor, 52 kW, 4WD	295000	73750	0.07	12	300	8
Tractor, 66 kW, 4WD, incl. transp. fertiliser to farm	400000	100000	0.07	12	550	8
Front-loader, 1500 kg, incl. transp. fertiliser to farm	60000	15000	0.20	12	15	2
Plough, four wings, semi-mounted	80000	20000	0.90	12	200	6
Harrow, 6 m	110000	27500	0.70	12	80	10
Precision seed drill, 9 rows[d]	110000	27500	0.80	12	70	10
Seed drill, 4.0 m[d]	100000	25000	0.50	15	100	10
Cambridge roller, 6 m	60000	15000	0.50	15	30	12
Fertiliser spreader, towed 4000 l, 12 m boom	200000	50000	0.65	10	70	14
Sprayer, 1000 l, carried, 12 m boom	110000	27500	1.25	12	30	6
Threshing machine, 3.0 m	525000	131250	0.30	15	130	32
Disc harrow, 3.6 m	115000	28750	0.50	15	160	20
Tipping trailer, 10 tonnes, incl. transp. fertiliser to farm (*2)	70000	17500	0.50	15	50	14
Hot air drier, incl. air heater, continuous flow drier, SLU (1989) costs assumed not to be increased	500000	0	0.05	50	530	100

[a] Replacement value (Henemo, 2002).
[b] Residual value assumed to be 25% of the replacement value.
[c] Maintenance cost (Henemo, 2002 and 2003) [SEK/h and 1000 SEK replacement value] (B).
[d] Precision seed drill, 9 rows used for rapeseed, and seed drill, 4.0 m used for wheat.

Capital costs (depreciation and interest) were calculated using the annuity method (Ljung & Högberg, 1988). The calculation interest was set at 7% for these calculations. Then the annual capital cost was (Equations 1-3):

$$Acc = (A - R * P) * An * \left(\frac{U}{D}\right) \quad (1)$$

where:
A = Replacement value;
R = Residual value;
U = Use [h/ha] and
D = Annual use [h/year].

The present value factor:

$$P = \frac{1}{\left(1 + \frac{i}{100}\right)^C} \quad (2)$$

where:
i = Calculation interest;
C = Length of life [years], calculated.

The fixed annual factor:

$$An = \frac{\frac{i}{100} * \left(1 + \frac{i}{100}\right)^C}{\left(1 + \frac{i}{100}\right)^C - 1} \tag{3}$$

In the calculation for cultivation machines, the residual value was assumed to be 25% of the replacement value for field machines and zero for the dryer (Tables 21 and 24).

Table 22. Basic data for cultivation machines used in economic calculation, rapeseed cultivation

Machine, use on 75 ha farm in the flatlands of Central Sweden	Use [h/ha]	Maint. cost [SEK/ha]	Keeping area costs [SEK/ha]	Tax and insurance [SEK/ha][a]	Annual capital cost [SEK/ha]
Tractor, 52 kW, 4WD	0.98	20.2	4.7	1.92	107.6
Tractor, 66 kW, 4WD, incl. transp. fertiliser to farm	3.60	100.7	9.4	5.23	292.9
Front-loader, 1500 kg, incl. transp. fertiliser to farm	0.06	0.8	1.5	0.26	28.7
Plough, four wings, semi-mounted	2.06	148.6	7.4	0.83	92.4
Harrow, 6 m, 2 times	0.54	41.7	8.1	0.74	83.3
Precision seed drill, 9 rows	0.45	39.9	7.8	0.71	79.8
Cambridge roller, 6 m	0.12	3.5	5.6	0.23	23.3
Fertiliser spreader, towed 4000 l, 12 m boom, 2 times	0.26	33.4	6.2	0.73	91.3
Sprayer, 1000 l, carried, 12 m boom, 2 times	0.15	20.6	3.6	0.55	61.6
Threshing machine, 3.0 m	1.36	214.8	40.3	11.01	549.9
Disc harrow, 3.6 m, 1 time	0.77	44.3	11.6	0.55	55.3
Tipping trailer, 10 tonnes, incl. transp. fertiliser to farm (*2)	0.20	7.0	6.7	0.28	27.8
Hot air drier, incl. air heater, continuous flow drier, SLU (1989) costs assumed not to be increased	3.20	80.0	72.5	3.02	218.7
Sum		755.5	185.3	26.08	1712.5

[a] Tax and insurance assumed to be 0.2% of replacement value for tractors and threshing machines and 0.1% of the replacement value for other machines (Henemo, 2002).

Table 23. Basic data for cultivation machines used in economic calculation, wheat cultivation

Machine, use on 75 ha farm in the flatlands of Central Sweden	Use [h/ha]	Maint. cost [SEK/ha]	Keeping area costs [SEK/ha]	Tax and insurance [SEK/ha][a]	Annual capital cost [SEK/ha]
Tractor, 52 kW, 4WD	1.02	21.0	4.9	2.00	111.9
Tractor, 66 kW, 4WD, incl. transp. fertiliser to farm	3.69	103.4	9.7	5.37	300.5
Front-loader, 1500 kg, incl. transp. fertiliser to farm	0.06	0.7	1.5	0.25	27.6
Plough, four wings, semi-mounted	2.06	148.6	7.4	0.83	92.4
Harrow, 6 m, 2 times	0.52	39.8	7.8	0.71	79.6
Seed drill, 4.0 m	0.43	21.7	5.2	0.43	43.2
Cambridge roller, 6 m	0.12	3.5	5.6	0.23	23.3
Fertiliser spreader, towed 4000 l, 12 m boom, 2 times	0.26	33.4	6.2	0.73	91.3
Sprayer, 1000 l, carried, 12 m boom, 2.8 times	0.21	28.9	5.0	0.77	86.2
Threshing machine, 3.0 m	1.36	214.8	40.3	11.01	549.9
Disc harrow, 3.6 m, 1 time	0.74	42.3	11.0	0.53	52.7
Tipping trailer, 10 tonnes, incl. transp. fertiliser to farm (*2)	0.35	12.2	11.7	0.49	48.6
Hot air drier, incl. air heater, continuous flow drier, SLU (1989) costs assumed not to be increased	7.70	192.5	174.3	7.26	526.4
Sum		862.6	290.5	30.62	2033.6

[a] Tax and insurance assumed to be 0.2% of replacement value for tractors and threshing machines and 0.1% of the replacement value for other machines (Henemo, 2002).

The summed values in Tables 21-23 are used in Tables 19 and 20.

In the scenario with a larger farm unit (Tables 24-26) the larger machines with approximately double the capacity were chosen with replacement values after Henemo (2002). For the drier a reasonable higher replacement value was assumed. The annual use of the machines was in most cases assumed to be doubled. An exception was the threshing machine, where an annual use of more than 180 hours would be difficult to achieve in Central Sweden because of the weather conditions during harvest. The threshing machine had to be comparably larger for this reason. The machine length of life was increased and because of that the residual values had to be decreased to a lower value, here assumed to be 10%. The total use of the machines was then close to what is possible and so are the machine costs.

The summed up values in Tables 24-26 are used in Tables 19 and 20.

Table 24. Basic economic data for cultivation machines, larger farm, rapeseed and wheat cultivation

Machine, use on 300 ha farm in the flatlands of Central Sweden	Repl. value [SEK] (A)[a]	Residual value[b]	Maintenance cost (B)[c]	Length of life [years] (C)	Annual use [hours] (D)	Keeping area [m^2]
Tractor, 100 kW, 4WD	565000	56500	0.07	20	600	10
Tractor, 140 kW, 4WD, incl. transp. fertiliser to farm	785000	78500	0.07	20	1100	10
Front-loader, larger, incl. transp. fertiliser to farm	75000	7500	0.20	20	30	2
Plough, eight wings, semi-mounted	160000	16000	0.90	20	400	10
Harrow, 12 m	200000	20000	0.70	20	160	16
Precision seed drill, 18 rows[d]	320000	32000	0.80	20	140	15
Seed drill, 8.0 m[d]	300000	30000	0.50	20	200	15
Cambridge roller, 12 m	150000	15000	0.50	35	60	18
Fertiliser spreader, towed 4000 l, 20 m boom	240000	24000	0.65	15	140	18
Sprayer, 3600 l, towed, 24 m boom	360000	36000	1.25	15	60	18
Threshing machine, 7.5 m	1700000	170000	0.30	20	180	50
Disc harrow, 7.2 m	200000	20000	0.50	20	320	25
Tipping trailer, 15 tonnes, incl. transp. fertiliser to farm (*2)	175000	17500	0.50	20	120	20
Hot air drier, incl. air heater, continuous flow drier, SLU (1989) costs assumed not to be increased	1000000	0	0.05	50	530	150

[a] Replacement value (Henemo, 2002).
[b] Residual value assumed to be 10% of the replacement value.
[c] Maintenance cost (Henemo, 2002 and 2003) [SEK/h and 1000 SEK replacement value] (B).
[d] Precision seed drill, 18 rows used for rapeseed, and seed drill, 8.0 m used for wheat.

Table 25. Basic data for cultivation machines used in economic calculation, larger farm, rapeseed cultivation

Machine, use on 300 ha farm in the flatlands of Central Sweden	Use [h/ha]	Maint. cost [SEK/ha]	Keeping area costs [SEK/ha]	Tax and insurance [SEK/ha][a]	Annual capital cost [SEK/ha]
Tractor, 100 kW, 4WD	0.49	19.3	1.5	0.92	42.3
Tractor, 140 kW, 4WD, incl. transp. fertiliser to farm	1.93	105.8	3.2	2.75	126.4
Front-loader, larger, incl. transp. fertiliser to farm	0.03	0.5	0.4	0.08	7.4
Plough, eight wings, semi-mounted	1.03	148.6	3.1	0.41	38.0
Harrow, 12 m, 2 times	0.27	37.9	3.2	0.34	31.1
Precision seed drill, 18 rows	0.23	58.1	2.9	0.52	47.7
Cambridge roller, 12 m	0.06	4.4	2.1	0.15	11.2
Fertiliser spreader, towed 4000 l, 20 m boom, 2 times	0.13	20.1	2.0	0.22	23.3
Sprayer, 3600 l, towed, 24 m boom, 2 times	0.08	33.8	2.7	0.45	47.6
Threshing machine, 7.5 m	0.68	347.7	22.7	12.88	592.1
Disc harrow, 7.2 m, 1 time	0.39	38.5	3.6	0.24	22.1
Tipping trailer, 15 tonnes, incl. transp. fertiliser to farm (*2)	0.20	17.4	4.0	0.29	26.7
Hot air drier, incl. air heater, continuous flow drier, SLU (1989) costs assumed not to be increased	0.80	40.0	27.2	1.51	109.4
Sum		872.0	78.5	20.75	1125.2

[a] Tax and insurance assumed to be 0.2% of replacement value for tractors and threshing machines and 0.1% of the replacement value for other machines (Henemo, 2002).

Table 26. Basic data for cultivation machines used in economic calculation, larger farm, wheat cultivation

Machine, use on 300 ha farm in the flatlands of Central Sweden	Use [h/ha]	Maint. cost [SEK/ha]	Keeping area costs [SEK/ha]	Tax and insurance [SEK/ha][a]	Annual capital cost [SEK/ha]
Tractor, 100 kW, 4WD	0.51	20.1	1.5	0.96	44.0
Tractor, 140 kW, 4WD, incl. transp. fertiliser to farm	2.04	112.2	3.3	2.91	134.0
Front-loader, larger, incl. transp. fertiliser to farm	0.03	0.5	0.4	0.08	7.1
Plough, eight wings, semi-mounted	1.03	148.6	3.1	0.41	38.0
Harrow, 12 m, 2 times	0.26	36.2	3.1	0.32	29.7
Seed drill, 8.0 m	0.22	32.5	1.9	0.32	29.9
Cambridge roller, 12 m	0.06	4.4	2.1	0.15	11.2
Fertiliser spreader, towed 4000 l, 20 m boom, 2 times	0.13	20.1	2.0	0.22	23.3
Sprayer, 3600 l, towed, 24 m boom, 2.8 times	0.11	47.3	3.8	0.63	66.7
Threshing machine, 7.5 m	0.68	347.7	22.7	12.88	592.1
Disc harrow, 7.2 m, 1 time	0.37	36.8	3.4	0.23	21.1
Tipping trailer, 15 tonnes, incl. transp. fertiliser to farm (*2)	0.35	30.4	7.0	0.51	46.6
Hot air drier, incl. air heater, continuous flow drier, SLU (1989) costs assumed not to be increased	1.93	96.3	65.4	3.63	263.2
Sum		932.9	119.8	23.25	1306.8

[a] Tax and insurance assumed to be 0.2% of replacement value for tractors and threshing machines and 0.1% of the replacement value for other machines (Henemo, 2002).

3.5 Fuel production: performance, requirement for energy and chemicals etc.

3.5.1 Oil extraction

The use of machinery was dependent on the size of the plant. The extraction in the smallest plant was made by a hole cylinder type of oil expeller and in the medium- and large-size plants by a strainer type of oil expeller. The extraction capacity of an oil expeller decreases with higher oil extraction efficiency and vice versa (Widmann, 1988; Maurer, 1991; Bernesson, 1993; Schön *et al.*, 1994; Bernesson, 1994). In the large-scale plant the extraction take place in two steps, pressing and hexane extraction. The more advanced solvent extraction technique with hexane was used in order to extract more oil from the seeds.

In extraction of rapeseed, oil extraction efficiencies of 58-82% (Widmann, 1988; Maurer, 1991; Bernesson, 1993; Schön *et al.*, 1994; Bernesson, 1994) have been attained with hole cylinder expellers, and extraction efficiencies of 70-88% (Thompson & Peterson, 1982; Widmann, 1988; Maurer, 1991; Head *et al.*, 1995) with strainer oil expellers. The lower range in the intervals normally represents oil presses used in practice and the upper range oil presses used in laboratory conditions. In this study, the oil extraction efficiencies were assumed to be 68% in the small-scale plant (Bernesson, 1993; Bernesson, 1994), 75% in the medium-scale plant (Head *et al*., 1995) and 98% in the large-scale plant (Maurer, 1991; Schön *et al*., 1994; Kaltschmitt & Reinhardt, 1997). The extraction efficiencies chosen correspond to oil extraction capacities that are realistic for each type of expeller in practice. In a scenario analysis, oil extraction efficiencies of 73% for small-scale plants and 80% for medium-scale plants were also studied.

The electricity consumption was 0.22-0.36 MJ/kg seed for the plant sizes studied (Table 27). Small oil presses have a higher consumption of energy. Medium- and large-scale oil extraction plants consume the same amount of energy due to the fact that the higher complexity at the large plant is compensated for by higher efficiency.

Table 27. Oil extraction efficiency and energy consumption for plants with different sizes

Plant size	Oil extraction efficiency	Energy consumption	
	[%]	[MJ_{el}/kg seed]	[MJ_{el}/kg oil]
Small-scale plant	68[ab]	0.359[a]	1.17[a]
Medium-scale plant	75[c]	0.216[d]	0.64[d]
Large-scale plant	98[d]	0.216[d]	0.49[d]

[a] After Bernesson (1993); Bernesson (1994); and Bernesson (1998).
[b] After Widmann (1988).
[c] After Head *et al*. (1995).
[d] After Kaltschmitt & Reinhardt (1997).

The electricity requirement for the small-scale extraction, 0.30 kWh/litre oil (approx. 0.36 MJ/kg seed) was calculated after Bernesson (1993) and Bernesson (1994). For medium- and large-scale extraction the electricity requirement was 60 kWh/tonne seed (0.216 MJ/kg seed) (Kaltschmitt & Reinhardt, 1997) (Table 27). All process energy was assumed to be electricity. The corresponding area electricity requirement [MJ_{el}/ha] (Table 50, Section 3.6.1) was obtained when the electricity requirement [MJ_{el}/kg seed] was multiplied by the seed harvest [kg seed/ha] (Section 3.4.1) or when the electricity requirement [MJ_{el}/kg oil] was multiplied by the oil harvest [kg oil/ha] (Table 28).

Some data for oil extraction in different production plants of seed with an oil content of 45% are given in Table 28. These data are necessary for the physical allocation in this study (Section 3.10).

Table 28. Some data for oil extraction in different production plants, including properties of the meal

Type of plant	Extraction efficiency	Share of total as:		Water-wastage during extraction	Share of total as:		Harvest of:	
		Oil	Meal		Sediment	of which oil	Oil	Expeller
	[%]	[%]	[%]	[%]	[%]	[%]	[kg/ha]	[kg/ha]
Small-scale plant	68	30.60	65.80	2	1.6	1.0	756	1625
Medium-scale plant	75	33.75	64.25	2	0	0	834	1587
Large-scale plant	98	44.10	53.90	2	0	0	1089	1331

Hexane was used for the solvent part of the oil extraction in large-scale plants. Solvent extraction was not used in medium- and small-scale plants. The losses of hexane during the extraction phase are 0.6-1.5 kg/tonnes rapeseed, with an average of 1.0 kg/tonne (Kaltschmitt & Reinhardt, 1997). 0.375 kg/tonne rapeseed of this hexane is lost as HC (hydrocarbons) from the extraction plant, which means 0.93 kg/ha if the seed harvest is 2470 kg/ha. In Table 29 emissions from production of and extraction with hexane are accounted for.

Table 29. Emissions from production of and use of hexane for extraction (Kaltschmitt & Reinhardt, 1997)

Factor of production	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	HCl	Particles	MJ
Production of hexane [g/kg hexane].	543	0.34	0.51	0.66	1.84	2.5	0.002	0.0131	0.0036	0.085	52.1
Emissions, production of hexane [g/ha]	1341	0.84	1.26	1.62	4.54	6.2	0.0049	0.032	0.0089	0.210	129
Hexane emission, extraction [g/ha]	0	0	0.93	0	0	0	0	0	0	0	0
Total emissions hexane [g/ha]	1341	0.84	2.19	1.62	4.54	6.2	0.0049	0.03	0.0089	0.210	129

For electricity see Section 3.6 and for transport see Section 3.7.

3.5.2 Transesterification

Contribution of emissions came from production of methanol, catalyst and electricity for transesterification.

The emissions to air during the transesterification process are probably negligibly small and contain probably methanol as the main part. Emissions to water may be higher especially if the ester after transesterification is washed by water. No data on emissions from the transesterification process were found in the available literature.

According to assumptions after Kaltschmitt & Reinhardt (1997), the consumption of electricity is 0.60 MJ_{el}/kg RME (also including thermal energy) for the transesterification.

Emissions from the production of electricity are described in Table 49, Section 3.6.1. The area electricity requirement (see Table 50) could be calculated from the RME yields: 727 kg/ha; 802 kg/ha; and 1048 kg/ha for small-; medium-; and large-scale plants respectively (see Section 3.6.1). More complexity at bigger plants was compensated for by higher efficiency. Therefore the energy demand was the same for all the plant sizes studied.

In Table 30, the emissions when methanol and catalyst are manufactured are accounted for. In the basic scenario, methanol produced from fossil natural gas was used. In the scenario analysis was also methanol produced from biomass *Salix* studied. Methanol has a lower heat value of 19.8 MJ/kg (Mörtstedt & Hellsten, 1982).

Table 30. Emissions and energy requirement from production of methanol and catalyst

Factor of production	CO_2	CO	HC	CH_4	NO_x	SO_x	N_2O	Particles	Input energy
Production of fossil methanol [g or MJ/ MJ methanol] (Furnander, 1996)	18	0.0050	0.0028	0.0023	0.040	0.00037	0.00029	0	0.63
Production of biomass methanol [g or MJ/ MJ methanol] (Furnander, 1996)	16	0.038	0.020	0.00010	0.145	0.0056	0.00048	0.00027	2.29
Production of NaOH catalyst [g or MJ/ kg NaOH] (Finnveden *et al.*, 1994)	364	0.111	0.0043	0.00065	1.51	1.29	0	0.00046	10.4
Production of KOH catalyst [g or MJ /kg KOH] (recalculated from NaOH)	260	0.079	0.003066	0.00047	1.08	0.92	0	0.00033	7.4

In the LCA-analysis, the emissions from the production of the potassium hydroxide are assumed to be the same, on a molar basis, as for sodium hydroxide (Table 30). This may be plausible when the heat of formation is the same (-425 kJ/mole) for both substances (Aylward & Findlay, 1994). The atomic weights are: potassium: 39.1 [g/mole]; sodium: 23.0 g/mole; oxygen: 16.0 [g/mole]; and hydrogen: 1.0 [g/mole] (Aylward & Findlay, 1994). This gives the mole weights for: KOH to 56.1 g and for NaOH to 40.0 g. With the same amount of emissions on a mole basis, the emissions for KOH will be reduced by a factor of 40.0/56.1=0.713 on a weight basis. More KOH will be consumed if the same amount is consumed on a mole basis: 56.1/40.0=1.40 * the amount of NaOH will be consumed on a weight basis. To produce 1 kg NaOH, 3.87 MJ thermal energy and 6.54 MJ electrical energy were consumed, in total 10.41 MJ/kg. With the same reasoning as above, the energy demand for producing 1 kg KOH is (40.0/56.1*10.41 MJ/kg) = 7.42 MJ/kg.

The demand for methanol is 110 kg / 1000 kg rapeseed oil (Norén, 1990) during the transesterification, assumed to be independent of plant size. The catalyst was potassium hydroxide (caustic potash, KOH). Potassium hydroxide was chosen over sodium hydroxide, because potassium may be used as fertiliser after the transesterification. Glycerine with potassium hydroxide is therefore assumed to be easy to get rid of. The demand for catalyst is 2000 kg / 200 m^3 rapeseed oil (Norén *et al.*, 1993). In Table 31 the demands for methanol and catalyst are given on an area basis.

Table 31. Demand for methanol and catalyst at the different plant sizes

Plant size	Demand for methanol [kg/ha]	Demand for catalyst [kg/ha]
Small-scale	83	8.2
Medium-scale	92	9.1
Large-scale	120	11.8

In Table 32, area emissions from the production of methanol and catalyst for the three studied plant sizes are accounted for. If the demand for methanol (Table 31) [kg/ha], the lower heat value for methanol (19.8 MJ/kg) and the emission value for production of fossil methanol (Table 30) [g/MJ methanol] are multiplied, the area emission values for production of methanol in Table 32 are obtained. The area emission values for biomass methanol, which is studied in a scenario analysis, can be calculated in the same way. If the demand for catalyst (Table 31) [kg/ha] and the emission value for production of KOH catalyst (Table 30) [g/kg KOH] are multiplied, the area emission values for production of catalyst in Table 32 are obtained.

Table 32. Area emissions and energy requirement from production and use of fossil methanol and catalyst

Chemical	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	N_2O [g/ha]	Particles [g/ha]	Input energy [MJ/ha]
Small-scale:									
Methanol	29782	8.21	4.66	3.80	66.0	0.613	0.478	0	1044
Catalyst	2130	0.649	0.0252	0.00383	8.84	7.55	0	0.00268	60.9
Medium-scale:									
Methanol	32848	9.05	5.13	4.19	72.8	0.676	0.527	0	1151
Catalyst	2349	0.716	0.0278	0.00422	9.75	8.33	0	0.00296	67.2
Large-scale:									
Methanol	42921	11.83	6.71	5.48	95.1	0.883	0.689	0	1504
Catalyst	3070	0.936	0.0363	0.00552	12.73	10.88	0	0.00386	87.8

For electricity see Section 3.6 and for transport see Section 3.7. Transportation of catalyst was neglected in the model because its contribution would be small (about 1% of that for methanol transported the same distance). The glycerine produced was assumed to be sold raw.

3.5.3 Production of ethanol fuel

The ethanol was produced from wheat in a conventional fermentation process, with hydrolysis (gelatinization, liquefication and saccharification), fermentation and distillation, in all the plant sizes studied. The wheat was ground to meal in a hammermill before the process (in this study included in the process). The process is described in Norén & Danfors (1981); Almemark (1996); Kaltschmitt & Reinhardt (1997); Jacques *et al.* (1999); Schmitz (2003); and Agroetanol (2003).

Wheat contains normally 58-65% (wet basis) of starch (Almemark, 1996; Kaltschmitt & Reinhardt, 1997; Jacques *et al.*, 1999; Schmitz, 2003; Agroetanol, 2003). Therefore the starch content in this study was assumed to be 60%. During the cooking process the starch is hydrolysed (Jacques *et al.*, 1999): 1) The meal is mixed with water and enzymes (*e.g.* α-amylase) and heated to break down the granular structure of the starch and make a viscous liquid gel (gelatinization); 2) During the liquefaction the gelatinized starch is partially hydrolysed (by *e.g.* α-amylase to give soluble dextrins (short-chain polymers of glucose molecules); 3) During the saccharification, dextrins are degraded to glucose with help from *e.g.* the enzyme glucoamylase. Chemically, Equation 4 could describe the hydrolysis:

$$\underset{\text{(starch)}}{(C_6H_{10}O_5)_n} + \underset{\text{(water)}}{n\,H_2O} \rightarrow \underset{\text{(glucose)}}{n\,C_6H_{12}O_6} \qquad (4)$$

After the hydrolysis a sugar-rich mash is obtained, the sugar in which could be fermented to ethanol if mixed with yeast (*e.g. Saccharomyces cerevisiae*). The optimal temperature for this type of yeast is 32°C (Jacques *et al.*, 1999). Chemically, Equation 5 could describe the fermentation:

$$\underset{\text{(glucose)}}{C_6H_{12}O_6} \rightarrow \underset{\text{(carbon dioxide)}}{2\,CO_2} + \underset{\text{(ethanol)}}{2\,C_2H_5OH} \qquad (5)$$

Finally the distillation is performed. For use as fuel in diesel engines with addition of ignition improver and denaturants, the ethanol does not need to be anhydrous and therefore there was no need for a final dehydration in this study. This is a divergence from other plants in the literature, where dehydration is included in the process (Almemark, 1996; Kaltschmitt & Reinhardt, 1997; Jacques *et al.*, 1999; Schmitz, 2003; Agroetanol, 2003).

Because the ethanol does not ignite properly if used pure in a diesel engine, it has to be mixed with an ignition improver before such use. In this study the ignition improver Beraid 3540 was assumed to be used. To prevent the use of the ethanol fuel as a drink it must also contain denaturants, in this study assumed to be MTBE (methyl-tertiary-butyl ether) and isobutanol (for composition of the fuel see Table 100).

In Table 33 inputs of grain, water, electricity and heat (as steam) with efficiencies when the ethanol is produced for the three plant sizes studied are accounted for. The output of ethanol, distiller's waste (feedstuff) and carbon dioxide is also accounted for. The distiller's waste was only dried (to DDGS: distiller's dried grain with solubles, Jacques *et al.* (1999)) in the largest plant. Larger plants were also assumed to utilize electricity and steam (heat) more efficiently than smaller plants.

Table 33. Some data for the ethanol plants studied

Factor of production	Plant size [ha]		
	40	1000	50000
Ethanol yield [tonne/tonne wheat]	0.296	0.296	0.296
Carbon dioxide yield [tonne/tonne wheat]	0.264	0.264	0.264
Feedstuff yield (dried, DDGS) [tonne/tonne wheat]	-	-	0.321
Feedstuff yield wet with 9.1% dry matter [tonne/tonne wheat]	3.21	3.21	-
Water requirement [tonne/tonne wheat]	3.78	3.78	0.897
Direct requirement of electricity:			
assumed increased requirement because of lower efficient technology in a smaller plants [%]	20	10	0
fermentation:			
which gives the following el. requirements [MJ/tonne ethanol]	528.3	484.3	440.3
equivalent to [MJ/tonne wheat]	156.5	143.5	130.4
distillation:			
which gives the following el. requirements [MJ/tonne ethanol]	316	290	263
equivalent to [MJ/tonne wheat]	94	86	78
drying of distiller's waste (large-scale); pumping (smaller scales):			
which gives the following el. requirements [MJ/tonne ethanol]	3.90	3.90	734
equivalent to [MJ/tonne wheat]	1.15	1.15	217
total electric energy [MJ/tonne wheat]	251	230	426
Steam requirement:			
assumed increased requirement because of lower efficient technology in a smaller plants [%]	20	10	0
fermentation:			
which gives the following steam requirements [MJ/tonne ethanol]	925	847	770
equivalent to [MJ/tonne wheat]	274	251	228
steam requirement (26 bar from water, 10°C) [tonne/tonne wheat]	0.099	0.091	0.083
distillation:			
which gives the following steam requirements [MJ/tonne ethanol]	5430	4977	4525
equivalent to [MJ/tonne wheat]	1608	1474	1340
steam requirement (26 bar from water, 10°C) [tonne/tonne wheat]	0.583	0.534	0.486
drying of distiller's waste:			
which gives the following steam requirements [MJ/tonne ethanol]	-	-	5283
equivalent to [MJ/tonne wheat]	-	-	1565
steam requirement (26 bar from water, 10°C) [tonne/tonne wheat]	-	-	0.567
total thermal energy [MJ/tonne wheat]	1882	1725	3134
efficiency during production of thermal energy [%]	75	84	87.5
supply of thermal energy as wood chips [MJ/tonne wheat]	2510	2054	3581
total requirement of steam [tonne/tonne wheat]	0.682	0.625	1.135
water + steam [tonne/tonne wheat]	4.47	4.41	2.03

The production of ethanol, carbon dioxide and feedstuff was calculated from the information from Agroetanol (2003) that 2.65 kg wheat gives 1 litre ethanol, 0.7 kg carbon dioxide and 0.85 kg dried feedstuff (91% dry matter). Undried distiller's waste has a dry matter content of 9.1% (SBI-Trading, 2003), in this study valid for small- and medium-sized plants. The difference in water content gives the extra water requirement in small- and medium-scale plants in comparison to large-scale plants. The requirements for water (Table 33) and chemicals (Table 38) are accounted for by Almemark (1996).

The electricity requirement of the large-scale plants was mainly calculated from the electricity requirement for the Agroetanol-ethanol plant in Norrköping (Agroetanol, 2003). The ethanol plant in Norrköping consumes 320 kWh electricity/1000 litres ethanol (Agroetanol, 2003) (1.152 MJ/litre ethanol = 1.468 MJ/kg ethanol) of which: approx. 30% is used before the distillation; approx. 20% is used for the distillation and dehydration; and approx. 50% is used for the dewatering of mash and feed (distiller's waste) handling (Werling, pers. comm.). These data for the electricity consumption were used in this study for the large-scale plant after the electricity requirement for dehydration (30.3 MJ/tonne ethanol: Jacques *et al.*, 1999) had been subtracted. When the distiller's waste was not dried in small- and medium-scale plants, they had no requirement for electricity for this application. In small- and medium-scale plants the distiller's waste was assumed to only be pumped out to the transport vehicle with a liquid manure pump with an electricity requirement of approx. 0.36 MJ/1000 kg pumped (wet) material (estimated after DLG, 1980). Because of less efficient techniques, the consumption of electricity was assumed to be 10 and 20% higher for medium- and small-scale plants respectively in comparison to large-scale plants. The electricity requirements in the ethanol plants studied are accounted for in Table 33. The production of electricity is described in Section 3.6.1 and the emissions during production of electricity are accounted for in Table 49.

The heat requirement of the large-scale plants was mainly calculated from the steam heat requirement of the Agroetanol-ethanol plant in Norrköping (Agroetanol, 2003). The ethanol plant in Norrköping consumes 2400 kWh steam heat/1000 litres ethanol (Agroetanol, 2003) (8.64 MJ/litre ethanol = 11.0 MJ/kg ethanol) of which: approx. 7% is used for heating of the products before the distillation; approx. 45% is used for the distillation and dehydration; and approx. 48% is used for the dewatering of mash and feed (distiller's waste) handling (Werling, pers. comm.). These data for the heat consumption were used in this study for the large-scale plant after the steam heat requirement for dehydration (1427 MJ/tonne ethanol (Jacques *et al.*, 1999) and it was assumed that 70% of that was possible to recover at other parts in the process if dehydration was not required. Therefore 30% of this steam heat, equivalent to 428 MJ/tonne ethanol, could be saved when the dehydration of the ethanol was excluded) had been subtracted. When the distiller's waste was not dried in small- and medium-scale plants there was no requirement of steam heat for this application. Because of less efficient technique the consumption of steam heat was assumed to be 10 and 20% higher for medium- and small-scale plants respectively in comparison to large-scale plants. The requirements for steam heat, in the studied ethanol plants, are accounted for in Table 33.

The emissions during production of the steam were assumed to be as accounted for by Kaltschmidt & Reinhardt (1997) for three different sized boilers (Table 34): 30 kW continuous combustion; 4 000 kW fed fire grate boiler; and 20 000 kW fluidized bed roaster. In this study spruce wood chips were the fuel in the basic scenario and *Salix* wood chips the fuel in a scenario analysis (Table 35). The efficiency for the large plant for production of steam was assumed to be 87.5%, estimated after the energy quotient for the Agroetanol plant: (energy in consumed steam: 2400 kWh / requirement of fuel energy to produce the steam: 2743 kWh) (Agroetanol, 2003). The efficiencies for the small-scale and medium-scale plants were assumed to be as for the 30 kW and 4000 kW heating plants in Kaltschmitt & Reinhardt (1997) (Table 33). The emissions during production of the spruce wood chips and *Salix* wood chips are accounted for in Table 35. The total emission values for use of the steam heat are obtained if the values for the studied type of fuel (Table 35) are added to the emission values for the types of heating plants studied (Table 34). In Table 36 the energy requirements (as fuel) of the main processes in the ethanol production are accounted for. These values are obtained when the values for energy requirement [MJ/tonne wheat] (Table 33) are divided by the efficiency during production of thermal heat (Table 33) and multiplied by the wheat harvest [tonne/ha] (Section 3.4.2). The emission and energy requirement values on an area basis (Table 37) are obtained if the values in Tables 34 and 35 are added and multiplied by the values for fuel energy requirement in Table 36. With this procedure it is possible to study some more scenarios (for the scenario analysis) than the basic scenario accounted for in Table 37. It is necessary to split up the emission and energy requirement values in Table 37 in the different processes because they are used in different ways during the allocation procedure (Section 3.10 and Tables A17-A22, Appendix 2).

Table 34. Combustion of wood chips for production of heat (steam) (Kaltschmidt & Reinhardt, 1997)

Type of plant	CO_2[e]	CO	HC	CH_4	NO_x	SO_2 (SO_x)	N_2O	HCl	Particles
	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]
Spuce wood chips, 30 kW[a]	105.9	0.054	0.0276	0.0096	0.06	0.011	0.0036	0.0058	0.0204
Spuce wood chips, 4000 kW[b]	105.9	0.042	0.005	0.002	0.13	0.0036	0.004	0.0033	0.0029
Spuce wood chips, 20000 kW[c]	105.9	0.0556	0.0017	0.0006	0.0972	0.0036	0.0057	0.0033	0.0029
Salix wood chips, 4000 kW[b]	105.4	0.042	0.005	0.002	0.1514	0.0111	0.004	0.0033	0.0029
Salix wood chips, 20000 kW[c]	105.4	0.0556	0.0017	0.0006	0.1133	0.0111	0.0057	0.0033	0.0029
Salix wood chips, 30 kW[ad]	105.4	0.054	0.0276	0.0096	0.0699	0.0339	0.0036	0.0058	0.0204

[a] Continuous combustion of wood chips, assumed to be equivalent to small-scale.
[b] Fed fire grate boiler, assumed to be equivalent to medium-scale.
[c] Fluidized bed roaster, assumed to be equivalent to large-scale.
[d] Estimated from 4 and 20 MW *Salix* wood chips and 30 kW spruce wood chips.
[e] During the calculations: 0 g/MJ_{fuel} because CO_2 has bio-origin and therefore does not contribute to the GWP.

Table 35. Production and distribution of chips from forest wood and Salix, emissions and energy requirement (Uppenberg et al., 2001)

Type of fuel	CO_2	CO	HC	NO_x	SO_2 (SO_x)	NH_3	Particles	Input energy
	[g/MJ$_{fuel}$]	[g/MJ$_{fuel}$]	[g/MJ$_{fuel}$]	[g/MJ$_{fuel}$]	[g/MJ$_{fuel}$]	[g/MJ$_{fuel}$]	[g/MJ$_{fuel}$]	[MJ/MJ$_{fuel}$]
Forest (spruce) wood chips	3	0.015	0.0043	0.047	0.0027	-	0.0039	0.040
Salix wood chips	3.3	0.011	0.0027	0.033	0.0021	0.00066	0.0026	0.047

Table 36. Requirement for steam heat in different parts of the process of importance for the allocation

Process / Plant size	Small-scale	Medium-scale	Large-scale
	[MJ$_{fuel}$/ha]	[MJ$_{fuel}$/ha]	[MJ$_{fuel}$/ha]
Ethanol fermentation	2154	1763	1539
Ethanol distillation	12653	10356	9038
Drying of distiller's waste etc.	0	0	10552
Total requirement of steam heat	14808	12119	21129

Table 37. Area emissions and energy requirement during steam production

Process	CO_2	CO	HC	CH_4	NO_x	SO_x	N_2O	HCl	Particles	Input energy
	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[MJ/ha]
Small-scale:										
Ethanol fermentation	6463	149	69	21	231	30	8	12	52	86
Ethanol distillation	37959	873	404	121	1354	173	46	73	307	506
Total requirement for steam heat	44423	1022	472	142	1584	203	53	86	360	592
Medium-scale:										
Ethanol fermentation	5290	101	16	4	312	11	7	6	12	71
Ethanol distillation	31068	590	96	21	1833	65	41	34	70	414
Total requirement for steam heat	36358	691	113	24	2145	76	48	40	82	485
Large-scale:										
Ethanol fermentation	4617	109	9	1	222	10	9	5	10	62
Ethanol distillation	27114	638	54	5	1303	57	52	30	61	362
Drying of distiller's waste etc.	31657	745	63	6	1522	66	60	35	72	422
Total requirement for steam heat	63388	1492	127	13	3047	133	120	70	144	845

When the same production processes were assumed to be used in the different ethanol production scales, the requirement of chemicals during the ethanol production did not differ between scales. In this study, the values for the requirements for chemicals and enzymes as accounted for in Almemark (1996) were used (Table 38). Finnveden *et al.* (1994) report that

0.3 kg yeast/1053 kg ethanol E95 equivalent to 0.3 kg yeast/1000 kg ethanol is used during ethanol production. The same amount of yeast was assumed to be used when ethanol was produced from wheat in this study. The yeast used was produced in the ethanol plants and did not require to be externally purchased. The emissions when the chemicals, enzymes and yeast were produced are accounted for in Table 39. These emissions on an area basis [g/ha] are accounted for in Table 40, calculated by multiplying the used amount [kg/ha] (Table 38) by the emissions [g/kg] (Table 39). The emissions when other chemicals and scum reduction agent were produced were assumed to be the average of when phosphoric acid, sulphuric acid, sodium hydroxide and calcium chloride were produced (Table 39) because of a lack of data in the literature. The emissions when enzymes were produced were assumed to be as for yeast (Table 39), also because of a lack of data in the literature. The total emissions during production of chemicals (Table 40) are also accounted for as: emissions from production of chemicals for ethanol production in Tables A17-A22, Appendix 2.

Table 38. The chemicals used during the production of ethanol

Chemical	Amount [kg/tonne wheat]	Pure [kg/tonne wheat]	Amount (pure) [kg/ha]
Phosphoric acid (75%)	0.160	0.120	0.71
Sulphuric acid (93%)	2.152	2.001	11.81
Sodium hydroxide (50%)	0.310	0.155	0.91
Calcium chloride (30%)	1.366	0.410	2.42
Other chemicals	0.177	0.177	1.04
Scum reduction agent	0.055	0.055	0.33
Novo BAN 240 L (enzyme)	0.249	0.249	1.47
Novo AMG 300 L (enzyme)	0.719	0.719	4.24
Econase CE 15 (enzyme)	0.183	0.183	1.08
Yeast	0.089	0.089	0.52
Total		4.158	24.53

Table 39. Emissions during production of chemicals used during ethanol production

Chemical	CO_2 [g/kg]	CO [g/kg]	HC [g/kg]	CH_4 [g/kg]	NO_x [g/kg]	SO_x [g/kg]	NH_3 [g/kg]	Particles [g/kg]	Input energy [MJ/kg]
Phosphoric acid[a]	1600	0.26			3.1	7.88		0.6	20
Sulphuric acid[a]	239	0.039			0.46	1.18		0.09	3
Sodium hydroxide[a]	364	0.111	0.0043	0.00065	1.51	1.29		0.00046	10.41
Calcium chloride[b]	141	0.045	0.0043		0.58	0.76			1.55
Other chemicals[c]	586	0.114	0.0043	0.00065	1.41	2.78		0.23	8.74
Scum reduction agent[c]	586	0.114	0.0043	0.00065	1.41	2.78		0.23	8.74
Novo BAN 240 L (enzyme)[d]	280	0.165	0.034	0.00024	1.66	1.17	0.014	0.077	6.32
Novo AMG 300 L (enzyme)[d]	280	0.165	0.034	0.00024	1.66	1.17	0.014	0.077	6.32
Econase CE 15 (enzyme)[d]	280	0.165	0.034	0.00024	1.66	1.17	0.014	0.077	6.32
Yeast[a]	280	0.165	0.034	0.00024	1.66	1.17	0.014	0.077	6.32

[a] Finnveden *et al.* (1994).
[b] LCA-emissions $CaCl_2$, assumed to be as for NaCl (Stripple, 2001) with transport NaCl (Finnveden *et al.*, 1994).
[c] Assumed to be as average of above.
[d] Assumed to be as yeast.

Table 40. Emissions during production of chemicals, on an area basis, used during ethanol production

Chemical	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	Particles [g/ha]	Input energy [MJ/ha]
Phosphoric acid	1136	0.185			2.19	5.59		0.4259	14.2
Sulphuric acid	2822	0.460			5.45	13.93		1.0625	35.4
Sodium hydroxide	333	0.101	0.0039	0.00060	1.38	1.18		0.0004	9.5
Calcium chloride	342	0.109	0.0104		1.41	1.83			3.8
Other chemicals	612	0.119	0.0045	0.00068	1.47	2.90		0.2403	9.1
Scum reduction agent	191	0.037	0.0014	0.00021	0.46	0.91		0.0751	2.9
Novo BAN 240 L (enzyme)	411	0.242	0.0499	0.00035	2.44	1.72	0.021	0.1134	9.3
Novo AMG 300 L (enzyme)	1188	0.700	0.1442	0.00102	7.04	4.96	0.059	0.3275	26.8
Econase CE 15 (enzyme)	302	0.178	0.0366	0.00026	1.79	1.26	0.015	0.0831	6.8
Yeast	147	0.087	0.0178	0.00013	0.87	0.61	0.007	0.0405	3.3
Total emissions during production of chemicals	7482	2.218	0.2688	0.00325	24.50	34.90	0.102	2.3687	121.1

The pollutants in the waste water from the ethanol plants was assumed to be the same, independent of plant size. In the large plant the waste water from dewatering of the distiller's waste was recirculated and therefore did not contribute to the BOD_7 (biological oxygen demand: oxygen demand during 7 days' decomposition of organic water under standard conditions) and COD (chemical oxygen demand: oxygen demand during complete decomposition of organic material) in the waste water from the plant. The waste water contains 0.996 kg BOD_7/tonne processed wheat and 1.49 kg COD/tonne processed wheat (Almemark, 1996). The energy requirements to remove BOD_7 and COD from waste water are 2.5 kWh/kg BOD_7 removed and 2.5*2.5=6.25 kWh/kg COD removed (Lindfors *et al*., 1995) if treated mechanically, chemically and biologically. If multiplied, the energy requirement to remove the organic material from the waste is obtained: 2.49 kWh/tonne wheat (8.96 MJ/tonne wheat) for BOD_7 and 9.33 kWh/tonne wheat (33.6 MJ/tonne wheat) for COD. For the further calculations the value for COD was chosen because it is the biggest. Only one value of BOD_7 and COD should be chosen because they are both a measure of the organic content in the waste water. The energy required was assumed to be electricity as consumed on the different plant scales with their conditions. On an area basis this requirement of electricity was 198 MJ_{el}/ha after multiplying by the seed yield (Section 3.4.2). The area emissions for the waste water treatment, with the assumptions above, as accounted for in Table 41 and Tables A17-A22 in Appendix 2, were obtained by multiplying the electricity requirement by the electricity emissions for the appropriate plant scale in Table 49.

Table 41. Emissions during treatment of waste water, at different plant sizes, if the energy used is electricity

Plant size	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	Particles [g/ha]	Input energy [MJ/ha]
Small-scale	1710	3.93	0.632	10.7	3.27	2.83	0.0480	0.155	0.545	425
Medium-scale	1671	3.84	0.618	10.4	3.20	2.77	0.0469	0.151	0.533	415
Large-scale	1632	3.75	0.604	10.2	3.12	2.71	0.0458	0.148	0.520	405

To make a legitimate diesel fuel from the ethanol it has to be mixed with ignition improver (Beraid 3540), denaturants (MTBE and isobutanol) and corrosion inhibitor (morpholine) (Table 42). Throughout this report, a fuel with the composition as in Table 42 is called ethanol fuel unless otherwise specified. This fuel corresponds to the fuel Etamax D marketed by Sekab (Sekab, 2003). The requirement of these components was the same independent of the size of the ethanol production plant. From the composition of the ethanol fuel (Table 100 in Section 3.9) the requirement of the chemicals described above (see also Table 42) could be calculated. The emissions to produce Beraid, MTBE and isobutanol (Table 43) are accounted by Ericson & Odéhn (1999). The emissions when morpholine was produced were assumed to be as the average of when Beraid, MTBE and isobutanol were produced (Table 43) because of a lack of data in the literature. These emissions on an area basis are accounted for in Table 44 (also in Tables A17-A22, Appendix 2), as are the total area emissions when chemicals used to make the ethanol into ethanol fuel are produced. They were obtained by multiplying the amount (pure) [kg/ha] (Table 42) of each chemical by the emissions [g/kg] (Table 43).

Table 42. Chemicals used to make the ethanol produced into a legal diesel fuel

Chemical	Amount [kg/tonne wheat]	Amount (pure) [kg/ha]
Beraid	24.59	145.1
MTBE	8.08	47.7
Isobutanol	1.76	10.4
Morpholine	0.0316	0.187
Total		203.3

Table 43. Emissions during production of chemicals used to make the ethanol produced into ethanol fuel

Chemical	CO_2 [g/kg]	CO [g/kg]	HC [g/kg]	CH_4 [g/kg]	NO_x [g/kg]	SO_x [g/kg]	Particles [g/kg]	Input energy [MJ/kg]
Beraid[a]	1024	0.354	4.69	0.0397	3.59	2.38	0.583	34.4
MTBE[a]	1150	0.069	3.90	0.0093	1.88	0.33	0.121	34.9
Isobutanol[a]	735	0.028	3.91	0.0243	1.27	0.44	0.064	36.7
Morpholine[b]	586	0.114	0.0043	0.00065	1.41	2.78	0.230	8.74

[a] Ericson & Odéhn (1999).
[b] Assumed to be as average for Beraid, MTBE and isobutanol used to make the ethanol produced into ethanol fuel.

In a scenario analysis the ignition improver Beraid and the denaturants MTBE and isobutanol were assumed to be produced of bio-origin. To estimate the emission and energy requirement for this production, the relationship between each emission (or energy requirement) was assumed to be as between production of biomass methanol and fossil methanol (Table 30) (the ratio between biomass methanol and fossil methanol). This ratio was multiplied by the emissions and energy requirement for fossil ignition improver and denaturants etc. to get the corresponding values for biomass ignition improver and denaturants etc. (Table 44).

Table 44. Area emissions during production of chemicals used to make the ethanol produced into ethanol fuel, also including estimated emissions for chemicals of bio-origin

Chemical	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	Particles [g/ha]	Input energy [MJ/ha]
Beraid[a]	148481	51.42	679.6	5.75	520.6	345.5	84.59	4993
MTBE[a]	54793	3.27	185.7	0.45	89.8	15.5	5.76	1666
Isobutanol[a]	7611	0.29	40.5	0.25	13.2	4.6	0.66	380
Morpholine[b]	109	0.021	0.00080	0.00012	0.26	0.52	0.043	1.63
Beraid + morpholine	148590	51.44	679.6	5.75	520.9	346.0	84.63	4995
Denaturants	62404	3.56	226.1	0.70	103.0	20.1	6.42	2046
Total	210994	55.00	905.8	6.45	623.9	366.1	91.05	7041
Beraid from biomass[c]	130609	396.20	4805.8	0.25	1889.8	5181.3		18043
MTBE from biomass[c]	48198	25.23	1312.9	0.02	326.0	232.7		6019
Isobutanol from biomass[c]	6695	2.22	286.1	0.01	47.9	68.6		1374
Morpholine from biomass[c]	96	0.163	0.00567	0.00001	0.95	7.77		5.89
Beraid + morpholine[c]	130705	396.36	4805.8	0.25	1890.7	5189.1		18049
Denaturants[c]	54893	27.45	1599.1	0.03	373.9	301.3		7393
Total[c]	185598	423.81	6404.9	0.28	2264.6	5490.4		25442

[a] Ericson & Odéhn (1999).
[b] Assumed to be as average for Beraid, MTBE and isobutanol used to make the ethanol produced into ethanol fuel.
[c] Estimated with help from the relationship in emissions and energy requirement between methanol with biomass origin and methanol with fossil origin. For further explanation see the text above the table.

3.5.4 Economics

3.5.4.1 Rapeseed oil and RME

Costs for labour and chemicals (hexane, methanol and catalyst) are important during the production of the rapeseed oil and RME fuels. These are also costs that are dependent on the plant size. In Table 45 the costs for labour, hexane, methanol and catalyst are accounted for on an area basis (see also Tables 123-124, 126-127 and 129-130). Costs for electricity are accounted for in Section 3.6.2.

Table 45. Various costs, oil extraction and transesterification

Plant sizes and production factors	Amount […/ha]	Price [SEK/…]	Cost [SEK/ha]
Small-scale:			
Labour, [h] extraction	3.63	180	654
Labour, [h] transesterification	7.50	180	1350
Methanol [kg]	83.1	3.45	287
Catalyst [kg]	8.21	9.00	74
Medium-scale:			
Labour, [h] extraction	2.70	240	648
Labour, [h] transesterification	2.70	240	648
Methanol [kg]	91.7	3.00	275
Catalyst [kg]	9.05	9.00	81
Large-scale:			
Labour, [h] extraction	0.72	300	216
Labour, [h] transesterification	0.34	300	101
Hexane [kg]	2.47	5.52	14
Methanol [kg]	119.8	2.40	288
Catalyst [kg]	11.83	9.00	106

The costs for labour (extraction and transesterification) were assumed to be as for an experienced farm machine operator 2002 for the small-scale plants: 180 SEK/hour (estimated after SCB, 2003; Agriwise, 2003; and Henemo, 2002 and 2003). For the large-scale plants the labour costs was estimated to be as for labour at Agroetanol (calculated after: Werling, pers. comm.): 300 SEK/hour. For medium-scale plants the labour costs were assumed to be as the average between large- and small-scale plants: 240 SEK/hour. Calculation of labour-time on an area basis was performed using the following assumptions:

- Small-scale extraction: 0.5 labour-hours for each 20 hours the oil press is working (Bernesson, 1993). This gives for: 145.2 h oil press/ha * 0.5 h labour / 20 h oil press = 3.63 h labour/ha;
- Small-scale transesterification: Assumed to be 1 hour labour work for each 20 hours the process is working. This gives: (1 h labour / 20 h process time) * 6000 h process time/year / 40 ha = 7.50 h labour/ha;
- Medium-scale extraction: 9 labour work hours for each 20 hours the oil press is working. This gives: (6000 h oil press / 1000 ha) * 9 h labour / 20 h oil press = 2.70 h labour/ha;
- Medium-scale transesterification: 9 hours labour work for each 20 hours the process is working. This gives: (6000 h process / 1000 ha) * 9 h labour / 20 h process = 2.70 h labour/ha;
- Large-scale extraction: Assumed to be 120 labour hours (15 men, one day) for each 20 hours the oil press is working: (120 h labour / 20 h oil press) * 6000 h oil press/year / 50000 ha/year = 0.72 h labour/ha;

- Large-scale transesterification: Assumed to be 56 labour hours (7 men, one day) for each 20 hours the oil press is working: (56 h labour / 20 h oil press) * 6000 h oil press/year / 50000 ha/year = 0.336 h labour/ha.

The price for hexane (hexane technical grade 65/75) was 5.52 SEK/kg if 100-150 m^3/year was purchased from Univar AB at least as 28 tonnes each time (Björck, pers. comm.). The price for methanol, purchased from MB Sveda AB, was: 3.45 SEK/kg if at least 4 m^3 was delivered at the same time if the annual consumption was 3-7 m^3 (small-scale); 3.00 SEK/kg if at least 30 tonnes was delivered at the same time if the annual consumption was 100-150 m^3 (medium-scale); and 2.40 SEK/kg if at least 30 tonnes was delivered at the same time if the annual consumption was 500-10 000 m^3 (large-scale) (Olsson, Pia, pers. comm.). The price for the catalyst was 9 SEK/kg (Norén *et al.*, 1993) and this price was not assumed to change during the past ten years.

Various costs have been assumed to be 5% in the calculations. Various costs consist of *e.g.* insurances, tax, water or chemicals (phosphorous acid or adsorbent for the transesterification) etc. (Tables 123-124, 126-127 and 129-130).

The receipts when the meal and glycerine were sold are accounted for in Table 107 in Section 3.10 on allocation. The prices for the products are accounted for in Table 105.

3.5.4.2 Ethanol fuel

Costs for labour, chemicals, electricity and heat are important during the production of the ethanol fuel. These are also costs that are dependent on the plant size (see also Tables 125, 128 and 131). The costs for electricity are accounted in Section 3.6.2. In Table 46, the costs for labour and chemicals are accounted for on an area basis.

Table 46. Labour and chemicals costs, ethanol fuel production

Production factors	Small-scale production			Medium-scale production			Large-scale production		
	Amount […/ha]	Price [SEK/…]	Cost [SEK/ha]	Amount […/ha]	Price [SEK/…]	Cost [SEK/ha]	Amount […/ha]	Price [SEK/…]	Cost [SEK/ha]
Labour [h]	21.5	180	3870	6.88	240	1651	1.03	300	310
Phosphoric acid (75%) [kg]	0.95	15.40	15	0.95	5.80	5	0.95	4.75	4
Sulphuric acid (93%) [kg]	12.69	3.92	50	12.69	2.95	38	12.69	1.94	25
Sodium hydroxide (50%) [kg]	1.83	6.71	12	1.83	3.09	6	1.83	1.48	3
Calcium chloride (30%) [kg]	8.06	3.04	25	8.06	2.28	18	8.06	2.06	17
Other chemicals [kg]	1.04	7.27	8	1.04	3.53	4	1.04	2.56	3
Scum reduction agent [kg]	0.33	80.00	26	0.33	40.00	13	0.33	20.00	7
Enzymes [kg]	6.79	42.80	291	6.79	37.80	257	6.79	32.80	223
Yeast [kg]	0.52	0	0	0.52	0	0	0.52	0	0
Sum[a]			425			340			280
Beraid [kg]	145.1	25.00	3627	145.1	20.00	2901	145.1	15.00	2176
MTBE [kg]	47.7	9.04	431	47.7	9.04	431	47.7	4.85	231
Isobutanol [kg]	10.4	15.00	155	10.4	10.00	104	10.4	6.25	65
Morpholine [kg]	0.19	30.00	6	0.19	30.00	6	0.19	20.24	4
Sum[b]			4218			3441			2476

[a] Sum for chemicals used in the ethanol production process.
[b] Sum for chemicals for making ethanol into ethanol fuel.

The costs for labour (ethanol fuel production) (Table 46) were assumed to be as for an experienced farm machine operator in 2002 for the small-scale plants: 180 SEK/hour (estimated after SCB, 2003; Agriwise, 2003; and Henemo, 2002 and 2003). For the large-scale plants the labour costs were estimated to be as for labour at Agroetanol (calculated after: Werling, pers. comm.): 300 SEK/hour. For medium-scale plants the labour costs were assumed to be as the average between large- and small-scale plants: 240 SEK/hour. Calculation of labour-time on an area basis was calculated using the following assumptions:

- Small-scale ethanol fuel production: Assumed to be 0.5 people working 40 hours/week, 43 weeks/year (estimated after: Schmitz, 2003, but a more simple plant without drying and marketing, and also estimated after the rapeseed extraction and transesterification above): 860 h labour work on an area of 40 ha gives 21.5 h labour work/ha.
  860 h labour work / 6000 h/year process time = 0.143 hours labour work each process-time hour;
- Medium-scale ethanol fuel production: Assumed to be 4 people working 40 hours/week, 43 weeks/year (estimated after: Schmitz, 2003, but a more simple plant without drying and marketing, and also estimated after the rapeseed extraction and transesterification above): 6880 h labour work on an area of 1000 ha gives 6.88 h labour work/ha.

6880 h labour work / 6000 h/year process time = 1.15 hours labour work each process-time hour; and

- Large-scale ethanol fuel production: Assumed to be 30 people working 40 hours/week, 43 weeks/year (estimated after: Schmitz, 2003; see also Table 95: plant size 360 m^3/day): gives 51 600 h labour work on an area of 50 000 ha gives: 1.03 h labour work/ha.
  51 600 h labour work / 6000 h/year process time = 8.60 hours labour work each process-time hour.

The price for the chemicals used (Table 46):
<u>Phosphoric acid:</u> The price for phosphoric acid (technical grade 75%) was 4.75 SEK/kg if 45-50 tonnes/year was purchased from Univar AB, at least as 28 tonnes each time (Björck, pers. comm.); 5.80 SEK/kg if 900-1000 kg/year was purchased from Univar AB as an 800 litre container each time (Björck, pers. comm.); and 15.40 SEK/kg if 30-40 kg/year was purchased from Univar AB as a 25 litre can each time (Björck, pers. comm.). Technical grade is good enough to use in a feedstuff (Janheden, pers. comm.).
<u>Sulphuric acid:</u> The price for sulphuric acid (food grade 96%) was 2.00 SEK/kg (93%: 1.94 SEK/kg) if 580-600 tonnes/year was purchased from Kemira AB, at least as 40 tonnes each time (Björck, pers. comm.; Olsson, Ulrika, pers. comm.); 3.05 SEK/kg (93%: 2.95 SEK/kg) if 10-15 tonnes/year was purchased from Kemira AB as an 800 litre container each time (Björck, pers. comm.; Olsson, Ulrika, pers. comm.); and 4.05 SEK/kg (93%: 3.92 SEK/kg) if 450-500 kg/year was purchased from Kemira AB as a 60 litre can each time (Björck, pers. comm.; Olsson, Ulrika, pers. comm.). Prices for sulphuric acid technical grade from Björck (pers. comm.), and these prices supplemented to food grade from Olsson, Ulrika (pers. comm.).
<u>Sodium hydroxide:</u> The price for sodium hydroxide (technical grade 45%) was given if purchased from Univar AB (Björck, pers. comm.). For food grade instead of technical grade, the price was 300 SEK/tonne higher (Gustafsson, pers. comm.). The price for sodium hydroxide (50%) food grade [SEK/kg] could then be calculated as: price NaOH (technical grade 45%) [SEK/kg] * (50/45) + extra price for food grade (100%) [SEK/kg] * (50/100). The price for sodium hydroxide (technical grade 45%) was 1.20 SEK/kg (food grade 50%: 1.48 SEK/kg) if 90-100 tonnes/year was purchased from Akzo Nobel Base Chemicals AB through Univar AB at least as 40 tonnes each time (Björck, pers. comm.; Gustafsson, pers. comm.); 2.65 SEK/kg (food grade 50%: 3.09 SEK/kg) if 1.5-2 tonnes/year was purchased from Akzo Nobel Base Chemicals AB through Univar AB as an 800 litre container each time (Björck, pers. comm.; Gustafsson, pers. comm.); and 5.90 SEK/kg (food grade 50%: 6.71 SEK/kg) if 70-90 kg/year was purchased from Akzo Nobel Base Chemicals AB through Univar AB as a 60 litre can each time (Björck, pers. comm.; Gustafsson, pers. comm.).
<u>Calcium chloride:</u> The price for calcium chloride (technical grade 33.5% or 36%) was given if purchased from Univar AB (Björck, pers. comm.). For food grade instead of technical grade the price was approx. 300 SEK/tonne higher (Lindgren, pers. comm.). The price for calcium chloride (30%) food grade [SEK/kg] could then be calculated as: price $CaCl_2$ (technical grade 33.5 or 36%) [SEK/kg] * (30/33.5 or 30/36) + extra price for food grade (33.5% or 36%) [SEK/kg] * (30/33.5 or 30/36). The price for calcium chloride (technical grade 33.5%) was 2.00 SEK/kg (food grade 30%: 2.06 SEK/kg) if approx. 400 tonnes/year was purchased from Kemira Kemi AB through Univar AB at least as 40 tonnes each time (Björck, pers. comm.; Lindgren, pers. comm.); the price for calcium chloride (technical grade 33.5%) was 2.25 SEK/kg (food grade 30%: 2.28 SEK/kg) if 7-10 tonnes/year was purchased from Kemira Kemi AB through Univar AB as an 800 litre container each time (Björck, pers. comm.; Lindgren, pers. comm.); and the price for calcium chloride (technical grade 36%) was 3.35

SEK/kg (food grade 30%: 3.04 SEK/kg) if 300-400 kg/year was purchased from Kemira Kemi AB through Univar AB as a 200 litre barrel each time (Björck, pers. comm.; Lindgren, pers. comm.).
Other chemicals: The price for other chemicals was calculated as the average price [SEK/kg] of: phosphoric acid (75%), sulphuric acid (93%), sodium hydroxide (50%) and calcium chloride (30%) purchased to the ethanol plants studied.
Scum reduction agent: The price for scum reduction agent (diluted, ready to be used) was 20 SEK/kg if 15-20 tonnes/year was purchased from Univar AB as a 1000 kg container each time (Börjesson, pers. comm.); 40 SEK/kg if 300-350 kg/year was purchased from Univar AB as a 200 kg barrel each time (Börjesson, pers. comm.); and 80 SEK/kg if 10-15 kg/year was purchased from Univar AB as a 25 kg can each time (Börjesson, pers. comm.).
Enzymes: The price for the enzymes was estimated from the costs for enzymes at Agroetanol in Norrköping. Costs for enzymes: 5 000 000 SEK/year (Werling, pers. comm.) when 50 000 m^3 ethanol/year is produced, equivalent to 39 250 tonnes ethanol/year. This gives an enzyme cost of 127.40 SEK/tonne ethanol. If 1.748 tonne ethanol/ha (Table 100) is produced, this gives an enzyme cost of 222.60 SEK/ha. Division by 6.79 kg enzyme/ha (Tables 46 and 38: three types of enzymes) gives an enzyme price of 32.80 SEK/kg. This was assumed to be the enzyme price in the large-scale plant. The enzyme price was assumed to be 5 SEK/kg higher (37.8 SEK/kg) in the medium-scale plant and 10 SEK/kg higher (42.8 SEK/kg) in the small-scale plant.
Yeast: The yeast was home grown and therefore did not contribute to any external cost. The cost was included in the ordinary operating cost (Werling, pers. comm.).
Beraid: The price for Beraid 3540 was 15 SEK/kg if 7000-8000 tonnes/year was purchased from Akzo Nobel Surface Chemistry AB as a 40 tonne lorry load each time (Lif, pers. comm.); 20 SEK/kg if 140-150 tonnes/year was purchased from Akzo Nobel as a 15 tonne lorry load each time (Lif, pers. comm.); and 25 SEK/kg if 5-10 tonnes/year was purchased from Akzo Nobel as an 800 kg container each time (Lif, pers. comm.).
MTBE: The price for MTBE was 3.59 SEK/litre (4.85 SEK/kg, density MTBE see Table 100) if 2000-2500 tonnes/year was purchased from Preem Petroleum AB as a 48 m^3 tank lorry load each time (Eriksson, Anders, pers. comm.); 6.69 SEK/litre (9.04 SEK/kg) if 140-150 tonnes/year was purchased from Preem Petroleum AB as a 15 m^3 tank lorry load each time (Eriksson, Anders, pers. comm.); and 6.69 SEK/litre (9.04 SEK/kg) if 400-500 kg/year was purchased from Preem Petroleum AB as a 3 m^3 tank lorry load each time (Eriksson, Anders, pers. comm.).
Isobutanol: The price for isobutanol was 6.25 SEK/kg if 500-600 tonnes/year was purchased from Perstorp AB as a 30-40 tonne lorry load each time (Svärd, pers. comm.); 10 SEK/kg if 10-15 tonnes/year was purchased from Perstorp AB as a 1000 litre container each time (Svärd, pers. comm.); and 15 SEK/kg if 400-500 kg/year was purchased from Perstorp AB as a 200 kg barrel each time (Svärd, pers. comm.).
Morpholine: The price for morpholine was 2.2 Euro/kg (20.24 SEK/kg if 9.2 SEK/Euro) if approx. 10 tonnes/year was purchased from BASF Chemicals Nordic - Cheadle/UK as a 200 kg barrel each time (Alm, pers. comm.); and 30 SEK/kg if 180-190 kg/year or 7-8 kg/year was purchased from BASF as a 200 kg barrel each time (Alm, pers. comm.).

In Table 47 (see also Tables 125, 128 and 131) the heat costs during the production of ethanol in the plants is accounted for (for technical details see also Table 33). The price for the wood chips is that price (excl. tax) large district heating plants pay for wood chips in the middle of Sweden 2002 (STEM, 2003).

Table 47. Costs for process heat as steam

	Process energy:			Drying of distiller's waste:		
	Plant size			Plant size		
	Small	Medium	Large	Small	Medium	Large
Heat requirement [kWh/ha]	3085	2828	2571	0	0	2565
as wood chips fuel [kWh/ha]	4113	3366	2938	0	0	2931
Heat cost [SEK/ha][a]	526	431	376	0	0	375

[a] Price for wood chips: 0.128 SEK/kWh_{fuel}.

The cost for treatment of waste water was assumed to be as the energy cost, as electricity, for degradation of COD (Table 52). Figures from Agroetanol (Werling, pers. comm.) about costs for both fresh water and handling of waste water indicate that the costs for fresh water are about the same size as for handling waste water with the assumption according to the above. The costs for the fresh water were therefore assumed to be as the energy costs for handling of waste water. Costs for fresh water and handling of waste water are accounted as a lump sum in Table 52 (see also Tables 125, 128 and 131).

Various costs were assumed to be 5% in the calculations (Tables 125, 128 and 131). Various costs consist of *e.g.* insurances, tax, chemicals not listed or water etc.

The receipts when the distiller's waste was sold are accounted for in Table 109 in Section 3.10, allocation. The prices for the products are accounted for in Table 105.

3.6 Electricity

3.6.1 Production of electricity

The electricity for the production of the rapeseed oil, RME and ethanol fuels were, in the basic scenario, assumed to be Swedish electricity (Table 49) (Uppenberg *et al.*, 2001). In the scenario analysis, this was replaced by electricity mainly produced from fossil fuels (Kaltschmitt & Reinhardt, 1997) for comparison. The Swedish electricity consists of mainly hydropower and nuclear power (Table 48).

The efficiency in Table 48 means total energy output [%] of fuel energy input. The efficiencies for different plants are valid for today's production (Brännström-Norberg *et al.*, 1996). Values for modern future plants, with somewhat higher efficiencies, are accounted for in Uppenberg *et al.* (2001). The efficiency of 85% could be used for combined power and heating plants because fuel energy and energy use for the production is allocated according to physical terms [MJ] where heat and electricity are treated in the same way.

Table 48. Swedish electricity, supply according to the 1999 statistics

Type of electricity	Share [%]	Ref.[b]	Efficiency [%]	Ref.[b]	Energy use [MJ/MJ_{el}]	Ref.[b]	Total energy use [MJ_{pr}/MJ_{el}]
Hydro power	48.2		100		0.0037	1	0.484
Nuclear power	44.3	1	33	2	0.061	1	1.369
Wind power	0.2		100		0.029	1	0.0024
CHP[a], oil	1.3	1	85	2	0.078	1	0.017
CHP[a], coal	2.4	1	85	2	0.050	1	0.030
CHP[a], natural gas	0.5	1	85	2	0.067	1	0.0058
CHP[a], biofuels	2.8	1	85	2	0.046	1	0.034
Cold condensing, oil	0.2	1	40	2	0.13	1	0.0053
Sum:	100.0				0.033		1.948
Grid loss, small-scale, rural area	10.0	2					0.195
Total:							2.142
Grid loss, medium-scale	7.5						0.146
Total:							2.094
Grid loss, large-scale, machinery	5.0	2					0.097
Total:							2.045

[a] Combined power and heating plant.
[b] Reference: 1) Uppenberg *et al.* (2001); 2) Brännström-Norberg *et al.* (1996).

Energy use (Table 48) includes energy for production of fuel with transport, construction of power plant, running of power plant, demolition of power plant and handling of remnants of the fuel used (Brännström-Norberg *et al.*, 1996). The sum of energy use is calculated as the sum of each energy use value multiplied by its share of the Swedish electricity production. This value could be compared with the energy use for production of Swedish electricity, 0.032 MJ/MJ_{el} (Uppenberg *et al.*, 2001). The values are almost the same.

In the total energy use (Table 49), efficiency and energy use for production are included. They are calculated as share of electricity production multiplied by inversion of efficiency added with energy use. The sum of the total energy use (Table 48) is that value the produced Swedish electricity should be multiplied by to get the total energy input for production of electricity. To get the total energy input for consumed electricity, this value has to be multiplied by the grid losses (Table 48) (assumed after Brännström-Norberg *et al.*, 1996): 5% for large-scale plants and energy tied up in machines and buildings; 7.5% for medium-scale plants; and 10% for small-scale plants and electricity consumed on the farm during seed production. The emission values for production of Swedish electricity (Uppenberg *et al.*, 2001) are multiplied by the grid losses in this way to get the emission values for electricity consumption (Table 49).

Table 49. Emissions from electricity production

Type of electricity	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	HCl	Particles	Input energy
	[g/ MJ_{el}]	[mg/ MJ_{el}]	[mg/ MJ_{el}]	[mg/ MJ_{el}]	[mg/ MJ_{el}]	[mg/ MJ_{el}]	[mg/ MJ_{el}]	[mg/ MJ_{el}]	[mg/ MJ_{el}]	[mg/ MJ_{el}]	[MJ/ MJ_{el}]
Swedish electricity (Uppenberg *et al*., 2001)	7.842	18.0	2.90	49.0	15.0	13.0	0.22	0.71		2.50	1.032
Grid loss (10%), small-scale, rural area	8.626	19.8	3.19	53.9	16.5	14.3	0.24	0.78		2.75	2.142
Grid loss (7.5%), medium-scale	8.430	19.4	3.12	52.7	16.1	14.0	0.24	0.76		2.69	2.094
Grid loss (5%), large-scale, machinery	8.234	18.9	3.05	51.5	15.8	13.7	0.23	0.75		2.63	2.045
Fossil fuel electricity (Kaltschmitt & Reinhardt, 1997)	201	48.9	5.19	400.0	174.7	143.3	0.04	7.50	11.67	1.86	3.167

The fossil fuel electricity (Table 49) is equivalent to German electricity produced in 1995 (Kaltschmitt & Reinhardt, 1997) which was based on: 26% coal; 30% brown coal; 5% natural gas; 1% heavy oil; 34% nuclear power; and 4% hydropower, which fact explains its higher emission values. Grid losses are included but not differentiated between production scales.

In Table 50, area electricity requirements for the main processes in the rapeseed oil, RME and ethanol fuel productions are accounted for. For oil extraction these values are obtained when the values for electricity requirement [MJ_{el}/kg seed] (Table 27) are multiplied by the seed yield [kg/ha] (Section 3.4.1) or the values for electricity requirement [MJ_{el}/kg oil] (Table 27) are multiplied by the oil yield [kg/ha] (Table 28). For transesterification, the area electricity requirements are obtained when the electricity requirement for transesterification [MJ_{el}/kg RME] (Section 3.5.2) is multiplied by the RME yield [kg/ha] (Section 3.5.2). For ethanol fuel, the electricity requirements according above are obtained when the values for electricity requirement [MJ/tonne wheat] (Table 33) are multiplied by the wheat harvest [tonne/ha] (Section 3.4.2).

The area emissions and energy requirement during the use of electricity for oil extraction, transesterification and ethanol fuel production are accounted for in Table 51 (see also Tables A3-A14 and A17-A22, Appendices 1 and 2). These values are obtained when the emission values [g/MJ_{el}] for electricity production (Table 49) are multiplied by the values for electricity requirement in Table 50. With this procedure it is possible to study some more scenarios (for the scenario analysis) than the basic scenario. The emission and energy requirement values in Table 50 have to be split up in the different processes because they are used in different ways during the allocation procedure (Section 3.10). The emissions for electricity assumed to be used for treatment of waste water from the production of ethanol are accounted for in Table 41. How these emissions were calculated is described in Section 3.5.3.

Table 50. Requirement of electricity in different parts of the process of importance for the allocation during production of rapeseed oil, RME and ethanol fuel

Process / Plant size	Small-scale [MJ_{el}/ha]	Medium-scale [MJ_{el}/ha]	Large-scale [MJ_{el}/ha]
Rapeseed oil and RME:			
Oil extraction	886	534	534
Transesterification	436	481	629
Total requirement of electricity	1323	1015	1162
Ethanol fuel:			
Ethanol fermentation	923	846	769
Ethanol distillation	552	506	460
Handling of distiller's waste etc.	7	7	1282
Total requirement of electricity	1482	1359	2512

Table 51. Area emissions and energy requirement during production of electricity

Process	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	Particles	Input energy
	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[MJ/ha]
Rapeseed oil and RME:										
Small-scale:										
Oil extraction	7645	17.5	2.83	47.8	14.6	12.7	0.214	0.692	2.44	1899
Transesterification	3763	8.6	1.39	23.5	7.2	6.2	0.106	0.341	1.20	935
Total	11409	26.2	4.22	71.3	21.8	18.9	0.320	1.033	3.64	2833
Medium-scale:										
Oil extraction	4498	10.3	1.66	28.1	8.6	7.5	0.126	0.407	1.43	1117
Transesterification	4056	9.3	1.50	25.3	7.8	6.7	0.114	0.367	1.29	1007
Total	8554	19.6	3.16	53.4	16.4	14.2	0.240	0.774	2.73	2124
Large-scale:										
Oil extraction	4393	10.1	1.62	27.4	8.4	7.3	0.123	0.398	1.40	1091
Transesterification	5177	11.9	1.91	32.3	9.9	8.6	0.145	0.469	1.65	1286
Total	9570	22.0	3.54	59.8	18.3	15.9	0.268	0.866	3.05	2377
Ethanol fuel:										
Small-scale:										
Ethanol fermentation	7965	18.3	2.95	49.8	15.2	13.2	0.223	0.721	2.54	1978
Ethanol distillation	4762	10.9	1.76	29.8	9.1	7.9	0.134	0.431	1.52	1183
Handling of distiller's waste etc.	59	0.13	0.022	0.37	0.11	0.10	0.0016	0.0053	0.019	15
Total	12786	29.3	4.73	79.9	24.5	21.2	0.359	1.158	4.08	3175
Medium-scale:										
Ethanol fermentation	7135	16.4	2.64	44.6	13.6	11.8	0.200	0.646	2.27	1772
Ethanol distillation	4266	9.8	1.58	26.7	8.2	7.1	0.120	0.386	1.36	1059
Handling of distiller's waste etc.	57	0.13	0.021	0.36	0.11	0.10	0.0016	0.0052	0.018	14
Total	11459	26.3	4.24	71.6	21.9	19.0	0.321	1.037	3.65	2846
Large-scale:										
Ethanol fermentation	6336	14.5	2.34	39.6	12.1	10.5	0.178	0.574	2.02	1573
Ethanol distillation	3788	8.7	1.40	23.7	7.2	6.3	0.106	0.343	1.21	941
Handling of distiller's waste etc.	10560	24.2	3.90	66.0	20.2	17.5	0.296	0.956	3.37	2622
Total	20683	47.5	7.65	129.2	39.6	34.3	0.580	1.873	6.59	5137

3.6.2 Electricity costs

The price of electricity depends on the size of the plant (Vattenfall, 2003; Brännström, pers. comm.; Roswall, pers. comm.). The price for the electricity consists of three main parts: the electricity (in kWh), tax and grid charge (grid charge and fixed grid charge). The reason that large plants can get lower prices (of both electricity and grid charge) is that they can buy high-tension electricity. Such electricity can be delivered with lower grid losses (Brännström-

Norberg *et al.*, 1996). The prices in Table 52 exclude value-added tax. The prices for the electricity are expected average prices for the years around 2003 (Brännström, pers. comm.). For small-plants, the fixed grid charge for a consumer around Uppsala consuming 75 000 kWh, with an 80 ampere main fuse, is 5507 SEK/year recalculated to approx. 0.07 SEK/kWh (Vattenfall, 2003). For medium-scale plants the grid charge (grid charge + fixed grid charge) is 0.015-0.02 SEK/kWh lower than for small plants (Brännström, pers. comm.), in this study assumed to be 0.02 SEK/kWh lower, making the total grid charge 0.202 SEK/kWh. For large plants the grid charge is about 0.15 SEK/kWh (Roswall, pers. comm.).

Table 52. Components of electricity prices for different scales of oil extraction, transesterification and ethanol fuel production

	Plant size		
	Small	Medium	Large
Electricity [SEK/kWh]	0.27	0.27	0.245
Tax [SEK/kWh]	0.227	0.227	0.227
Grid charge [SEK/kWh]	0.152	0.202	0.15
Fixed grid charge [SEK/kWh]	0.07	0	0
Total [SEK/kWh]	0.719	0.699	0.622
Oil extraction, electricity requirement [kWh/ha]	246	148	148
Electricity cost, oil extraction [SEK/ha]	177	104	92
Transesterification, electricity requirement [kWh/ha]	121	134	175
Electricity cost, transesterification [SEK/ha]	87	93	109
Ethanol fuel production, electricity requirement [kWh/ha]	412	378	698
Electricity cost, ethanol fuel production [SEK/ha]	296	264	434
Ethanol prod., electricity, treatment of waste water [kWh/ha]	55	55	55
Electricity cost, treatment of waste water [SEK/ha]	40	38	34
As above, also including fresh water for the process [SEK/ha]	79	77	69

3.7 Transport

3.7.1 Transport data

Transport of rapeseed, meal, wheat and dried distiller's waste was assumed to be carried out by an open-sided lorry (total weight 60 tonnes, load weight 40 tonnes, see Table 75) if the transport distance was longer than 20 km. At shorter distances, transport was by tractors with wagons carrying a load of 20 metric tonnes (10 tonnes each) (Table 74), for fertilisers metric 16 tonnes (Table 72) (see Section 3.4.4). A tractor with a 20 tonne tank wagon (Table 74), for medium-sized ethanol plants, transported wet distiller's waste. This tank wagon was assumed to have a weight and rolling resistance corresponding to the two above-described wagons together. A tank lorry with a load weight of 36.5 tonnes (see Table 75) transported rapeseed oil, RME and ethanol fuel. Methanol, glycerine, chemicals for ethanol production (large-scale plant) and chemicals to make the ethanol into ethanol fuel (medium- and large-scale plant) were transported by the same type of tank lorry. Chemicals for ethanol production (medium- and small-scale plant) and chemicals to make the ethanol into ethanol fuel (small-scale plant) were transported by a lorry carrying a load weight of 40 tonnes.

For the calculations (Berggren, 1999) it was assumed that the lorries were powered by a 12.1 litre, 309 kW Volvo D12A engine with turbo-charger and intercooler. For the calculations (Berggren, 1999) it was assumed that the tractor was powered by a 4.4 litre, 70 kW Valmet 420 DS engine with turbo-charger (66 kW on the power take-off).

Transport distances were: 110 km for all plant sizes for methanol, glycerine, chemicals for ethanol production and chemicals to make the ethanol into ethanol fuel; 110 km for large-scale plants for rapeseed, meal, rapeseed oil, RME, wheat, ethanol as ethanol fuel and dried distiller's waste; and 7 km for medium-scale plants for rapeseed, meal, rapeseed oil, RME, wheat, ethanol as ethanol fuel and wet distiller's waste. At small-scale plants, rapeseed, meal, rapeseed oil, RME, wheat, ethanol as ethanol fuel and wet distiller's waste were not transported outside the farm, because the processing was performed on farm. At allocation with expanded system (Section 3.10), soymeal with added soyoil was assumed to be transported by an open-sided lorry carrying 40 tonnes, 110 km.

Transport included emissions from burning of the transport fuel, manufacturing of the transport fuel, lubrication oil and transport machinery.

During transport of the chemicals, the load capacity of the transporting lorries was assumed not to be fully utilized. This was because lorries used for this task will transport different chemicals to a lot of customers, where they will load or unload. The assumed figures are high because empty return trips were assumed, even if it is not so in reality. Packaging of the chemicals and coverage of the lorries also reduced the amount of each chemical transported. For transport of chemicals: 65% of the load capacity was assumed to be used when chemicals for production of ethanol and chemicals for making ethanol into ethanol fuel were transported to small-scale plants; 75% of the load capacity was assumed to be used when chemicals for production of ethanol and chemicals for making ethanol into ethanol fuel were transported to medium-scale plants; 90% of the load capacity was assumed to be used when chemicals for production of ethanol were transported to large-scale plants; and 100% of the load capacity was assumed to be used when chemicals for making ethanol into ethanol fuel were transported to large-scale plants. To take the above-described effect into consideration in the calculations, energy requirement and emission values were divided by the above-described values. As described above, no consideration was given to chemicals used for production of rapeseed oil or RME. After transport of methanol and glycerine, the return trips were assumed to be empty.

To get the total emissions and fuel consumption for a transport, emissions and fuel consumption for full load transport have to be added to them for empty transport (Tables 55 and 56). When rapeseed was transported from the farm to extraction, meal was transported back to the farm on the return trip if there were enough meal to fill up the transport vehicle. When wheat was transported from the farm to ethanol production (only large-scale), dried distiller's waste was transported back to the farm on the return trip if there were enough distiller's waste to fill up the transport vehicle. This meant that the empty return trips were reduced when seed or wheat were transported and fully eliminated when meal or dried distiller's waste were transported back to the farm. Transport of soymeal during allocation with expanded system was assumed to be with empty return trips.

Calculation of share of transport that carries meal on return trip is: (yield of meal or dried distiller's waste / hectare) / (yield of rapeseed or wheat / hectare). For medium-scale extraction: 1587 kg meal/ha / 2470 kg rapeseed/ha = 64.25% of the transport; for large-scale extraction: 1331 kg meal/ha / 2470 kg rapeseed/ha = 53.90% of the transport; and for large-scale ethanol production: 1892 kg dried distiller's waste/ha / 5900 kg wheat/ha = 32.08% of the transport. The part of the return transport, which is not filled with meal or dried distiller's waste (not utilized return transport) was added to emissions and fuel consumption for the full loaded rapeseed or wheat transport to get total fuel consumption and emissions for the transport of seed and was calculated thus: for medium-scale extraction: (2470 – 1587) / 2470 = 35.75%; for large-scale extraction: (2470 – 1331) / 2470 = 46.10%; and for large-scale ethanol production: (5900 – 1892) / 5900 = 67.92%.

The quantity of lubrication oil consumed was assumed to be 0.7% of the volumetric diesel fuel used, for both lorries and tractors, based on data from ASAE (2000), including oil used for transmissions and hydraulics (for descriptions and assumptions see Section 3.4.4.1: Requirement of fuels and oils).

3.7.1.1 Estimation of some missing values for an open-sided lorry

From the fuel consumption and emissions values with MK1 fuel for lorries and tractors in Berggren (1999), values including acceleration on public roads were chosen for this study. Three types of lorries were studied, all with a vehicle total weight of 60 tonnes. The three types were: timber lorry (max load 42.5 tonnes, empty weight 17.5 tonnes); bulk lorry (max load 36.5 tonnes, empty weight 23.5 tonnes); and container lorry (max load 32.5 tonnes, empty weight 27.5 tonnes) (see Table 54).

In this study, a tank lorry was used for transport of the fluids. For the tank lorry, the data for the bulk lorry were assumed to be valid (max load 36.5 tonnes, Table 75). Seed and meal were assumed to be transported with an open-sided lorry (max load 40.0 tonnes, empty weight 20.0 tonnes, Table 75) that was missing in Berggren (1999). The missing fuel consumption and emission values, for this lorry empty, were assumed to be possible to calculate with Newton's general interpolation formula from the corresponding values for the lorries described above (for explanation see: Equation 6; Table 53; Equation 7; and Table 54) (Eldén & Wittmeyer-Koch, 1992). The interpolation was made on empty lorries when all types of fully loaded lorries have the same total weight and fuel consumptions with emissions. The general formula is given in Equation 6, a calculation schedule in Table 53 that is put together in Equation 7. The results from the calculation are accounted in Table 54.

The general polynomial for Newton's general interpolation formula (Eldén & Wittmeyer-Koch, 1992) is:

$$\begin{aligned} P_n(x) = {} & f_1 + f[x_1,x_2]*(x-x_1) + f[x_1,x_2,x_3]*(x-x_1)*(x-x_2) + \\ & \ldots + f[x_1,x_2,\ldots,x_{n+1}]*(x-x_1)*(x-x_2)*\ldots*(x-x_n) \end{aligned} \quad (6)$$

of degree $\leq$ n fulfil $\mathrm{P_n}(x_i) = f_i, \quad \mathrm{i} = 1,2,\ldots,\mathrm{n}+1.$

Table 53. Calculation schedule with Newton's general interpolation formula (Eldén & Wittmeyer-Koch, 1992)

x	f(x)	f[-,-]	f[-,-,-]
x_1	$f(x_1)$		
		$\frac{f(x_2)-f(x_1)}{x_2-x_1}$	
x_2	$f(x_2)$		$\frac{\frac{f(x_3)-f(x_2)}{x_3-x_2}-\frac{f(x_2)-f(x_1)}{x_2-x_1}}{x_3-x_1}$
		$\frac{f(x_3)-f(x_2)}{x_3-x_2}$	
x_3	$f(x_3)$		

The polynomial obtained is:

$$P(x)=f(x_1)+\frac{f(x_2)-f(x_1)}{x_2-x_1}*(x-x_1)+\left(\frac{\frac{f(x_3)-f(x_2)}{x_3-x_2}-\frac{f(x_2)-f(x_1)}{x_2-x_1}}{x_3-x_1}\right)*(x-x_1)*(x-x_2) \quad (7)$$

Table 54. Results from calculations with Newton's general interpolation formula, energy requirement and emissions for a lorry with 20 tonnes empty weight

	Empty weight [metric tonnes]	Fuel consumption [g/km]	Energy requirement [kWh_{engine}/km]	CO-emissions [g/km]	NO_x-emissions [g/km]	HC-emissions [g/km]
	x	$f_1(x)$	$f_2(x)$	$f_3(x)$	$f_4(x)$	$f_5(x)$
x_1	17.5	263.8	1.18	1.00	7.42	0.240
x_2	23.5	305.7	1.41	1.17	8.79	0.220
x_3	27.5	334.6	1.56	1.25	9.71	0.220
x	*20.0*	$P_1(x) = 281.1$	$P_2(x) = 1.28$	$P_3(x) = 1.08$	$P_4(x) = 7.99$	$P_5(x) = 0.229$

3.7.1.2 Emissions and input energy

The emission and energy requirement values in Table 54 from Berggren (1990) could be converted to the values for MK1 fuel in Tables 55-56 by division by the load [tonnes] for each type of lorry. In Tables 55 and 56, ton-kilometre is expressed as tonkm.

In the basic scenario, transport was made with diesel oil MK1. For the scenario analysis, rapeseed oil, RME or ethanol fuel were used as fuels for the transport depending on the fuel studied. Consumption of diesel oil MK3, RME, rapeseed oil, and ethanol fuel in Tables 55 and 56 was calculated from the consumption of diesel oil MK1 in Berggren (1999). Consumption of and emissions from the use of MK3 diesel oil (Tables 55-56) were only used in the calculations to get engine efficiencies for MK1 and RME (Table 102) and fuel consumption and emissions for rapeseed oil (Tables 101 and 102). The energy outputs from the engines during the transport were assumed to be the same independent of the fuel used. In Table 99, Section 3.9, properties for all these fuels are given. In SMP (1993) the engine efficiencies are given for an engine running at its best operating point with MK3, MK1 and RME (Table 99, Section 3.9). In Aakko *et al.* (2000) the engine efficiency with MK3, measured according to ECE R49, is given. With assumption of the same relationship between the efficiencies according to ECE R49 for MK3, MK1 and RME as measured in SMP (1993), the efficiencies according to ECE R49 for MK1 and RME could be estimated and used for the fuel consumption calculations (see Table 99). From the fuel consumptions in Haupt *et al.* (1999) the engine efficiency with the ethanol fuel assumed to be used in this study, measured according to ECE R49, could be calculated (Table 99).

The emissions and fuel consumption values for the transport with the MK3, RME and ethanol fuel were calculated during comparison to the values for MK1. This was conducted by comparison by emission and fuel requirement data from other fuels (SMP, 1993; Berggren, 1999; Haupt *et al.*, 1999; Aakko *et al.*, 2000).

- Fuel consumption MK3, RME or ethanol fuel [g/tonkm] (Tables 55-56) could be calculated as: fuel consumption MK1 [g/tonkm] (Tables 55-56) * (engine efficiency MK1 (Table 99) / engine efficiency new fuel) (Table 99) * (lower heat value MK1 [MJ/kg] (Table 99) / lower heat value new fuel [MJ/kg] (Table 99)).
- Emissions MK3, RME or ethanol fuel [g/tonkm] (Tables 55-56) could be calculated as: emission value MK1 [g/tonkm] (Tables 55-56) * (emission new fuel [g/MJ_{engine}] (Table 102) / (emission MK1 [g/MJ_{engine}] (Table 102)).
- Particle emissions ethanol fuel [g/tonkm] (Tables 55-56) could be calculated as: emission value MK1 [g/tonkm] (Tables 55-56) * (emission ethanol fuel [g/MJ_{fuel}] (Table 102) / (emission MK1[a] [g/MJ_{fuel}] (Table 102)) * (engine efficiency MK1 (Table 99) / engine efficiency ethanol fuel) (Table 99).
  [a] calculated as: ((A/B) * (C/D)) / ((E * (F/1000)) where:
  A = 0.057 g/kWh_{engine} (Aakko *et al.*, 2000);
  B = 3.6 kWh/MJ;
  C = 1660.68 MJ_{engine} out for lorry and 920.232 MJ_{engine} out for tractor (Berggren, 1999);
  D = 171.594 km driven distance for lorry and 171.428 km driven distance for tractor (Berggren, 1999);
  E = 43.3 MJ/kg MK1;
  F = 558.54 g MK1/km for lorry and 338.15 g MK1/km for tractor (Berggren, 1999).
- Energy use for MK3, RME or ethanol fuel [MJ_{fuel}/tonkm] (Tables 55-56) could be calculated as: energy use for MK1 [MJ_{fuel}/tonkm] (Tables 55-56) * (engine efficiency MK1 (Table 102) / engine efficiency new fuel (Table 102)).

The volumetric fuel consumption with rapeseed oil in Elsbett engines was approx. 12% higher than with diesel oil MK3 in conventional direct injected diesel engines (Bernesson, 1993 and 1994; Thuneke, 1999) (Section 3.9, Table 99). The emissions with rapeseed oil in relation to diesel oil MK3 are accounted for in Table 101 (Section 3.9), and from these values the emissions and fuel consumption with rapeseed oil fuel could be calculated.

- Fuel consumption rapeseed oil [g/tonkm] (Tables 55-56) could be calculated as: fuel consumption MK3 [g/tonkm] (Tables 55-56) * 1.12 * (density rapeseed oil (Table 99) / density diesel fuel MK3 (Table 99)).
- Emissions rapeseed oil [g/tonkm] (Tables 55-56) could be calculated as: emission value in relation to MK3 (Table 101) * emission value MK3 [g/tonkm] (Tables 55-56).
- Energy use for rapeseed oil [MJ_{fuel}/tonkm] (Tables 55-56) could be calculated as: energy use for MK3 [MJ_{fuel}/tonkm] * 1.12 * ((density rapeseed oil [kg/litre] (Table 99) * lower heat value rapeseed oil [MJ/kg] (Table 99)) / (density MK3 [kg/litre] (Table 99) * lower heat value MK3 [MJ/kg] (Table 99))).

During the scenario analysis, with catalysts in the transport vehicles used, the reduction of emissions was assumed to roughly follow results from Aakko *et al.* (2000) for MK3, MK1, RME and rapeseed oil fuels. Therefore CO- HC- and NO_x-emissions were reduced by 81%; 77.5%; and 6% respectively. Particulate emissions were not influenced. For ethanol fuel, the reduction of emissions, with catalysts in the vehicles used, was assumed to roughly follow results from Haupt *et al.* (1999). Therefore CO- and HC-emissions were reduced by 93%; and 45% respectively. NO_x-and particulate-emissions were not influenced.

Table 55. Emissions lorry transport, by road driving (after Berggren, 1999)

Total emissions transport	Load [metric tonnes]	Fuel [g/ton-km]	CO [g/ton-km]	NO_x [g/ton-km]	HC [g/ton-km]	Particles [g/ton-km]	Energy [MJ_{engine}/ tonkm]	Energy [MJ_{fuel}/ tonkm]
MK1 diesel oil:								
bulk lorry or tank lorry, full load	36.5	15.3	0.046	0.46	0.0066	0.0042	0.265	0.663
bulk lorry or tank lorry, empty	0	8.4	0.032	0.24	0.0060	0.0022	0.139	0.363
open-sided lorry, full load	40	14.0	0.042	0.42	0.0060	0.0038	0.242	0.605
open-sided lorry, empty	0	7.0	0.027	0.20	0.0057	0.0018	0.115	0.304
MK3 diesel oil:								
bulk lorry or tank lorry, full load	36.5	15.1	0.041	0.54	0.0053	0.0055	0.265	0.646
bulk lorry or tank lorry, empty	0	8.3	0.029	0.28	0.0049	0.0029	0.139	0.353
open-sided lorry, full load	40	13.8	0.038	0.49	0.0049	0.0050	0.242	0.589
open-sided lorry, empty	0	6.9	0.024	0.23	0.0046	0.0024	0.115	0.296
RME:								
bulk lorry or tank lorry, full load	36.5	17.4	0.034	0.60	0.0025	0.0022	0.265	0.671
bulk lorry or tank lorry, empty	0	9.5	0.024	0.31	0.0023	0.0012	0.139	0.367
open-sided lorry, full load	40	15.9	0.031	0.55	0.0023	0.0020	0.242	0.613
open-sided lorry, empty	0	8.0	0.020	0.26	0.0022	0.0010	0.115	0.308
Rapeseed oil:								
bulk lorry or tank lorry, full load	36.5	18.8	0.041	0.56	0.0029	0.0039	0.265	0.721
bulk lorry or tank lorry, empty	0	10.3	0.029	0.29	0.0027	0.0020	0.139	0.395
open-sided lorry, full load	40	17.2	0.038	0.51	0.0027	0.0035	0.242	0.658
open-sided lorry, empty	0	8.6	0.024	0.24	0.0025	0.0017	0.115	0.331
Ethanol fuel:								
bulk lorry or tank lorry, full load	36.5	23.5	0.206	0.31	0.0101	0.0013	0.265	0.591
bulk lorry or tank lorry, empty	0	12.9	0.144	0.16	0.0092	0.0007	0.139	0.324
open-sided lorry, full load	40	21.5	0.188	0.28	0.0092	0.0012	0.242	0.539
open-sided lorry, empty	0	10.8	0.121	0.13	0.0087	0.0006	0.115	0.271

Table 56. Emissions tractor transport by road driving (after Berggren, 1999)

Total emissions transport	Load [metric tonnes]	Fuel [g/ton-km]	CO [g/ton-km]	NO_x [g/ton-km]	HC [g/ton-km]	Particles [g/ton-km]	Energy [MJ_{engine}/ tonkm]	Energy [MJ_{fuel}/ tonkm]
MK1 diesel oil: full load	20	16.9	0.044	0.59	0.0155	0.0042	0.268	0.732
empty	0	11.1	0.053	0.30	0.0175	0.0023	0.147	0.482
MK3 diesel oil: full load	20	16.7	0.040	0.68	0.0125	0.0056	0.268	0.713
empty	0	11.0	0.048	0.35	0.0142	0.0031	0.147	0.469
RME: full load	20	19.3	0.033	0.77	0.0059	0.0022	0.268	0.742
empty	0	12.7	0.040	0.39	0.0067	0.0012	0.147	0.488
Rapeseed oil: full load	20	20.8	0.040	0.72	0.0069	0.0039	0.268	0.797
empty	0	13.7	0.048	0.36	0.0078	0.0021	0.147	0.525
Ethanol fuel: full load	20	26.0	0.197	0.39	0.0237	0.0014	0.268	0.653
empty	0	17.1	0.238	0.20	0.0268	0.0009	0.147	0.430

The fuel consumption and emission values in Tables 55 and 56 (given per ton-kilometre) could be converted to values on an area basis (per hectare) when the values for full load and empty transport were added. However, empty transport was eliminated if return transport could be used for transport: for medium- and large-scale transport of rapeseed and large-scale transport of wheat, the return transport was partly used for transport of meal and dried distiller's waste respectively. The value for the return transport has to be multiplied by this value (see above: Calculation of share of transport that carries meal on return trip is…, etc.) before the addition according to the above could be performed. No return transport was required for medium- and large-scale meal transport and large-scale transport of distiller's waste because such transport was made as return transport for rapeseed and wheat respectively.

- Emissions (CO, HC NO_x and particles) [g/ha], and fuel consumption [g/ha or MJ_{fuel}/ha] for transport of rapeseed, meal, rapeseed oil RME, methanol, glycerine, wheat, wet distillers waste, dried distiller's waste and soybean meal (expanded system, see Section 3.10.2) (Tables 57 and 58) were calculated as: Emissions [g/tonkm] or fuel consumption [g/tonkm or MJ_{fuel}/tonkm] full load transport (Tables 55-56) + (share 'not utilized return transport' (see above) * emissions [g/tonkm] or fuel consumption [g/tonkm or MJ_{fuel}/tonkm] empty transport (Tables 55-56)) * (yield/requirement of transported product [kg/ha] (Tables 65-66) / 1000 [kg/tonne]) * transport distance [km] (see above).
- Emissions (CO, HC NO_x and particles) [g/ha], and fuel consumption [g/ha or MJ_{fuel}/ha] for transport of production chemicals and fuel chemicals used during production of ethanol fuel (Table 58) were calculated as: ((Emissions [g/tonkm] or fuel consumption [g/tonkm or MJ_{fuel}/tonkm] full load transport (Tables 55-56) + emissions [g/tonkm] or fuel consumption [g/tonkm or MJ_{fuel}/tonkm] empty transport (Tables 55-56)) / share of load capacity assumed to be used (see above and Table 66)) * (requirement of transported product [kg/ha] (Table 66) / 1000 [kg/tonne]) * transport distance [km] (see above).

The way in which CO_2-, SO_X- and particle-emissions were calculated and the assumptions made are accounted for in Section 3.4.4.2. CO_2-emissions [g/ha] (Tables 57-58) were calculated by multiplying fossil CO_2-emissions [g/MJ_{fuel}] (Section 3.4.4.2) by the fuel consumption as energy in fuel [MJ_{fuel}/ha] (Tables 57-58). The SO_x-emissions [g/ha] (Tables 57-58) were calculated as: (sulphur content in fuel [ppm] (Section 3.4.4.2) / 1000000) * 2.00 (1.00 g sulphur gives 2.00 g SO_2, Section 3.4.4.2) * fuel consumption [g/ha] (Tables 57-58). The particles emissions in Tables 57-58 could be calculated from the values in Tables 55-56 in the same way as the other emissions.

Table 57. Vehicle emissions and energy requirement for transport during production of rapeseed oil and RME

Type of transport and vehicle	Fuel cons. [g/ha]	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	NO_x [g/ha]	SO_x [g/ha]	Particles [g/ha]	Energy in fuel [MJ_{fuel}/ha]
Small-scale:								
methanol, tank lorry	217	684	0.71	0.115	6.4	0.0043	0.059	9.4
glycerine, tank lorry	207	656	0.68	0.110	6.2	0.0041	0.056	9.0
Medium-scale:								
methanol, tank lorry	239	755	0.79	0.127	7.1	0.0048	0.065	10.3
glycerine, tank lorry	229	723	0.75	0.122	6.8	0.0046	0.062	9.9
RME, tank lorry	133	420	0.44	0.071	4.0	0.0027	0.036	5.8
rapeseed oil, tank lorry	138	437	0.46	0.074	4.1	0.0028	0.037	6.0
rapeseed, tractor, two wagons	361	1141	1.09	0.376	12.0	0.0072	0.088	15.6
meal, tractor, two wagons	188	594	0.49	0.172	6.6	0.0038	0.047	8.1
Large-scale:								
methanol, tank lorry	312	986	1.03	0.166	9.3	0.0062	0.084	13.5
glycerine, tank lorry	299	945	0.99	0.159	8.9	0.0060	0.081	12.9
RME, tank lorry	2729	8627	9.00	1.453	81.2	0.0545	0.737	118.2
rapeseed oil, tank lorry	2837	8968	9.36	1.510	84.4	0.0567	0.766	122.8
rapeseed, open-sided lorry	4674	14774	14.79	2.346	140.0	0.0933	1.269	202.4
meal, open-sided lorry	2045	6464	6.15	0.879	62.0	0.0408	0.561	88.5
Small-scale, total: rapeseed oil	0	0	0	0	0	0	0	0
RME	424	1340	1.40	0.226	12.6	0.0085	0.115	18.4
Medium-scale, total: rapeseed oil	687	2172	2.03	0.622	22.7	0.0137	0.172	29.8
RME	1149	3633	3.56	0.868	36.5	0.0230	0.297	49.8
Large-scale, total: rapeseed oil	9556	30205	30.29	4.735	286.4	0.1908	2.596	413.8
RME	10059	31796	31.95	5.003	301.4	0.2009	2.732	435.6
Small-scale soymeal, open-sided lorry	3449	10901	11.33	1.925	102.4	0.0689	0.928	149.3
Medium-scale soymeal, open-sided lorry	3357	10610	11.03	1.874	99.6	0.0670	0.904	145.3
Large-scale soymeal, open-sided lorry	2767	8745	9.09	1.545	82.1	0.0552	0.745	119.8

Table 58. Vehicle emissions and energy requirement for transport during production of ethanol and ethanol fuel

Type of transport and vehicle	Fuel cons. [g/ha]	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	NO_x [g/ha]	SO_x [g/ha]	Particles [g/ha]	Energy in fuel [MJ_{fuel}/ha]
Small-scale:								
production chemicals, open-sided lorry	114	362	0.38	0.064	3.4	0.0023	0.031	5.0
fuel chemicals, open-sided lorry	722	2282	2.37	0.403	21.4	0.0144	0.194	31.3
Medium-scale:								
production chemicals, open-sided lorry	99	313	0.33	0.055	2.9	0.0020	0.027	4.3
fuel chemicals, tank lorry	706	2231	2.33	0.376	21.0	0.0141	0.191	30.6
wheat, tractor, two wagons	1158	3660	4.01	1.363	36.7	0.0231	0.271	50.1
distiller's waste, tractor, tank wagon	3714	11738	12.85	4.372	117.8	0.0742	0.871	160.8
ethanol fuel, tank lorry	343	1086	1.13	0.183	10.2	0.0069	0.093	14.9
Large-scale:								
production chemicals, tank lorry	93	295	0.31	0.050	2.8	0.0019	0.025	4.0
fuel chemicals, tank lorry	529	1674	1.75	0.282	15.8	0.0106	0.143	22.9
wheat, open-sided lorry	12160	38436	39.14	6.415	362.7	0.2428	3.288	526.5
distiller's waste, open-sided lorry	2907	9188	8.74	1.249	88.1	0.0580	0.797	125.9
ethanol fuel, tank lorry	5397	17061	17.80	2.873	160.6	0.1078	1.458	233.7
Small-scale, total	836	2644	2.75	0.467	24.8	0.0167	0.225	36.2
Medium-scale, total	6020	19028	20.64	6.348	188.7	0.1202	1.452	260.7
Large-scale, total	21087	66653	67.74	10.868	630.0	0.4211	5.712	913.1
Small-scale soymeal, open-sided lorry	3952	12492	12.98	2.206	117.3	0.0789	1.064	171.1
Medium-scale soymeal, open-sided lorry	3952	12492	12.98	2.206	117.3	0.0789	1.064	171.1
Large-scale soymeal, open-sided lorry	3952	12492	12.98	2.206	117.3	0.0789	1.064	171.1

To get the total emissions for the transport (Tables 63 and 64, see also Tables A3-A14 and A17-A22, Appendices 1-2), the energy requirement and emissions for production of the fuel used (Tables 59 and 60) and the lubrication oil used (Tables 61 and 62) have to be added to the emission values during the transport (Tables 57 and 58).

- The emission and energy requirement for manufacture of the required fuel (Tables 59 and 60) could be calculated as: fuel consumption [g/ha] (Tables 57 and 58) * (lower heat value for fuel used [MJ/kg] (Table 99) / 1000 [g/kg]) * emissions and energy requirement for fuel production [g/MJ_{fuel}] (MK1: see Table 13; rapeseed oil, RME and ethanol fuel an iterative procedure, also depending on the plant size).
- The emissions and energy requirement for manufacturing of the lubrication oil used (Tables 61 and 62) could be calculated as: 0.7% (see above) * (fuel consumption [g/ha] (Tables 57 and 58) / (density of fuel used [kg/l] (Table 99) * 1000 [g/kg])) * density MK3 [kg/l] (Table 99: assumed to be as for MK3) * lower heat value MK3

[MJ/kg] (Table 99: assumed to be as for MK3) * emissions and energy requirement for fuel production of MK1 [g/MJ_{fuel}] (MK1: see Table 13, assumed also to be valid for lubrication oil).

Table 59. Emissions and energy requirement for production of the MK1 fuel used for transport during production of rapeseed oil and RME

Type of transport and vehicle	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	NO_x [g/ha]	SO_x [g/ha]	CH_4 [g/ha]	Particles [g/ha]	Input energy [MJ/ha]
Small-scale:								
methanol, tank lorry	33	0.019	0.31	0.29	0.18	0.019	0.0094	0.56
glycerine, tank lorry	31	0.018	0.30	0.28	0.17	0.018	0.0090	0.54
Medium-scale:								
methanol, tank lorry	36	0.021	0.34	0.32	0.20	0.021	0.0103	0.62
glycerine, tank lorry	35	0.020	0.33	0.31	0.19	0.020	0.0099	0.59
RME, tank lorry	20	0.012	0.19	0.18	0.11	0.012	0.0058	0.35
rapeseed oil, tank lorry	21	0.012	0.20	0.19	0.11	0.012	0.0060	0.36
rapeseed, tractor, two wagons	55	0.031	0.52	0.48	0.30	0.031	0.0156	0.94
meal, tractor, two wagons	28	0.016	0.27	0.25	0.15	0.016	0.0081	0.49
Large-scale:								
methanol, tank lorry	47	0.027	0.45	0.42	0.26	0.027	0.0135	0.81
glycerine, tank lorry	45	0.026	0.43	0.40	0.25	0.026	0.0129	0.78
RME, tank lorry	414	0.236	3.90	3.66	2.25	0.236	0.1182	7.09
rapeseed oil, tank lorry	430	0.246	4.05	3.81	2.33	0.246	0.1228	7.37
rapeseed, open-sided lorry	708	0.405	6.68	6.27	3.85	0.405	0.2024	12.14
meal, open-sided lorry	310	0.177	2.92	2.74	1.68	0.177	0.0885	5.31
Small-scale, total: rapeseed oil	0	0	0	0	0	0	0	0
RME	64	0.037	0.61	0.57	0.35	0.037	0.0184	1.10
Medium-scale, total: rapeseed oil	104	0.060	0.98	0.92	0.57	0.060	0.0298	1.79
RME	174	0.100	1.64	1.54	0.95	0.100	0.0498	2.99
Large-scale, total: rapeseed oil	1448	0.828	13.65	12.83	7.86	0.828	0.4138	24.83
RME	1524	0.871	14.37	13.50	8.28	0.871	0.4356	26.13
Small-scale soymeal, open-sided lorry	523	0.299	4.93	4.63	2.84	0.299	0.1493	8.96
Medium-scale soymeal, open-sided lorry	509	0.291	4.80	4.51	2.76	0.291	0.1453	8.72
Large-scale soymeal, open-sided lorry	419	0.240	3.95	3.71	2.28	0.240	0.1198	7.19

Table 60. Emissions and energy requirement for production of the MK1 fuel used for transport during production of ethanol and ethanol fuel

Type of transport and vehicle	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	NO_x [g/ha]	SO_x [g/ha]	CH_4 [g/ha]	Particles [g/ha]	Input energy [MJ/ha]
Small-scale:								
production chemicals, open-sided lorry	17	0.0099	0.16	0.15	0.094	0.0099	0.0050	0.30
fuel chemicals, open-sided lorry	109	0.0625	1.03	0.97	0.594	0.0625	0.0313	1.88
Medium-scale:								
production chemicals, open-sided lorry	15	0.0086	0.14	0.13	0.082	0.0086	0.0043	0.26
fuel chemicals, tank lorry	107	0.0611	1.01	0.95	0.581	0.0611	0.0306	1.83
wheat, tractor, two wagons	175	0.1003	1.65	1.55	0.952	0.1003	0.0501	3.01
distiller's waste, tractor, tank wagon	563	0.3216	5.31	4.98	3.055	0.3216	0.1608	9.65
ethanol fuel, tank lorry	52	0.0297	0.49	0.46	0.283	0.0297	0.0149	0.89
Large-scale:								
production chemicals, tank lorry	14	0.0081	0.13	0.13	0.077	0.0081	0.0040	0.24
fuel chemicals, tank lorry	80	0.0458	0.76	0.71	0.436	0.0458	0.0229	1.38
wheat, open-sided lorry	1843	1.0530	17.38	16.32	10.004	1.0530	0.5265	31.59
distiller's waste, open-sided lorry	441	0.2517	4.15	3.90	2.391	0.2517	0.1259	7.55
ethanol fuel, tank lorry	818	0.4674	7.71	7.25	4.441	0.4674	0.2337	14.02
Small-scale, total	127	0.0724	1.20	1.12	0.688	0.0724	0.0362	2.17
Medium-scale, total	912	0.5213	8.60	8.08	4.953	0.5213	0.2607	15.64
Large-scale, total	3196	1.8261	30.13	28.30	17.348	1.8261	0.9131	54.78
Small-scale soymeal, open-sided lorry	599	0.3422	5.65	5.30	3.251	0.3422	0.1711	10.27
Medium-scale soymeal, open-sided lorry	599	0.3422	5.65	5.30	3.251	0.3422	0.1711	10.27
Large-scale soymeal, open-sided lorry	599	0.3422	5.65	5.30	3.251	0.3422	0.1711	10.27

Table 61. Emissions and energy requirement for production of the lubrication oil used for transport during production of rapeseed oil and RME

Type of transport and vehicle	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	NO_x [g/ha]	SO_x [g/ha]	CH_4 [g/ha]	Particles [g/ha]	Input energy [MJ/ha]
Small-scale:								
methanol, tank lorry	0.23	0.000132	0.0022	0.0020	0.00125	0.000132	0.000066	0.0040
glycerine, tank lorry	0.22	0.000126	0.0021	0.0020	0.00120	0.000126	0.000063	0.0038
Medium-scale:								
methanol, tank lorry	0.25	0.000145	0.0024	0.0023	0.00138	0.000145	0.000073	0.0044
glycerine, tank lorry	0.24	0.000139	0.0023	0.0022	0.00132	0.000139	0.000070	0.0042
RME, tank lorry	0.14	0.000081	0.0013	0.0013	0.00077	0.000081	0.000040	0.0024
rapeseed oil, tank lorry	0.15	0.000084	0.0014	0.0013	0.00080	0.000084	0.000042	0.0025
rapeseed, tractor, two wagons	0.38	0.000220	0.0036	0.0034	0.00209	0.000220	0.000110	0.0066
meal, tractor, two wagons	0.20	0.000114	0.0019	0.0018	0.00109	0.000114	0.000057	0.0034
Large-scale:								
methanol, tank lorry	0.33	0.000190	0.0031	0.0029	0.00180	0.000190	0.000095	0.0057
glycerine, tank lorry	0.32	0.000182	0.0030	0.0028	0.00173	0.000182	0.000091	0.0055
RME, tank lorry	2.91	0.001662	0.0274	0.0258	0.01578	0.001662	0.000831	0.0498
rapeseed oil, tank lorry	3.02	0.001727	0.0285	0.0268	0.01641	0.001727	0.000864	0.0518
rapeseed, open-sided lorry	4.98	0.002845	0.0469	0.0441	0.02703	0.002845	0.001423	0.0854
meal, open-sided lorry	2.18	0.001245	0.0205	0.0193	0.01183	0.001245	0.000622	0.0373
Small-scale, total: rapeseed oil	0	0	0	0	0	0	0	0
RME	0.45	0.000258	0.0043	0.0040	0.00245	0.000258	0.000129	0.0077
Medium-scale, total: rapeseed oil	0.73	0.000418	0.0069	0.0065	0.00397	0.000418	0.000209	0.0125
RME	1.22	0.000700	0.0115	0.0108	0.00665	0.000700	0.000350	0.0210
Large-scale, total: rapeseed oil	10.18	0.005817	0.0960	0.0902	0.05527	0.005817	0.002909	0.1745
RME	10.72	0.006124	0.1010	0.0949	0.05818	0.006124	0.003062	0.1837
Small-scale soymeal, open-sided lorry	3.67	0.002099	0.0346	0.0325	0.01995	0.002099	0.001050	0.0630
Medium-scale soymeal, open-sided lorry	3.58	0.002044	0.0337	0.0317	0.01941	0.002044	0.001022	0.0613
Large-scale soymeal, open-sided lorry	2.95	0.001684	0.0278	0.0261	0.01600	0.001684	0.000842	0.0505

Table 62. Emissions and energy requirement for production of the lubrication oil used for transport during production of ethanol and ethanol fuel

Type of transport and vehicle	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	NO_x [g/ha]	SO_x [g/ha]	CH_4 [g/ha]	Particles [g/ha]	Input energy [MJ/ha]
Small-scale:								
production chemicals, open-sided lorry	0.12	0.000070	0.00115	0.00108	0.00066	0.000070	0.000035	0.0021
fuel chemicals, open-sided lorry	0.77	0.000440	0.00725	0.00681	0.00418	0.000440	0.000220	0.0132
Medium-scale:								
production chemicals, open-sided lorry	0.11	0.000060	0.00100	0.00094	0.00057	0.000060	0.000030	0.0018
fuel chemicals, tank lorry	0.75	0.000430	0.00709	0.00666	0.00408	0.000430	0.000215	0.0129
wheat, tractor, two wagons	1.23	0.000705	0.01163	0.01092	0.00670	0.000705	0.000352	0.0211
distiller's waste, tractor, tank wagon	3.96	0.002261	0.03730	0.03504	0.02148	0.002261	0.001130	0.0678
ethanol fuel, tank lorry	0.37	0.000209	0.00345	0.00324	0.00199	0.000209	0.000105	0.0063
Large-scale:								
production chemicals, tank lorry	0.10	0.000057	0.00094	0.00088	0.00054	0.000057	0.000028	0.0017
fuel chemicals, tank lorry	0.56	0.000322	0.00532	0.00500	0.00306	0.000322	0.000161	0.0097
wheat, open-sided lorry	12.95	0.007403	0.12214	0.11474	0.07033	0.007403	0.003701	0.2221
distiller's waste, open-sided lorry	3.10	0.001770	0.02920	0.02743	0.01681	0.001770	0.000885	0.0531
ethanol fuel, tank lorry	5.75	0.003286	0.05422	0.05093	0.03122	0.003286	0.001643	0.0986
Small-scale, total	0.89	0.000509	0.00840	0.00789	0.00484	0.000509	0.000255	0.0153
Medium-scale, total	6.41	0.003665	0.06047	0.05680	0.03482	0.003665	0.001832	0.1099
Large-scale, total	22.47	0.012837	0.21181	0.19898	0.12195	0.012837	0.006419	0.3851
Small-scale soymeal, open-sided lorry	4.21	0.002406	0.03970	0.03729	0.02286	0.002406	0.001203	0.0722
Medium-scale soymeal, open-sided lorry	4.21	0.002406	0.03970	0.03729	0.02286	0.002406	0.001203	0.0722
Large-scale soymeal, open-sided lorry	4.21	0.002406	0.03970	0.03729	0.02286	0.002406	0.001203	0.0722

Table 63. Total emissions and energy requirement for transport during production of rapeseed oil and RME

Type of transport and vehicle	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	NO_x [g/ha]	SO_x [g/ha]	CH_4 [g/ha]	Particles [g/ha]	Input energy [MJ/ha]
Small-scale:								
methanol, tank lorry	718	0.73	0.43	6.7	0.18	0.019	0.068	9.9
glycerine, tank lorry	687	0.70	0.41	6.5	0.18	0.018	0.065	9.5
Medium-scale:								
methanol, tank lorry	791	0.81	0.47	7.4	0.20	0.021	0.075	11.0
glycerine, tank lorry	758	0.77	0.45	7.1	0.19	0.020	0.072	10.5
RME, tank lorry	440	0.45	0.26	4.1	0.11	0.012	0.042	6.1
rapeseed oil, tank lorry	458	0.47	0.27	4.3	0.12	0.012	0.043	6.3
rapeseed, tractor, two wagons	1196	1.12	0.90	12.5	0.31	0.031	0.104	16.6
meal, tractor, two wagons	622	0.51	0.44	6.8	0.16	0.016	0.055	8.6
Large-scale:								
methanol, tank lorry	1034	1.06	0.62	9.7	0.26	0.027	0.098	14.3
glycerine, tank lorry	991	1.01	0.59	9.3	0.25	0.026	0.094	13.7
RME, tank lorry	9043	9.24	5.38	84.9	2.32	0.238	0.856	125.3
rapeseed oil, tank lorry	9401	9.60	5.59	88.3	2.41	0.247	0.890	130.3
rapeseed, open-sided lorry	15487	15.19	9.07	146.3	3.97	0.408	1.472	214.6
meal, open-sided lorry	6776	6.33	3.82	64.7	1.74	0.178	0.650	93.9
Small-scale, total: rapeseed oil	0	0	0	0	0	0	0	0
RME	1405	1.44	0.84	13.2	0.36	0.037	0.133	19.5
Medium-scale, total: rapeseed oil	2277	2.09	1.61	23.6	0.58	0.060	0.202	31.5
RME	3809	3.66	2.52	38.0	0.98	0.100	0.347	52.8
Large-scale, total: rapeseed oil	31664	31.13	18.49	299.3	8.11	0.833	3.013	438.8
RME	33331	32.83	19.48	315.0	8.53	0.877	3.171	461.9
Small-scale soymeal, open-sided lorry	11427	11.63	6.89	107.0	2.93	0.301	1.079	158.3
Medium-scale soymeal, open-sided lorry	11123	11.32	6.70	104.2	2.85	0.293	1.050	154.1
Large-scale soymeal, open-sided lorry	9167	9.33	5.53	85.8	2.35	0.241	0.865	127.0

Table 64. Total emissions and energy requirement for transport during production of ethanol and ethanol fuel

Type of transport and vehicle	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	NO_x [g/ha]	SO_x [g/ha]	CH_4 [g/ha]	Particles [g/ha]	Input energy [MJ/ha]
Small-scale:								
production chemicals, open-sided lorry	379	0.39	0.23	3.6	0.097	0.0100	0.036	5.25
fuel chemicals, open-sided lorry	2393	2.43	1.44	22.4	0.613	0.0630	0.226	33.15
Medium-scale:								
production chemicals, open-sided lorry	329	0.33	0.20	3.1	0.084	0.0086	0.031	4.55
fuel chemicals, tank lorry	2339	2.39	1.39	22.0	0.599	0.0616	0.221	32.41
wheat, tractor, two wagons	3836	4.11	3.03	38.3	0.982	0.1010	0.322	53.16
distiller's waste, tractor, tank wagon	12305	13.17	9.72	122.8	3.151	0.3239	1.032	170.51
ethanol fuel, tank lorry	1138	1.16	0.68	10.7	0.291	0.0300	0.108	15.77
Large-scale:								
production chemicals, tank lorry	309	0.32	0.18	2.9	0.079	0.0081	0.029	4.28
fuel chemicals, tank lorry	1754	1.79	1.04	16.5	0.449	0.0462	0.166	24.31
wheat, open-sided lorry	40292	40.20	23.91	379.2	10.317	1.0604	3.818	558.33
distiller's waste, open-sided lorry	9632	9.00	5.43	92.0	2.466	0.2535	0.924	133.47
ethanol fuel, tank lorry	17885	18.27	10.64	167.9	4.580	0.4707	1.694	247.83
Small-scale, total	2772	2.82	1.67	26.0	0.710	0.0729	0.262	38.41
Medium-scale, total	19947	21.17	15.01	196.8	5.108	0.5250	1.715	276.41
Large-scale, total	69871	69.57	41.21	658.5	17.891	1.8389	6.631	968.22
Small-scale soymeal, open-sided lorry	13095	13.33	7.89	122.6	3.353	0.3446	1.236	181.46
Medium-scale soymeal, open-sided lorry	13095	13.33	7.89	122.6	3.353	0.3446	1.236	181.46
Large-scale soymeal, open-sided lorry	13095	13.33	7.89	122.6	3.353	0.3446	1.236	181.46

3.7.2 Transportation costs

According to Agriwise (2003) the costs for lorry transport 30, 40 and 100 km are: 0.035; 0.041; and 0.070 SEK/kg transported material respectively. With minor changes these figures can be expressed as the equation: transport cost (Tables 65 and 66) [SEK/kg transported material] = 0.02 + 0.0005 * distance [km] (Section 3.7.1). These costs are valid for transport with a fully loaded open-sided lorry. When an open-sided lorry carries 40.0 tonnes and a tank lorry 36.5 tonnes, a difference of approx. 10% arises, and since the tank lorry is more complicated and therefore more expensive the costs for transport with a tank lorry were assumed to be 15% higher. Choices of transport distances for different transport are described above in Section 3.7.1. Transport costs [SEK/ha] could be calculated by multiplying product weight [kg/ha] and transport cost [SEK/kg product] (Tables 65 and 66).

If return load was taken, the transport cost [SEK/kg transported material] could be calculated as: 0.5 * (1 + share of return trips empty (Section 3.7.1)) * (0.02 + 0.0005 * distance [km]

(Section 3.7.1)). The way in which share of empty trips was calculated using figures and products transported is accounted for in Section 3.7.1.

If the share of the lorry's loading capacity used for transport [%] is less than 100% (Table 66) the transport cost [SEK/ha] is calculated as: product weight [kg/ha] * transport cost [SEK/kg transported material] / (share of the lorry's loading capacity used for transport [%] / 100).

Labour time [h/ha] for loading (Table 65 for rapeseed oil and RME and Table 66 for ethanol fuel) and unloading a lorry could be calculated as: time for loading and unloading [h] (see below) / (load on lorry [kg] (Table 75) / weight of product [kg/ha] (Tables 65 and 66)). For both an open-sided lorry and a tank lorry, the time for loading and unloading was assumed to be 1.5 hours. Exceptions are chemicals and enzymes for ethanol production (all scales) and chemicals for making the ethanol into a diesel fuel for medium- and small-scale plants where the time for loading and unloading was assumed to be 3.0 hours. This was because transport was assumed not only to be used for the transport in question and therefore correspondingly more work was required for the actual loading and unloading. If the lorry's loading capacity is not fully utilized (Table 66) the labour time for loading and unloading is calculated as: (time for loading and unloading [h] (see above) / (load on lorry [kg] (Table 75) / weight of product [kg/ha] (Tables 65 and 66))) / (share of the lorry's loading capacity used for transport [%] (Table 66) / 100).

The weight of each transported product on an area basis [kg/ha] is given in Table 65 for rapeseed oil and RME, and in Table 66 for ethanol fuel. The cost for the lorry transportation labour was assumed to be 180 SEK/h, the cost for an experienced machine operator in 2002 (estimated after SCB, 2003; Agriwise, 2003; and Henemo, 2002 and 2003). Then the labour part of the transportation cost [SEK/ha] could be calculated by multiplying the labour time [h/ha] by the labour cost [SEK/h] (Tables 65 and 66).

The total transport cost (Tables 65 and 66; and Tables 123-131) was obtained by adding the labour and transport costs.

Table 65. Costs of transport by lorry, production of rapeseed oil and RME

Type of plant and material transported		Loading and unloading		Transporting		Total
	Product weight [kg/ha]	Labour time [h/ha]	Labour cost [SEK/ha]	Transport cost [SEK/kg product]	Transport cost [SEK/ha]	transport cost [SEK/ha]
Small-scale plant:						
transport of methanol	83.1	0.00342	0.615	0.0863	7.2	7.8
transport of glycerine	79.7	0.00327	0.589	0.0863	6.9	7.5
Medium-scale plant:						
transport of methanol	91.7	0.00377	0.678	0.0863	7.9	8.6
transport of glycerine	87.9	0.00361	0.650	0.0863	7.6	8.2
transport of RME	802	0.0330	5.93	0.0270	21.7	27.6
transport of rapeseed oil	834	0.0343	6.17	0.0270	22.5	28.7
Large-scale plant:						
transport of seed	2470	0.0926	16.67	0.0548	135.3	152.0
transport of meal	1331	0.0499	8.99	0.0375	49.9	58.9
transport of methanol	120	0.00492	0.886	0.0863	10.3	11.2
transport of glycerine	115	0.00472	0.849	0.0863	9.9	10.8
transport of RME	1048	0.0431	7.75	0.0863	90.4	98.1
transport of rapeseed oil	1089	0.0448	8.06	0.0863	93.9	102.0

Table 66. Costs of transport by lorry, production of ethanol and ethanol fuel

Type of plant and material transported	Product weight [kg/ha]	Loading and unloading: Labour time [h/ha]	Loading and unloading: Labour cost [SEK/ha]	Transporting: Transport cost [SEK/kg product]	Transporting: Transport cost [SEK/ha]	Total transport cost [SEK/ha]	Share of the lorry's loading capacity used for transport [%]
Small-scale plant:							
transport of chemicals	32.2	0.00372	0.669	0.0750	3.7	4.4	65
transport of chemicals to make ethanol fuel	203.3	0.02345	4.222	0.0750	23.5	27.7	65
Medium-scale plant:							
transport of chemicals	32.2	0.00322	0.580	0.0750	3.2	3.8	75
transport of chemicals to make ethanol fuel	203.3	0.02228	4.010	0.0863	23.4	27.4	75
transport of ethanol fuel	2072	0.0852	15.33	0.0270	56.0	71.3	100
Large-scale plant:							
transport of chemicals	32.2	0.00294	0.529	0.0863	3.1	3.6	90
transport of chemicals to make ethanol fuel	203.3	0.00835	1.50	0.0863	17.5	19.0	100
transport of wheat	5900	0.2213	39.83	0.0630	371.5	411.4	
transport of distiller's waste	1892	0.07097	12.77	0.0375	71.0	83.7	
transport of ethanol fuel	2072	0.08516	15.33	0.0863	178.7	194.1	100

The fuel consumption [l/ha] (Tables 67 and 68) for tractor transport could be calculated as: ((fuel consumption, full load [g/tonkm] (Table 56) + share of return load empty (Section 3.7.1) * fuel consumption, empty [g/tonkm] (Table 56)) / fuel density (813 g/litre for MK1, see also Table 99)) * the yield [tonne/ha] (rapeseed 2470 kg/ha; meal (medium-scale) 1587 kg/ha; wheat 5900 kg/ha; or wet distiller's waste 18925 kg/ha) * the transport distance (7 km, Section 3.7.1). During transport of rapeseed, the wagons were fully loaded one way and empty 35.75% (see Section 3.7.1) of the return trips. During transport of meal, the return trips were fully used for transport of rapeseed (0% empty). During medium-scale production of ethanol fuel, the return transport was empty (100% empty) after transport of wheat and distiller's waste. Transport costs [SEK/ha] could be obtained by multiplying by the fuel price (5.70 SEK/l: *i.e.* what farmers paid for MK1 diesel oil in 2002 and 2003 (Henemo, 2002 and 2003)) (Tables 67 and 68).

Labour time was assumed to be 0.70 hours for loading and 0.30 hours for unloading, together 1.0 hour for rapeseed, meal and wheat. Labour time was assumed to be 0.50 hours for loading and 0.50 hours for unloading, together 1.0 hour for wet distiller's waste. Labour time for transport of seed 7 km and return at an average speed of 20 km/h and empty on 35.75% of the return trips (for explanation see above) gives: 7 km / 20 km/h + 0.3575 * 7 km / 20 km/h = 0.475 hours, with loading and unloading 1.475 hours. Calculated in the same way, the labour time for transporting (7 km): meal was 0.35 hours when no return trips were required (used for seed transport) and 1.35 hours with loading and unloading added; wheat 0.70 hours when return trips were included and 1.70 hours with loading and unloading added; and distiller's waste 0.70 hours when return trips were included and 1.70 hours with loading and unloading added. Labour time [h/ha] (Tables 67 and 68) could then be calculated as: (yield [kg/ha] (see above) / 20 000 kg load) * labour loading, unloading and transport [h] (see above). Use of machines [h/ha] (Table 70) is obtained if only transport time is included in the above calculations (of labour time).

The cost for the tractor transportation labour was assumed to be 180 SEK/h, the cost for an experienced machine operator in 2002 (estimated after SCB, 2003; Agriwise, 2003; and Henemo, 2002 and 2003). Then the labour part of the transportation cost [SEK/ha] could be calculated by multiplying (Tables 67-68) by the labour time [h/ha].

The calculations in Tables 69 and 70 are described in Section 3.4.5: Economics of rapeseed and wheat production. The same assumptions were deemed to be valid in these calculations. Here, calculations were only performed for machines used on the basis of farm size (75 ha). This was because using machines from the bigger farm would only have small or negligible effects on the production costs for rapeseed oil, RME and ethanol fuel. The use [h/ha] of the wagons in Table 70 is twice as big as the use of the tractor because 2 wagons were used and therefore the factor was multiplied by 2. The summed up values in Table 70 are used in Tables 67 and 68. Summed up values in Tables 67 and 68 are used for calculations in Tables 126-128.

Table 67. Costs of transport by tractor, production of rapeseed oil and RME

Factors of production	Transport of rapeseed			Transport of meal		
	Quantity [.../ha]	Price [SEK/...]	Cost [SEK/ha]	Quantity [.../ha]	Price [SEK/...]	Cost [SEK/ha]
Tractor fuel transport [litres]	0.44	5.70	2.53	0.23	5.70	1.32
Lubrication oil etc. tractive power, etc.[a]			0.38			0.20
Machinery maintenance			5.75			2.72
Machinery depreciation and interest			21.18			10.02
Tax and insurance, machines			0.25			0.12
Keeping area costs, machines			4.10			1.94
Sum costs (excl. labour)			34.19			16.32
Labour costs [h]	0.18	180	32.79	0.11	180	19.28
Sum costs (incl. labour)			66.98			35.60

[a] Lubrication oil costs was assumed to be 15% of fuel costs (Agriwise, 2002 and 2003).

Table 68. Costs of transport by tractor, production of ethanol and ethanol fuel

Factors of production	Transport of wheat			Transport of distiller's waste		
	Quantity […/ha]	Price [SEK/…]	Cost [SEK/ha]	Quantity […/ha]	Price [SEK/…]	Cost [SEK/ha]
Tractor fuel transport [litres]	1.42	5.70	8.12	4.57	5.70	26.04
Lubrication oil etc. tractive power, etc.[a]			1.22			3.91
Machinery maintenance			20.24			64.91
Machinery depreciation and interest			74.54			239.09
Tax and insurance, machines			0.88			2.82
Keeping area costs, machines			14.42			23.99
Sum costs (excl. labour)			119.41			360.75
Labour costs [h]	0.50	180	90.27	1.61	180	289.55
Sum costs (incl. labour)			209.68			650.30

[a] Lubrication oil costs was assumed to be 15% of fuel costs (Agriwise, 2002 and 2003).

Table 69. Costs of transport by tractor, basic data for transportation of rapeseed, meal, wheat and distiller's waste used for medium-scale plants in economic calculation, part 1

Machines, used for the transportation	Repl. value [SEK] (A)[a]	Residual value[b]	Maintenance cost (B)[c]	Length of life [years] (C)	Annual use [hours] (D)	Keeping area [m^2]
Tractor, 66 kW, 4WD	400000	100000	0.07	12	550	8
Rapeseed, meal and wheat:						
Tipping trailer, 10 tonnes (*2)	70000	17500	0.50	15	50	14
Distiller's waste:						
Tank wagon, 20 tonnes	140000	35000	0.50	15	50	14

[a] Replacement value (Henemo, 2002).
[b] Residual value assumed to be 25% of the replacement value.
[c] Maintenance cost (Henemo, 2002 and 2003) [SEK/h and 1000 SEK replacement value] (B).

Table 70. Costs of transport by tractor, basic data for transportation of rapeseed, meal, wheat and distiller's waste used for medium-scale plants in economic calculation, part 2

Machines, used for the transportation	Use [h/ha]	Maint. cost [SEK/ha]	Keeping area costs [SEK/ha]	Tax and insurance [SEK/ha][a]	Annual capital cost [SEK/ha]
Transport of rapeseed:					
Tractor, 66 kW, 4WD.	0.06	1.6	0.15	0.09	4.8
Tipping trailer, 10 tonnes (*2).	0.12	4.1	3.94	0.16	16.4
Sum		5.8	4.10	0.25	21.2
Transport of meal:					
Tractor, 66 kW, 4WD.	0.03	0.8	0.07	0.04	2.3
Tipping trailer, 10 tonnes (*2).	0.06	1.9	1.87	0.08	7.8
Sum		2.7	1.94	0.12	10.0
Transport of wheat:					
Tractor, 66 kW, 4WD.	0.21	5.8	0.54	0.30	16.8
Tipping trailer, 10 tonnes (*2).	0.41	14.5	13.88	0.58	57.7
Sum		20.2	14.42	0.88	74.5
Transport of distiller's waste:					
Tractor, 66 kW, 4WD.	0.66	18.5	1.73	0.96	53.9
Tank wagon, 20 tonnes.	0.66	46.4	22.26	1.85	185.2
Sum		64.9	23.99	2.82	239.1

[a] Tax and insurance assumed to be 0.2% of replacement value for tractors and threshing machines and 0.1% of the replacement value for other machines (Henemo, 2002).

3.7.3 *Derivation of transportation formulas*

The transport distances were estimated with equations according to Overend (1982) from the chosen areas (40, 1000 and 50 000 ha) and the annual yield. The collection areas were assumed to be circular. For areas up to 300 ha, 10% of the ground was assumed to be cultivated with rapeseed or ethanol wheat; up to 5000 ha, 5% of the ground was assumed to be cultivated with rapeseed or ethanol wheat; and above 5000 ha, 1% of the ground was assumed to be cultivated with rapeseed or ethanol wheat. The reduction in share of total area with rapeseed or wheat for larger plants was a result of the increased share of non-farm area as the territory included was enlarged. On farm level, still one seventh of the cultivated area was rapeseed or ethanol wheat. The average transport distance was estimated using Equations 8-12:

where:

$$\overline{R} = \tfrac{2}{3} * R * \tau \qquad (8)$$

and

$$R = \sqrt{\frac{n * A}{\pi}} \text{ (km)} \qquad (9)$$

and

$$A = \frac{p * 330\,(\text{days})}{100 * M * \phi} = \frac{P}{100 * M * \phi} \qquad (10)$$

and

$$p = \frac{A_{crop} * M}{330} \qquad (11)$$

which makes:

$$\overline{R} = \tfrac{2}{3} * \tau * \sqrt{\frac{n}{\phi} * \frac{A_{crop}}{\pi * 100}} \qquad (12)$$

when Equations 8-11 are combined.

R = Maximum extent (km).
$\overline{R}$ = Average haulage distance (km).
τ = Tortuosity factor *i.e.* ratio of actual distance travelled to line of sight distance. The tortuosity factor has a value of about 1.3 where the roads make a pattern with straight angles, which was assumed to be the situation in this study.
n = Assuming a 'pie slice' shape to the harvest area with the processing plant at the apex, n is the number of 'slices' to complete a circular geometry (in this study n = 1).
A = Area (km^2).
A_{crop} = Area of the studied crop (ha).
ø = Fraction of A planted with the crop.
M = Biomass productivity (harvest) (tonne / (ha * year).
p = Plant size (tonne / day).
P = Plant size (tonne / year).

Calculations with Equation 12 above gave for 40 ha (small-scale) a transport distance of 1 km, assumed to be the distance the seed was transported from field to farm (in this study). For 1000 ha a transport distance of 6.9 km was obtained and therefore 7 km was assumed to be the distance for the medium-scale plants. For the large-scale plants (50 000 ha) a transport distance of 109.3 km was obtained and therefore 110 km was assumed to be the transport distance for these plants in this study.

3.8 Machinery and manufacturing

Energy and material consumption (weight) for manufacturing of agricultural machines, transport lorries, oil extraction, transesterification and ethanol fuel production machinery with spare parts was calculated after data from Pimentel (1980) and Bowers (1992), revised by Börjesson (1994).

The emissions for manufacturing and use of the machines and buildings could be calculated if life cycle data were available on manufacturing and use of the machines. Unfortunately no such data were available for this study, but data on the energy requirement for machines were available and used (Pimentel, 1980; Bowers, 1992; Börjesson, 1994) and also for building material (Spugnoli *et al*., 1992). In this study, this energy was assumed to be electricity. In

Tables 71-74 and 76-77 and 85-90, the requirement of machines on an area basis [kg/ha] was also accounted for to make it possible for a reader with access to life cycle machinery data to easily understand its importance.

The energy for manufacturing the machines and the buildings was assumed to be produced by Swedish electricity (Uppenberg *et al.*, 2001) in the basic scenario and in the scenario analysis with fossil fuel electricity (for description see Section 3.6.1).

- Emissions values on an area basis [g/ha] (Tables 78-79 and 91-92) were obtained when the energy demand on an area basis [MJ/ha] (Tables 71-74 (agricultural machines and fertiliser transport), Tables 76-77 (transport), Tables 85-87 (machinery) and Tables 88-90 (buildings, when values for wood and concrete is added)) were multiplied by emissions values [g/MJ_{el}] (Table 49) for the production of electricity.
- Energy requirement values on an area basis [MJ/ha] (Tables 78-79 and 91-92) were obtained when the energy demand on an area basis [MJ/ha] (Tables 71-74 (agricultural machines and fertiliser transport), Tables 76-77 (transport), Tables 85-87 (machinery) and Tables 88-90 (buildings, when values for wood and concrete is added)) was multiplied by energy requirement values [MJ/MJ_{el}] (Table 49) for the production of electricity.

Energy requirement for production of raw material for agricultural machines was estimated to 21.6 MJ/kg (Börjesson, 1994) (Tables 71-73). The same was assumed for lorries (Table 75) and machines, machinery equipment and tanks for oil extraction (Table 82), transesterification (Table 83) and ethanol production (Table 84).

The energy requirement for manufacturing of agricultural machines (tied-up energy) (Tables 71-73) was estimated at: 9.72 MJ/kg machine for tractors; 8.28 MJ/kg machine for threshing machines; 5.76 MJ/kg machine for ploughs; 5.40 MJ/kg machine for other tilling machines; and 4.68 MJ/kg machine for seed drills, sprayers, fertiliser spreaders, front-loaders and wagons (Pimentel, 1980 and Bowers, 1992, revised by Börjesson, 1994). For a lorry with a wagon 24 m long, the energy demand was assumed to be the average between tractors and wagons: 7.20 MJ/kg machine (Table 75). For oil presses the energy requirement was assumed to be 9.72 MJ/kg machine (Table 82) (20% of the total machinery weight for medium- and large-scale plants) as for tractors because both mainly consist of steel and cast iron. For equipment for grain drying (Tables 71 and 73), oil seed and expeller handling and the sedimentation tanks, the energy requirement was assumed to be 4.68 MJ/kg machine (Table 82) as for seed drills, sprayers, fertiliser spreaders, front-loaders and wagons. They consist mainly of the same materials. Equipment for transesterification (Table 83) or ethanol production (Table 84) was assumed to consist of 25% heavier machines that like *e.g.* tractors require 9.72 MJ/kg machine for manufacturing and of 75% lighter machines that like *e.g.* wagons require 4.68 MJ/kg machine for manufacturing.

Energy in spare parts was calculated using the Equation 13 (Pimentel, 1980 and Bowers, 1992, revised by Börjesson, 1994):

$$EE_p = EE_{am} * 1/3 * M_{TAR} * 1.5 \qquad (13)$$

where:
EE_p = embodied energy in parts (MJ);
EE_{am} = embodied energy in assembled machine (MJ) (energy for raw material and manufacturing);

1/3 = only 1/3 of the repair cost is assumed to be spare parts, the remaining 2/3 is cost of labour and not included here;
M_{TAR} = multiplier for total accumulated repairs;
1.5 = factor used to get better agreement with the conditions of today, since the above formula had been proven to give too low values.
Multiplier for total accumulated repair (M_{TAR}) according to Pimentel (1980) that is the proportion between the cost of each machine new and the repair cost during the life time of the machine (Tables 71-73): tilling machines, M_{TAR} = 0.93; fertiliser spreaders, M_{TAR} = 0.91; tractors, M_{TAR} = 0.82; seed drills, sprayers, wagons, M_{TAR} = 0.76; threshing machines, front-loaders, M_{TAR} = 0.46. For a lorry with a wagon 24 m long (Table 75), M_{TAR} was assumed to be the average between tractors and wagons: M_{TAR} = 0.79. For oil presses the multiplier for total accumulated repair energy requirement was assumed as for heavy machines *e.g.* tractors: M_{TAR} = 0.82. For grain drying (Tables 71 and 73): M_{TAR} = 0.76 as for *e.g.* seed drills. For equipment for oil seed and expeller handling and the sedimentation tanks (Table 82): M_{TAR} = 0.46 as for *e.g.* front-loaders and threshing machines. For transesterification (Table 83) and ethanol production (Table 84) equipment, the multiplier for total accumulated repair (M_{TAR}) was assumed to be M_{TAR} = 0.46 as for *e.g.* front-loaders and threshing machines. They consist of similar materials.

3.8.1 Agricultural machines and transport

For calculation of the emissions and energy demand tied-up to machinery (agricultural etc.) the following values are important (Tables 71-74):

- Input machinery [kg/ha] was calculated as: use [h/ha] * weight [kg] / durability [h].
- Machine energy [MJ/ha] was calculated as: use [h/ha] * total energy demand [MJ/kg machine] * weight [kg] / durability [h].

The calculation of total tied-up energy in agricultural machines [MJ/kg machine and MJ/ha] for production of rapeseed and wheat including hot air drying is accounted for in Tables 71 and 73 respectively. Calculation of total tied-up energy in machines [MJ/kg machine and MJ/ha] for transporting fertilisers to the farm is accounted for in Table 72. In the basic scenario the energy required to manufacture those machines was assumed to be Swedish electricity with 5% grid losses [g/MJ_{el} or MJ/MJ_{el}] (Table 49). Calculations of area emissions and energy requirement (Tables 78-79) are described above.

Table 71. Calculation of tied-up energy in machines for production of rapeseed (inputs kg/ha: Norén et al., 1999; Hansson & Mattsson, 1999; SLU, 1989; Bernesson, 1993; Sonesson, 1993; and MJ/ha: Börjesson, 1994; Pimentel, 1980)

Machinery	Use	Weight	Durability	Input	Tied-up energy [MJ/kg machine] for:				Energy
	[h/ha]	[kg]	[h]	[kg/ha]	Raw material	Manu-facture	Spare parts	Total	[MJ/ha]
Tractor, 52 kW[a]	0.98	3500	10000	0.34	21.6	9.72	12.84	44.16	15.1
Tractor, 66 kW[a]	3.54	5000	10000	1.77	21.6	9.72	12.84	44.16	78.2
Plough	2.06	1200	3000	0.83	21.6	5.76	12.72	40.08	33.1
Harrow, 2 times[a]	0.54	1700	1000	0.92	21.6	5.40	12.56	39.56	36.4
Seed drill[a]	0.45	800	1200	0.30	21.6	4.68	9.99	36.27	11.0
Cambridge roller	0.12	2500	1000	0.29	21.6	5.40	12.56	39.56	11.5
Fertiliser spreader, 2 times	0.26	1500	1000	0.39	21.6	4.68	11.96	38.24	14.7
Sprayer, 2 times	0.15	600	450	0.20	21.6	4.68	9.99	36.27	7.3
Threshing machine	1.36	6000	2500	3.27	21.6	8.28	6.87	36.75	120.3
Disc harrow, 1 time[a]	0.77	2500	3500	0.55	21.6	5.40	12.56	39.56	21.8
Tipping trailer (field – farm)	0.12	3000	1000	0.36	21.6	4.68	9.99	36.27	12.9
Front-loader	0.05	560	300	0.09	21.6	4.68	6.04	32.32	3.0
Hot air drier	3.20	4150	10000	1.33	21.6	4.68	9.99	36.27	48.2
Air heater	3.20	850	5000	0.54	21.6	4.68	9.99	36.27	19.7
Sum				11.18					433.2

[a] Machines used for resowing at 10% outwintering.

Table 72. Calculation of tied-up energy in machines for transport of fertiliser to the farm (inputs kg/ha: Norén et al., 1999; Hansson & Mattsson, 1999; SLU, 1989; Bernesson, 1993; Sonesson, 1993; and MJ/ha: Börjesson, 1994; Pimentel, 1980)

Machinery	Use	Weight	Durability	Input	Tied-up energy [MJ/kg machine] for:				Energy
	[h/ha]	[kg]	[h]	[kg/ha]	Raw material	Manu-facture	Spare parts	Total	[MJ/ha]
Rapeseed:									
Tractor, 66 kW	0.054	5000	10000	0.027	21.6	9.72	12.84	44.16	1.20
2 * Tipping trailer	0.040	6000	1000	0.242	21.6	4.68	9.99	36.27	8.77
Front-loader	0.014	560	300	0.026	21.6	4.68	6.04	32.32	0.85
Sum				0.295					10.82
Wheat:									
Tractor, 66 kW	0.045	5000	10000	0.023	21.6	9.72	12.84	44.16	1.00
2 * Tipping trailer	0.033	6000	1000	0.201	21.6	4.68	9.99	36.27	7.28
Front-loader	0.012	560	300	0.022	21.6	4.68	6.04	32.32	0.71
Sum				0.245					8.98

Table 73. Calculation of tied-up energy in machines for production of wheat (inputs kg/ha: Norén et al., 1999; Hansson & Mattsson, 1999; SLU, 1989; Bernesson, 1993; Sonesson, 1993; and MJ/ha: Börjesson, 1994; Pimentel, 1980)

Machinery	Use	Weight	Durability	Input	Tied-up energy [MJ/kg machine] for:				Energy
	[h/ha]	[kg]	[h]	[kg/ha]	Raw material	Manu-facture	Spare parts	Total	[MJ/ha]
Tractor, 52 kW[a]	1.02	3500	10000	0.36	21.6	9.72	12.84	44.16	15.7
Tractor, 66 kW[a]	3.65	5000	10000	1.82	21.6	9.72	12.84	44.16	80.5
Plough	2.06	1200	3000	0.83	21.6	5.76	12.72	40.08	33.1
Harrow, 2 times[a]	0.52	1700	1000	0.88	21.6	5.40	12.56	39.56	34.8
Seed drill[a]	0.43	800	1200	0.29	21.6	4.68	9.99	36.27	10.5
Cambridge roller	0.12	2500	1000	0.29	21.6	5.40	12.56	39.56	11.5
Fertiliser spreader, 2 times	0.26	1500	1000	0.39	21.6	4.68	11.96	38.24	14.7
Sprayer, 2 times	0.21	600	450	0.28	21.6	4.68	9.99	36.27	10.2
Threshing machine	1.36	6000	2500	3.27	21.6	8.28	6.87	36.75	120.3
Disc harrow, 1 time[a]	0.74	2500	3500	0.53	21.6	5.40	12.56	39.56	20.8
Tipping trailer (field - farm)	0.28	3000	1000	0.84	21.6	4.68	9.99	36.27	30.5
Front-loader	0.05	560	300	0.09	21.6	4.68	6.04	32.32	3.0
Hot air drier	7.70	4150	10000	3.20	21.6	4.68	9.99	36.27	115.9
Air heater	7.70	850	5000	1.31	21.6	4.68	9.99	36.27	47.5
Sum				14.37					549.0

[a] Machines used for resowing at 5% outwintering.

At medium-scale extraction or ethanol production, the rapeseed or wheat respectively was transported the 7 km to the extraction or ethanol production plant by tractor transport. The meal from the oil extraction was transported back on the return trip if there was enough meal to fill up a transport, which was a tractor pulling two wagons with a total load of 20 metric tonnes and the average speed was assumed to be 20 km/h. The wet distiller's waste was transported back to the farm with a tractor pulling a tank wagon with a total load of 20 metric tonnes and the average speed was assumed to be 20 km/h.

- Total time for the rapeseed transport (including empty return trips): (rapeseed transport + share of return transport empty) * (distance / speed): (1 + (1 – 1587 kg meal/ha / 2470 kg seed/ha)) * 7 km / 20 km/h = 0.475 hours. When this time was divided by the area from which one tractor-load carried (20 tonnes / 2.47 ton rapeseed/ha), the time during which the machines were used for transporting seed for 1 hectare was obtained (0.059 hours/ha) (see Tables 74 and 76).
- Total time for meal transport: 7 km / 20 km/h = 0.35 hours. When this time was divided by the area from which one tractor-load carried (20 tonnes / 1.587 tonne meal/ha), the time during which the machines were used for transporting seed for 1 hectare was obtained (0.028 hours/ha) (see Tables 74 and 76).
- Total time for the wheat transport (including empty return trips): (wheat transport + return transport empty) * (distance / speed): 2 * 7 km / 20 km/h = 0.70 hours. When this time was divided by the area from which one tractor-load carried (20 tonnes / 5.90 tonne wheat/ha), the time during which the machines were used for transporting wheat for 1 hectare was obtained (0.2065 hours/ha) (see Tables 74 and 77).

- Total time for the transport of wet distiller's waste (including empty return trips): (distiller's waste transport + return transport empty) * (distance / speed): 2 * 7 km / 20 km/h = 0.70 hours. When this time was divided by the area from which one tractor-load carried (20 tonnes / 18.925 tonne wet distiller's waste/ha) the time during which the machines were used for transporting wheat for 1 hectare was obtained (0.6624 hours/ha) (see Tables 74 and 77).

Table 74. Calculation of tied-up energy in machines for tractor transportation (inputs kg/ha: Norén et al., 1999; Hansson & Mattsson, 1999; SLU, 1989; Bernesson, 1993; Sonesson, 1993; and MJ/ha: Börjesson, 1994; Pimentel, 1980)

Machinery	Use	Weight	Durability	Input	Tied-up energy [MJ/kg machine] for:				Machine energy
	[h/ha]	[kg]	[h]	[kg/ha]	Raw material	Manu-facture	Spare parts	Total	[MJ/ha]
Medium-scale transport of rapeseed:									
Tractor, 66 kW	0.059	5000	10000	0.029	21.6	9.72	12.84	44.16	1.30
2 * Tipping trailer (3000 kg each)	0.059	6000	1000	0.352	21.6	4.68	9.99	36.27	12.77
Total machinery, transport of rapeseed				0.381					14.06
Medium-scale transport of meal:									
Tractor, 66 kW	0.028	5000	10000	0.014	21.6	9.72	12.84	44.16	0.61
2 * Tipping trailer (3000 kg each)	0.028	6000	1000	0.167	21.6	4.68	9.99	36.27	6.04
Total machinery, transport of meal				0.181					6.66
Medium-scale transport of wheat:									
Tractor, 66 kW	0.207	5000	10000	0.103	21.6	9.72	12.84	44.16	4.56
2 * Tipping trailer (3000 kg each)	0.207	6000	1000	1.239	21.6	4.68	9.99	36.27	44.93
Total machinery, transport of wheat				1.342					49.49
Medium-scale transport of distiller's waste:									
Tractor, 66 kW	0.662	5000	10000	0.331	21.6	9.72	12.84	44.16	14.63
Tank wagon (6000 kg)	0.662	6000	1000	3.974	21.6	4.68	9.99	36.27	144.13
Total machinery, transport of distiller's waste				4.305					158.75

During the transport by lorry the average speed was assumed to be 70 km/h. The distance was 110 km for transport of methanol, glycerine, chemicals for ethanol production and chemicals to make ethanol into a legal diesel fuel independent of plant scale. The distance was also 110 km for transport of rapeseed, meal, rapeseed oil, RME, wheat, distiller's waste, and ethanol fuel to/from the large-scale plant and 7 km for transport of rapeseed oil, RME and ethanol fuel from the medium-scale plant. The time for the transport was:

- 2 * 110 km / 70 km/h = 3.14 hours for transport of methanol, glycerine, chemicals for ethanol production and chemicals to make ethanol into a legal diesel fuel for all plant sizes; this transport time was also valid for rapeseed oil, RME and ethanol fuel transport from large-scale plants.
- 2 * 7 km / 70 km/h = 0.20 hours for transport of rapeseed oil, RME and ethanol fuel from medium-scale plants.

- (1 + (1 – 1331 kg meal/ha / 2470 kg seed/ha)) * 110 km / 70 km/h = 2.30 hours (seed transport + share of return transport empty) * (distance / speed) for transport of rapeseed during large-scale extraction (including empty return trips).
- (1 + (1 – 1892 kg meal/ha / 5900 kg seed/ha)) * 110 km / 70 km/h = 2.64 hours for transport of wheat during large-scale ethanol fuel production (including empty return trips).
- 110 km / 70 km/h = 1.57 hours for large-scale meal and distiller's waste transport.

Calculation of the other parameters in Tables 76 and 77:

- The distance travelled per area basis (distance input [km/ha]) was calculated as: distance [km] (one way and often (+) also return: see above and Section 3.7.1) * product weight [tonne/ha] (Tables 65 and 66) / lorry max load [tonne] (Table 75) (type of lorry used: see Tables 76-77).
- The distance travelled per area basis (distance input [km/ha], Table 77) for tied-up energy in transportation of chemicals for production of ethanol and to make the ethanol into a legal diesel fuel was calculated as: (the distance [km] (one way and (+) return: see above) * product weight [tonne/ha] (Table 66) / lorry max load [tonne] (Table 75) (used type of lorry: see Table 77)) / (share of capacity utilized value [%] (Table 77) / 100). Utilized load capacity during transport and its reasons is explained in Section 3.7.1
- Lorry time input on an area basis (time input [hours/ha]) was calculated as: time for transport [hours] (see above) * product weight [tonne/ha] (Tables 65 and 66) / lorry max load [tonne] (Table 75). For tractor transport see calculation description above and Table 74.
- Lorry time input on an area basis (time input [hours/ha], Table 77) for tied-up energy in transportation of chemicals for production of ethanol and to make the ethanol into a legal diesel fuel was calculated as: time for transport [hours] (see above) * (product weight [tonne/ha] (Table 66) / lorry max load [tonne] (Table 75)) / (share of capacity utilized value [%] (Table 77) / 100).
- Machine input on an area basis [kg/ha] was calculated as: distance input [km/ha] (Tables 76 and 77) * input [kg/km] (Table 75). For tractor transport see calculation description above and Table 74.
- Machine energy on an area basis [MJ/ha] was calculated as: distance input [km/ha] (Tables 76 and 77) * machine energy [MJ/km] (Table 75). For tractor transport see calculation description above and Table 74.

Table 75. Conditions for the two types of lorries for calculation of tied-up energy in machines, after Berggren (1999), Börjesson, (1994) and Pimentel (1980)

Machinery	Max load	Weight	Durability	Input	Tied-up energy [MJ/kg machine] for:				Machine energy	Machine energy
	[tonne]	[tonne]	[km]	[kg/km]	Raw material	Manu-facture	Spare parts	Total	[MJ/km]	[MJ/tonkm]
Tank lorry	36.5	23.5	1200000	0.0196	21.6	7.20	11.38	40.18	0.787	0.022
Open-sided lorry	40.0	20.0	1200000	0.0167	21.6	7.20	11.38	40.18	0.670	0.017

Table 76. Some area-based data for the lorry and tractor transport during production of rapeseed oil and RME

Type of transport and vehicle	Distance input [km/ha]	Time input [hours/ha]	Machine input [kg/ha]	Machine energy [MJ/ha]
Small-scale:				
methanol, tank lorry	0.50	0.0072	0.0098	0.39
glycerine, tank lorry	0.48	0.0069	0.0094	0.38
Medium-scale:				
methanol, tank lorry	0.55	0.0079	0.0108	0.43
glycerine, tank lorry	0.53	0.0076	0.0104	0.42
RME, tank lorry	0.31	0.0044	0.0060	0.24
rapeseed oil, tank lorry	0.32	0.0046	0.0063	0.25
rapeseed, tractor, two wagons		0.0587	0.3814	14.06
meal, tractor, two wagons		0.0278	0.1805	6.66
Large-scale:				
methanol, tank lorry	0.72	0.0103	0.0141	0.57
glycerine, tank lorry	0.69	0.0099	0.0135	0.54
RME, tank lorry	6.32	0.0902	0.1237	4.97
rapeseed oil, tank lorry	6.57	0.0938	0.1286	5.17
rapeseed, open-sided lorry	9.92	0.1418	0.1654	6.65
meal, open-sided lorry	3.66	0.0523	0.0610	2.45
Small-scale, total: rapeseed oil		0	0	0
RME		0.0140	0.0192	0.77
Medium-scale, total: rapeseed oil		0.0910	0.5682	20.97
RME		0.1063	0.5891	21.81
Large-scale, total: rapeseed oil		0.2879	0.3550	14.26
RME		0.3045	0.3778	15.18
Small-scale soymeal, open-sided lorry	4.11	0.1174	0.0685	2.75
Medium-scale soymeal, open-sided lorry	4.00	0.1142	0.0666	2.68
Large-scale soymeal, open-sided lorry	3.30	0.0941	0.0549	2.21

Table 77. Some area-based data for the lorry and tractor transport during production of ethanol fuel

Type of transport and vehicle	Distance input	Time input	Machine input	Machine energy	Share of capacity utilized
	[km/ha]	[hours/ha]	[kg/ha]	[MJ/ha]	[%]
Small-scale:					
production chemicals, open-sided lorry	0.27	0.0039	0.0045	0.18	65
fuel chemicals, open-sided lorry	1.72	0.0246	0.0287	1.15	65
Medium-scale:					
production chemicals, open-sided lorry	0.24	0.0034	0.0039	0.16	75
fuel chemicals, tank lorry	1.63	0.0233	0.0320	1.29	75
wheat, tractor, two wagons		0.2065	1.3423	49.49	100
distiller's waste, tractor, tank wagon		0.6624	4.3053	158.75	100
ethanol fuel, tank lorry	0.79	0.0114	0.0156	0.63	100
Large-scale:					
production chemicals, tank lorry	0.22	0.0031	0.0042	0.17	90
fuel chemicals, tank lorry	1.23	0.0175	0.0240	0.96	100
wheat, open-sided lorry	27.25	0.3892	0.4541	18.24	100
distiller's waste, open-sided lorry	5.20	0.0743	0.0867	3.48	100
ethanol fuel, tank lorry	12.49	0.1784	0.2446	9.83	100
Small-scale, total		0.0285	0.0332	1.33	
Medium-scale, total		0.9069	5.6991	210.32	
Large-scale, total		0.6626	0.8137	32.69	
Small-scale soymeal, open-sided lorry	4.71	0.1345	0.0784	3.15	100
Medium-scale soymeal, open-sided lorry	4.71	0.1345	0.0784	3.15	100
Large-scale soymeal, open-sided lorry	4.71	0.1345	0.0784	3.15	100

The emissions and energy requirement values for machinery inputs for agricultural operations and for the transport, if the machines were produced with energy originating in Swedish electricity (Tables 78 and 79, see also Tables A1-A22, Appendices 1-2) could be calculated as: machine energy [MJ/ha] (Tables 76 and 77) * emissions production of electricity [g/MJ_{el}] (electricity produced with 5% grid losses: Table 49). In a scenario analysis the influence of producing the machines with electricity with a large proportion of fossil energy was studied.

Table 78. Emissions and energy requirements for production of machinery for agricultural machines and transport, during production of rapeseed oil and RME, if assumed to be produced with Swedish electricity

Type of machines	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	Particles	Input energy
	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[MJ/ha]
Agricultural operations	3567	8.19	1.32	22.3	6.82	5.91	0.100	0.323	1.14	886
Fertiliser transport	89.1	0.205	0.0330	0.557	0.170	0.148	0.00250	0.00807	0.0284	22.1
Small-scale:										
transport of methanol	3.25	0.00745	0.00120	0.0203	0.00621	0.00538	0.0000911	0.000294	0.00103	0.806
transport of glycerine	3.11	0.00714	0.00115	0.0194	0.00595	0.00516	0.0000873	0.000282	0.000992	0.772
transport of soymeal	22.6	0.0520	0.00837	0.142	0.0433	0.0375	0.000635	0.00205	0.00722	5.62
Medium-scale:										
transport of rapeseed	116	0.266	0.0428	0.724	0.222	0.192	0.00325	0.0105	0.0369	28.8
transport of meal	54.8	0.126	0.0203	0.342	0.105	0.0909	0.00154	0.00496	0.0175	13.6
transport of rapeseed oil	2.07	0.00475	0.000766	0.0129	0.00396	0.00343	0.0000581	0.000188	0.000660	0.514
transport of methanol	3.58	0.00822	0.00132	0.0224	0.00685	0.00594	0.000100	0.000324	0.00114	0.889
transport of glycerine	3.43	0.00787	0.00127	0.0214	0.00656	0.00569	0.0000962	0.000311	0.00109	0.852
transport of RME	1.99	0.00457	0.000737	0.0125	0.00381	0.00330	0.0000559	0.000180	0.000635	0.495
transport of soymeal	22.0	0.0506	0.00815	0.138	0.0422	0.0365	0.000618	0.00200	0.00703	5.47
Large-scale:										
transport of rapeseed	54.7	0.126	0.0202	0.342	0.105	0.0907	0.00153	0.00495	0.0174	13.6
transport of meal	20.2	0.0463	0.00746	0.126	0.0386	0.0335	0.000566	0.00183	0.00644	5.01
transport of rapeseed oil	42.5	0.0976	0.0157	0.266	0.0814	0.0705	0.00119	0.00385	0.0136	10.6
transport of methanol	4.68	0.0107	0.00173	0.0292	0.00895	0.00776	0.000131	0.000424	0.00149	1.16
transport of glycerine	4.48	0.0103	0.00166	0.0280	0.00857	0.00743	0.000126	0.000406	0.00143	1.11
transport of RME	40.9	0.0939	0.0151	0.256	0.0783	0.0678	0.00115	0.00370	0.0130	10.2
transport of soymeal	18.2	0.0417	0.00672	0.114	0.0348	0.0301	0.000510	0.00164	0.00579	4.51
Small-scale, total[a]:										
rapeseed oil	0	0	0	0	0	0	0	0	0	0
RME	6.4	0.0146	0.0024	0.040	0.0122	0.0105	0.00018	0.00058	0.0020	1.6
Medium-scale, total[a]:										
rapeseed oil	172.7	0.3964	0.0639	1.079	0.3303	0.2863	0.00484	0.01563	0.0551	42.9
RME	179.6	0.4123	0.0664	1.122	0.3436	0.2978	0.00504	0.01626	0.0573	44.6
Large-scale, total[a]:										
rapeseed oil	117.4	0.2696	0.0434	0.734	0.2246	0.1947	0.00329	0.01063	0.0374	29.2
RME	125.0	0.2869	0.0462	0.781	0.2391	0.2072	0.00351	0.01132	0.0398	31.0

[a] Physical allocation, fuel production.

Table 79. Emissions and energy requirements for production of machinery for agricultural machines and transport, during production of ethanol fuel, if assumed to be produced with Swedish electricity

Type of machines	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	Particles	Input energy
	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[MJ/ha]
Agricultural operations	4520	10.4	1.67	28.2	8.65	7.49	0.127	0.409	1.44	1123
Fertiliser transport	73.9	0.170	0.0273	0.462	0.141	0.123	0.00207	0.00669	0.0236	18.4
Small-scale:										
transport of chemicals for ethanol production	1.50	0.00345	0.000556	0.00939	0.00287	0.00249	0.0000422	0.000136	0.000479	0.373
transport of chemicals to make ethanol into a legal diesel fuel	9.48	0.0218	0.00351	0.0593	0.0181	0.0157	0.000266	0.000859	0.00302	2.36
transport of soymeal	25.95	0.0596	0.00960	0.162	0.0496	0.0430	0.000728	0.00235	0.00827	6.45
Medium-scale:										
transport of chemicals for ethanol production	1.30	0.00299	0.000482	0.00814	0.00249	0.00216	0.0000365	0.000118	0.000415	0.323
transport of chemicals to make ethanol into a legal diesel fuel	10.58	0.0243	0.00391	0.0661	0.0202	0.0175	0.000297	0.000958	0.00337	2.63
transport of wheat	408	0.935	0.151	2.55	0.780	0.676	0.0114	0.0369	0.130	101
transport of distiller's waste	1307	3.00	0.483	8.17	2.50	2.17	0.0367	0.118	0.417	325
transport of ethanol fuel	5.15	0.0118	0.00190	0.0322	0.00985	0.00854	0.000144	0.000466	0.00164	1.28
transport of soymeal	25.95	0.0596	0.00960	0.162	0.0496	0.0430	0.000728	0.00235	0.00827	6.45
Large-scale:										
transport of chemicals for ethanol production	1.40	0.00321	0.000517	0.00873	0.00267	0.00232	0.0000392	0.000127	0.000446	0.347
transport of chemicals to make ethanol into a legal diesel fuel	7.94	0.0182	0.00294	0.0496	0.0152	0.0132	0.000223	0.000719	0.00253	1.97
transport of wheat	150	0.345	0.0556	0.939	0.287	0.249	0.00421	0.0136	0.0479	37.3
transport of distiller's waste	28.7	0.0659	0.0106	0.179	0.0549	0.0476	0.000805	0.00260	0.00915	7.13
transport of ethanol fuel	80.9	0.186	0.0299	0.506	0.155	0.134	0.00227	0.00733	0.0258	20.1
transport of soymeal	25.95	0.0596	0.00960	0.162	0.0496	0.0430	0.000728	0.00235	0.00827	6.45
Small-scale, total[a]	11.0	0.025	0.0041	0.069	0.021	0.018	0.00031	0.00099	0.0035	2.7
Medium-scale, total[a]	1731.8	3.975	0.6404	10.821	3.312	2.871	0.04858	0.15679	0.5521	430.1
Large-scale, total[a]	269.17	0.618	0.0995	1.682	0.515	0.446	0.00755	0.02437	0.0858	66.8

[a] Physical allocation, fuel production.

The reasons that the machinery contribution was higher for medium-scale transport of rapeseed, meal, wheat and distiller's waste (Tables 76-79) in comparison to large-scale transport were the following (see also Tables 57-64):

1) Medium-scale transport was made with farm tractors and wagons that during their lifetime (especially the wagons) are used much less than the lorries, which are used only for transport every day during their life time;

2) The amount of wet distiller's waste (18925 kg/ha) transported was much higher from medium-scale plants than the amount of dried distiller's waste (1892 kg/ha) transported from large-scale plants;
3) During the medium-scale transport of wheat and distiller's waste, no return load was taken because wet distiller's waste requires to be transported in a tank wagon. During large-scale transport of wheat, dried distiller's waste can be transported on the return trip. This makes the advantage even greater for the tied-up machine energy in large-scale transport of wheat and distiller's waste.

The reason that the area emissions (Table 79) and machinery inputs (Table 77) sometimes rose when transport of chemicals for production of ethanol or transport of chemicals for making ethanol into a legal diesel fuel was compared with a larger-scale plant is that a tank lorry, which is heavier (Table 75) and therefore carries less load, was used instead of an open-sided lorry.

3.8.2 Machines and buildings

This section deals with an estimation of energy and emissions bound to the machinery and buildings used to produce rapeseed oil, RME and ethanol fuel. The aim was to estimate the magnitude of these values (no exact values) to evaluate whether they have any importance for the production of the fuels studied. To do this, the approximate weight of the machines and buildings had to be estimated. From these weights it was possible to calculate the energy requirement and emissions from the manufacturing (construction).

To estimate the weight of oil extraction, transesterification and ethanol fuel production plants at different sizes, the material demand for building plants with different sizes had to be estimated. To do this, mathematical formulas for how the material demands relates to the size of a plant were derived (Equations 14-24). This relationship may be dependent on the area of the vessels in the plant or the total processed volume. The processed volume is proportional to the processed weight because:

$$M = \rho * V \qquad (14)$$

where: m = weight [kg]; ρ = density [kg/m^3]; V = volume [m^3].

The wall area of a cylinder is:

$$A = \pi * d * h + 2 * \frac{\pi * d^2}{4} \qquad (15)$$

where: A = cylinder area [m^2]; d = diameter [m]; h = height [m].

If the diameter is equivalent to the height: d = h:

$$A = \pi * d^2 + \frac{\pi * d^2}{2} = \frac{3 * \pi * d^2}{2} \qquad (16)$$

The volume of a cylinder:

$$V = \frac{\pi * d^2}{4} * h \text{ ; if } d = h\text{: } V = \frac{\pi * d^3}{4} \text{ [m}^3\text{]} \quad (17)$$

Then the cylinder diameter when the volume is known will be (after rewriting the Equation 17):

$$d = \sqrt[3]{\frac{4 * V}{\pi}} \quad (18)$$

If this Equation (18) is put into Equation 16 for the wall area of a cylinder, then:

$$A = \pi * \frac{3}{2} * \left(\frac{4 * V}{\pi}\right)^{\frac{2}{3}} \quad (19)$$

If the constant F replaces the numerals in Equation 19, the equation for the cylinder area will be:

$$A = F * V^{\frac{2}{3}} \quad (20)$$

and $F = \pi * \frac{3}{2} * \left(\frac{4}{\pi}\right)^{\frac{2}{3}} \approx 5.54$.

If the material demand (M) for building the extraction or transesterification plant is proportional to the cylinder area:

$$M = F * V^{\frac{2}{3}} \quad (21)$$

if the volume or weight of the processed material is known. The exponent is equal to 2/3.

Another possibility is that the material demand (M) for building the oil extraction, transesterification or ethanol fuel production plant is proportional to the cylinder volume. Then the material demand for building the plant will be:

$$M = F * V^1 \quad (22)$$

To find out which of these two Equations (21 and 22) was the most correct to use, the weights of cisterns with known volume were compared with these two formulae. The same was done for some oil presses. The results indicated that the reality would be something in between. Therefore another formula was suggested where the exponent was the mean of the exponents in the derived formulas:

$$\frac{\frac{2}{3} + 1}{2} = \frac{5}{6} \quad (23)$$

The third derived formula is thus:

$$M = F * V^{\frac{5}{6}} \tag{24}$$

This formula (Equation 24) was used in the basic scenario in the model and the other two formulas (Equations 21 and 22) were used for scenario analysis as well. In the following Tables (80-81 and 85-90) the exponent from Equations 21; 22; and 24 called ‘y’ and the whole equation is shortened to x^y for simplicity.

For the medium-scale oil extraction plant the machinery, wood in buildings and concrete in building weights were assumed to be 10 000 kg, 30 000 kg and 120 000 kg respectively (Table 80). For the medium-scale transesterification plant the machinery, wood in buildings and concrete in buildings weights were assumed to be 5 000 kg, 15 000 kg and 60 000 kg respectively (Table 80). The weights of the medium-scale transesterification plants were assumed to be half the weights for the corresponding parts of the oil extraction plants. The weights mentioned above were estimated with some help from drawings in Norén *et al.* (1993). To estimate the weights for ethanol fuel production plants, the weights for oil extraction and transesterification plants were added and multiplied by the constant 2.8 for machine parts and 2.0 for building parts (Table 81). In this way the weights 42 000 kg, 90 000 kg and 360 000 kg for machinery, wood in buildings and concrete in buildings respectively were obtained. The reason for these higher weights was that ethanol plants produced almost twice as much fuel on an area basis compared to oil extraction and transesterification plants, they processed approx. 2.4 times as much material and the investments costs were approx. 3.8 and 3 times as much, as for oil extraction and transesterification plants for machinery and buildings respectively, mainly based on investment data in Schmitz (2003). Ethanol plants were also more complicated than oil extraction and transesterification plants.

For the small-scale plant the weight of the oil press (heavy) was 62 kg (after Ferchau, 2000) and the weight of the sedimentation vessels (not heavy) was 200 kg (4 sedimentation vessels * 50 kg) (Tables 80 and 81). The weight of other equipment (not heavy) varied depending on the chosen exponent ‘y’. For medium- and large-scale extraction plants 20% of the total machine weight was assumed to be oil press equipment (heavy) and 80% other equipment (not heavy) (Table 80). Equipment for transesterification and ethanol fuel production was assumed to consist of 25% heavier machines and of 75% lighter equipment independent of the chosen exponent ‘y’ (Table 83: transesterification and Table 84: ethanol fuel production).

Table 80. Weight of machines and buildings for different plant sizes for oil extraction and transesterification

Production factors / The exponent 'y'	5/6	5/6	5/6	2/3	2/3	2/3	1	1	1
Plant size [ha]	40	1000	50000	40	1000	50000	40	1000	50000
Amount of harvested oil [kg/ha]	756	834	1089	756	834	1089	756	834	1089
Amount of harvested oil [kg]	30233	833625	54463500	30233	833625	54463500	30233	833625	54463500
Oil extraction:									
Oil extraction machinery [kg]	684	10000	260500	1170	10000	135721	400	10000	500000
Wood in buildings [kg]	2052	30000	781501	3509	30000	407163	1200	30000	1500000
Concrete in buildings [kg]	8208	120000	3126004	14035	120000	1628651	4800	120000	6000000
Transesterification:									
Transesterification machinery [kg]	315	5000	162773	548	5000	81107	181	5000	326667
Wood in buildings [kg]	946	15000	488319	1643	15000	243322	544	15000	980000
Concrete in buildings [kg]	3782	60000	1953276	6574	60000	973287	2176	60000	3920000

Table 81. Weight of machines and buildings for different plant sizes for ethanol fuel production

Production factors / The exponent 'y'	5/6	5/6	5/6	2/3	2/3	2/3	1	1	1
Plant size [ha]	40	1000	50000	40	1000	50000	40	1000	50000
Amount of harvested ethanol [kg/ha]	1748	1748	1748	1748	1748	1748	1748	1748	1748
Amount of harvested ethanol [kg]	69909	1747736	87386792	69909	1747736	87386792	69909	1747736	87386792
Ethanol fuel production:									
Machine weight [kg]	2873	42000	1094102	4912	42000	570028	1680	42000	2100000
Wood in buildings [kg]	6156	90000	2344503	10526	90000	1221488	3600	90000	4500000
Concrete in buildings [kg]	24624	360000	9378013	42106	360000	4885952	14400	360000	18000000

For the oil extraction plants, it was the processed area of rapeseed (proportional to the volume/weight of extracted rapeseed) that was used to calculate the weights of the small- and large-scale plants. However, for the transesterification plants, it was the weight of processed rapeseed oil that was used to calculate the weights of the small- and large-scale plants. The advantage with this procedure was that different oil extraction efficiencies in oil extraction plants of different sizes could be taken into consideration. For the ethanol plants it was the processed area of wheat (proportional to the weight of processed wheat and the weight of obtained ethanol) that was used to calculate the weights of the small- and large-scale plants.

The weights (Tables 80 and 81) were calculated from the machinery weight of a medium-sized plant (1000 ha) with the formula x^y where y = (2/3+1)/2 = 5/6, in the basic scenario (y = 2/3 or 1 in the scenario analyses), and x was the relationship between the area of rapeseed or wheat cultivated for a medium-sized plant and the area of rapeseed or wheat cultivated for the actual plant size (1000 ha / area of cultivated rapeseed or wheat for actual plant size: 40; 1000; or 50000 ha) for oil extraction and ethanol fuel production plants respectively. The assumed weight of the machinery or building material for the medium-sized plant (*e.g.* 10000 kg machinery) was divided by the value of x^y and the result was assumed to be the weight of the machinery or building material for the actual plant size (Table 80: oil extraction and Table 81: ethanol fuel production).

For transesterification plants, x was the relationship between the weight of total harvested oil [kg] (oil yield [kg/ha] (Table 80) * plant size [ha] (Table 80)) for a medium-scale plant (833625 kg) and the weight of total harvested oil for the actual plant size (833625 kg oil / 30233; 833624; or 54463500 kg oil). The assumed weight of the machinery or building material for the medium-sized plant (*e.g.* 5000 kg machinery) was divided by the value of x^y and the result was assumed to be the weight of the machinery or building material for the actual plant size (Table 80).

The area use [h/ha] (Table 82) of the machine equipment in the small-scale plant was calculated as: area seed yield [kg/ha] / process or machine capacity [kg/h]. With a capacity of 17 kg seed/h (Bernesson, 1993) and a seed yield of 2470 kg/ha, one hectare would be processed in 145 hours and 40 hectares processed in 5812 hours, which should be possible to achieve during commercial operation (Bernesson, 1993). For medium- and large-scale extraction and all sizes of transesterification and ethanol fuel production, the annual time of operation was assumed to be 6000 hours. The area use [h/ha] (Tables 82-84) was obtained after dividing the annual time of operation [h] (see above) by the processed annual area [ha] (Tables 81-82). The area use [h/ha] for fixed installations (like sedimentation vessels) and buildings (oil extraction, transesterification and ethanol fuel production) was calculated as annual time (8760 h/year) / processed area [ha/year] (see above). This gave for small-, medium- and large-scale plants: 219 h/ha; 8.76 h/ha; and 0.1752 h/ha respectively.

How tied-up energy for machines was calculated is described early in Section 3.8 (see also Tables 82-84). For wood, the tied-up energy for production etc. is 2.52 MJ/kg and for steel reinforced concrete 2.94 MJ/kg (Spugnoli *et al.*, 1992). Tied-up energy for machines is accounted for in Tables 85-87 and tied-up energy for buildings is accounted for in Tables 88-90.

The durability of small-scale machinery was assumed to be 60 000 hours, and for medium- and large-scale machinery 100 000 hours (Tables 82-84). For sedimentation vessels the durability was assumed to be 25 years (219 000 hours) and for building parts (all plant sizes) 50 years (438 000 hours).

For calculation of the emissions, the machine or building input [kg/ha] or the machine or building energy [MJ/ha] was required (Tables 85-90). The machine and building input [kg/ha] was calculated as: area use [h/ha] (machines: Tables 82-84; buildings: see above) * weight [kg] (machines: Tables 85-87, buildings: Tables 80-81) / durability [h] (machines: Tables 82-84; buildings: see above). When the values obtained were multiplied by emissions [g/kg machine or building material] the emission values [g/ha] on an area basis were obtained. This was not done in this study because of difficulties in getting good emission values for machine and building materials. Machine input is accounted for in Tables 85-87 and building input is accounted for in Tables 88-90.

The machine (Tables 85-87) and building (Tables 88-90) energy (tied-up) [MJ/ha] could be calculated as: annual use [h/ha] (machines: Tables 82-84; buildings: see above) * weight [kg] (machines: Tables 85-87, buildings: Tables 80-81) * tied-up energy in machines (Tables 82-

84) or buildings (see above)) [MJ/kg] / durability [h] (machines: Tables 82-84; buildings: see above). In this study this energy requirement was assumed to be Swedish electricity (all machines and buildings assumed to be produced with electrical energy with 5% grid losses). In a scenario analysis, the use of electricity produced from mainly fossil resources was studied (Table 49). The area emissions [g/ha] and input energy [MJ/ha] (Tables 91-92, see also Tables A3-A14 and A17-A22, Appendices 1-2) could be calculated from this tied up energy by multiplication by the emissions [g/MJ_{el}] and energy requirement [MJ/MJ_{el}] for the production of electricity (Table 49).

Table 82. Calculation of tied-up energy in machines for extraction (Börjesson, 1994; Pimentel, 1980)

Machinery	Use [h/ha]	Durability [h]	Tied-up energy [MJ/kg machine] for: Raw material	Manufacture	Spare parts	Total
Small-scale extraction:						
Oil press	145	60000	21.6	9.72	12.84	44.16
Transportation equipment	145	60000	21.6	4.68	6.04	32.32
Sedimentation vessels	219	219000	21.6	4.68	6.04	32.32
Medium-scale extraction:						
Oil press equipment (20% of total machinery weight)	6.00	100000	21.6	9.72	12.84	44.16
Other equipment (80% of total machinery weight)	6.00	100000	21.6	4.68	6.04	32.32
Large-scale extraction:						
Oil press equipment (20% of total machinery weight)	0.12	100000	21.6	9.72	12.84	44.16
Other equipment (80% of total machinery weight)	0.12	100000	21.6	4.68	6.04	32.32

Table 83. Calculation of tied-up energy in machines for transesterification (Börjesson, 1994; Pimentel, 1980)

Machinery	Use	Durability	Tied-up energy [MJ/kg machine] for:			
	[h/ha]	[h]	Raw material	Manufacture	Spare parts	Total
Small-scale transesterification:						
Heavier equipment (25% of total machinery weight)	150	60000	21.6	9.72	7.20	38.52
Other equipment (75% of total machinery weight)	150	60000	21.6	4.68	6.04	32.32
Medium-scale transesterification:						
Heavier equipment (25% of total machinery weight)	6.00	100000	21.6	9.72	7.20	38.52
Other equipment (75% of total machinery weight)	6.00	100000	21.6	4.68	6.04	32.32
Large-scale transesterification:						
Heavier equipment (25% of total machinery weight)	0.12	100000	21.6	9.72	7.20	38.52
Other equipment (75% of total machinery weight)	0.12	100000	21.6	4.68	6.04	32.32

Table 84. Calculation of tied-up energy in machines for ethanol fuel production (Börjesson, 1994; Pimentel, 1980)

Machinery	Use	Durability	Tied-up energy [MJ/kg machine] for:			
	[h/ha]	[h]	Raw material	Manufacture	Spare parts	Total
Small-scale ethanol fuel production:						
Heavier equipment (25% of the machine weight)	150	60000	21.6	9.72	7.20	38.52
Other equipment (75% of the machine weight)	150	60000	21.6	4.68	6.04	32.32
Medium-scale ethanol fuel production:						
Heavier equipment (25% of the machine weight)	6.00	100000	21.6	9.72	7.20	38.52
Other equipment (75% of the machine weight)	6.00	100000	21.6	4.68	6.04	32.32
Large-scale ethanol fuel production:						
Heavier equipment (25% of the machine weight)	0.12	100000	21.6	9.72	7.20	38.52
Other equipment (75% of the machine weight)	0.12	100000	21.6	4.68	6.04	32.32

Table 85. Some area-based data for the oil extraction machinery

Machinery	Machine weight [kg]	Machine input [kg/ha]	Machine energy [MJ/ha]	Machine weight [kg]	Machine input [kg/ha]	Machine energy [MJ/ha]	Machine weight [kg]	Machine input [kg/ha]	Machine energy [MJ/ha]
The exponent 'y'	5/6	5/6	5/6	2/3	2/3	2/3	1	1	1
Small-scale extraction:									
Oil press	62	0.15	6.63	62	0.15	6.63	62	0.15	6.63
Transportation equipment	422	1.02	33.03	908	2.20	71.04	138	0.33	10.80
Sedimentation vessels	200	0.20	6.46	200	0.20	6.46	200	0.20	6.46
Total	684	1.37	46.13	1170	2.55	84.14	400	0.68	23.90
Medium-scale extraction:									
Oil press equipment (20% of total machinery weight)	2000	0.12	5.30	2000	0.12	5.30	2000	0.12	5.30
Other equipment (80% of total machinery weight)	8000	0.48	15.52	8000	0.48	15.52	8000	0.48	15.52
Total	10000	0.60	20.82	10000	0.60	20.82	10000	0.60	20.82
Large-scale extraction:									
Oil press equipment (20% of total machinery weight)	52100	0.06	2.76	27144	0.03	1.44	100000	0.12	5.30
Other equipment (80% of total machinery weight)	208400	0.25	8.08	108577	0.13	4.21	400000	0.48	15.52
Total	260500	0.31	10.84	135721	0.16	5.65	500000	0.60	20.82

Table 86. Some area-based data for the oil transesterification machinery

Machinery	Machine weight [kg]	Machine input [kg/ha]	Machine energy [MJ/ha]	Machine weight [kg]	Machine input [kg/ha]	Machine energy [MJ/ha]	Machine weight [kg]	Machine input [kg/ha]	Machine energy [MJ/ha]
The exponent 'y'	5/6	5/6	5/6	2/3	2/3	2/3	1	1	1
Small-scale transesterification:									
Heavier equipment (25% of total machinery weight)	79	0.20	7.59	137	0.34	13.19	45	0.11	4.37
Other equipment (75% of total machinery weight)	236	0.59	19.10	411	1.03	33.20	136	0.34	10.99
Total	315	0.79	26.69	548	1.37	46.39	181	0.45	15.36
Medium-scale transesterification:									
Heavier equipment (25% of total machinery weight)	1250	0.08	2.89	1250	0.08	2.89	1250	0.08	2.89
Other equipment (75% of total machinery weight)	3750	0.23	7.27	3750	0.23	7.27	3750	0.23	7.27
Total	5000	0.30	10.16	5000	0.30	10.16	5000	0.30	10.16
Large-scale transesterification:									
Heavier equipment (25% of total machinery weight)	40693	0.05	1.88	20277	0.02	0.94	81667	0.10	3.78
Other equipment (75% of total machinery weight)	122080	0.15	4.74	60830	0.07	2.36	245000	0.29	9.50
Total	162773	0.20	6.62	81107	0.10	3.30	326667	0.39	13.28

Table 87. Some area-based data for the ethanol fuel production machinery

Machinery	Machine weight [kg]	Machine input [kg/ha]	Machine energy [MJ/ha]	Machine weight [kg]	Machine input [kg/ha]	Machine energy [MJ/ha]	Machine weight [kg]	Machine input [kg/ha]	Machine energy [MJ/ha]
The exponent 'y'	5/6	5/6	5/6	2/3	2/3	2/3	1	1	1
Small-scale ethanol fuel production:									
Heavier equipment (25% of the machine weight)	718	1.80	69.17	1228	3.07	118.28	420	1.05	40.45
Other equipment (75% of the machine weight)	2155	5.39	174.11	3684	9.21	297.73	1260	3.15	101.82
Total	2873	7.18	243.28	4912	12.28	416.00	1680	4.20	142.27
Medium-scale ethanol fuel production:									
Heavier equipment (25% of the machine weight)	10500	0.63	24.27	10500	0.63	24.27	10500	0.63	24.27
Other equipment (75% of the machine weight)	31500	1.89	61.09	31500	1.89	61.09	31500	1.89	61.09
Total	42000	2.52	85.36	42000	2.52	85.36	42000	2.52	85.36
Large-scale ethanol fuel production:									
Heavier equipment (25% of the machine weight)	273525	0.33	12.64	142507	0.17	6.59	525000	0.63	24.27
Other equipment (75% of the machine weight)	820576	0.98	31.83	427521	0.51	16.58	1575000	1.89	61.09
Total	1094102	1.31	44.47	570028	0.68	23.17	2100000	2.52	85.36

Table 88. Some area-based data for the oil extraction buildings

Building parts	Building input [kg/ha]	Building energy [MJ/ha]	Building input [kg/ha]	Building energy [MJ/ha]	Building input [kg/ha]	Building energy [MJ/ha]
The exponent 'y'	5/6	5/6	2/3	2/3	1	1
Small-scale extraction:						
Wood in buildings	1.03	2.59	1.75	4.42	0.60	1.51
Concrete in buildings	4.10	12.07	7.02	20.63	2.40	7.06
Total buildings	5.13	14.65	8.77	25.05	3.00	8.57
Medium-scale extraction:						
Wood in buildings	0.60	1.51	0.60	1.51	0.60	1.51
Concrete in buildings	2.40	7.06	2.40	7.06	2.40	7.06
Total buildings	3.00	8.57	3.00	8.57	3.00	8.57
Large-scale extraction:						
Wood in buildings	0.31	0.79	0.16	0.41	0.60	1.51
Concrete in buildings	1.25	3.68	0.65	1.92	2.40	7.06
Total buildings	1.56	4.46	0.81	2.33	3.00	8.57

Table 89. Some area-based data for the transesterification buildings

Building parts	Building input [kg/ha]	Building energy [MJ/ha]	Building input [kg/ha]	Building energy [MJ/ha]	Building input [kg/ha]	Building energy [MJ/ha]
The exponent 'y'	5/6	5/6	2/3	2/3	1	1
Small-scale transesterification:						
Wood in buildings	0.47	1.19	0.82	2.07	0.27	0.69
Concrete in buildings	1.89	5.56	3.29	9.66	1.09	3.20
Total buildings	2.36	6.75	4.11	11.73	1.36	3.88
Medium-scale transesterification:						
Wood in buildings	0.30	0.76	0.30	0.76	0.30	0.76
Concrete in buildings	1.20	3.53	1.20	3.53	1.20	3.53
Total buildings	1.50	4.28	1.50	4.28	1.50	4.28
Large-scale transesterification:						
Wood in buildings	0.20	0.49	0.10	0.25	0.39	0.99
Concrete in buildings	0.78	2.30	0.39	1.14	1.57	4.61
Total buildings	0.98	2.79	0.49	1.39	1.96	5.60

Table 90. Some area-based data for the ethanol fuel production buildings

Building parts	Building input [kg/ha]	Building energy [MJ/ha]	Building input [kg/ha]	Building energy [MJ/ha]	Building input [kg/ha]	Building energy [MJ/ha]
The exponent 'y'	5/6	5/6	2/3	2/3	1	1
Small-scale ethanol fuel production:						
Wood in buildings	3.08	7.76	5.26	13.26	1.80	4.54
Concrete in buildings	12.31	36.20	21.05	61.90	7.20	21.17
Total buildings	15.39	43.95	26.32	75.16	9.00	25.70
Medium-scale ethanol fuel production:						
Wood in buildings	1.80	4.54	1.80	4.54	1.80	4.54
Concrete in buildings	7.20	21.17	7.20	21.17	7.20	21.17
Total buildings	9.00	25.70	9.00	25.70	9.00	25.70
Large-scale ethanol fuel production:						
Wood in buildings	0.94	2.36	0.49	1.23	1.80	4.54
Concrete in buildings	3.75	11.03	1.95	5.75	7.20	21.17
Total buildings	4.69	13.39	2.44	6.98	9.00	25.70

Table 91. Emissions and energy requirements for production of machinery and buildings, for oil extraction and transesterification plants, if assumed to be produced with Swedish electricity

Type of machines	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	Particles	Input energy
	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[MJ/ha]
Small-scale:										
Machinery oil extraction	380	0.872	0.140	2.37	0.726	0.630	0.0107	0.0344	0.121	94.3
Buildings oil extraction	121	0.277	0.0446	0.754	0.231	0.200	0.00338	0.0109	0.0385	30.0
Machinery transesterification	220	0.504	0.0813	1.37	0.420	0.364	0.00617	0.0199	0.0701	54.6
Buildings transesterification	55.6	0.128	0.0206	0.347	0.106	0.0922	0.00156	0.00503	0.0177	13.8
Medium-scale:										
Machinery oil extraction	171	0.393	0.0634	1.07	0.328	0.284	0.00481	0.0155	0.0546	42.6
Buildings oil extraction	70.5	0.162	0.0261	0.441	0.135	0.117	0.00198	0.00639	0.0225	17.5
Machinery transesterification	83.7	0.192	0.0309	0.523	0.160	0.139	0.00235	0.00758	0.0267	20.8
Buildings transesterification	35.3	0.0810	0.0130	0.220	0.0675	0.0585	0.000990	0.00319	0.0112	8.76
Large-scale:										
Machinery oil extraction	89.3	0.205	0.0330	0.558	0.171	0.148	0.00251	0.00808	0.0285	22.2
Buildings oil extraction	36.8	0.0844	0.0136	0.230	0.0703	0.0609	0.00103	0.00333	0.0117	9.13
Machinery transesterification	54.5	0.125	0.0201	0.340	0.104	0.0903	0.00153	0.00493	0.0174	13.5
Buildings transesterification	23.0	0.0527	0.00849	0.144	0.0439	0.0381	0.000644	0.00208	0.00732	5.70

Table 92. Emissions and energy requirements for production of machinery and buildings, for ethanol fuel production plants, if assumed to be produced with Swedish electricity

Type of machines	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	Particles	Input energy
	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[MJ/ha]
Small-scale:										
Machinery	2003	4.60	0.741	12.5	3.83	3.32	0.0562	0.181	0.639	497
Buildings	362	0.831	0.134	2.26	0.692	0.600	0.0102	0.0328	0.115	89.9
Medium-scale:										
Machinery	703	1.61	0.260	4.39	1.34	1.17	0.0197	0.0636	0.224	175
Buildings	212	0.486	0.0783	1.32	0.405	0.351	0.00594	0.0192	0.0675	52.6
Large-scale:										
Machinery	366	0.841	0.135	2.29	0.700	0.607	0.0103	0.0332	0.117	90.9
Buildings	110	0.253	0.0408	0.689	0.211	0.183	0.00309	0.0100	0.0352	27.4

3.8.3 Investment costs for machines and buildings

For calculation of the production costs for the studied scales of rapeseed oil, RME and ethanol fuel, the investment costs of the plants must be estimated. Table 93 shows how the investment costs used in small- and medium-scale plants in this study were estimated from earlier studies (Norén *et al*., 1993; Norén *et al*., 1994) with oil extraction and transesterification when they were compared with more recent prices on oil presses (Ferchau, 2000; Oilpress, 2003). For large-scale plants the costs were estimated from costs in a study made by Conneman & Fischer (1998). The investment costs for small- and medium-scale plants (this study), in Table 93, are used for the investment costs in Table 94.

For large-scale plants the costs were estimated in this way:

- The plant studied in Conneman & Fischer (1998) produced 75 000 tonnes RME/year, and the processed area could be calculated as: 75 000 tonnes/year / 1.048 tonnes RME/ha = 71 565 ha, which can be compared with 50 000 ha in this study.
- Investment cost: 25 000 000 DM * 4.5 SEK/DM (Riksbanken, 2003) = 112 500 000 SEK.
- Annual RME production in the plant studied: 50 000 ha/year * 1.048 tonnes RME/ha = 52 400 tonnes RME/year.
- The relationship: 52 400 / 75 000 = 0.7, with assumed price increase of 0.85 gives an investment of 112 500 000 * 0.85 = 95 625 000 SEK, which is almost 100 000 000 SEK for the transesterification plant alone (not together with oil extraction).

For a plant with only transesterification or extraction, the investment for buildings was assumed to be 1/3 of the total investment. For a plant with transesterification and extraction together, the investment for buildings was assumed to be 1/4 of the total investment. This gives: 67 000 000 SEK invested in the machines, and 33 000 000 invested in the buildings if the plant only contained transesterification or oil extraction (Table 94). SEK 23 000 000 was invested in buildings for each part (transesterification and oil extraction) for a building containing both oil extraction and transesterification, together 46 000 000 SEK (Table 94). The increased share for the oil extraction compared to medium-scale extraction was justified because solvent hexane extraction was added to the mechanical extraction.

Table 93. Investment costs [SEK] for some small- and medium-scale oil extraction and transesterification plants to estimate the costs in this study

	Small plant[a]	Small plant, today's prices[b]	Small plant, this study	Medium plant[c]	Medium plant, today's prices[d]	Medium plant, this study
Oil press capacity [kg seed/h]	15	17	17	100	400	400
Oil press	33000	47000	50000	160000	580000	580000
Screw conveyer, seed to oil press	6000	8545	8000	15000	54375	50000
Seed bin			1000	1000	3625	4000
Flat belt conveyer for expeller	10000	14242	14000	20000	72500	70000
Floor for storing of expeller			10000	50000	181250	180000
Sedimentation tanks	3000	4273	5000	40000	145000	150000
Pre-sedimentation tank			2000	8000	29000	30000
Screw conveyer for sediment			6000	10000	36250	36000
Tank for sediment			1000	5000	18125	20000
Tank for oil after sedimentation	5000	7121	9000	20000	72500	72500
Electric installation	6000	8545	8500	20000	72500	72500
Electric mounting	5000	7121	7500	20000	72500	72500
Other mounting	15000	21364	22000	20000	72500	72500
Unforeseen			16000	41000	148625	150000
Total machinery, oil extraction	83000	118212	160000	430000	1558750	1560000
Transesterification equipment:						
Reactor-tank with heating and stirring		47414	44000	150000	543750	550000
Intermediate storage		6034	3000	20000	72500	70000
Mixing tank methanol + catalyst		6034	12000	20000	72500	70000
Distillation equipment for methanol and water		7759	15000	25000	90625	90000
Methanol tank with concrete slab		10345	10000	35000	126875	120000
RME tank with concrete slab		34483	35000	120000	435000	400000
Pumps		8621	9000	30000	108750	100000
Valves		3448	2000	10000	36250	40000
Piping		3448	2000	10000	36250	40000
Electric and control installation		34483	20000	110000	398750	400000
Mounting		8621	10000	30000	108750	100000
Unforeseen		18966	18000	60000	217500	220000
		189655	180000	620000	2247500	2200000
Planning approx. 10%			35000	100000	362500	360000
Check-up, management, examination etc. approx. 5%			15000	50000	181250	180000
Total machinery			390000	1200000	4350000	4300000
Of this 50% is oil extraction and 50% transesterification.						
Free-standing, building incl. concrete slab			70000	200000	725000	720000
Build-in of pressing plant			30000	150000	543750	550000
Total buildings			100000	350000	1268750	1270000
Building only for oil extraction assumed to be 70% of these costs:			70000	245000	888125	889000

[a] Norén *et al.* (1994).
[b] Oilpress Skeppsta Maskin 26:th March 2003, (Oilpress, 2003). Price Skeppsta oil press Type 55: 47000 SEK / price oil press 15 kg/h (Norén *et al.*, 1994) = 1.424. All investment costs below the oil press were derived by multiplying by the ratio (47000 / 33000) = 1.424.
[c] Norén *et al.* (1993).
[d] Price Reinartz AP10/06: 124640 DKK (Ferchau, 2000) * 1.23 SEK/DKK (Riksbanken, 2003) = 153307 SEK almost = 160000 SEK (Norén *et al.*, 1993). The price for AP14/30: 471200 DKK * 1.23 SEK/DKK = 579576 SEK almost 580000 SEK. All investment costs below the oil press were derived by multiplying by the ratio (580000 / 160000) = 3.625. (Price Reinartz: oil press 100 kg/h / oil press 400 kg/h).

Table 94. Investment costs oil extraction and transesterification plants

Type of investment	Small-scale [SEK]	Medium-scale [SEK]	Large-scale [SEK]
Oil extraction (only):			
Machinery	160000	1560000	
Planning, check-up, examination etc.	25000	270000	
Total machinery extraction	185000	1830000	67000000
Buildings oil extraction	70000	889000	33000000
Total oil extraction	255000	2719000	100000000
Oil extraction with transesterification:			
Oil extraction:			
Machinery	160000	1560000	
Planning, check-up, examination etc.	25000	270000	
Total machinery extraction	185000	1830000	67000000
Buildings oil extraction	50000	635000	23000000
Transesterification:			
Machinery	180000	2200000	
Planning, check-up, examination etc.	25000	270000	
Total machinery extraction	205000	2470000	67000000
Buildings oil extraction	50000	635000	23000000
Total oil extraction and transesterification	490000	5570000	180000000

In Table 95, some data for ethanol plants that produce ethanol from wheat (Schmitz, 2003) are accounted for. One of these plants is only slightly larger than for the large plant in this study (serviced area with assumptions as in this study: 53 844 ha in comparison to 50 000 ha). The investment for that plant of 639.3 MSEK may be compared with 180 MSEK (Table 94) for an oil extraction plant with transesterification of about the same size. The investment of approx. 420 MSEK for the Swedish ethanol plant in Norrköping (Werling, pers. comm.) indicates that the price for an ethanol plant in Sweden will be somewhat higher than for a plant of the same size in Germany ((50 000 m^3 ethanol/year / 60 000 m^3 ethanol/year) * 446 MSEK (Table 95) = 371 MSEK). This together with the ethanol plant in this study not having the equipment to dehydrate the ethanol indicates that an investment cost of approx. 650 MSEK for the large-scale plant would be reasonable. If the costs of building an ethanol plant, in comparison to building an combined oil extraction and transesterification plant, were assumed to be 200% more for building parts and 280% more for machine parts, the total investment cost would be 647.2 MSEK (Table 96) and the above line of argument would be fulfilled. Therefore it was assumed that the investment costs for constructing modern ethanol plants on all scales were 200% more for building parts and 280% more for machine parts, in comparison to combined oil extraction and transesterification plants in this study. The investment costs for constructing of modern small- and medium-scale ethanol plants were not accounted for in the literature.

Table 95. Data for ethanol plants in Schmitz (2003)

Plant size [m^3/day]	60	180	360	720
Plant size [m^3/year][a]	19980	59940	119880	239760
Investment ethanol plant [Euro*10^6]	31.63	48.49	69.49	105.64
Buildings ethanol plant [SEK*10^6][b]	291.0	446.1	639.3	971.9
Area as in this study [ha]	8974	26922	53844	107689
Staff [number full time working]	18	26	30	34
Staff [h/year][c]	30960	44720	51600	58480
Work [h/ha]	3.45	1.66	0.96	0.54

[a] Plant in operation 333 days a year.
[b] 1 Euro = 9.2 SEK (Riksbanken, 2003).
[c] Annual working time if staff is working 43 weeks / year.

Table 96. Estimated investment costs for the ethanol plants

Type of investment / Plant size [ha]	40	1000	50000
Machinery ethanol plant [SEK]	1482000	16340000	509200000
Buildings ethanol plant [SEK]	300000	3810000	138000000
Total [SEK]	1782000	20150000	647200000

Capital costs (depreciation and interest) were calculated using the annuity method (Ljung & Högberg, 1988) (Tables 97-98). The calculation interest was chosen to be 7% for these calculations. For description of calculations see Section 3.4.5. Residual values were assumed to be 10% of replacement values for machinery and 0% of replacement values for buildings.

Maintenance costs [SEK/ha] (Tables 97-98) (6% of replacement values) were calculated as: (replacement value [SEK] * (maintenance cost, [%] of replacement value / 100)) / serviced area [ha]. Length of life was assumed to be 15 years for machinery and 50 years for buildings (Tables 97-98). For calculation of use [h/ha] (Tables 97-98) and description of annual use [hours] (Tables 97-98) see Section 3.8.2.

Maintenance costs [SEK/ha] and annual capital costs [SEK/ha] (Tables 97 and 98) are also accounted for in the economic calculations in Tables 123-131.

Table 97. Basic data for machinery and buildings used for oil extraction and transesterification

Production scale and use	Use [h/ha]	Replacement value [SEK] (A)[a]	Maintenance cost [SEK/ha] (B)[b]	Length of life [years] (C)	Annual use [hours] (D)	Residual value [SEK][c]	Annual capital cost [SEK/ha]
Small-scale extraction:							
Machinery	145	185000	277.5	15	5812	18500	489
Buildings	219	70000	105.0	50	8760	0	127
Sum			382.5				616
Small-scale transesterification:							
Machinery, extraction	145	185000	277.5	15	5812	18500	489
Machinery, transesterification	150	205000	307.5	15	6000	20500	542
Buildings, extraction	219	50000	75	50	8760	0	91
Buildings, transesterification	219	50000	75	50	8760	0	91
Sum			735				1213
Medium-scale extraction:							
Machinery	6.00	1830000	109.8	15	6000	183000	194
Buildings	8.76	889000	53.34	50	8760	0	64
Sum			163.14				258
Medium-scale transesterification:							
Machinery, extraction	6.00	1830000	109.8	15	6000	183000	194
Machinery, transesterification	6.00	2470000	148.2	15	6000	247000	261
Buildings, extraction	8.76	635000	38.1	50	8760	0	46
Buildings, transesterification	8.76	635000	38.1	50	8760	0	46
Sum			334.2				547
Large-scale extraction:							
Machinery	0.12	67000000	80.4	15	6000	6700000	142
Buildings	0.18	33000000	39.6	50	8760	0	48
Sum			120				190
Large-scale transesterification:							
Machinery, extraction	0.12	67000000	80.4	15	6000	6700000	142
Machinery, transesterification	0.12	67000000	80.4	15	6000	6700000	142
Buildings, extraction	0.18	23000000	27.6	50	8760	0	33
Buildings, transesterification	0.18	23000000	27.6	50	8760	0	33
Sum			216				350

[a] Replacement value (Table 94).
[b] Maintenance costs [SEK/ha] assumed to be 6% of the replacement value for both machinery and buildings.
[c] Residual value assumed to be 10% of the replacement value for machinery and 0% of the replacement value for buildings.

Table 98. Basic data for machinery and buildings used for ethanol fuel production

Production scale and use	Use [h/ha]	Replace-ment value [SEK] (A)[a]	Mainten-ance cost [SEK/ha] (B)[b]	Length of life [years] (C)	Annual use [hours] (D)	Residual value [SEK][c]	Annual capital cost [SEK/ha]
Small-scale:							
Machinery	150	1482000	2223	15	6000	148200	3920
Buildings	219	300000	450	50	8760	0	543
Sum			2673				4464
Medium-scale:							
Machinery	6.00	16340000	980.4	15	6000	1634000	1729
Buildings	8.76	3810000	229	50	8760	0	276
Sum			1209				2005
Large-scale:							
Machinery	0.12	509200000	611	15	6000	50920000	1078
Buildings	0.18	138000000	166	50	8760	0	200
Sum			777				1278

[a] Replacement value (Table 96).
[b] Maintenance costs [SEK/ha] assumed to be 6% of the replacement value for both machinery and buildings.
[c] Residual value assumed to be 10% of the replacement value for machinery and 0% of the replacement value for buildings.

3.9 Use of the fuels produced

The rapeseed oil, RME and ethanol fuel produced were assumed to be used in up to date diesel engines. Therefore, emissions data were chosen from Aakko *et al.* (2000) who made tests with RME, MK1 and MK3 fuels according to the European 13 mode, ECE R49 on a 210 kW, Volvo DH10A-285 engine with turbo-charger and intercooler (Table 102). Emissions with rapeseed oil fuels were assumed to be influenced in comparison to MK3 in the same way as is accounted for in Thuneke (1999) (Table 101). Ethanol fuel was tested by Haupt *et al.* (1999) according to the European 13 mode, ECE R49 in a 191 kW, 11 litre, in-line 6 cylinder Scania DSE1101 engine with a compression ratio of 24:1, turbo-charger, intercooler and a Bosch injection pump. In tests of ethanol fuel with a catalyst, a Scania catalyst was used. The name used for the ethanol fuel in Haupt *et al.* (1999) was ET7. Aakko *et al.* (2000) was preferred before Haupt *et al.* (1999) as a source for MK1 engines because newer engines with lower emissions were used in the their tests. Section 3.4.4.2 describes how emissions of CO_2 and SO_x were calculated when MK1, MK3, rapeseed oil, RME and ethanol fuels were consumed. Emissions on an area basis are accounted for in Table 103.

Aakko *et al.* (2000) accounts only for the fuel consumption when MK3 fuel is used [kg/MJ_{engine} = (mg/MJ_{engine} / 1 000 000)] (Table 102) from which the efficiency could be calculated by inversion after multiplying by the heat value [MJ_{fuel}/kg] (Table 99). The efficiency for ethanol fuel in Haupt *et al.* (1999) could be calculated in the same way after conversion of kWh to MJ. The efficiency for RME was calculated using the assumption that the efficiencies for different fuels on the engine measured by Aakko *et al.* (2000) have the same relationships as were measured by SMP (1993) (Table 99) (*e.g.* efficiency RME =

efficiency MK3 (Tables 99 and 102) * (efficiency RME (Table 99: SMP, 1993) / efficiency MK3 (Table 99: SMP, 1993))). The volumetric fuel consumption with rapeseed oil fuel was 12% bigger than with MK3 fuel (Bernesson, 1993 and 1994) (Table 99). The efficiency with rapeseed oil (Table 102) could be calculated as (all factors accounted for in Table 99): (volume MK3 * density MK3 * lower heat value MK3 * efficiency MK3) / (volume rapeseed oil * density rapeseed oil * lower heat value rapeseed oil).

Table 99. Properties of the fuels (SMP, 1993 and 1994; Bernesson, 1993 and 1994; Aylward & Findlay, 1994; Solomons, 1996; Haupt et al., 1999; Thuneke, 1999; Aakko et al., 2000; Schmitz, 2003; Lif, pers. comm.; and Sekab, 2003)

Fuel	Density [kg/l]	Heat value[a] [MJ/kg]	Volumetric consumption compared to MK3[b]	Engine efficiency [%][c]	[%][d]
Diesel fuel oil MK3 (fossil)	0.826[e]	42.8[e]	1	39	36.3
Diesel fuel oil MK1 (fossil)	0.813[e]	43.3[e]	1.03	38	35.3
RME (rape methyl ester)	0.886[e]	38.5[e]	1.08	37.5	34.9
Rapeseed oil	0.921[f]	38.3[f]	1.12		
Ethanol fuel	0.830[g]	25.1[h]			39.6

[a] Lower (effective) heat value.
[b] Calculated as: (lower heat value MK3 * density MK3 * engine efficiency MK3) / (lower heat value new fuel * density new fuel * engine efficiency new fuel) for MK1 and RME; for straight rapeseed oil fuel in an Elsbett engine is measured to be approx. 12% higher than for diesel oil fuel (MK3) in a conventional direct injected engine (Bernesson, 1993 and 1994; Thuneke, 1999).
[c] Efficiency measured at maximum power at a Valmet 420 DS engine (70-71 kW) (SMP, 1993).
[d] Efficiency measured according to ECE R49 (Aakko *et al.*, 2000: MK3) (calculated from Aakko *et al.* (2000) by assuming the same relationship between engine efficiencies as in SMP (1993) for MK1 and RME; and Haupt *et al.* (1999) for ethanol fuel).
[e] SMP (1993).
[f] SMP (1994).
[g] Sekab (2003).
[h] Calculated after Aylward & Findlay (1994); Schmitz (2003); Solomons (1996); Lif (pers. comm.); and Sekab (2003).

Table 100 presents components, with properties, included in the ethanol fuel. The composition of this fuel could be used for calculation of its lower heat value and emissions of fossil carbon dioxide. Hydrous ethanol used during the production of ethanol fuel contains 6.5% water by weight (Sekab, 2003). When the composition and lower heat values for all components in the ethanol fuel are known, it is possible to calculate its lower heat value (Table 99). It could be calculated as the sum of the product of the composition [%] (/ 100) and the lower heat values [MJ/kg] of all components (Table 100) that are included in the ethanol fuel. The ethanol fuel also contains also 90 ppm morpholine (not mentioned in Table 100) as a corrosion inhibitor.

Table 100. Components with properties included in the ethanol fuel (Aylward & Findlay, 1994; Schmitz, 2003; Sekab, 2003; Lif, pers. comm.)

Component	Composition of fuel [%]	Density [kg/l]	Amount [kg/ha]	Lower heat value[a] [MJ/kg]	Heat content[c] [MJ/ha]
Ethanol	84.337	0.785	1747.7	26.8	46854
Water	5.863	1.000	121.5	-2.442[b]	-297
Beraid 3540	7		145.1	24.0	3482
MTBE	2.3	0.740	47.7	35.3	1681
Isobutanol	0.5	0.798	10.4	33.0	342
Sum equivalent to ethanol fuel	100		2072.3		52062

[a] Lower heat value: ethanol, water and isobutanol (Aylward & Findlay, 1994); MTBE (Schmitz, 2003); and Beraid (Lif, pers. comm.).
[b] For water: heat of vaporization (Aylward & Findlay, 1994) (negative sign because of endothermic reaction in opposite to the exothermic combustion reactions).
[c] Calculated as amount [kg/ha] * lower heat value [MJ/kg].

Table 101. Emissions from engines running on straight rapeseed oil in relation to diesel oil (MK3) after Thuneke (1999)

Emissions	Emission value in relation to MK3 [$(g/MJ_{engine}) / (g/MJ_{engine})$]
CO	1.00
HC	0.55
NO_x	1.05
Particulates	0.70

Table 102. Emissions when driving on the fuels, European 13 mode, ECE R49 (Bernesson, 1993; SMP, 1993; Haupt et al., 1999; Aakko et al., 2000)

Type of fuel	CO	HC	NO_x	Particles	Fuel consumption	Efficiency[d]
	[mg/MJ_{engine}]	[mg/MJ_{engine}]	[mg/MJ_{engine}]	[mg/MJ_{engine}]	[mg/MJ_{engine}]	[MJ_{engine}/MJ_{fuel}]
EN590, (Eur. Diesel = MK3)[a]	147	47.2	1639	20.83	64444	0.363
MK1[a]	164	58.3	1417	15.83		0.353
RME[a]	122	22.2	1847	8.33		0.349
Rapeseed oil[c]	147	26.0	1721	14.58		0.324
Ethanol fuel[b]	735	89.2	938	-	100517	0.396
Emissions recalculated to mg/MJ_{fuel}[e]	[mg/MJ_{fuel}]	[mg/MJ_{fuel}]	[mg/MJ_{fuel}]	[mg/MJ_{fuel}]	[mg/MJ_{fuel}]	
EN590, (Eur. Diesel = MK3)	53.4	17.12	594	7.55	23364	
MK1	57.9	20.61	500	5.59		
RME	42.6	7.75	644	2.91		
Rapeseed oil	47.8	8.43	558	4.73		
Ethanol fuel	291.1	35.33	372	2.2[f]	39805	

[a] Aakko *et al.* (2000).
[b] Haupt *et al.* (1999).
[c] Emissions from rapeseed oil calculated from MK3 emissions, see Table 101.
[d] The relationship between efficiencies for the fuels were assumed to be as in SMP (1993). From these values, the efficiencies for MK1 and RME were calculated from the efficiency for MK3 measured by Aakko *et al.* (2000). The efficiency for rapeseed oil was calculated from 12% higher volumetric consumption of rapeseed oil compared to diesel fuel oil MK3 reported by Bernesson (1993). Calculations described in footnotes to Table 99.
[e] Emissions [mg/MJ_{fuel}] are calculated from emissions [mg/MJ_{engine}] by multiplying by the engine efficiency.
[f] Uppenberg *et al.* (2001).

The quantity of harvested energy [MJ/ha] (Table 103) was calculated as: lower heat value for each fuel [MJ/kg] (Table 99) * quantity yield of each fuel [kg/ha] (Tables 106 and 108). Emission values [g/ha] Table 103 were calculated as: Quantity fuel energy in [MJ/ha] Table 103 * (emission values [mg/MJ_{fuel}] (Table 102) /1000). How the emissions of CO_2 and SO_x were obtained is accounted for in Section 3.4.4.2. The emissions (Table 103) were calculated in a corresponding way as described above. The area emissions [g/ha] (Table 103) are also accounted for in Tables A3, A5, A7, A9, A11, A13, A17, A19 and A21, Appendices 1-2.

Table 103. Harvest of fuels and emissions during consumption, on an area basis, for the fuel systems studied

Fuel system	Quantity		CO_2	CO	HC	NO_x	SO_x	Particles
	[kg/ha]	[MJ/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]
Small-scale rapeseed oil	756	28948	0	1383	244	16161	119	137
Medium-scale rapeseed oil	834	31928	0	1525	269	17825	132	151
Large-scale rapeseed oil	1089	41719	0	1993	352	23291	172	197
Small-scale RME	727	27993	108300	1193	217	18026	115	81
Medium-scale RME	802	30875	119449	1316	239	19882	127	90
Large-scale RME	1048	40343	156080	1719	313	25979	165	117
Small-scale ethanol fuel	2072	52062	433447	15156	1839	19344	0	115
Medium-scale ethanol fuel	2072	52062	433447	15156	1839	19344	0	115
Large-scale ethanol fuel	2072	52062	433447	15156	1839	19344	0	115

In the scenario analysis (Section 3.11.2) catalysts were used to reduce the CO-, HC- and NO_X-emissions. For rapeseed oil and RME the CO-, HC- and NO_X-emissions were assumed to be reduced by 81%, 77.5% and 6% respectively as measured by Aakko *et al.* (2000) with a catalyst provided by Johnson Matthey on a Volvo DH10A engine when MK3, MK1 and RME fuels were used. For ethanol fuel the CO-, HC- and NO_X-emissions were assumed to be reduced by 93%, 45% and 0% respectively as measured by Haupt *et al.* (1999) with a catalyst provided by Scania on a Scania DSE1101 engine when ethanol fuel (ET7) fuel was used. See also Section 3.4.4.2 and 3.7.1.2.

3.10 Allocation

When the environmental load for production of *e.g.* RME was studied there was a need to allocate environmental burdens between RME and its by-products meal and glycerine (Tables 106-107). Correspondingly, for ethanol fuel production, the environmental load was shared between the ethanol fuel and the distiller's waste (Tables 108-109). Allocation means that the environmental impacts in the LCA are spread out over the products produced (Lindfors *et al.*, 1995; Wenzel *et al.*, 1997; Lindahl *et al.*, 2001; Rydh *et al.*, 2002). That can be done by different methods. It may be done according to the product's energy content (physical allocation), economic value (economic allocation) or with an expanded system (to avoid allocation) where the products replace products (from the expanded system) whose environmental effects are subtracted from the system studied. With the expanded system, the system was expanded in a way so the meal or distiller's waste replaced imported (overseas) soymeal and the glycerine replaced glycerine produced from fossil products. The above-described systems were also compared with systems that were not allocated (no allocation).

For RME during the physical, economic and no allocations it was difficult to consider that carbon atoms, with biomass origin, might replace fossil carbon atoms in replaced glycerine (see Tables A5-A6, A9-A10 and A13-A14, Appendix 1). Therefore this had to be considered, on a discussion basis. This process is normally not considered by these three allocation methods. However, with an expanded system, the replacement of fossil glycerine with glycerine from the transesterification of biomass origin was also included in the system. For the ethanol fuel it was no problem to find out which carbon atoms had fossil origin. There, it was those originating from the ignition improver and the denaturants and they were all in the fuel. The replaced soymeal was of biomass-origin and assumed to give the same emissions as rapemeal when consumed and therefore not to have any influence on the systems studied. During the allocation procedures distiller's waste was handled in the same way as rapemeal.

In the scenario analysis with straw harvested, the straw was also involved in the allocation procedures described above (excl. expanded system) (Tables 106-109).

3.10.1 Physical and economic allocation

During physical and economic allocation the calculations were made in the same way (Tables 106-109). First, the production values (MJ/ha in energy terms or SEK/ha in economic terms) were calculated for each product by multiplying harvest [kg/ha] and the lower heat value [MJ/kg] or the price [SEK/kg]. Second, shares of total values were calculated for each product (Tables 106-109). Third, the calculated share values were distributed to each part-production process in the production chain (see description for rapeseed oil fuels and ethanol fuel in Section 3.10.1.2, see also Tables A3-A14 and A17-A22, Appendices 1 and 2), depending on the products emerging after the each of the part-production processes. Fourth, the calculated share-values [%] were multiplied by the emissions [g/ha] or energy requirements [MJ/ha] for each part-production process (Tables A3-A14 and A17-A22, Appendices 1 and 2). Fifth, the values obtained were added and the allocated emission [g/ha] or energy requirement values [MJ/ha] were obtained (Tables A3-A14 and A17-A22, Appendices 1 and 2).

Before physical allocation [MJ] could be performed, the lower heat values of all products included had to be known (see below and Table 104). For the meal, the lower heat value depends on the oil extraction efficiency and must be calculated for each production size and therefore a model for calculating the lower heat value of the meal was developed. For calculating this heat value the content of water and oil in the meal first had to be calculated. The heat value of oil and water-free meal also had to be calculated. Below follows a description of how these values were calculated.

The prices used for the products in the economic allocation were assumed to be valid at the farm in all three production scales. For medium- and large-scale plants, the prices corresponded to the products being transported back to the farm and used there. The allocation according to economic terms was calculated from the price of rapeseed oil (5.32 SEK/kg), rapemeal (1.45 SEK/kg) and feed fat (3.80 SEK/kg) (Herland, pers. comm.) and raw glycerine (4.44 SEK/kg) (Eriksson, Alf, pers. comm.). From the prices of the rapemeal and the feed fat, the prices for rape expeller with different contents of oil were calculated and used in the allocation (Equations 47-49 and Table 105). The same model was used to calculate the oil and water content in the expeller as was used for the physical allocation. Straw prices were used in a scenario analysis with harvested straw (Tables 105, 107 and 109).

3.10.1.1 Equations and factors, physical and economic allocation

Calculation of the lower heat value in rapemeal:

The lower heat value for meal with different composition after oil extraction in plants of different sizes was calculated using Equations 25-46 below.

O_{seed}:	Share of oil in seed, in this study assumed to be 45%.
W_{seed}:	Share of water in seed, in this study assumed to be 8%.
M_{seed}:	Share of oil and water-free part of seed, in this study assumed to be 47%.
W_{lost}:	Share of water in seed lost as steam during extraction, in this study assumed to be 2%.
O_{sedi}:	Share of oil in seed lost as oil in sediment, 1% for small-scale extraction, 0% for other sizes.
M_{sedi}:	Share as oil-free part in sediment, 0.6% for small-scale extraction, 0% for other sizes.
Sedi:	The total share of sediment is 1.6% for small-plants and 0% for other sizes.
Ext_{eff}:	Extraction efficiency = Share of oil in seed gained as oil: 68% for small-scale, 75% for medium-scale and 98% for large-scale extraction.

Share of seed extracted as oil:

$$O_{extseed} = Ext_{eff} * O_{seed} \tag{25}$$

Share of oil left in seed:

$$O_{meal} = O_{seed} - (O_{extseed} + O_{sedi}) \tag{26}$$

Total share of meal from seed:

$$M_{totmeal} = 1 - (O_{extseed} + W_{lost} + O_{sedi} + M_{sedi}) \tag{27}$$

Share as oil-free substance in meal:

$$M_{meal} = M_{totmeal} - O_{meal} = 1 - (W_{lost} + M_{sedi} + O_{seed}) \tag{28}$$

Share of water of oil-free substance in meal and sediment:

$$W_{oilfreeM+S} = \frac{W_{seed} - W_{lost}}{M_{meal} + M_{sedi}} = \frac{W_{seed} - W_{lost}}{1 - (W_{lost} + O_{seed})} \tag{29}$$

Share as water in meal:

$$W_{inmeal} = W_{oilfreeM+S} * M_{meal} \tag{30}$$

Share of water in meal:

$$W_{meal} = \frac{W_{inmeal}}{M_{totmeal}} \tag{31}$$

Share as water in sediment:

$$W_{insedi} = W_{oilfreeM+S} * M_{sedi} \tag{32}$$

Share as oil and water-free substance in meal:

$$M_{oilfreeO+W} = M_{meal} - W_{inmeal} \quad (33)$$

Share as oil and water-free substance in sediment:

$$M_{sedioilfreeO+W} = M_{sedi} - W_{insedi} \quad (34)$$

Share of oil and water-free substance in water-free meal:

$$M_{oilfreeinO+W} = \frac{M_{meal} - W_{inmeal}}{M_{totmeal} * (1 - W_{meal})} \quad (35)$$

Share of oil in water-free substance in meal:

$$O_{mealO+Wfree} = \frac{O_{meal}}{M_{totmeal} * (1 - W_{meal})} \quad (36)$$

Share of oil in meal:

$$O_{inmeal} = O_{mealO+Wfree} * (1 - W_{meal}) \quad (37)$$

Share of oil and water-free substance in meal:

$$M_{inmealO+Wfree} = M_{oilfreeinO+W} * (1 - W_{meal}) \quad (38)$$

Composition of seed:

$$Seed = O_{seed} + W_{seed} + M_{seed} = 1\,(100\,\%) \quad (39)$$

Composition of oil in seed:

$$O_{seed} = O_{extseed} + O_{meal} + O_{sedi} \quad (40)$$

Composition of water in seed:

$$W_{seed} = W_{inmeal} + W_{insedi} + W_{lost} \quad (41)$$

Composition of oil and water-free part of seed:

$$M_{seed} = M_{oilfreeO+W} + M_{sedioilfreeO+W} \quad (42)$$

Composition of meal:

$$M_{totmeal} = M_{meal} + O_{meal} = M_{oilfreeO+W} + W_{inmeal} + O_{meal} \quad (43)$$

Composition of water-free substance in meal (used for calculation of lower heat value):

$$M_{oilfreeinO+W} + O_{mealO+Wfree} = 1\,(100\,\%) \quad (44)$$

Composition of meal (used for economic calculations):

$$O_{inmeal} + M_{inmealO+Wfree} + W_{meal} = 1\,(100\,\%) \quad (45)$$

Lower heat value of meal [MJ/kg]:

$$H_{imeal} = (M_{oilfreeinO+W} * H_{imealO+Wfree} + O_{mealO+Wfree} * H_{ioil}) - (21.23 * W_{meal}) \quad (46)$$

Lower heat value of oil: H_{ioil} = 38.3 MJ/kg (SMP, 1994).
Lower heat value of oil and water-free meal: $H_{imeal0+Wfree}$ = 17.26 MJ/kg (calculated).

17.26 is an estimated lower heat value for oil and water-free meal substance [MJ/kg] from a meal sample from Sjösa farm. This sample had a lower heat value of 22.52 MJ/kg water-free substance that contained 25% of oil (Praks, 1993a; Bernesson, 1993). The oil had a lower heat value of 38.3 MJ/kg (SMP, 1994). The lower heat value for oil and water-free substance of meal can be calculated as: (22.52 - (0.25 * 38.3)) / 0.75 = 17.26 MJ/kg. The value 21.23 is given in Mörtstedt & Hellsten (1982) in an equation for calculating the lower heat value for wood according to Widell: $H_i = 18.73 - 21.23 * H_2O$ MJ/kg, where 18.73 was changed to the above-mentioned value calculated for meal after its oil content was measured. Measured lower heat value for meal that contained 10.9% of water and 25% of oil in water-free substance was 19.8 MJ/kg. The corresponding calculated value was 20.21 MJ/kg. The bias from the true value was (20.21 / 19.80) = 1.021 = 2.1%.

Calculation of lower heat value in straw (scenario analysis, straw harvested):

For straw from rape and wheat, the lower heat values (Kaltschmitt & Reinhardt, 1997) are 17.0 and 17.5 MJ/kg dry matter respectively. The lower heat values for straw with 15% water (wet basis) (Table 104) was calculated as: (1 – straw water content) * straw dry matter lower heat value [MJ/kg] – straw water content * (44 MJ/kmol enthalpy of vaporisation of water / 18.016 kg/kmol water) (Aylward & Findlay, 1994).

Calculation of meal price:

The price for meal with different composition after oil extraction in plants of different sizes was calculated using Equations 47-49 below.

Price of rapemeal with:
oil content: $O_p = 3.7\%$ and
water content: $W_p = 10.5\%$
is: $P_{M3.7W10.5} = 1.45$ SEK/kg (Herland, pers. comm.).
Price of fodder fat: $P_{FF} = 3.80$ SEK/kg

Price of water-free meal:

$$P_{Mwaterfree} = \frac{P_{M3.7W10.5}}{1 - w_p} \tag{47}$$

Price of oil-free and water-free meal:

$$P_{Mwaterandoilfree} = \frac{P_{M3.7W10.5} - (O_p * P_{FF})}{1 - (O_p - W_p)} \tag{48}$$

Some physical factors were also required for the economic calculations:

Price of rapemeal:

$$P_{meal} = O_{inmeal} * P_{FF} + W_{meal} * 0 + M_{inmealO+Wfree} * P_{Mwaterandoilfree} \tag{49}$$

Calculation of straw price (scenario analysis, straw harvested):

The price for straw on the field was 0.070 SEK/kg (Nilsson, 1999) (Table 105). This straw was assumed to be wheat. The price for rape straw (Table 105) was then calculated as: price for wheat straw [SEK/kg] * (lower heat value for rape straw (15% water) (Table 104) / lower heat value for wheat straw (15% water)) (Table 104).

Calculation of lower heat value in distiller's waste:

The lower heat value in distiller's waste was calculated from the lower heat value for dried distiller's waste (Belab, 2002) (see Equations 50–51). Below follows a description of the calculations.

Lower heat value of dry substance from distiller's waste: H_{idsdw} = 19.755 MJ/kg (Belab, 2002).
Share of water in dried distiller's waste: W_{ddw} = 9%.
Share of water in wet distiller's waste: W_{wdw} = 90.9%.
The molar enthalpy of vaporisation (Aylward & Findlay, 1994): $H_{vapwater}$ = 44 kJ/mol is valid for the standard state pressure of 105 Pa (or 1 bar) and a temperature of 25°C (or 298.15 K).
The molecular weight of water (calculated after Aylward & Findlay, 1994): M_{water} = 18.016 g/mol.
Lower heat value of dried distiller's waste [MJ/kg]:

$$H_{iddw} = (1 - W_{ddw}) * H_{idsdw} - W_{ddw} * \left(\frac{H_{vapwater}}{M_{water}} \right) \quad (50)$$

which gives H_{iddw} = 17.76 MJ/kg.

Lower heat value of wet distiller's waste [MJ/kg]:

$$H_{iwdw} = (1 - W_{wdw}) * H_{idsdw} - W_{wdw} * \left(\frac{H_{vapwater}}{M_{water}} \right) \quad (51)$$

which gives H_{iwdw} = -0.422 MJ/kg. The negative sign is not relevant for the calculation. Because wet distiller's waste is not inferior to dried distiller's waste when used as feed, as in this study, this justifies the values for dried distiller's waste also being used for small- and medium-scale plants for the physical allocation (Tables 104 and 108).

Calculation of the price for dried distiller's waste:

The price for dried distiller's waste (with 10% water) is 1.00 SEK/kg (Werling, pers. comm.) and when this is recalculated to distiller's waste with 9% water as in this study, the following is valid: 1.00 SEK/kg * (0.91 / 0.90) = 1.01 SEK/kg (Tables 105 and 109). The price for wet distiller's waste is 0.0415 SEK/kg (SBI-Trading, 2003) (Tables 105 and 109).

3.10.1.2 General, physical and economic allocation

In the study of rapeseed oil fuels, the share-values of the total value (see description of the calculation process in Section 3.10.1 above; Tables 106-107 and Tables A3-A14, Appendix 1) was calculated for rapeseed oil or RME in the production steps: cultivation of rapeseed; transport of seed to extraction (fuel + machinery); electricity for oil extraction; total machinery for oil extraction; buildings for oil extraction; and hexane extraction. Multiplied by share-values for rapeseed oil or RME from Tables 106 or 107 during the addition in Tables A3-A14, Appendix 1.
For RME-production a part-value for RME in the RME + glycerine production chain (Tables 106-107) was calculated for: methanol production; transport of methanol (fuel + machinery); production of catalyst; electricity transesterification; total machinery transesterification; and buildings transesterification. Multiplied by share-values for RME from Tables 106 or 107 during the addition in Tables A5-A6, A9-A10 and A13-A14, Appendix 1.
No allocation was made for production steps where only rapeseed oil or RME participated: emissions when driving on the rapeseed oil or RME; and transport of rapeseed oil or RME (fuel + machinery). Multiplied by 1 (one) during the addition in Tables A3-A14, Appendix 1.
Part-processes not containing rapeseed oil or RME were excluded from the allocation: transport of meal (fuel + machinery) and transport of glycerine (fuel + machinery). Multiplied by 0 (zero) during the addition in Tables A3-A14, Appendix 1.

In the study of ethanol fuel production, the share-values of the total value (see description of the calculation process in Section 3.10.1 above; Tables 108-109 and Tables A17-A22, Appendix 2) were calculated for ethanol fuel in the production steps: cultivation of wheat; transport of wheat to ethanol fuel production (fuel + machinery); electricity fermentation; steam (heat) fermentation; total machinery for ethanol fuel production; buildings for ethanol fuel production; production of chemicals for ethanol production; transport of chemicals for ethanol production (fuel + machinery); and handling of waste water. Multiplied by share-values for ethanol fuel from Tables 108 or 109 during the addition in Tables A17-A22, Appendix 2.
No allocation was made for production steps where only ethanol fuel participated: electricity distillation; steam (heat) distillation; production of ignition improver and corrosion inhibitor; production of denaturants; transport of chemicals for ethanol fuel production (fuel + machinery); transport of ethanol fuel (fuel + machinery); and emissions when driving on the ethanol fuel. Multiplied by 1 (one) during the addition in Tables A17-A22, Appendix 2.
Part-processes not containing ethanol fuel were excluded from the allocation: electricity handling (drying or pumping) of distiller's waste; steam (heat) handling (drying) of distiller's waste; and transport of distiller's waste (fuel + machinery). Multiplied by 0 (zero) during the addition in Tables A17-A22, Appendix 2.

Table 104. Data for physical allocation according to lower heat value

Product	Lower heat value [MJ/kg]	Original source
Rapeseed oil	38.3	SMP, 1994
RME	38.5	SMP, 1993
Glycerine	17.1	Kaltschmitt & Reinhardt, 1997
Meal, small-scale	20.06	calculated after: Bernesson, 1993
Meal, medium-scale	19.34	calculated after: Bernesson, 1993
Meal, large-scale	15.29	calculated after: Bernesson, 1993
Straw winter rape[a]	14.08	calculated after: Kaltschmitt & Reinhardt, 1997
Ethanol fuel	25.12	calculated after: Aylward & Findlay, 1994; Schmitz, 2003; Solomons, 1996; Lif, pers. comm.; and Sekab, 2003
Distiller's waste (91% dry matter)	17.76	calculated after: Belab, 2002; Aylward & Findlay, 1994
Distiller's waste (9.1% dry matter)	-0.42	calculated after: Belab, 2002; Aylward & Findlay, 1994
Carbon dioxide	0.00	because it is an end product from biological processes and combustion
Straw winter wheat[a]	14.51	calculated after: Kaltschmitt & Reinhardt, 1997

[a] Only used in the scenario analysis.

Table 105. Data for economic allocation according to Swedish crowns [SEK]

Product	Price [SEK/kg]	Original source
Rapeseed oil	5.32	Herland, pers. comm.
RME	6.33	Lindkvist, pers. comm.: 5610 SEK/m^3 direct from manufacturer
Glycerine (raw and water-free)	4.44	calculated after: Eriksson, Alf, pers. comm.
Meal, small-scale	1.85	calculated after: Herland, pers. comm.
Meal, medium-scale	1.78	calculated after: Herland, pers. comm.
Meal, large-scale	1.39	calculated after: Herland, pers. comm.
Straw winter rape[a]	0.068	calculated after: Nilsson, 1999 and Kaltschmitt & Reinhardt, 1997
Ethanol fuel	6.30	Elfving, pers. comm.
Distiller's waste (91% dry matter)	1.01	calculated after: Werling, pers. comm.
Distiller's waste (9.1% dry matter)	0.0415	SBI-Trading, 2003
Carbon dioxide	0.00	Gebro, pers. comm.
Straw winter wheat[a]	0.070	Nilsson, 1999

[a] Only used in the scenario analysis.

Table 106. Critical values for physical allocation, oil extraction and transesterification

Type of product	Product [kg/ha]	Heat value [MJ/kg]	Ordinary production: Production [MJ/ha][a]	Share [%]	Production [MJ/ha][b]	Share [%]	Scenario analysis[c]: Production [MJ/ha]	Share [%]
Small-scale production:								
Rapeseed oil	756	38.30	28948	47.0			28948	27.1
Meal	1625	20.06	32595	53.0			32595	30.5
Straw[c]	3211	14.08					45223	42.4
Total extraction			61543	100.0			106766	100.0
RME	727	38.50	27993	45.2	27993	95.4	27993	26.1
Glycerine	80	17.10	1362	2.2	1362	4.6	1362	1.3
Meal	1625	20.06	32595	52.6			32595	30.4
Straw[c]	3211	14.08					45223	42.2
Total transesterification			61950	100.0	29355	100.0	107173	100.0
Medium-scale production:								
Rapeseed oil	834	38.30	31928	51.0			31928	29.6
Meal	1587	19.34	30694	49.0			30694	28.5
Straw[c]	3211	14.08					45223	41.9
Total extraction			62621	100.0			107844	100.0
RME	802	38.50	30875	49.0	30875	95.4	30875	28.5
Glycerine	88	17.10	1502	2.4	1502	4.6	1502	1.4
Meal	1587	19.34	30694	48.7			30694	28.3
Straw[c]	3211	14.08					45223	41.8
Total transesterification			63071	100.0	32377	100.0	108293	100.0
Large-scale production:								
Rapeseed oil	1089	38.30	41719	67.2			41719	38.9
Meal	1331	15.29	20359	32.8			20359	19.0
Straw[c]	3211	14.08					45223	42.1
Total extraction			62078	100.0			107300	100.0
RME	1048	38.50	40343	64.4	40343	95.4	40343	37.4
Glycerine	115	17.10	1963	3.1	1963	4.6	1963	1.8
Meal	1331	15.29	20359	32.5			20359	18.9
Straw[c]	3211	14.08					45223	41.9
Total transesterification			62665	100.0	42306	100.0	107888	100.0

[a] Allocation of rapeseed oil and meal or RME, glycerine and meal.
[b] Allocation of RME and glycerine.
[c] Only used in the scenario analysis, straw harvested.

Table 107. Critical values for economic allocation, oil extraction and transesterification

Type of product			Ordinary production				Scenario analysis[c]	
	Product [kg/ha]	Price [SEK/kg]	Production [SEK/ha][a]	Share [%]	Production [SEK/ha][b]	Share [%]	Production [SEK/ha]	Share [%]
Small-scale production:								
Rapeseed oil	756	5.32	4021	57.2			4021	55.5
Meal	1625	1.85	3009	42.8			3009	41.5
Straw[c]	3211	0.068					218	3.0
Total extraction			7030	100.0			7248	100.0
RME	727	6.33	4604	57.8	4604	92.9	4604	56.2
Glycerine	80	4.44	354	4.4	354	7.1	354	4.3
Meal	1625	1.85	3009	37.8			3009	36.8
Straw[c]	3211	0.068					218	2.7
Total transesterification			7967	100.0	4958	100.0	8185	100.0
Medium-scale production:								
Rapeseed oil	834	5.32	4435	61.1			4435	59.3
Meal	1587	1.78	2828	38.9			2828	37.8
Straw[c]	3211	0.068					218	2.9
Total extraction			7262	100.0			7481	100.0
RME	802	6.33	5078	61.2	5078	92.9	5078	59.6
Glycerine	88	4.44	390	4.7	390	7.1	390	4.6
Meal	1587	1.78	2828	34.1			2828	33.2
Straw[c]	3211	0.068					218	2.6
Total transesterification			8295	100.0	5468	100.0	8514	100.0
Large-scale production:								
Rapeseed oil	1089	5.32	5795	75.7			5795	73.6
Meal	1331	1.39	1856	24.3			1856	23.6
Straw[c]	3211	0.068					218	2.8
Total extraction			7651	100.0			7869	100.0
RME	1048	6.33	6635	73.7	6635	92.9	6635	72.0
Glycerine	115	4.44	510	5.7	510	7.1	510	5.5
Meal	1331	1.39	1856	20.6			1856	20.1
Straw[c]	3211	0.068					218	2.4
Total transesterification			9001	100.0	7145	100.0	9219	100.0

[a] Allocation of rapeseed oil and meal or RME, glycerine and meal.
[b] Allocation of RME and glycerine.
[c] Only used in the scenario analysis, straw harvested.

Table 108. Critical values for physical allocation, ethanol fuel production

Type of product	Product [kg/ha]	Heat value[a] [MJ/kg]	Ordinary system: Production [MJ/ha]	Ordinary system: Share [%]	Scenario analysis[b]: Production [MJ/ha]	Scenario analysis[b]: Share [%]
Small-scale production:						
Ethanol fuel	2072	25.12	52062	60.8	52062	32.9
Distiller's waste (9.0% water)	1892	17.76	33605	39.2	33605	21.2
Straw[b]	5015	14.51			72761	45.9
Total			85666	100.0	158427	100.0
Medium-scale production:						
Ethanol fuel	2072	25.12	52062	60.8	52062	32.9
Distiller's waste (9.0% water)	1892	17.76	33605	39.2	33605	21.2
Straw[b]	5015	14.51			72761	45.9
Total			85666	100.0	158427	100.0
Large-scale production:						
Ethanol fuel	2072	25.12	52062	60.8	52062	32.9
Distiller's waste (9.0% water)	1892	17.76	33605	39.2	33605	21.2
Straw[b]	5015	14.51			72761	45.9
Total			85666	100.0	158427	100.0

[a] Lower heat value ethanol fuel: calculated after Aylward & Findlay (1994); Schmitz (2003); Solomons (1996); Lif (pers. comm.) and Sekab (2003); distiller's waste calculated after Belab (2002); Aylward & Findlay (1994).
[b] Only used in the scenario analysis, straw harvested.

Table 109. Critical values for economic allocation, ethanol fuel production

Type of product			Ordinary system		Scenario analysis[b]	
	Product	Price[a]	Production	Share	Production	Share
	[kg/ha]	[SEK/kg]	[SEK/ha]	[%]	[SEK/ha]	[%]
Small-scale production:						
Ethanol fuel	2072	6.30	13056	94.3	13056	92.0
Distiller's waste (90.9% water)	18925	0.0415	785	5.7	785	5.5
Straw[b]	5015	0.070			351	2.5
Total			13841	100.0	14192	100.0
Medium-scale production:						
Ethanol fuel	2072	6.30	13056	94.3	13056	92.0
Distiller's waste (90.9% water)	18925	0.0415	785	5.7	785	5.5
Straw[b]	5015	0.070			351	2.5
Total			13841	100.0	14192	100.0
Large-scale production:						
Ethanol fuel	2072	6.30	13056	87.2	13056	85.2
Distiller's waste (9.0% water)	1892	1.01	1913	12.8	1913	12.5
Straw[b]	5015	0.070			351	2.3
Total			14969	100.0	15320	100.0

[a] Prices: ethanol fuel (Elfving, pers. comm.); distiller's waste (9.0% water) calculated after Werling (pers. comm.); distiller's waste (90.9% water) (SBI-Trading, 2003).
[b] Only used in the scenario analysis, straw harvested.

3.10.2 Allocation with expanded system

In the third allocation method, the system was expanded in such a way that the rapemeal replaced imported soymeal and rape expeller with high oil content replaced soymeal mixed with soyoil until the original protein and oil contents were reached. During production of ethanol fuel the distiller's waste produced was assumed to replace soymeal mixed with soyoil in the same way as rapemeal. The soymeal or soymeal mixed with soyoil was assumed to be transported from a harbour by an open-sided lorry to the farm for consumption (110 km). The glycerine from the transesterification was assumed to replace glycerine produced from fossil propane gas. The emissions and energy requirement for the production of soymeal, soyoil and fossil glycerine (Jungk *et al.*, 2000) were subtracted from the emissions and energy required to produce the rapeseed oil fuels or ethanol fuel during the allocation procedure with expanded system.

Model for allocation with expanded system, rapemeal replacing soymeal and soyoil:

The question was: How much soymeal was required to be replaced by the protein in the rapemeal? There follow some protein data for rapeseed: The amount of soymeal and soyoil to be replaced by the rapemeal was calculated using Equations 52-61 below.

P_{dmseed}: Share as raw protein of dry matter in rapeseed, assumed to be 23% after data in Norén *et al.* (1994).
H_{seed}: Harvest of seed: 2470 kg/ha with 9% water.

Harvest of oil:

$$H_{oil} = H_{seed} * O_{seed} * Ext_{eff} \tag{52}$$

Harvest of meal:

$$H_{meal} = H_{seed} * M_{totmeal} = H_{seed} * (1 - (Ext_{eff} * O_{seed} + W_{lost} + O_{sedi} + M_{sedi})) \tag{53}$$

Protein in oil and water-free part of rapemeal:

$$P_{oilandwaterfree} = \frac{P_{dmseed}}{\left(\frac{M_{seed}}{O_{seed} + M_{seed}}\right)} \tag{54}$$

If 45% of seed incl. water is oil, then the protein content is, $P_{oilandwaterfree}$ = 45.02%.

The harvest of raw protein in meal will then be (516.7 kg/ha for small-scale extraction and 522.7 kg/ha for medium- and large-scale extraction):

$$H_{protmeal} = H_{meal} * (1 - W_{meal}) * M_{oilfreeinO+W} * P_{oilandwaterfree} \tag{55}$$

The total harvest of protein in rapeseed is (522.7 kg/ha):

$$H_{protseed} = H_{seed} * (1 - (W_{seed} + O_{seed})) * P_{oilandwaterfree} \tag{56}$$

Typical composition of solvent extracted soymeal (ASA, 2002) is: 44% protein = $P_{soymeal}$; 1% fat = $F_{soymeal}$; 7% fibre; 6% ash; and 12% moisture = $W_{soymeal}$. Then the amount of soymeal to be replaced by the protein in rapemeal is:

$$M_{soybeanreplace} = H_{protmeal} / P_{soymeal} \tag{57}$$

(1174 kg small-scale extraction; 1188 kg medium-scale extraction; and 1188 kg large-scale extraction).

To get the right energy content in the soymeal compared to the rapemeal, it must contain a higher amount of oil (soyoil) than the solvent extracted. This is here calculated as a supply of soyoil to the soymeal until it contains the right amount of fat. The amount of rapemeal oil that requires to be used for replacing soyoil when soymeal and soyoil are mixed to get an equivalent feed to be replaced can be calculated as:

Amount of oil in soymeal [kg/ha]:

$$O_{weightsoymeal} = F_{soymeal} * M_{soybeanreplace} \tag{58}$$

Amount of oil in rapemeal [kg/ha]:

$$O_{weightrapemeal} = O_{inmeal} * H_{meal} \tag{59}$$

Amount of oil in rapemeal that replaces soyoil added to soymeal to get a product equivalent to the replacing rapemeal (with a high oil content from small- and medium-scale extraction) [kg/ha rapeseed] could then be calculated. In this study the soymeal and soyoil were assumed to be mixed before transportation to the farm:

$$O_{replace} = O_{weightrapemeal} - O_{weightsoymeal} \quad (60)$$

(319.2 kg small-scale extraction; 266.0 kg medium-scale extraction; and 10.4 kg large-scale extraction).

Weight of soymeal mixed with soyoil replaced by rapemeal [kg / ha rapeseed]:

$$M_{totreplaceM+O} = M_{soybeanreplace} + O_{replace} \quad (61)$$

This product containing soymeal and soyoil was assumed to be transported to the farm before being replaced by rapemeal (1494 kg small-scale extraction; 1454 kg medium-scale extraction; and 1198 kg large-scale extraction).

Table 110 shows emissions and energy requirement during production of soymeal and soyoil that are replaced by rapemeal in an expanded system. Emissions and energy requirement when replaced soymeal and soyoil were produced [g/ha] or [MJ/ha] (Table 110; see also Tables A3-A14, Appendix 1) were calculated as: amount of soymeal to be replaced by the protein in rapemeal ($M_{soybeanreplace}$) [kg/ha] * emissions or energy requirement for production of soymeal (Table 110) [g/kg] or [MJ/kg] + amount of oil in rapemeal that replaced soyoil ($O_{replace}$) [kg/ha] * emissions or energy requirement for production of soyoil (Table 110) [g/kg] or [MJ/kg].

Emissions and energy requirements for production of fuel and machinery for transport (Tables 57, 59, 61, 63, 76 and 78) were calculated in the same way as for other transport in this study. Their emissions and energy requirement were subtracted from the total emissions for production of the rapeseed oil fuels as the emissions for production of soymeal (Tables A3-A14, Appendix 1).

Table 110. Emissions from production of overseas soymeal and soyoil replaced by rapeseed oil (Jungk et al., 2000)

Product / Emissions	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	HCl	Particles	Input energy
Soymeal [g/kg] and [MJ/kg]	307.5	0.76	0.165	0.75	2.76	2.68	0.119	0.120	0.0191	0.215	6.26
Soyoil [g/kg] and [MJ/kg]	1325.0	3.29	0.713	3.24	11.90	11.56	0.514	0.515	0.0822	0.924	26.97
Production of soymeal and soyoil replaced by rapemeal:											
Small-scale [g/ha] or [MJ/ha]	784112	1949	422	1918	7044	6837	304	305	48.6	547	15957
Medium-scale [g/ha] or [MJ/ha]	717706	1784	386	1756	6447	6258	278	279	44.5	501	14606
Large-scale [g/ha] or [MJ/ha]	378981	942	204	927	3404	3304	147	147	23.5	264	7711
Production of soymeal and soyoil replaced by distiller's waste:											
Small-scale [g/ha] or [MJ/ha]	875545	2177	471	2142	7865	7635	339	341	54.3	611	17818
Medium-scale [g/ha] or [MJ/ha]	875545	2177	471	2142	7865	7635	339	341	54.3	611	17818
Large-scale [g/ha] or [MJ/ha]	875545	2177	471	2142	7865	7635	339	341	54.3	611	17818

Model for allocation with expanded system, distiller's waste replacing soymeal and soyoil:

The question was: How much soymeal was required to be replaced by the protein in the distiller's waste? There follow some protein data for distiller's waste. Soyoil was assumed to be added until the feed had the same energy content (here based on lower heat value) as in the replacing distiller's waste feed. The amount of soymeal and soyoil to be replaced by the distiller's waste were calculated using Equations 62-68 below.

P_{dmdw}: Share as raw protein of dry matter in distiller's waste, assumed to be 35% after data in SBI-Trading (2003).
H_{dw}: Harvest of distiller's waste: 1892 kg/ha with 9.0% water (W_{ddw}).
H_{iddw}: Lower heat value of distiller's waste with 9.0% water: 17.76 MJ/kg (see Equation 50 above).

Amount of raw protein in distiller's waste:

$$P_{dw} = H_{dw} * (1 - W_{ddw}) * P_{dmdw} \tag{62}$$

gives 602 kg/ha raw protein in distiller's waste.

Amount of soymeal to be replaced by the protein in the distiller's waste:

$$M_{soymealrpdw} = \frac{P_{dw}}{P_{soymeal}} \tag{63}$$

gives 1368 kg soymeal/ha to be replaced by the protein in distiller's waste.

Lower heat value of soymeal if assumed to be possible to calculate as for rapemeal [MJ/kg]: ((Share of oil and water-free substance in water-free soymeal * 17.26) + (share of oil in water-free substance in soymeal * 38.3)) - (21.23 * share of water in soymeal) (see above, Equation 46; composition soymeal: see above):

$$H_{isoymeal} = \frac{H_{imeal0+Wfree} * (1 - W_{soymeal} - F_{soymeal}) + H_{ioil} * F_{soymeal}}{(1 - W_{soymeal})} - 21.23 * W_{soymeal} \tag{64}$$

gives: $H_{isoymeal}$ = 14.95 MJ/kg.

Amount of energy in soymeal, if based on the lower heat value, that contained the same amount of raw protein as the distiller's waste that replaced soymeal to get an equivalent feed:

$$E_{soymeal} = M_{soymealrpdw} * H_{isoymeal} \tag{65}$$

gives: 20459 MJ.

Energy in distiller's waste from 1 ha:

$$E_{dw} = H_{dw} * H_{iddw} \tag{66}$$

gives: 33605 MJ/ha.

Requirement of additional energy as soyoil:

$$E_{ad} = E_{dw} - E_{soymeal} \tag{67}$$

gives: 13146 MJ/ha, which is equivalent to a specific amount of soyoil:

$$M_{soyoildw} = \frac{E_{ad}}{H_{ioil}} \qquad (68)$$

that gives: 343.2 kg soyoil/ha to add to the soymeal to get a feed with the same energy content (based on lower heat value) as in the replacing distiller's waste.

The amount of replacing distiller's waste was assumed to be the same independent of whether it was dried or not. Therefore the same amount of soymeal and soyoil was replaced by the distiller's waste in all three production plant sizes in this study.

Table 110 shows emissions and energy requirement during production of soymeal and soyoil that are replaced by distiller's waste in an expanded system. Emissions or energy requirement when replaced soymeal and soyoil were produced [g/ha] (Table 110; see also Tables A17-A22, Appendix 2) were calculated as: amount of soymeal to be replaced by the protein in distiller's waste ($M_{soymealrpdw}$) [kg/ha] * emissions or energy requirement for production of soymeal (Table 110) [g/kg] or [MJ/kg] + amount of oil in distiller's waste that replaced soyoil ($M_{soyoildw}$) [kg/ha] * emissions or energy requirement for production of soyoil (Table 110) [g/kg] or [MJ/kg].

Emissions and energy requirements for production of fuel and machinery for transport (Tables 58, 60, 62, 64, 77 and 79) were calculated in the same way as for other transport in this study. Their emissions were subtracted from the total emissions for production of the ethanol fuel as the emissions for production of soymeal (Tables A17-A22, Appendix 2).

Replacement of fossil glycerine:

Table 111 presents emissions and energy requirement during production of fossil glycerine replaced by rapeseed glycerine in an expanded system with transesterification of rapeseed oil. The CO_2-emissions in Table 111 also include the carbon atoms in the glycerine produced. Emissions or energy requirement when the replaced fossil glycerine is produced [g/ha] or [MJ/ha] (Table 111) is calculated as: amount of fossil glycerine (the same amount as rapeseed glycerine, see Table 106) to be replaced by rapeseed glycerine [kg/ha] * emissions or energy requirement for production fossil glycerine [g/kg] or [MJ/kg] (Table 111). The calculated emission or energy requirement values were subtracted from the total emissions for production of the rape methyl ester (Tables A5-A6, A9-A10 and A13-A14, Appendix 1). No transport was needed for the fossil glycerine because it was assumed to be available on the site to which the rapeseed glycerine was assumed to be transported.

With the system expansion when expanded system allocation was performed, it was considered that carbon atoms, with biomass origin, replaced fossil carbon atoms in replaced fossil glycerine in the GWP-emissions. This reduction in the CO_2-emissions could be calculated as: 3.87 g CO_2/MJ_{fuel} (see Section 3.4.4.2 for explanation) / engine efficiency (Table 102) = 11.1 g CO_2/MJ_{engine}; or on an area basis [g CO_2/ha] (Tables A5-A6, A9-A10 and A13-A14, Appendix 1): 3.87 g CO_2/MJ_{fuel} * area quantity of RME [kg/ha] (Table 103) * lower heat value RME [MJ/kg] (Table 99).

Table 111. Emissions from production of fossil glycerine (Jungk et al., 2000)

Product / Emissions	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	HCl	Particles	Input energy
Fossil glycerine [g/kg] or [MJ/kg]	5291	3.31	2.50	9.45	10.82	11.35	0.0039	0.196	0.382	0.692	126.6
Production of fossil glycerine replaced by rape glycerine:											
Small-scale [g/ha] or [MJ/ha]	421420	264	199	752	862	904	0.311	15.6	30.4	55.1	10083
Medium-scale [g/ha] or [MJ/ha]	464801	291	220	830	950	997	0.343	17.2	33.5	60.8	11121
Large-scale [g/ha] or [MJ/ha]	607340	380	287	1084	1242	1303	0.448	22.5	43.8	79.4	14532

3.10.3 Functional unit after allocation

The functional unit was handled in the same way independent of the studied method of allocation (Tables A3-A14 and A17-A22, Appendices 1-2). Values with energy on the engine shaft [MJ_{engine}] as the functional unit were obtained by dividing the sums obtained (Tables A3-A14 and A17-A22) by the total fuel harvest [MJ/ha] (Tables 106 and 108) and the engine efficiency [MJ_{engine}/MJ_{fuel}] (Table 102). Values with energy in the produced fuel delivered to the final consumer [MJ_{fuel}] as the functional unit were obtained by: first subtracting the sums obtained (Tables A3-A14 and A17-A22) from the emissions when driving on the produced fuel; and second by dividing the results by the total fuel harvest [MJ/ha] (Tables 106 and 108).

3.11 Sensitivity analyses

The three types of sensitivity analyses (traditional sensitivity analysis where only one parameter was studied at a time; scenario analysis where different production scenarios were studied; and Monte Carlo simulation where the uncertainty for some result parameters was studied) were studied on small-scale production of rapeseed oil, rape methyl ester and ethanol fuel production. Physical allocation and no allocation were applied on the investigated systems for sensitivity and scenario analysis. For description of used functional unit see Section 3.2.

3.11.1 Sensitivity analysis

First, a traditional sensitivity analysis was conducted to find out how sensitive the model was to changes in some important input parameters (see Section 4.8). One parameter at a time was changed (±20%) and the influence on the results was studied. Parameters that in the basic scenario had an influence on any of the GWP-, AP-, EP- or POCP-emissions or energy requirement of more than about one per cent were studied. The chosen parameters for rapeseed oil and RME were: seed harvest; use of fertiliser; soil emissions; use of pesticides; use of tractive power; use of machinery for cultivation; use of oil for seed drying; use of electricity for oil extraction; use of electricity for transesterification (only RME); emissions during production of methanol (only RME); and emissions when driving on the produced rapeseed oil or RME fuel. The chosen parameters for ethanol fuel production were: seed harvest; use of fertiliser; soil emissions; use of pesticides; use of tractive power; use of machinery for cultivation; use of oil for seed drying; use of electricity for ethanol production; use of steam for ethanol production; emissions during production of chemicals, enzymes etc.; emissions during production of ignition improver; emissions during production of denaturants; emissions during handling of waste water; and emissions when driving on the ethanol fuel produced. The purpose of the sensitivity analysis was to analyse to what extent uncertainty in input data affected the results.

For testing whether the difference between the studied plant scales had changed, the ratio between large- and small-scale production of rapeseed oil, RME or ethanol fuel was calculated for each test case. The ratios show the change in comparison to the denominator. These ratios were recalculated (expressed) as percentage change: ((ratio – 1) *100) to make the figures easier to handle in a table. The values obtained were compared with the original case to detect changes in the conclusions.

The sensitivity analysis for the economic calculations (see Section 4.10) was also made as described above. The chosen parameters for rapeseed oil and RME were: seed harvest; labour price; fertiliser price; electricity price; meal price; methanol price (only RME); glycerine price (only RME); transport price; and price for machinery and buildings. The chosen parameters for ethanol fuel production were: seed harvest; labour price; fertiliser price; electricity price; steam price; chemicals price; ignition improver price; denaturants price; transport price; price for machinery and buildings; and price for distiller's waste.

3.11.2 Scenario analysis

Second, in a scenario analysis the effects of some changes in production strategies were analysed (see Section 4.9). The following scenarios for rapeseed oil and RME were studied:

- Straw harvested, also studied with economic allocation to show the influence of the large difference in the evaluation of the straw between physical and economic allocation. The straw was assumed to leave the system studied dried on the field. Therefore no machine chains for straw harvesting or straw combustion required to be evaluated. For physical allocation the lower heat value for straw with 15% (wet basis) water was calculated (Section 3.10). For the economic allocation the price for the straw on the field was also estimated (Section 3.10). The results are not valid for expanded system because no choice of straw harvesting, combustion and replaced systems was made. A part of the environmental load for the cultivation was allocated away with the physical and economic allocations (see Section 3.10, Tables 106-107);
- Ploughless tillage (for description see Section 3.4.4.2);
- Use of *Salix*, which is a biofuel, as a raw material for the methanol production instead of natural gas (this makes the RME a 100% biofuel) (for description see Section 3.5.2 and Table 30) (only RME);
- Use of electricity mainly produced from fossil fuels (fossil fuel electricity) (for description see Section 3.6.1 and Table 49) instead of Swedish electricity for primary electric applications as oil extraction etc., or secondary electric applications as production of machinery and buildings or for all electric applications both primary and secondary;

- Use of catalysts for reduction of the CO-, HC- and NO_X-emissions from diesel engines used in cultivation operations, in transport or when the produced fuels were used, or in all these three applications (see also Section 3.4.4.2, 3.7.1.2 and 3.9);
- Use of the rapeseed oil and RME fuels produced for cultivation and transport (see also Section 3.4.4.2, 3.7.1.2 and 3.9);
- Use of plants at locations where all transport distances were doubled or halved;
- Machinery and building mass coefficient changed to 2/3 or 1 (for description see Section 3.8.2);
- Improved oil extraction efficiencies for the small- and medium-scale plants, from 68 to 73%, and from 75 to 80%, respectively. The oil extraction efficiency was not changed for large-scale plants;
- Use of the same oil extraction efficiency (with hexane) for small-scale extraction as for large-scale extraction (98%); and
- Small-scale extraction as large-scale extraction, which means the last described scenario with also the same use of electricity in the small-scale plant as in the large-scale plant.

Differences from the basic scenario were registered. The purpose of the scenario analyses was to analyse to what extent some alternative realistic scenarios affected the results.

The following scenarios for ethanol fuel production were studied:

- Straw harvested, also studied with economic allocation to show the influence of the large difference in the evaluation of the straw between physical and economic allocation. The straw was assumed to leave the system studied dried on the field. Therefore no machine chains for straw harvesting or straw combustion required to be evaluated. For physical allocation the lower heat value for straw with 15% (wet basis) water was calculated (Section 3.10). For the economic allocation the price for the straw on the field was also estimated (Section 3.10). The results are not valid for expanded system because no choice of straw harvesting, combustion and replaced systems was made. A part of the environmental load for the cultivation was allocated away with the physical and economic allocations (see Section 3.10, Tables 108-109);
- Ploughless tillage (for description see Section 3.4.4.2);
- Steam produced from *Salix* wood chips instead of spruce wood chips (for description see Section 3.5.3 and Tables 34-35);
- Use of ignition improver and corrosion inhibitor of bio-origin as raw material instead of raw material with fossil origin (for description see Section 3.5.3 and Table 44);
- Use of denaturants of bio-origin as a raw material instead of raw material with fossil origin (for description see Section 3.5.3 and Table 44);
- Use of ignition improver, corrosion inhibitor and denaturants of bio-origin as raw material instead of raw material with fossil origin (this makes the ethanol fuel a 100% biofuel) (for description see Section 3.5.3 and Table 44);
- Use of electricity mainly produced from fossil fuels (fossil fuel electricity) (for description see Section 3.6.1 and Table 49) instead of Swedish electricity for primary electric applications as extraction etc., or secondary electric applications as production of machinery and buildings or for all electric applications both primary and secondary;
- Use of catalysts for reduction of the CO-, HC- and NO_X-emissions from diesel engines used in cultivation operations, in transport or when the produced fuels were used, or in all these three applications (see also Section 3.4.4.2, 3.7.1.2 and 3.9);
- Use of the ethanol fuel produced for cultivation and transport (see also Section 3.4.4.2, 3.7.1.2 and 3.9);

- Use of the ethanol fuel produced for cultivation and transport if the ethanol fuel was produced with ignition improver and denaturants of bio-origin (this makes the ethanol fuel a 100% biofuel) (for description see Section 3.5.3) (see also Section 3.4.4.2, 3.7.1.2 and 3.9);
- Use of plants at locations where all transport distances were doubled or halved;
- Machinery and building mass coefficient changed to 2/3 or 1 (for description see Section 3.8.2);
- Small- and medium-scale production with large-scale energy efficiencies for electricity and steam use (see Section 3.5.3, Table 33);
- Small- and medium-scale production as large-scale production, higher efficiencies and drying of distillers waste which also gives more efficient transport of distiller's waste on return after wheat transport (see Section 3.5.3, Table 33).

Differences from the basic scenario were registered. The purpose with this scenario analysis was the same as for the rapeseed oil and RME scenario analyses.

For testing whether the difference between the plant scales studied had changed, the ratio between large- and small-scale production of rapeseed oil, RME or ethanol fuel was calculated for each test case. The ratios show the change in comparison to the denominator. These ratios were recalculated (expressed) as percentage change: ((ratio – 1) *100) to make the figures easier to handle in a table. The obtained values were compared with the original case to detect changes in the conclusions.

3.11.3 Monte Carlo simulation of error propagation

Third, an uncertainty analysis was made with Monte Carlo simulation (Vose, 1996) of error propagation to estimate the uncertainties when each fuel was produced alone, compared with other production scales or the other fuels studied here (see Section 4.11). The purpose of the Monte Carlo simulation of error propagation was to estimate uncertainty values for the results from the LCA-study. Furthermore, the purpose was to investigate whether it was possible, in a scientific way, to find out if there were differences between production scales and between fuels studied.

There follows an explanation of how the uncertainties were calculated. First, an explanation is given of how variances (squared uncertainties) of independent values add up during error propagation in simple systems (Equations 69-77). This is followed by an explanation of how Monte Carlo simulation could be used to add up variances in more complicated systems like LCAs (Figure 5 and Equations 78-83).

For a linear combination, the final value, y, is calculated from the values a, b, c, etc. by:

$$y = k + k_a * a + k_b * b + k_c * c + \ldots \qquad (69)$$

where k, k_a, k_b, k_c, etc. are constants (Miller & Miller, 1993; Bevington, 1969; Young, 1962). They have the uncertainty values u_a, u_b, u_c, etc. which are equivalent to the standard deviations (*i.e.* a measure for the average error) σ_a, σ_b, σ_c, etc. calculated from a combination of observable quantities. Variance (defined as the square of the standard deviation or here uncertainty value) has the important property that the variance of a sum or difference of independent quantities is equal to the sum of their variances. The uncertainty value, u_y for the final value could be calculated as:

$$u_y = \sqrt{(k_a * u_a)^2 + (k_b * u_b)^2 + (k_c * u_c)^2 + \ldots} \tag{70}$$

where u_y is equivalent to the standard deviation σ_y, of the linear combination.

For a multiplicative expression of the following type, where the final value 'y' is calculated from the values a, b, c and d by (Miller & Miller, 1993; Bevington, 1969; Young, 1962):

$$y = k * \frac{a * b}{c * d} \tag{71}$$

where k is a constant and a, b, c and d are independent quantities. For this expression there is a relationship between the squares of the relative uncertainty values (or for measured values the relative standard deviations):

$$\frac{u_y}{y} \approx \sqrt{\left(\frac{u_a}{a}\right)^2 + \left(\frac{u_b}{b}\right)^2 + \left(\frac{u_c}{c}\right)^2 + \left(\frac{u_d}{d}\right)^2} \tag{72}$$

which could be rewritten as an expression for the final uncertainty value:

$$u_y \approx y * \sqrt{\left(\frac{u_a}{a}\right)^2 + \left(\frac{u_b}{b}\right)^2 + \left(\frac{u_c}{c}\right)^2 + \left(\frac{u_d}{d}\right)^2} \tag{73}$$

If linear combinations and multiplicative expressions are combined as in:

$$y = \frac{a + b}{c + d} \tag{74}$$

its uncertainty value (or for measured values the relative standard deviations) has to be solved step by step as (a, b, c, and d are independent):

$$u_{a+b} = \sqrt{u_a^2 + u_b^2} \text{ and } u_{c+d} = \sqrt{u_c^2 + u_d^2} \Rightarrow u_y \approx y * \sqrt{\frac{u_a^2 + u_b^2}{(a+b)^2} + \frac{u_c^2 + u_d^2}{(c+d)^2}} \tag{75}$$

A general formula could be written as (a, b, c, etc. are independent):

$$y = y(a, b, c \ldots) \tag{76}$$

which gives a general expression for the uncertainty value for the final value y (Miller & Miller, 1993; Bevington, 1969; Young, 1962):

$$u_y \approx \sqrt{\left(\frac{\partial y}{\partial a} * u_a\right)^2 + \left(\frac{\partial y}{\partial b} * u_b\right)^2 + \left(\frac{\partial y}{\partial c} * u_c\right)^2 + \ldots} \tag{77}$$

This behaviour is similar to Pythagoras' theorem, which tells us that the squares of the lengths of orthogonal sides add up (Dupire, 1998). However, the method of error propagation has some drawbacks (Vose, 1996):

- It assumes all variables in the model are uncorrelated.
- The result is approximate for nonlinear functions such as divisions, exponents, power functions, etc.

If error propagation (according to Equations 69-77 above) is applied on such a complicated system as an LCA-study, the result will be impossibly complicated. Therefore, the error propagation was calculated as a quantitative risk analysis with Monte Carlo simulation (Vose, 1996) instead. This technique involves the random sampling (with a random number generator) of each probability distribution within the model to produce hundreds or even thousands of scenarios (also called iterations or trials). Each probability distribution is sampled in a manner that reproduces the distribution's shape. The distribution of the values calculated for the model outcome therefore reflects the probability of the values that could occur. Monte Carlo simulation offers some important advantages over the error propagation analysis described above (Vose, 1996):

- The distributions of the model's variables do not need to be approximated in any way.
- Correlations and other inter-dependencies can be modelled.
- The level of mathematics required to perform a Monte Carlo simulation is quite basic.
- The computer does all work required in determining the outcome distribution.
- Software is commercially available to automate the tasks involved in the simulation.
- Greater levels of precision can be achieved by simply increasing the number of iterations that are calculated.
- Complex mathematics can be included (*e.g.* power functions, logs, IF statements, etc.) with no extra difficulty.
- Monte Carlo simulation is widely recognised as a valid technique so its results are more likely to be accepted.
- The behaviour of the model can be investigated with great ease.
- Changes in the model can be made very quickly and the results compared with previous models.

The core principle of Monte Carlo method is the central limit theorem (CLT), which establishes how the empirical average of random samples converges to the true expectation (Montgomery, 1991; Vose, 1996; Dupire, 1998). It says that the mean $\bar{x}$ of a set of n variables (where n is large), drawn independently from the same distribution $f(x)$ will be approximately normally distributed:

$$\bar{x} = \text{Normal}(\mu, \sigma/\sqrt{n}) \tag{78}$$

where μ and σ are the mean and standard deviation of the $f(x)$ distribution from which the n samples were drawn. The theorem, described above, is probably the most important for risk analysis modelling.

Examples where quantitative risk analysis with Monte Carlo simulation is used in LCA are given by Wenzel *et al.* (1997), Emblemsvåg (2003), General Motors Corporation *et al.* (2001) and L-B-Systemtechnik (2002). Fuels from agricultural crops are included in General Motors Corporation *et al.* (2001) and L-B-Systemtechnik (2002).

For the simulations RISKSIM.XLA (RiskSim) by Middleton (1995) was used in Excel 7. RiskSim is an add-in for Excel that provides: statistical random generator function (*e.g.* normal distribution); ability to set the seed for random number generation; automatic repeated sampling for simulation; frequency distribution of simulation results; histogram and cumulative distribution charts.

During the simulations the number of iterations was chosen to be 1000 to get good enough repeatability, frequency distribution and cumulative distribution. The random number start seed was chosen to 0.5 in all simulations. The factors to be studied in the Monte Carlo simulation were chosen from the criteria that they should have an influence of at least approx. 2% on any of the environmental factors studied (physical allocation) in any of the scales studied for each fuel. The studied factors were then:

1) For cultivation (assumed to be dependent between production scales): seed harvest; fertiliser production; soil emissions; use of tractive power; and seed drying;
2) For production of rapeseed oil and RME (assumed to be independent between production scales): requirement of electricity in oil extraction; oil extraction losses (1 – oil extraction efficiency); requirement of electricity in transesterification (only RME); and production of methanol (only RME); (with expanded system replaced soybean meal mixed with soyoil and replaced fossil glycerine (only RME) were also included);
3) For production of ethanol fuel (assumed to be independent between production scales): requirement of electricity; requirement of steam; boiler losses (1 – boiler efficiency); production of Beraid (ignition improver); production of MTBE (denaturant); and production of isobutanol (denaturant); (with expanded system replaced soybean meal mixed with soyoil was also included);
4) Use of fuels produced in engines (assumed to be dependent between production scales). CO_2-emissions were not included in the randomisation because these emissions depend on the use of methanol during production of RME and the use of ignition improver and denaturants during production of ethanol fuel. The CO_2-emissions therefore do not depend on how the fuel is used in the engine.

The soil emissions were assumed to be dependent between fuels. All other factors for the cultivation were assumed to be independent between fuels. All studied factors were assumed to be normally distributed. The coefficients of variation were assumed to be 10% for each studied environmental factor. GWP-, AP-, EP- and POCP-emissions and energy requirement were studied with physical allocation. During comparison of fuels allocation with expanded system was also studied. For ethanol fuel production in a scenario where cultivation and use of the produced fuel were excluded during comparison of small- and large-scale plants, systems with input coefficients of variation of 5, 10 and 15% were studied.

The results from the Monte Carlo simulations (separate fuels, comparison of production scales and comparison of fuels) were assumed to be normally distributed or sufficiently normally distributed for the following calculations. The value of the standard deviation (s), obtained from the Monte Carlo simulation was considered to be the uncertainty value ‘u’.

The average values (emissions and energy requirement) from the Monte Carlo simulations ($\overline{x_1}$ and $\overline{x_2}$) were checked against their original values from the LCA calculations (μ_1 and μ_2). Bigger differences than a few per cent for absolute values and approx. 10% for comparisons could indicate that the Monte Carlo simulation does not work as expected if the difference is not very small.

Uncertainty values for differences between scales and fuels were calculated using separate Monte Carlo simulations. The comparisons of production scales and fuels were made with one-tailed z-tests (Equation 79) calculated as student's t-tests (Montgomery, 1991; Miller & Miller, 1993) with an infinite number of degrees of freedom (in Excel 1 000 000 number degrees of freedom chosen because almost infinite). The t-test calculations were made in Excel 7 (Equation 80). Before the t-test, the standard deviation for the comparison was calculated as described above.

During the comparison (production scales and fuels) of LCA-values the z-values (Equation 79) could be calculated as:

$$z = \frac{\mu_1 - \mu_2}{s} \qquad (79)$$

Since the student's t-test in Excel could not handle negative values, these were calculated as absolute values:

$$t = \left| \frac{\mu_1 - \mu_2}{s} \right| \qquad (80)$$

where μ_1 is the first value in the comparison, μ_2 is the second value in the comparison and s is the standard deviation from the comparison with degrees of freedom as described above. A normal distribution with variable r and the standard deviation σ (σ = 1 during standard conditions) is described by Equation 81 (Montgomery, 1991; Miller & Miller, 1993):

$$f(r) = \frac{1}{\sigma * \sqrt{2 * \pi}} * e^{-\frac{r^2}{2*\sigma^2}} \qquad -\infty < r < \infty \qquad (81)$$

The variable r could be described as:

$$r = (\mu_1 - \mu_2) - \mu \qquad (82)$$

where the mean $\mu = 0$ during standard conditions.

The integral from z to infinity ∞ over the equation f(r) (Equation 81) gives the probability P (Equation 83 and Figure 5) that case 1 is less than case 2 with the conditions given in the model:

$$P(\text{case } 1 < \text{case } 2) = \int_z^{\infty} f(r)\, dr \qquad (83)$$

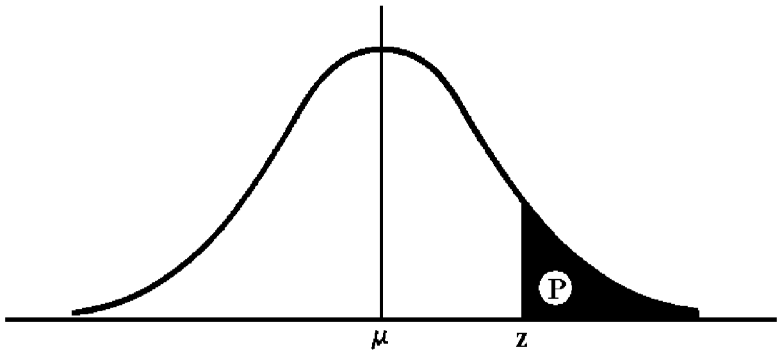

Figure 5. Illustration of how the probability P is calculated from the normal distribution.

4 RESULTS AND DISCUSSION

4.1 Cultivation

The cultivation of the rapeseed and wheat consumes a major proportion of the energy resources to produce rapeseed oil or ethanol fuels and gives correspondingly high environmental impacts from emissions. The energy consumed during the cultivation, 11.8 GJ (Table 112), corresponds to 65-90% (Tables 114-115, 117-118 and 120-121) of the energy consumed in producing the rapeseed oil or RME fuels and 13.1 GJ (Table 113) corresponding to 43-44% (Tables 116, 119 and 122) of the energy to produce ethanol fuel. The corresponding figures for emissions during production of rapeseed oil and RME were 87–99.4% for GWP and 31–39% for AP, EP and POCP; and during production of ethanol fuel 63-64% for GWP, 32-34% for AP and EP and 6-7% for POCP. This shows that the cultivation represents the main part of the energy consumption and emissions during the production of rapeseed oil fuels and ethanol fuel. The figures in Tables 112-122 were calculated using physical allocation. Data with no allocation, economic allocation and allocation with expanded system are presented in Tables A1-A22, Appendices 1-2, as are the raw emission data. When the energy content in the seed was calculated using the assumptions and the equations to calculate the energy content in the meal (Equations 25-46 with 0% oil extraction efficiency and no losses as sediment and steam) in Section 3.10.1.1, the energy content in the rapeseed produced was 63.9 GJ. This resulted in an energy ratio (lower heating value in rapeseed / requirement of process energy) of 5.4. When the energy content in the wheat was calculated after Praks (1993b)[a] the energy content in the wheat produced was 85.4 GJ. This resulted in an energy ratio (lower heating value in wheat / requirement of process energy) of 6.5.

[a] The lower heat value for wheat by Praks (1993b) was given to 17.23 MJ/kg dry matter. The lower heat value for a product with 14% water (as in this study) could then be calculated as: (1 - share of water) * lower heat value (dry matter) - share of water * (molar enthalpy of vaporisation / molecular weight): (1 – 0.14) * 17.23 – 0.14 * (44 [kJ/mole water] / 18.016 [g/mole water]) = 14.48 MJ/kg wheat with 14% water. Heat of evaporation for water is given by Aylward & Findlay (1994). The energy content in the wheat could then be calculated: 5900 kg wheat/ha * 0.01448 GJ/kg wheat = 85.4 GJ/ha.

Table 112. Environmental impacts from air-emissions and energy consumption when winter rapeseed was cultivated

Production factor	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Seed	0.32	0.32	0.32	0.32	0.32
Production of fertilisers	55.03	15.50	6.73	59.54	59.45
Soil emissions	33.78	73.08	81.33	0	0
Production of pesticides	0.23	0.16	0.040	0.12	1.69
Tractive power	7.34	10.36	11.14	31.03	20.71
Heat for seed drying	3.02	0.41	0.31	8.05	8.49
Electricity for drying and cleaning of the seed	0.034	0.015	0.007	0.10	1.46
Machinery inputs (Swedish electricity)	0.17	0.075	0.038	0.52	7.52
Transport of fertiliser	0.057	0.071	0.08	0.32	0.16
Machinery inputs, transport of fertiliser, (Sw. el.)	0.0044	0.0019	0.00095	0.013	0.188
Total emissions cultivation of rapeseed fuel	100	100	100	100	100
in g (CO_2; SO_2; PO_4^{3-}; C_2H_4)-eq/ha or MJ/ha	2400000	14400	2400	194	11800

Table 113. Environmental impacts from air-emissions and energy consumption when winter wheat was cultivated

Production factor	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Seed	3.73	3.73	3.73	3.73	3.73
Production of fertilisers	47.80	15.80	6.38	48.88	43.69
Soil emissions	31.48	67.64	76.51	0	0
Production of pesticides	0.36	0.25	0.064	0.15	2.23
Tractive power	8.04	11.28	12.32	28.21	18.69
Heat for seed drying	8.18	1.09	0.85	17.93	18.93
Electricity for drying and cleaning of the seed	0.111	0.048	0.024	0.27	3.93
Machinery inputs (Swedish electricity)	0.24	0.103	0.053	0.59	8.54
Transport of fertiliser	0.052	0.064	0.07	0.23	0.12
Machinery inputs, transport of fertiliser, (Sw. el.)	0.0039	0.0017	0.00087	0.010	0.140
Total emissions cultivation of wheat	100	100	100	100	100
in g (CO_2; SO_2; PO_4^{3-}; C_2H_4)-eq/ha or MJ/ha	2210000	13300	2180	217	13100

During the cultivation of rapeseed and wheat, production of fertilisers was responsible for 59% and 44% of the energy consumption respectively and 55-60% and 48-49% of the GWP and POCP respectively (Tables 112-113). Production of fertilisers, together with emissions of NH_3 and N_2O from the soil, was responsible for more than 88% and 79-83% of the GWP, AP and EP during cultivation of rapeseed and wheat respectively. The dominating position for the fertilisers, for energy consumption and emissions during the cultivation indicates that there may be a reason to find new ways to fertilise the crops or more fertiliser-efficient methods of cultivation. The cultivation must also be carried out in a way that gives less emission of ammonia and nitrous oxide.

Fuel for tractive power, during cultivation of rapeseed and wheat, was responsible for approx. 20% of the energy consumption, approx. 30% of the POCP and 7-12% of the GWP, AP and EP (Tables 112-113). The GWP could be reduced if the fuels produced were used for powering (see scenario analysis, Section 4.9) and the AP, EP and POCP especially could be reduced if the tractors were equipped with catalysts (see scenario analysis, Section 4.9). Oil for drying of rapeseed and wheat was responsible for approx. 8-9% and 18-19% of the energy consumption respectively, approx. 8% and approx. 18% of the POCP respectively, and approx. 3% and approx. 8% of the GWP respectively (Tables 112-113). The GWP could be reduced if biofuels were used for the drying. Energy consumption and emissions from other parameters during the rapeseed and wheat productions were small or negligible.

When the energy consumption and the emissions during the cultivation are independent of how the seed, meal, oil, RME, glycerine, wheat, distiller's waste or ethanol are prepared after the cultivation, the absolute values from cultivation are not influenced by whether the oil etc. or ethanol etc. was extracted/produced on a small- or large-scale etc.

4.2 LCA of the fuel production

During the extraction of rapeseed oil, the energy demand for the oil extraction was 8%- (large-and medium-scale extraction) 14% (small-scale extraction) (Tables 114, 117 and 120) of the total energy requirement (physical allocation). Larger oil presses were more energy efficient than smaller. When driving on the rapeseed oil fuels produced, AP-, EP- and POCP-emissions were about twice as high as from the cultivation. GWP-emissions were negligible when driving on rapeseed oil and approx. 9% of total GWP-emissions when driving on the RME produced, depending on the use of methanol of fossil origin for the transesterification. If the methanol had its origin in biomass (*e.g. Salix*) these GWP-emissions would be negligible even for RME-fuel (studied in the scenario analysis, Section 4.9).

The oil extraction efficiency was also higher for larger plants (Table 27), which gives more oil to spread the energy consumption and emissions over and during the transesterification a higher demand for methanol and energy. During the transesterification the demand for energy (electricity) was approx. 11% of the total energy requirement (Table 115, 118 and 121). Correspondingly the energy bound in the methanol and methanol manufacturing was 12-13% of the total energy demand.

During production (fermentation and distillation) of ethanol fuel, the total requirement of electricity and steam heat energy was 12.5%- (large-scale ethanol production) 16% (small-scale ethanol production) (Tables 116, 119 and 122) of the total energy requirement (physical allocation). Larger production was more energy-efficient than smaller (see also Table 33). The energy in the ignition improver and denaturants used corresponded to about 38% of the energy used (Tables 116, 119 and 122). However, the use of energy to produce the chemicals for the ethanol production just corresponded to 0.4% of the energy used (Tables 116, 119 and 122). When driving on the ethanol fuel produced, AP- and EP-emissions were almost twice as high as from the cultivation, but the POCP-emissions were about ten times as high as from the cultivation. GWP-emissions were about 22% of the total when driving on the ethanol fuel produced, depending on the use of fossil ignition improver and fossil denaturants. If the ignition improver and denaturants had their origin in biomass (*e.g. Salix*) these GWP-emissions would be about 2% of the total (studied in the scenario analysis, Section 4.9). The energy requirement during the cultivation was 42-44% of the total during the production of ethanol fuel.

For medium- and large-scale plants for production of rapeseed oil or RME, emissions and energy consumption for transport also appeared (Tables 114-115, 117-118 and 120-121), but were small, for medium-scale plants approx. 0.5% of the energy requirement and for large-scale plants 2-3% of the energy requirement. For medium- and large-scale plants for production of ethanol fuel, emissions and energy consumption for transport (Tables 116, 119 and 122) were also small, for medium-scale plants approx. 0.8% of the energy requirement and for large-scale plants 3-4% of the energy requirement. This depended on large load weights and the fact that transport of the materials 110 km (for large-scale plants), as in this example, was not long enough to give these emissions and energy consumption a greater influence.

Emissions that have their origin in buildings or machines were negligible, usually for GWP and POCP hundredths of one per cent of the total or less and for AP and EP thousandths of one per cent or less, if their origin was in Swedish electricity (Tables 114-122). The energy consumption was usually a tenth of one per cent of the total up to 1-2% for small-scale ethanol fuel production and small-scale transesterification. These factors could therefore be neglected. An exception was energy consumption for manufacturing of agricultural machines (Tables 112-113), which was a few per cent of the total energy for consumption.

Parameter, not discussed above were small (less than or around 1% of total of GWP, AP, EP, POCP or energy requirement).

4.2.1 Small-scale rapeseed oil

This system was the most simple of the systems studied (Figure 3 and Tables 114-122, A3-A14 and A17-A22). There was no need for transportation of seed to extraction and no need for transportation of oil and meal back to the farm (Table 114). There was also no need for a catalyst and methanol for transesterification (Table 114). The absolute emission values were lowest because of the lowest consumption of resources (Tables A3-A14, Appendix 1). Because of lower oil extraction efficiency, and therefore lower oil yield to spread the emissions over, the emissions on engine work output were not the best (Table 133).

Table 114. Environmental impacts from air-emissions and energy consumption during small-scale production of rapeseed oil, physical allocation

Production factor	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Cultivation of rapeseed	99.36	37.19	35.07	37.22	85.35
Electricity, small-scale oil extraction	0.37	0.060	0.029	0.42	13.75
Total machinery, oil extraction, Swedish el.	0.018	0.0030	0.0014	0.021	0.68
Building material, Swedish el.	0.0059	0.00095	0.00045	0.0066	0.22
Emissions when driving on the rapeseed oil	0.24	62.74	64.90	62.34	0
Total; cultivation, - driving	100	100	100	100	100
in g (CO_2;SO_2;PO_4^{3-};C_2H_4)-eq/MJ_{engine} or MJ/MJ_{engine}	121.2	1.94	0.343	0.0261	0.692

4.2.2 Small-scale RME

This system was the most simple of the transesterification systems studied (Figure 3 and Tables 115, 118 and 121). There was no need for transportation of seed to extraction and no need for transportation of oil and meal back to the farm (Table 115). Catalyst and methanol were required for the transesterification (Table 115). The absolute emission values were the lowest for the transesterification plant sizes, because of the lowest consumption of resources (Tables A5-A6, A9-A10 and A13-A14, Appendix 1). Because of lower oil extraction efficiency, and therefore lower oil yield to spread the emissions over, the emissions on engine work output were not the best (Table 133).

Table 115. Environmental impacts from air-emissions and energy consumption during small-scale production of RME, physical allocation

Production factor	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Cultivation of rapeseed	87.81	33.68	31.65	38.69	64.47
Electricity, small-scale oil extraction	0.33	0.055	0.026	0.43	10.39
Total machinery, oil extraction, Swedish el.	0.016	0.0027	0.0013	0.021	0.52
Building material, Swedish el.	0.0052	0.00086	0.00041	0.0068	0.16
Methanol, natural gas, best case	2.31	0.23	0.24	0.93	12.05
Transport of methanol	0.055	0.024	0.024	0.084	0.11
Transport of methanol, machinery, Swedish el.	0.00029	0.000049	0.000023	0.00039	0.0093
Catalyst, KOH	0.16	0.068	0.032	0.015	0.70
Electricity, transesterification	0.34	0.057	0.027	0.45	10.79
Machinery, transesterification, Swedish el.	0.020	0.0033	0.0016	0.026	0.63
Building material, transesterification, Swedish el.	0.0050	0.00084	0.00040	0.0066	0.16
Transport of glycerine	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport of glycerine, machinery, Swedish el.	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Emissions when driving on the RME, fossil methanol	8.94	65.88	68.00	59.33	0
Total; cultivation, - driving	100	100	100	100	100
in g (CO_2;SO_2;PO_4^{3-};C_2H_4)-eq/MJ_{engine} or MJ/MJ_{engine}	126.8	1.98	0.351	0.0232	0.846

[a] Not relevant because of physical allocation.

4.2.3 Small-scale ethanol

This system was the most simple of the ethanol fuel production systems studied (Figure 4 and Tables 116, 119 and 122). There was no need for transportation of wheat to the ethanol production plant and no need for transportation of the ethanol fuel and distiller's waste (wet) back to the farm (Table 116). Chemicals were needed for both the ethanol production and to mix with the ethanol to make the ethanol fuel (Table 116). Electricity and steam heat was used less efficiently (Table 33). The by-product wet distiller's waste was allocated away with the physical allocation method (Section 3.10.1 and Tables A17-A22, Appendix 2).

Table 116. Environmental impacts from air-emissions and energy consumption during small-scale production of ethanol fuel, physical allocation

Production factor	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Cultivation of wheat	63.92	33.99	32.31	6.39	42.71
Electricity, small-scale ethanol fermentation	0.27	0.062	0.030	0.067	6.43
Steam (heat), small-scale ethanol fermentation	0.28	0.51	0.44	0.99	0.28
Electricity, small-scale ethanol distillation	0.27	0.061	0.030	0.066	6.33
Steam (heat), small-scale ethanol distillation	2.66	4.97	4.26	9.57	2.71
Electricity, handling of distiller's waste	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Steam (heat), handling of distiller's waste	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Total machinery, ethanol production, Swedish el.	0.068	0.016	0.0076	0.017	1.62
Building material, Swedish el.	0.012	0.0028	0.0014	0.0030	0.29
Handling of waste water, Swedish el.	0.058	0.013	0.0065	0.014	1.38
Production of chemicals for ethanol production	0.22	0.13	0.047	0.0058	0.39
Transport of chemicals for ethanol production	0.011	0.0066	0.0068	0.0032	0.017
Transport of chemicals for ethanol production, machinery, Swedish el.	0.000051	0.000012	0.0000057	0.000013	0.0012
Production of ignition improver and corrosion inhibitor	7.08	2.98	1.64	13.30	26.72
Production of denaturant	2.97	0.39	0.32	4.40	10.94
Transport of chemicals for ethanol fuel production	0.114	0.068	0.070	0.033	0.18
Transport of chemicals for ethanol fuel production, machinery, Swedish el.	0.00053	0.00012	0.000059	0.00013	0.013
Emissions when driving on ethanol fuel	22.07	56.79	60.83	65.14	0
Total; cultivation, - driving	100	100	100	100	100
in g (CO_2;SO_2;PO_4^{3-};C_2H_4)-eq/MJ_{engine} or MJ/MJ_{engine}	101.9	1.16	0.199	0.100	0.907

[a] Not relevant because of physical allocation.

4.2.4 Medium-scale rapeseed oil

This system had a requirement of a shorter transport of the seed to the extraction plant and of transportation of the oil and meal back to the farm (Table 117). There was no need for a catalyst and methanol for transesterification (Table 117). The absolute emission values were intermediate because of the intermediate consumption of resources (Tables A3-A4, A7-A8 and A11-A12, Appendix 1). Intermediate oil extraction efficiency gave intermediate oil yield (Table 28). The emissions on engine work output were the best with physical allocation (Table 133) for rapeseed oil fuel.

Table 117. Environmental impacts from air-emissions and energy consumption during medium-scale production of rapeseed oil, physical allocation

Production factor	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Cultivation of rapeseed	99.43	36.78	34.67	36.84	90.51
Transport seed to extraction, fuel	0.050	0.023	0.023	0.077	0.13
Transport seed to extraction, machinery	0.0056	0.00090	0.00043	0.0062	0.22
Electricity, medium-scale oil extraction	0.22	0.035	0.017	0.24	8.58
Total machinery, oil extraction, Swedish el.	0.0083	0.0013	0.00064	0.0092	0.33
Building material, Swedish el.	0.0034	0.00055	0.00026	0.0038	0.13
Transport meal from extraction, fuel	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport meal from extraction, machinery	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport oil from extraction, fuel	0.037	0.016	0.016	0.048	0.10
Transport oil from extraction, machinery	0.00020	0.000032	0.000015	0.00022	0.0077
Emissions when driving on the rapeseed oil	0.25	63.14	65.27	62.78	0
Total; cultivation, - driving	100	100	100	100	100
in g (CO_2;SO_2;PO_4^{3-};C_2H_4)-eq/MJ_{engine} or MJ/MJ_{engine}	119.0	1.93	0.341	0.0259	0.641

[a] Not relevant because of physical allocation.

4.2.5 Medium-scale RME

This system had a requirement of a shorter transport of the seed to the extraction plant and of transportation of the RME and meal back to the farm (Table 118). Catalyst and methanol were required for the transesterification (Table 118). The absolute emission values were intermediate because of the intermediate consumption of resources (Tables A5-A6, A9-A10 and A13-A14, Appendix 1). Intermediate oil extraction efficiency gave intermediate oil yield (Table 28). The emissions on engine work output, for RME, were the best with physical allocation (Table 133).

Table 118. Environmental impacts from air-emissions and energy consumption during medium-scale production of RME, physical allocation

Production factor	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Cultivation of rapeseed	87.70	33.28	31.26	38.31	67.58
Transport seed to extraction, fuel	0.044	0.021	0.021	0.080	0.095
Transport seed to extraction, machinery	0.0050	0.00082	0.00039	0.0065	0.16
Electricity, medium-scale oil extraction	0.19	0.032	0.015	0.25	6.41
Total machinery, oil extraction, Swedish el.	0.0073	0.0012	0.00057	0.0096	0.24
Building material, Swedish el.	0.0030	0.00050	0.00024	0.0039	0.10
Methanol, natural gas, best case	2.35	0.23	0.24	0.94	12.86
Transport of methanol	0.056	0.024	0.024	0.085	0.12
Transport of methanol, machinery, Swedish el.	0.00030	0.000049	0.000023	0.00039	0.010
Catalyst, KOH	0.17	0.068	0.032	0.015	0.75
Electricity, transesterification	0.34	0.056	0.026	0.44	11.25
Machinery, transesterification, Swedish el.	0.0070	0.0011	0.00055	0.0091	0.23
Building material, transesterification, Swedish el.	0.0029	0.00048	0.00023	0.0038	0.10
Transport meal from extraction, fuel	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport meal from extraction, machinery	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport RME from transesterification, fuel	0.033	0.014	0.014	0.050	0.072
Transport RME from transesterification, machinery	0.00017	0.000029	0.000014	0.00023	0.0058
Transport of glycerine	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport of glycerine, machinery, Swedish el.	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Emissions when driving on the RME, fossil methanol	9.09	66.27	68.37	59.80	0
Total; cultivation, - driving	100	100	100	100	100
in g (CO_2;SO_2;PO_4^{3-};C_2H_4)-eq/MJ_{engine} or MJ/MJ_{engine}	124.7	1.97	0.349	0.0230	0.793

[a] Not relevant because of physical allocation.

4.2.6 *Medium-scale ethanol*

This system had a requirement of a shorter transport of the wheat to the ethanol fuel production plant and of transportation of the ethanol fuel and distiller's waste (wet) back to the farm (Table 119). Chemicals were required both for the ethanol production and to mix with the ethanol to make the ethanol fuel (Table 119). Electricity and steam heat was used with intermediate efficiency (Table 33). The by-product distiller's waste was allocated away with the physical allocation method (Section 3.10.1 and Tables A17-A22, Appendix 2).

Table 119. Environmental impacts from air-emissions and energy consumption during medium-scale production of ethanol fuel, physical allocation

Production factor	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Cultivation of wheat	64.25	33.66	31.75	6.88	43.80
Electricity, medium-scale ethanol fermentation	0.24	0.055	0.027	0.064	5.91
Steam (heat), medium-scale ethanol fermentation	0.22	0.59	0.59	0.34	0.24
Electricity, medium-scale ethanol distillation	0.24	0.054	0.026	0.063	5.81
Steam (heat), medium-scale ethanol distillation	2.15	5.73	5.66	3.26	2.27
Electricity, handling of distiller's waste	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Steam (heat), handling of distiller's waste	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Total machinery, ethanol production, Swedish el.	0.024	0.0054	0.0026	0.0063	0.58
Building material, Swedish el.	0.0072	0.0016	0.00079	0.0019	0.18
Handling of waste water, Swedish el.	0.057	0.013	0.0062	0.015	1.38
Production of chemicals for ethanol production	0.22	0.13	0.047	0.0062	0.40
Transport of chemicals for ethanol production	0.0096	0.0056	0.0058	0.0029	0.015
Transport of chemicals for ethanol production, machinery, Swedish el.	0.000044	0.000010	0.0000049	0.000012	0.0011
Production of ignition improver and corrosion inhibitor	7.12	2.95	1.61	14.33	27.40
Production of denaturant	2.99	0.38	0.32	4.74	11.22
Transport of chemicals for ethanol fuel production	0.112	0.066	0.068	0.034	0.18
Transport of chemicals for ethanol fuel production, machinery, Swedish el.	0.00059	0.00013	0.000065	0.00016	0.014
Transport of wheat to ethanol production	0.11	0.070	0.072	0.044	0.18
Transport of wheat to ethanol production, machinery, Swedish el.	0.014	0.0031	0.0015	0.0037	0.34
Transport of distiller's waste from ethanol production	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport of distiller's waste from ethanol production, machinery, Swedish el.	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport of produced ethanol	0.055	0.032	0.033	0.017	0.087
Transport of produced ethanol, machinery, Swedish el.	0.00029	0.000065	0.000032	0.000076	0.0070
Emissions when driving on the ethanol fuel, fossil chemicals added	22.18	56.25	59.78	70.19	0
Total; cultivation, - driving	100	100	100	100	100
in g (CO_2;SO_2;PO_4^{3-};C_2H_4)-eq/MJ_{engine} or MJ/MJ_{engine}	101.4	1.17	0.203	0.0927	0.884

[a] Not relevant because of physical allocation.

4.2.7 Large-scale rapeseed oil

This system had a requirement of a longer transport of the seed to the extraction plant and of transportation of the oil and meal back to the farm (Table 120). Hexane was required for the second solvent step in the oil extraction. There was no need for catalyst and methanol for transesterification (Table 120). The absolute emission values were higher because of the higher consumption of resources in a more complicated system (Tables A3-A4, A7-A8 and

A11-A12, Appendix 1). The best oil extraction efficiency gave the highest oil yield (Table 28). The emissions on engine work output were the best with no allocation and with economic allocation (Tables 136 and 137).

Table 120. Environmental impacts from air-emissions and energy consumption during large-scale production of rapeseed oil, physical allocation

Production factor	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Cultivation of rapeseed	98.27	36.80	34.70	36.46	87.47
Transport seed to extraction, fuel	0.63	0.27	0.27	0.80	1.59
Transport seed to extraction, machinery	0.0026	0.00043	0.00020	0.0029	0.10
Electricity, large-scale oil extraction	0.21	0.034	0.016	0.23	8.10
Total machinery, oil extraction, Swedish el.	0.0043	0.00070	0.00033	0.0048	0.16
Building material, Swedish el.	0.0018	0.00029	0.00014	0.0020	0.068
Hexane	0.057	0.024	0.0085	0.17	0.95
Transport meal from extraction, fuel	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport meal from extraction, machinery	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport oil from extraction, fuel	0.57	0.24	0.25	0.73	1.44
Transport oil from extraction, machinery	0.0030	0.00049	0.00024	0.0034	0.12
Emissions when driving on the rapeseed oil	0.24	62.62	64.76	61.59	0
Total; cultivation, - driving	100	100	100	100	100
in g (CO_2;SO_2;PO_4^{3-};C_2H_4)-eq/MJ_{engine} or MJ/MJ_{engine}	121.5	1.94	0.343	0.0264	0.669

[a] Not relevant because of physical allocation.

4.2.8 Large-scale RME

This system had a requirement of a longer transport of the seed to the extraction plant and of transportation of the RME and meal back to the farm (Table 121). Hexane was required for the second solvent step in the oil extraction. Catalyst and methanol were required for the transesterification (Table 121). The absolute emission values were higher because of the higher consumption of resources in a more complicated system (Tables A5-A6, A9-A10 and A13-A14, Appendix 1). The best oil extraction efficiency gave the highest oil yield (Table 28). The emissions on engine work output, for RME, were the best with no allocation and with economic allocation (Tables 136 and 137).

Table 121. Environmental impacts from air-emissions and energy consumption during large-scale production of RME, physical allocation

Production factor	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Cultivation of rapeseed	86.87	33.27	31.26	37.84	66.25
Transport seed to extraction, fuel	0.56	0.25	0.25	0.83	1.21
Transport seed to extraction, machinery	0.0023	0.00039	0.00018	0.0030	0.076
Electricity, large-scale oil extraction	0.19	0.031	0.015	0.24	6.13
Total machinery, oil extraction, Swedish el.	0.0038	0.00063	0.00030	0.0049	0.12
Building material, Swedish el.	0.0016	0.00026	0.00012	0.0020	0.051
Hexane	0.050	0.022	0.0077	0.18	0.72
Methanol, natural gas, best case	2.32	0.23	0.24	0.92	12.53
Transport of methanol	0.055	0.024	0.024	0.083	0.12
Transport of methanol, machinery, Swedish el.	0.00029	0.000049	0.000023	0.00038	0.010
Catalyst, KOH	0.16	0.068	0.032	0.015	0.73
Electricity, transesterification	0.33	0.054	0.026	0.42	10.71
Machinery, transesterification, Swedish el.	0.0034	0.00057	0.00027	0.0045	0.11
Building material, transesterification, Swedish el.	0.0014	0.00024	0.00011	0.0019	0.047
Transport meal from extraction, fuel	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport meal from extraction, machinery	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport RME from transesterification, fuel	0.51	0.22	0.22	0.76	1.09
Transport RME from transesterification, machinery	0.0027	0.00045	0.00021	0.0035	0.089
Transport of glycerine	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport of glycerine, machinery, Swedish el.	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Emissions when driving on the RME, fossil methanol	8.95	65.83	67.93	58.68	0
Total; cultivation, - driving	100	100	100	100	100
in g (CO_2;SO_2;PO_4^{3-};C_2H_4)-eq/MJ_{engine} or MJ/MJ_{engine}	126.7	1.98	0.351	0.0235	0.814

[a] Not relevant because of physical allocation.

4.2.9 Large-scale ethanol

This system had a requirement of a longer transport of the wheat to the ethanol fuel production plant and of transportation of the ethanol fuel and dried distiller's waste back to the farm (Table 122). Chemicals were required for both the ethanol production and to mix with the ethanol to make the ethanol fuel (Table 122). Electricity and steam heat was used more efficiently in a more sophisticated system with less loss (Table 33). The by-product distiller's waste was allocated away with the physical allocation method (Section 3.10.1 and Tables A17-A22, Appendix 2).

Table 122. Environmental impacts from air-emissions and energy consumption during large-scale production of ethanol fuel, physical allocation

Production factor	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Cultivation of wheat	63.18	33.90	31.98	6.91	43.46
Electricity, large-scale ethanol fermentation	0.21	0.049	0.024	0.057	5.20
Steam (heat), large-scale ethanol fermentation	0.21	0.43	0.42	0.26	0.20
Electricity, large-scale ethanol distillation	0.21	0.048	0.023	0.056	5.12
Steam (heat), large-scale ethanol distillation	2.06	4.16	4.06	2.48	1.97
Electricity, drying of distiller's waste	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Steam (heat), drying of distiller's waste	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Total machinery, ethanol fuel production, Swedish el.	0.012	0.0028	0.0014	0.0033	0.30
Building material, Swedish el.	0.0037	0.00085	0.00041	0.0010	0.09
Handling of waste water, Swedish el.	0.055	0.013	0.0061	0.015	1.34
Production of chemicals for ethanol production	0.21	0.13	0.047	0.0063	0.40
Transport of chemicals for ethanol production	0.0089	0.0054	0.0055	0.0027	0.014
Transport of chemicals for ethanol production, machinery, Swedish el.	0.000047	0.000011	0.0000053	0.000013	0.0011
Production of ignition improver and corrosion inhibitor	7.00	2.97	1.62	14.38	27.19
Production of denaturant	2.94	0.39	0.32	4.76	11.14
Transport of chemicals for ethanol fuel production	0.083	0.050	0.051	0.026	0.13
Transport of chemicals for ethanol fuel production, machinery, Swedish el.	0.00044	0.00010	0.000049	0.00012	0.011
Transport of wheat to ethanol production	1.15	0.70	0.72	0.36	1.85
Transport of wheat to ethanol production, machinery, Swedish el.	0.0050	0.0012	0.00056	0.0014	0.12
Transport of distiller's waste from ethanol production	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport of distiller's waste from ethanol production, machinery, Swedish el.	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]	n.r.[a]
Transport of produced ethanol fuel	0.84	0.51	0.52	0.26	1.35
Transport of produced ethanol fuel , machinery, Swedish el.	0.0045	0.0010	0.00050	0.0012	0.11
Emissions when driving on the ethanol fuel, fossil chemicals added	21.81	56.64	60.20	70.43	0.00
Total; cultivation, - driving	100	100	100	100	100
in g (CO_2;SO_2;PO_4^{3-};C_2H_4)-eq/MJ_{engine} or MJ/MJ_{engine}	103.1	1.16	0.201	0.0924	0.891

[a] Not relevant because of physical allocation.

4.3 Economic calculations

The economic calculations were performed for all three plant sizes for the three fuels studied. For the rapeseed and wheat cultivation, scenarios with EU area compensation and with a larger farm unit were also studied. For comparison, a scenario was also studied in which rapeseed with 9% water (wet basis) (amount seed (9% water as the trade water content in rapeseed) [kg/ha] = amount seed (8% water as in this report) [kg/ha] * ((1 – 0.08) / (1 – 0.09))) was purchased for 2.00 SEK/kg and wheat with 0.97 SEK/kg with 14% water (wet basis) (Agriwise, 2003). The corresponding area yields were 2470 kg rapeseed/ha (8% water wet basis) = 2497 kg rapeseed/ha with 9% water wet basis and 5900 kg wheat/ha (14% water wet basis).

For all type of plants and fuels, the cultivation of the rapeseed (Table 19) or wheat (Table 20) was the dominating cost (Tables 123–131), for small- and medium-scale plants followed by labour and/or depreciation and interest for machines and buildings and for ethanol fuel production costs for ignition improver (Beraid). For large-scale oil extraction and transesterification plants, transport costs, depreciation and interest for machines and buildings and labour costs were about the same size, followed the cultivation costs. For large-scale ethanol fuel production, the cultivation costs were followed by costs for ignition improver (Beraid), depreciation and interest for machines and buildings and energy costs (electricity and heat as steam). For large-scale oil extraction and transesterification plants the receipts from the by-product (meal) covered the least share of the costs because of the higher oil extraction efficiency, which gives a meal with a lower heating value. Because of that the meal also had a lower economic value (see Table 105), but the higher yield of rapeseed oil or RME and the by-product glycerine was more than enough to make up for this (Tables 123-124, 126-127 and 129-130). About the same share of the costs was covered by by-products during rapeseed oil or RME production. The distiller's waste from the ethanol fuel production contributed a much lower economic value (Tables 125, 128 and 131) compared with the value for the meal and glycerine during production of rapeseed oil and RME, especially for small- and medium-scale plants where the distiller's waste was not dried.

If the rapeseed or wheat was produced on a larger farm (Tables 123–131) the production cost was reduced by 15% and 16% respectively (20% and 21% respectively if the EU area compensation was included). If the rapeseed and wheat were purchased for 2.00 SEK/kg and 0.97 SEK/kg respectively, the seed cost was reduced by 45% and 44% respectively in comparison to costs for growing on a smaller farm excluding EU area compensation. The EU area compensation reduced the production costs for rapeseed and wheat by 26-30% and 23-27% respectively.

If the rapeseed oil was extracted in a medium-scale plant instead of a small-scale plant (Tables 123 and 126), the production cost [SEK/ha] (excl. receipts from meal) was reduced by 5-6% (by 6-8% if EU area compensation was included and by 8% if the seed was purchased for 2.00 SEK/kg). If the rapeseed oil was extracted in a large-scale plant instead of a small-scale plant (Tables 123 and 129), the production cost (excl. receipts from meal) was reduced by 8-9% (by 11-12% if EU area compensation was included and by 13% if the seed was purchased for 2.00 SEK/kg).

If the RME was produced in a medium-scale plant instead of a small-scale plant (Tables 124 and 127), the production cost [SEK/ha] (excl. receipts from meal and glycerine) was reduced by 13-14% (by 15-17% if EU area compensation was included and by 18% if the seed was purchased for 2.00 SEK/kg). If the RME was produced in a large-scale plant (Tables 124 and 130), instead of a small-scale plant, the production cost (excl. receipts from meal and glycerine) was reduced by 20-23% (by 25-28% if EU area compensation was included and by 29% if the seed was purchased for 2.00 SEK/kg).

If the ethanol fuel was produced in a medium-scale plant instead of a small-scale plant (Tables 125 and 128), the production cost [SEK/ha] (excl. receipts from distiller's waste) was reduced by 23-25% (by 25-27% if EU area compensation was included and by 28% if the wheat was purchased for 0.97 SEK/kg). If the ethanol fuel was produced in a large-scale plant instead of a small-scale plant (Tables 125 and 131), the production cost (excl. receipts from distiller's waste) was reduced by 36-38% (by 39-42% if EU area compensation was included and by 43% if the wheat was purchased for 0.97 SEK/kg). The cost reduction for producing ethanol fuel in larger plants was much greater than the cost reduction for producing rapeseed oil or RME in larger plants.

4.3.1 *Small-scale extraction*

The costs were dominated by the cultivation (73-83% of sum of costs (incl. labour)) followed by labour (6-10% of sum of costs (incl. labour) and depreciation and interest for machines and buildings (6-9% of sum of costs (incl. labour)) (Table 123). The receipts from selling the meal covered 27-44% of the sum of costs (incl. labour).

Table 123. Economic calculation, small-scale extraction of rapeseed oil

Operation	Small farm [SEK/ha]		Large farm [SEK/ha]		Purchased
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	seed [SEK/ha]
Cultivation of rapeseed	9092	6754	7740	5402	4994
Electricity, small-scale oil extraction	177	177	177	177	177
Machinery, maintenance	278	278	278	278	278
Building, maintenance	105	105	105	105	105
Machinery, depreciation and interest	489	489	489	489	489
Building, depreciation and interest	127	127	127	127	127
Various costs *e.g.* insurance etc. 5% of above	59	59	59	59	59
Sum costs (excl. labour)	10327	7989	8975	6637	6229
Labour	654	654	654	654	654
Sum costs (incl. labour)	10981	8643	9629	7291	6883
Receipts from meal	3009	3009	3009	3009	3009
Total	7971	5633	6619	4281	3873

4.3.2 *Small-scale transesterification*

The costs were dominated by the cultivation (51-66% of sum of costs (incl. labour)) followed by labour (15-21% of sum of costs (incl. labour)) and depreciation and interest for machines and buildings (9-12% of sum of costs (incl. labour)) (Table 124). The receipts from selling the meal and glycerine covered 24-35% of the sum of costs (incl. labour).

Table 124. Economic calculation, small-scale transesterification of rapeseed oil

Operation	Small farm [SEK/ha]		Large farm [SEK/ha]		Purchased
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	seed [SEK/ha]
Cultivation of rapeseed	9092	6754	7740	5402	4994
Electricity, small-scale oil extraction	177	177	177	177	177
Electricity, small-scale oil transesterification	87	87	87	87	87
Methanol	287	287	287	287	287
Catalyst	74	74	74	74	74
Transport, methanol	8	8	8	8	8
Transport, glycerine	7	7	7	7	7
Machinery, extraction, maintenance	278	278	278	278	278
Machinery, transesterification, maintenance	308	308	308	308	308
Building, extraction, maintenance	75	75	75	75	75
Building, transesterification, maintenance	75	75	75	75	75
Machinery, extraction, depreciation and interest	489	489	489	489	489
Machinery, transesterification, depreciation and interest	542	542	542	542	542
Building, extraction, depreciation and interest	91	91	91	91	91
Building, transesterification, depreciation and interest	91	91	91	91	91
Various costs *e.g.* insurance etc. 5% of above	129	129	129	129	129
Sum costs (excl. labour)	11810	9472	10458	8120	7712
Labour, extraction	654	654	654	654	654
Labour, transesterification	1350	1350	1350	1350	1350
Sum costs (incl. labour)	13814	11476	12461	10123	9715
Receipts from meal	3009	3009	3009	3009	3009
Receipts from glycerine	354	354	354	354	354
Total	10451	8113	9098	6760	6352

4.3.3 Small-scale ethanol

The costs were dominated by the cultivation (25-37% of sum of costs (incl. labour)) followed by depreciation and interest for machines and buildings (16-19% of sum of costs (incl. labour)) and labour (14-17% of sum of costs (incl. labour)) (Table 125). The receipts from selling the distiller's waste covered approx. 3% of the sum of costs (incl. labour).

Table 125. Economic calculation, small-scale ethanol fuel production

Operation	Small farm [SEK/ha]		Large farm [SEK/ha]		Purchased
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	seed [SEK/ha]
Cultivation of wheat	10226	7888	8588	6250	5723
Electricity ethanol production (fermentation and distillation)	296	296	296	296	296
Steam from wood chips	526	526	526	526	526
Phosphoric acid (75%)	15	15	15	15	15
Sulphuric acid (93%)	50	50	50	50	50
Sodium hydroxide (50%)	12	12	12	12	12
Calcium chloride (30%)	25	25	25	25	25
Other chemicals	8	8	8	8	8
Scum reduction agent	26	26	26	26	26
Enzymes	291	291	291	291	291
Yeast	0	0	0	0	0
Transport, production chemicals	4	4	4	4	4
Beraid	3627	3627	3627	3627	3627
MTBE	431	431	431	431	431
Isobutanol	155	155	155	155	155
Morpholine	6	6	6	6	6
Transport, fuel chemicals	28	28	28	28	28
Machinery, ethanol fuel production, maintenance	2223	2223	2223	2223	2223
Building, ethanol fuel production, maintenance	450	450	450	450	450
Machinery, ethanol fuel production, depreciation and interest	3920	3920	3920	3920	3920
Building, ethanol fuel production, depreciation and interest	543	543	543	543	543
Handling of waste water and fresh water	79	79	79	79	79
Various costs *e.g.* insurance etc. 5% of above	636	636	636	636	636
Sum costs (excl. labour)	23576	21238	21939	19601	19073
Labour	3870	3870	3870	3870	3870
Sum costs (incl. labour)	27446	25108	25809	23471	22943
Receipts from distiller's waste	785	785	785	785	785
Total	26661	24323	25023	22685	22158

4.3.4 Medium-scale extraction

The costs were dominated by the cultivation (79-87% of sum of costs (incl. labour)) followed by labour (6-10% of sum of costs (incl. labour)) and depreciation and interest for machines and buildings (2-4% of sum of costs (incl. labour)) (Table 126). The receipts from selling the meal covered 27-45% of the sum of costs (incl. labour).

Table 126. Economic calculation, medium-scale extraction of rapeseed oil

Operation	Small farm [SEK/ha]		Large farm [SEK/ha]		Purchased
	Total	EU area	Total	EU area	seed
	production	comp. incl.	production	comp. incl.	[SEK/ha]
Cultivation of rapeseed	9092	6754	7740	5402	4994
Electricity, medium-scale oil extraction	104	104	104	104	104
Transport, seed	67	67	67	67	67
Transport, meal	36	36	36	36	36
Transport, oil	29	29	29	29	29
Machinery, maintenance	110	110	110	110	110
Building, maintenance	53	53	53	53	53
Machinery, depreciation and interest	194	194	194	194	194
Building, depreciation and interest	64	64	64	64	64
Various costs *e.g.* insurance etc. 5% of above	33	33	33	33	33
Sum costs (excl. labour)	9781	7443	8429	6091	5683
Labour	648	648	648	648	648
Sum costs (incl. labour)	10429	8091	9077	6739	6331
Receipts from meal	2828	2828	2828	2828	2828
Total	7602	5264	6249	3911	3504

4.3.5 Medium-scale transesterification

The costs were dominated by the cultivation (63-75% of sum of costs (incl. labour)) followed by labour (11-16% of sum of costs (incl. labour)) and depreciation and interest for machines and buildings (5-7% of sum of costs (incl. labour)) (Table 127). The receipts from selling the meal and glycerine covered 27-40% of the sum of costs (incl. labour).

Table 127. Economic calculation, medium-scale transesterification of rapeseed oil

Operation	Small farm [SEK/ha]		Large farm [SEK/ha]		Purchased
	Total	EU area	Total	EU area	seed
	production	comp. incl.	production	comp. incl.	[SEK/ha]
Cultivation of rapeseed	9092	6754	7740	5402	4994
Electricity, medium-scale oil extraction	104	104	104	104	104
Electricity, medium-scale oil transesterification	93	93	93	93	93
Methanol	275	275	275	275	275
Catalyst	81	81	81	81	81
Transport, methanol	9	9	9	9	9
Transport, glycerine	8	8	8	8	8
Transport, seed	67	67	67	67	67
Transport, meal	36	36	36	36	36
Transport, RME	28	28	28	28	28
Machinery, extraction, maintenance	110	110	110	110	110
Machinery, transesterification, maintenance	148	148	148	148	148
Building, extraction, maintenance	38	38	38	38	38
Building, transesterification, maintenance	38	38	38	38	38
Machinery, extraction, depreciation and interest	194	194	194	194	194
Machinery, transesterification, depreciation and interest	261	261	261	261	261
Building, extraction, depreciation and interest	46	46	46	46	46
Building, transesterification, depreciation and interest	46	46	46	46	46
Various costs *e.g.* insurance etc. 5% of above	79	79	79	79	79
Sum costs (excl. labour)	10753	8415	9401	7063	6655
Labour, extraction	648	648	648	648	648
Labour, transesterification	648	648	648	648	648
Sum costs (incl. labour)	12049	9711	10697	8359	7951
Receipts from meal	2828	2828	2828	2828	2828
Receipts from glycerine	390	390	390	390	390
Total	8832	6494	7479	5141	4734

4.3.6 Medium-scale ethanol

The costs were dominated by the cultivation (35-49% of sum of costs (incl. labour)) followed by ignition improver (Beraid) (14-18% of sum of costs (incl. labour)) and depreciation and interest for machines and buildings (10-12% of sum of costs (incl. labour)) (Table 128). The receipts from selling the distiller's waste covered 4-5% of the sum of costs (incl. labour).

Table 128. Economic calculation, medium-scale ethanol fuel production

Operation	Small farm [SEK/ha]		Large farm [SEK/ha]		Purchased
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	seed [SEK/ha]
Cultivation of wheat	10226	7888	8588	6250	5723
Electricity ethanol production (fermentation and distillation)	264	264	264	264	264
Steam from wood chips	431	431	431	431	431
Phosphoric acid (75%)	5	5	5	5	5
Sulphuric acid (93%)	38	38	38	38	38
Sodium hydroxide (50%)	6	6	6	6	6
Calcium chloride (30%)	18	18	18	18	18
Other chemicals	4	4	4	4	4
Scum reduction agent	13	13	13	13	13
Enzymes	257	257	257	257	257
Yeast	0	0	0	0	0
Transport, production chemicals	4	4	4	4	4
Beraid	2901	2901	2901	2901	2901
MTBE	431	431	431	431	431
Isobutanol	104	104	104	104	104
Morpholine	6	6	6	6	6
Transport, fuel chemicals	27	27	27	27	27
Transport, wheat	210	210	210	210	210
Transport, distiller's waste	650	650	650	650	650
Transport, ethanol fuel	71	71	71	71	71
Machinery, ethanol fuel production, maintenance	980	980	980	980	980
Building, ethanol fuel production, maintenance	229	229	229	229	229
Machinery, ethanol fuel production, depreciation and interest	1729	1729	1729	1729	1729
Building, fuel production, depreciation and interest	276	276	276	276	276
Handling of waste water and fresh water	77	77	77	77	77
Various costs *e.g.* insurance etc. 5% of above	437	437	437	437	437
Sum costs (excl. labour)	19392	17054	17755	15417	14890
Labour	1651	1651	1651	1651	1651
Sum costs (incl. labour)	21044	18706	19406	17068	16541
Receipts from distiller's waste	785	785	785	785	785
Total	20258	17920	18621	16283	15755

4.3.7 Large-scale extraction

The costs were dominated by the cultivation (84-90% of sum of costs (incl. labour)) followed by transport (3-5% of sum of costs (incl. labour)) and labour (2-4% of sum of costs (incl. labour)) (Table 129). The receipts from selling the meal covered 18-31% of the sum of costs (incl. labour).

Table 129. Economic calculation, large-scale extraction of rapeseed oil

Operation	Small farm [SEK/ha]		Large farm [SEK/ha]		Purchased
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	seed [SEK/ha]
Cultivation of rapeseed	9092	6754	7740	5402	4994
Electricity, large-scale oil extraction	92	92	92	92	92
Hexane	14	14	14	14	14
Transport, seed	152	152	152	152	152
Transport, meal	59	59	59	59	59
Transport, oil	102	102	102	102	102
Machinery, maintenance	80	80	80	80	80
Building, maintenance	40	40	40	40	40
Machinery, depreciation and interest	142	142	142	142	142
Building, depreciation and interest	48	48	48	48	48
Various costs *e.g.* insurance etc. 5% of above	36	36	36	36	36
Sum costs (excl. labour)	9856	7518	8504	6166	5758
Labour	216	216	216	216	216
Sum costs (incl. labour)	10072	7734	8720	6382	5974
Receipts from meal	1856	1856	1856	1856	1856
Total	8216	5878	6864	4526	4118

4.3.8 Large-scale transesterification

The costs were dominated by the cultivation (72-83% of sum of costs (incl. labour)) followed by depreciation and interest for machines and buildings (3-5% of sum of costs (incl. labour)) and transport (3-5% of sum of costs (incl. labour)) (Table 130). The receipts from selling the meal and glycerine covered 22-34% of the sum of costs (incl. labour).

Table 130. Economic calculation, large-scale transesterification of rapeseed oil

Operation	Small farm [SEK/ha]		Large farm [SEK/ha]		Purchased
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	seed [SEK/ha]
Cultivation of rapeseed	9092	6754	7740	5402	4994
Electricity, large-scale oil extraction	92	92	92	92	92
Electricity, large-scale oil transesterification	109	109	109	109	109
Hexane	14	14	14	14	14
Methanol	288	288	288	288	288
Catalyst	106	106	106	106	106
Transport, methanol	11	11	11	11	11
Transport, glycerine	11	11	11	11	11
Transport, seed	152	152	152	152	152
Transport, meal	59	59	59	59	59
Transport, RME	98	98	98	98	98
Machinery, extraction, maintenance	80	80	80	80	80
Machinery, transesterification, maintenance	80	80	80	80	80
Building, extraction, maintenance	28	28	28	28	28
Building, transesterification, maintenance	28	28	28	28	28
Machinery, extraction, depreciation and interest	142	142	142	142	142
Machinery, transesterification, depreciation and interest	142	142	142	142	142
Building, extraction, depreciation and interest	33	33	33	33	33
Building, transesterification, depreciation and interest	33	33	33	33	33
Various costs *e.g.* insurance etc. 5% of above	75	75	75	75	75
Sum costs (excl. labour)	10673	8335	9321	6983	6575
Labour, extraction	216	216	216	216	216
Labour, transesterification	101	101	101	101	101
Sum costs (incl. labour)	10990	8652	9638	7300	6892
Receipts from meal	1856	1856	1856	1856	1856
Receipts from glycerine	510	510	510	510	510
Total	8624	6286	7272	4934	4526

4.3.9 Large-scale ethanol

The costs were dominated by the cultivation (44-58% of sum of costs (incl. labour)) followed by ignition improver (Beraid) (12-17% of sum of costs (incl. labour)) and depreciation and interest for machines and buildings (7-10% of sum of costs (incl. labour)) (Table 131). The receipts from selling the distiller's waste covered 11-15% of the sum of costs (incl. labour).

Table 131. Economic calculation, large-scale ethanol fuel production

Operation	Small farm [SEK/ha]		Large farm [SEK/ha]		Purchased
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	seed [SEK/ha]
Cultivation of wheat	10226	7888	8588	6250	5723
Electricity ethanol production (fermentation and distillation)	212	212	212	212	212
Steam from wood chips ethanol production excl. drying of distiller's waste	376	376	376	376	376
Electricity drying of distiller's waste	222	222	222	222	222
Steam from wood chips drying of distiller's waste	375	375	375	375	375
Phosphoric acid (75%)	4	4	4	4	4
Sulphuric acid (93%)	25	25	25	25	25
Sodium hydroxide (50%)	3	3	3	3	3
Calcium chloride (30%)	17	17	17	17	17
Other chemicals	3	3	3	3	3
Scum reduction agent	7	7	7	7	7
Enzymes	223	223	223	223	223
Yeast	0	0	0	0	0
Transport, production chemicals	4	4	4	4	4
Beraid	2176	2176	2176	2176	2176
MTBE	231	231	231	231	231
Isobutanol	65	65	65	65	65
Morpholine	4	4	4	4	4
Transport, fuel chemicals	19	19	19	19	19
Transport, wheat	411	411	411	411	411
Transport, distiller's waste	84	84	84	84	84
Transport, ethanol fuel	194	194	194	194	194
Machinery, ethanol fuel production, maintenance	611	611	611	611	611
Building, ethanol fuel production, maintenance	166	166	166	166	166
Machinery, ethanol fuel production, depreciation and interest	1078	1078	1078	1078	1078
Building, ethanol fuel production, depreciation and interest	200	200	200	200	200
Handling of waste water and fresh water	69	69	69	69	69
Various costs *e.g.* insurance etc. 5% of above	339	339	339	339	339
Sum costs (excl. labour)	17340	15002	15703	13365	12838
Labour	310	310	310	310	310
Sum costs (incl. labour)	17650	15312	16013	13675	13147
Receipts from distiller's waste	1913	1913	1913	1913	1913
Total	15737	13399	14099	11761	11234

4.4 Comparison between production scales

4.4.1 Rapeseed oil and RME

When different sizes of oil extraction and transesterification plants were compared, with physical allocation, the medium-scale plants had the lowest total emissions and energy requirement, but the differences were small (requirement of three digits to distinguish the differences) (Tables 133-134). For medium-scale plants: GWP-emissions were approx. 1.6-2% lower than for small- and large-scale plants; AP- and EP-emissions approx. 0.5-0.8% lower; POCP-emissions approx. 0.7-1.9% lower; and energy requirement approx. 3-7% lower (Tables 133 and 134; and Tables A4, A6, A8, A10, A12 and A14, Appendix 1). The differences between the small-scale plants and large-scale plants were even smaller and not unequivocal between different emission categories (GWP-, AP- and EP-emissions approx. 0.1-0.2%; POCP-emissions approx. 1%; and energy requirement approx. 3-4%, Tables 133 and 134; and Tables A4, A6, A8, A10, A12 and A14, Appendix 1). Absolute differences are accounted for in Table 175 (Section 4.11.1) with probabilities for the differences in Table 179.

The difference in oil extraction efficiency was rather great between plants of different sizes, from 68% at a small-scale plant to 98% at a large-scale plant (Tables 27 and 28). This made the oil harvest increase from 756 kg/ha to 1089 kg/ha (an increase of 44%). At a large-scale plant there was so much more oil to use as fuel and to spread out the emissions on from cultivation and production. This is a determining factor in large-scale plants in many cases getting better results than smaller plants, even if their energy requirement and emissions are greater on an area basis.

Large- and medium- scale extraction plants consumed about the same amount of electricity per weight unit of seed (Table 27) for the extraction. But the large-scale plant had an extraction efficiency of 98% instead of 75%. This meant that the large-scale plant consumed 0.49 MJ/kg oil and the medium-scale plant 0.64 MJ/kg oil. This energy has been assumed to be Swedish electricity (Table 49). Here the large-scale plant would get an increasing advantage over the smaller plant if the electricity had been produced with technology or energy sources that gave more emissions *e.g.* fossil fuel electricity (for description: see Section 3.6.1) (Table 49). The small plant had an energy demand of 1.17 MJ/kg oil (Table 27). The energy demand for extraction was approx. 14% of the total energy requirement for small-scale extraction plants (Table 114) and 8-9% for medium- and large-scale extraction plants (Tables 117 and 120). This was large enough to influence the conclusions, but if the electricity consumed was Swedish electricity the emissions would be small. Emissions are proportional to the energy demand and GWP- and POCP-emissions were some tenths of one per cent and AP- and EP-emissions some hundredths of one per cent of the total (Tables 114, 117 and 120). With electricity produced from environmentally inferior energy sources, the emissions would be higher and have an influence on the conclusions in favour of larger plants.

Only large-scale oil extraction plants use hexane to extract the last oil from the meal. Some hexane is lost which gives HC-emissions that influence the POCP-emissions. Lost hexane also creates emissions and requirement of energy when produced. The hexane contributed to some hundredths of one per cent of the GWP-, AP- and EP-emissions and some tenths of one per cent of the POCP-emissions (Table 120). It contributed to almost 1% of the energy demand. For GWP-emissions this was lower than the absolute difference between small- and large-scale oil extractions and much lower than the absolute difference between small- and large-scale oil extraction for AP-, EP- and POCP-emissions and for energy requirements (Tables 114, 117, 120 and 134; and Tables A3-A4, A7-A8 and A11-A12, Appendix 1). The contribution from hexane was much lower than that from the transport together.

4.4.2 Ethanol fuel

The ethanol plants of different sizes were assumed to use the same process to ferment the ethanol but the larger plants used the process energy more efficiently. The distiller's waste was only dried in the largest plant. This drying was very energy-demanding but was allocated away during the physical and economic allocations.

When different sizes of ethanol fuel production plants were compared, with physical allocation, the differences were small and not unequivocal between emission categories and energy requirement (Tables 133 and 135). AP- and EP-emissions were lowest for small-scale plants (0.3-1.7% lower than for other scales) which depended on lower NO_x-emissions during the steam production compared to medium- and large-scale plants (Tables 34, 116, 119, 122, 133 and 135; and Tables A17-A22, Appendix 2). GWP-emissions and energy requirements lowest for medium-scale plants (0.5-1.7% and 0.8-2.5% respectively lower than for other scales), which depended on the lower requirement of transport compared to large-scale plants and a more efficient use of electricity and steam (heat) compared to small-scale plants (Tables 33, 116, 119, 122, 133 and 135; and Tables A17-A22, Appendix 2). POCP-emissions were lowest for large-scale plants (0.3-7.5% lower than for other scales) which mainly depended on low emissions of HC during production of steam (heat) in comparison to smaller plants (Tables 34, 116, 119, 122, 133 and 135; and Tables A17-A22, Appendix 2). Because of the lack of unequivocal results above, it may be hard to find an optimal plant size for the ethanol fuel production plants. Absolute differences are accounted for in Table 175 (Section 4.11.1) with probabilities for the differences in Table 179. The need for electricity and steam for drying of distiller's waste were the main reasons for higher GWP-, AP- and EP-emissions and energy requirement for large-scale plants during no allocation and allocation with expanded system (Tables 33, 136 and 138; and Tables A17-A22, Appendix 2).

The energy demand for electricity was 10-13% of the total, the GWP-, AP- and POCP-emissions a few tenths of one per cent, and EP-emissions a few hundredths of one per cent of the total (Tables 116, 119 and 122). With electricity produced from environmentally inferior energy sources, the emissions would be higher and have an influence on the results in favour of larger plants. The energy demand for heat (steam) was 2-3% of the total, the GWP-, AP- and EP-emissions were 2-6%, and POCP-emissions were 3-11% of the total (Tables 116, 119 and 122).

The manufacturing of ignition improver (Beraid) and denaturants was very dominant, but in absolute terms the same independent of the plant size. The energy demand was 38-39% of the total, the GWP-emissions approx. 10%, AP- and EP-emissions 2-3%, and POCP-emissions 18-19% of the total (Tables 116, 119 and 122). However, the chemicals used during the ethanol production were of minor importance. The requirement of these was also assumed to be independent of plant size. The energy demand, GWP- and AP-emissions were some tenths of one per cent of the total, EP-emissions hundredths of one per cent and POCP-emissions thousandths of one per cent of the total (Tables 116, 119 and 122).

Handling of waste water and production of clean water for the process were also of minor importance for the energy demand and the emissions during the ethanol fuel production. The energy demand was just above 1% of the total, GWP-, AP- and POCP-emissions were hundredths of one per cent of the total and EP-emissions thousandths of one per cent of the total (Tables 116, 119 and 122).

4.4.3 General

For larger plants the transport distances for the products were longer, which generated sufficient emissions and energy demand so the largest plants were not the best on emissions. The rapeseed, wheat, meal, distiller's waste, rapeseed oil, RME and/or ethanol fuel were transported 7 km for medium-sized plants and 110 km for large-sized plants. These stuffs were not transported for small-scale plants. For medium-scale oil extraction and RME plants, transport energy requirement, GWP- and POCP-emissions were some tenths of one per cent of the total and AP- and EP-emissions were some hundredths of one per cent of the total (Tables 117-118). For medium-scale ethanol plants, transport energy requirement was almost 1% of the total and GWP-, AP-, EP- and POCP-emissions were some tenths of one per cent of the total (Table 119). For large-scale oil extraction and RME plants, transport energy requirement was about 3% of the total, GWP- and POCP-emissions were about 1-2% of the total and AP- and EP-emissions were about 0.5% of the total (Tables 120-121). For large-scale ethanol plants, transport energy requirement was about 3-4% of the total, GWP- AP- and EP-emissions were about 1-2% of the total and POCP-emissions were 0.6-0.7% of the total (Table 122). During physical allocation, transport for large-scale plants had higher emissions (all four types) than the difference to small-scale plants (Tables 114-122 and 134-135). This implies that transport of seed, wheat, meal, distiller's waste, rapeseed oil, RME and ethanol fuel had a vital (decisive) importance for the conclusions about which type of plant was the best environmentally. Longer transport distances than 110 km would be even worse. There was only one exception, POCP-emissions for ethanol plants (Tables 116, 119, 122 and 135). However, energy requirement for the transport was lower than the difference to small-scale plants for oil extraction and RME plants (Tables 114-115, 117-118, 120-121 and 134), but not for ethanol plants (Tables 116, 119, 122 and 135).

Differences in energy requirement and emissions for machinery manufacturing and production of buildings were large. The larger the plant, the better it made use of the material in its machines and buildings. But compared with total energy requirement and total emissions this energy requirement and emissions was very small (Tables 114-122). The energy requirement for machinery and buildings together, depending on plant size, was from some tenths of one per cent to approx. 1.9% of the total, GWP- and POCP-emissions were some thousandths to some hundredths of one per cent and AP- and EP-emissions were some ten thousandths to some hundredths of one per cent of the total (Tables 114-122). Ethanol plants had the biggest requirement of machinery and buildings (Tables 91-92 and Tables A3-A14 and A17-A22, Appendices 1-2). All these together meant that emissions from machinery and buildings were negligible even for small plants and that it was not important, for the results, that the amount of material in machines and buildings was not well known.

The most significant statements above pointed out, for oil extraction and transesterification, that better oil extraction efficiency with higher oil yield and demand for long transport to/from larger plants were the two most important factors for the results. However they were contradictory and this indicated the existence of an optimal plant size. This was supported by the fact that medium-sized plants, with physical allocation, had the lowest energy requirement and emissions (Table 133). For ethanol plants, the more efficient use of energy (electricity and steam heat) for larger plants and the longer transport for larger plants indicated an optimum in the same way. However, no unequivocal optimum could be found for the ethanol plants with physical allocation (Table 133). With no allocation (Table 136) and allocation with expanded system (Table 138) energy requirement and GWP-, AP-, and EP-emissions were biggest for large-scale plants due to the distiller's waste also being dried in an energy-consuming process (Table 33 and Tables A17-A22, Appendix 2).

Larger plants have a demand for transport with lower emissions. GWP-emissions were influenced in a positive way for large-scale plants when the fuels for the transport vehicles were changed to fuels with biomass origin. AP-, EP- and especially POCP-emissions can be reduced with vehicles equipped by catalysts. Transport could be more energy-efficient if trains replaced lorries.

4.5 Comparison between fuels

When straight rapeseed oil and RME were compared as fuels, during physical allocation, rapeseed oil had a lower energy requirement (18-19%, Tables 133-134) and lower GWP-, AP- and EP-emissions (2-5%, Tables 133-134). Only the POCP-emissions were higher (12-13%, Tables 133-134). The reason for these lower emissions etc. for rapeseed oil fuel was that for RME fuel, resources (electricity and methanol etc.) were added for the transesterification that generated emissions and had a requirement for energy. The reasons for the higher POCP-emissions are explained below.

When driving on (use of) the fuel produced, GWP-emissions were 40 times larger when driving on RME compared with rapeseed oil fuel, due to fossil natural gas being used as a raw material when the methanol for the transesterification was produced (see Section 3.4.4.2 for explanation and Tables A3-A14, Appendix 1). This was in spite of the fact that RME gave approx. 3.9% more engine work, on an area basis, compared to rapeseed oil (Table 132) mainly depending on higher efficiency in the engine (Table 102). AP- and EP-emissions were higher when driving on RME due to higher NO_x-emissions, whereas POCP-emissions were lower due to lower HC-emissions (Tables 102 and 133). It was possible to reduce the GWP-emissions to the same level or lower (more efficient in engine) than for rapeseed oil if the raw material for the methanol was produced from biomass, *e.g. Salix*. Absolute differences are accounted for in Table 181 (Section 4.11.2) with probabilities for the differences in Table 185.

The requirement of energy during the transesterification was not dependent on the size of the plant. It was about 0.6 MJ/kg RME for all the plant sizes (Section 3.5.2). However, this means that compared to the oil extraction with physical allocation, it was somewhat higher for small-scale plants, and almost twice as high for medium- and large-scale plants due to the higher oil yields in large-scale plants (Tables 115, 118 and 121). The energy demand was about 10% of the total, the GWP- and POCP-emissions a few tenths of one per cent, and AP- and EP-emissions a few hundredths of one per cent of the total (Tables 115, 118 and 121).

The demand for methanol gave a requirement for energy of 12-13% of the total, GWP-emissions 2.3-2.4% of the total and AP-, EP- and POCP-emissions a few tenths of one per cent of the total (Tables 115, 118 and 121). GWP-emissions could be reduced to the same level as with straight rapeseed oil fuel with methanol from biomass *e.g. Salix* (see scenario analysis, Section 4.9). But because methanol from biomass is more complicated to produce and *e.g.* the *Salix* requires it being cultivated, most emissions would increase: HC and CO by a factor of 7-8 and NO_x by a factor of 3-4 (Table 30). The energy requirement for producing the methanol would increase by a factor of 3-4 (Table 30). The demand for catalyst gave a requirement for energy and GWP-emissions of a few tenths of one per cent of the total and AP-, EP- and POCP-emissions a few hundredths of one per cent of the total (Tables 115, 118 and 121).

When it was considered that carbon atoms of biomass origin replaced fossil carbon atoms in the replaced fossil glycerine, the GWP decreased by 11.1 g CO_2-eq/MJ_{engine} for all three RME plant sizes studied (Table 133 and Tables A6, A10 and A14, Appendix 1).

The most significant statements above point out that the methanol was the most important factor for emissions and energy requirement during the transesterification. The influence from the manufacturing of catalyst was negligible.

When ethanol fuel was compared with rapeseed oil and RME during physical allocation, the energy requirement was higher (7-38%), the GWP-emissions lower (15-20%), the AP- and EP-emissions lower (39-43%) and the POCP-emissions much higher (250-330%) (Table 133, see also normalised values in Figure 6, Section 6). The reasons for the higher requirement of energy were mainly the high energy input for manufacturing of ignition improver (Beraid) and denaturants but also the higher requirement of process energy as heat (steam) (Tables 114-122 and Tables A3-A14 and A17-A22, Appendices 1-2). The lower GWP-emissions depended mainly on the fact that the ethanol fuel gave a higher yield (52000 MJ/ha compared to 28000-42000 MJ/ha, Table 132) compared to rapeseed oil and RME, which gave more energy in the harvested product [MJ/ha] to spread out the emissions over. However, this effect was somewhat counteracted by the fact that the production of ignition improver and denaturants gave high emissions. The lower AP- and EP-emissions depended on lower NO_x-emissions when the fuel produced was used (Table 102) compared to rapeseed oil and RME and higher yields (see above for explanation). The higher POCP-emissions depended on higher HC-emissions when the fuel produced was used (Table 102) compared to rapeseed oil and RME. Absolute differences are accounted for in Table 181 (Section 4.11.2) with probabilities for the differences in Table 185.

Table 132. Energy produced from the different plants

Type of plant	Fuel		Work
	[kg/ha]	[MJ/ha]	[MJ_{engine}/ha]
Small-scale rapeseed oil	756	28948	9392
Small-scale RME	727	27993	9759
Small-scale ethanol fuel	2072	52062	20617
Medium-scale rapeseed oil	834	31928	10358
Medium-scale RME	802	30875	10763
Medium-scale ethanol fuel	2072	52062	20617
Large-scale rapeseed oil	1089	41719	13535
Large-scale RME	1048	40343	14064
Large-scale ethanol fuel	2072	52062	20617

Table 133. Comparison of small-, medium- and large-scale production of rapeseed oil, RME and ethanol fuel with physical allocation

Type of plant	GWP	AP	EP	POCP	Input energy
	[g/MJ_{engine}]	[g/MJ_{engine}]	[g/MJ_{engine}]	[g/MJ_{engine}]	[MJ/MJ_{engine}]
Small-scale extraction, rapeseed oil	121	1.94	0.343	0.0261	0.692
Small-scale transesterification, RME (fossil methanol)	127	1.98	0.351	0.0232	0.846
Small-scale ethanol fuel	102	1.16	0.199	0.0999	0.907
Medium-scale extraction, rapeseed oil	119	1.93	0.341	0.0259	0.641
Medium-scale transesterification, RME (fossil methanol)	125	1.97	0.349	0.0230	0.793
Medium-scale ethanol fuel	101	1.17	0.203	0.0927	0.884
Large-scale extraction, rapeseed oil	122	1.94	0.343	0.0264	0.669
Large-scale transesterification, RME (fossil methanol)	127	1.98	0.351	0.0235	0.814
Large-scale ethanol fuel	103	1.16	0.201	0.0924	0.891

Table 134. Comparison of small-, medium- and large-scale production of rapeseed oil and RME with physical allocation, relationship in per cent between different parameters

Type of plants compared	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Medium- / small-scale rapeseed oil	-1.79	-0.63	-0.58	-0.70	-7.33
Large- / small-scale rapeseed oil	+0.24	+0.19	+0.21	+1.21	-3.26
Large- / medium-scale rapeseed oil	+2.07	+0.83	+0.80	+1.92	+4.38
Medium- / small-scale RME	-1.65	-0.59	-0.54	-0.78	-6.30
Large- / small-scale RME	-0.07	+0.07	+0.10	+1.10	-3.79
Large- / medium-scale RME	+1.61	+0.67	+0.64	+1.89	+2.67
Small-scale rapeseed oil / RME	-4.41	-2.05	-2.39	+12.45	-18.29
Medium-scale rapeseed oil / RME	-4.55	-2.08	-2.43	+12.54	-19.19
Large-scale rapeseed oil / RME	-4.12	-1.93	-2.28	+12.57	-17.84

Table 135. Comparison of small-, medium- and large-scale production of ethanol fuel with physical allocation, relationship in per cent between different parameters

Type of plants compared	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Medium- / small-scale ethanol	-0.51	+0.97	+1.76	-7.20	-2.49
Large- / small-scale ethanol	+1.18	+0.28	+1.04	-7.51	-1.73
Large- / medium-scale ethanol	+1.70	-0.69	-0.71	-0.34	+0.77
Medium- / small-scale ethanol[a]	-3.63	+10.55	+25.61	-25.28	-4.34
Large- / small-scale ethanol[a]	+8.42	+3.01	+15.14	-26.39	-3.03
Large- / medium-scale ethanol[a]	+12.51	-6.82	-8.34	-1.48	+1.37

[a] Cultivation and use of fuel excluded from calculations.

4.6 Influence of allocation method

The alternative allocation methods to physical allocation (above), studied here were: no allocation, economic allocation and allocation with expanded system.

The beginning of Section 3.10.1 describes generally how the physical and economic allocations were performed step by step. The beginning of Section 3.10.1.2 describes in detail how the physical and economic allocations were performed for rapeseed oil, RME and ethanol fuels (see also Tables 114-122 and Tables A3-A14 and A17-A22, Appendices 1-2). Section 3.10.2 describes in detail how allocation with expanded system was performed (see also Tables A3-A14 and A17-A22, Appendices 1-2).

With no allocation, both energy requirement and emissions were lowest for large-scale plants when rapeseed oil or RME was produced (Table 136). However, when ethanol fuel was produced, the GWP-, AP- and EP-emissions were lowest from small-scale plants and the POCP-emissions and energy requirements were lowest from medium-scale plants.

No allocation gave, for emissions and energy requirement, the same results as physical allocation but with greater differences when small-scale plants were compared with medium-scale plants both for rapeseed oil fuel and RME. However, when small-scale plants were compared with large-scale plants and when medium-scale plants were compared with large-scale plants, no allocation gave different results with much greater differences for impacts from emissions and energy requirement, to the advantage of large-scale plants (Tables 133 and 136). This explains the divergence from the physical allocation. When rapeseed oil production was compared with RME production, no allocation gave the same results with about the same differences as physical allocation (Table 136).

For AP-, EP- and POCP-emissions and energy requirement, no allocation gave the same results as physical allocation when small-scale plants were compared with medium-scale plants for production of ethanol fuel. For GWP-, AP-, EP- and POCP-emissions, no allocation also gave the same results as physical allocation when small-scale plants were compared with large-scale plants for production of ethanol fuel. However, when small-scale plants were compared with large-scale plants, energy requirements gave different results, and when medium-scale plants were compared with large-scale plants AP-, EP- and POCP-emissions with no allocation gave different results in comparison to physical allocation (Tables 133 and 136). This explains the divergence from the physical allocation. When ethanol fuel production was compared to rapeseed oil and RME production, no allocation gave the same results for GWP-, AP-, EP-, and POCP-emissions with about the same differences as physical allocation (Table 136). However, the results for the energy requirement were contradictory during the above comparison.

Table 136. Comparison of small-, medium- and large-scale production of rapeseed oil, RME and ethanol fuel with no allocation

Type of plant	GWP $[g/MJ_{engine}]$	AP $[g/MJ_{engine}]$	EP $[g/MJ_{engine}]$	POCP $[g/MJ_{engine}]$	Input energy $[MJ/MJ_{engine}]$
Small-scale extraction, rapeseed oil	257	2.75	0.478	0.0372	1.47
Small-scale transesterification, RME (fossil methanol)	263	2.79	0.486	0.0343	1.63
Small-scale ethanol fuel	145	1.42	0.242	0.1048	1.22
Medium-scale extraction, rapeseed oil	233	2.61	0.454	0.0352	1.26
Medium-scale transesterification, RME (fossil methanol)	239	2.65	0.463	0.0324	1.42
Medium-scale ethanol fuel	145	1.43	0.246	0.0974	1.21
Large-scale extraction, rapeseed oil	181	2.30	0.403	0.0314	1.00
Large-scale transesterification, RME (fossil methanol)	189	2.35	0.413	0.0287	1.17
Large-scale ethanol fuel	150	1.48	0.255	0.0999	1.35

With economic allocation, both energy requirement and emissions were lowest for large-scale plants independent of whether rapeseed oil, RME or ethanol fuel was produced (Table 137). For rapeseed oil and RME this was the same result as with no allocation (Tables 136 and 137).

For emissions and energy requirement, economic allocation gave the same results as physical allocation but with slightly larger differences when small-scale plants were compared with medium-scale plants for production of rapeseed oil, RME and ethanol fuels (Tables 133 and 137). However, when small-scale plants were compared with large-scale plants and when medium-scale plants were compared with large-scale plants, economic allocation gave different results with about the same differences for impacts from emissions and energy requirements in favour of large-scale plants (Tables 133 and 137). This explained the divergence from physical allocation. When rapeseed oil production was compared to RME production, economic allocation gave the same results with about the same differences as physical allocation (Tables 133 and 137) *i.e.* lower GWP-, AP- and EP-emissions and lower energy requirements for production of rapeseed oil. When production of ethanol fuel was compared with rapeseed oil and RME production, the results were the same as for physical allocation (Tables 133 and 137) *i.e.* lower GWP-, AP- and EP- emissions but higher POCP-emissions and energy requirements.

Table 137. Comparison of small-, medium- and large-scale production of rapeseed oil, RME and ethanol fuel with economic allocation

Type of plant	GWP $[g/MJ_{engine}]$	AP $[g/MJ_{engine}]$	EP $[g/MJ_{engine}]$	POCP $[g/MJ_{engine}]$	Input energy $[MJ/MJ_{engine}]$
Small-scale extraction, rapeseed oil	147	2.10	0.369	0.0282	0.84
Small-scale transesterification, RME (fossil methanol)	158	2.17	0.382	0.0257	1.02
Small-scale ethanol fuel	138	1.38	0.235	0.1041	1.17
Medium-scale extraction, rapeseed oil	143	2.07	0.364	0.0278	0.77
Medium-scale transesterification, RME (fossil methanol)	152	2.13	0.376	0.0253	0.94
Medium-scale ethanol fuel	138	1.39	0.239	0.0965	1.14
Large-scale extraction, rapeseed oil	137	2.04	0.359	0.0277	0.75
Large-scale transesterification, RME (fossil methanol)	143	2.08	0.367	0.0248	0.90
Large-scale ethanol fuel	132	1.34	0.230	0.0955	1.10

For all plant sizes, allocation with expanded system gave the lowest energy requirement and POCP-emissions if RME was produced and the lowest emissions for GWP-, AP- and EP-emissions if ethanol fuel was produced (Table 138).

When rapeseed oil and RME production was compared, the GWP-, and AP-emissions and the energy requirements were least for RME production (Table 138). This is the opposite result in comparison to physical allocation (Table 133) (see also the Monte Carlo simulation in Section 4.11.2) and was due to a high environmental load being replaced when the glycerine produced replaced glycerine produced from fossil raw material (see Tables A5-A6, A9-A10 and A13-A14, Appendices 1-2). POCP-emissions were also lower for RME production (Table 138) but this result agreed with the result from the physical allocation (Table 133). However, the EP-emissions were slightly lower for the rapeseed oil production (Table 138) and this result also agreed with the physical allocation (Table 133).

For GWP-emissions when rapeseed oil or RME was produced, the results were the same as for no allocation and economic allocation, that large-scale plants had the lowest environmental impact (Tables 136, 137 and 138). For the same type of emissions when ethanol fuel was produced, small-scale plants gave the lowest emissions, the same result as with no allocation (Tables 136 and 138). For AP-emissions, allocation with expanded system gave a diverging result from all other allocation methods, that small-scale plants gave the lowest environmental impact when rapeseed oil fuel or RME was produced (Tables 133 and 136-138). For EP-emissions allocation with expanded system gave the same result as physical allocation, that medium-scale plants gave the lowest environmental impact when rapeseed oil fuel or RME was produced (Tables 133 and 138). AP- and EP-emissions were lowest for small-scale production of ethanol fuel, which is the same result as for physical and no allocation (Tables 133, 136 and 138). POCP-emissions and energy requirement were lowest for small-scale plants when rapeseed oil or RME fuel was produced, a diverging result from all other allocation methods (Tables 133 and 136-138). POCP-emissions and energy requirement were lowest for medium-scale plants when ethanol fuel was produced, the same result as for no allocation and for energy requirement also physical allocation (Tables 133, 136 and 138).

Negative values meant that the total emissions or energy requirement for the studied systems decreased instead of the normal increase. This was possible because the emissions and energy requirement subtracted from replaced by-products were greater than total emissions and energy requirement from the system studied.

Normalised results from allocation with expanded system are accounted for in Figure 7, Section 6.

Table 138. Comparison of small-, medium- and large-scale production of rapeseed oil, RME and ethanol fuel with allocation according to expanded system (soybean)

Type of plant	GWP [g/MJ$_{engine}$]	AP [g/MJ$_{engine}$]	EP [g/MJ$_{engine}$]	POCP [g/MJ$_{engine}$]	Input energy [MJ/MJ$_{engine}$]
Small-scale extraction, rapeseed oil	158	1.43	0.368	0.0091	-0.246
Small-scale transesterification, RME (fossil methanol)	110	1.36	0.369	-0.0025	-1.052
Small-scale ethanol fuel	94	0.74	0.186	0.0905	0.345
Medium-scale extraction, rapeseed oil	151	1.51	0.363	0.0119	-0.167
Medium-scale transesterification, RME (fossil methanol)	103	1.44	0.364	0.0002	-0.982
Medium-scale ethanol fuel	94	0.76	0.190	0.0831	0.338
Large-scale extraction, rapeseed oil	147	1.85	0.365	0.0219	0.418
Large-scale transesterification, RME (fossil methanol)	100	1.77	0.366	0.0098	-0.423
Large-scale ethanol fuel	99	0.81	0.199	0.0856	0.477

During production of ethanol fuel, the GWP-, AP- and EP-emissions were lower for all production scales and allocation methods studied in comparison to rapeseed oil and RME fuels (Tables 133, 136, 137 and 138). During production of ethanol fuel the POCP-emissions and energy requirements were higher for nearly all production scales and allocation methods studied in comparison to rapeseed oil and RME fuels (Tables 133, 136, 137 and 138). The exception was energy requirements for small- and medium-scale plants with no allocation. The reason for higher POCP-emissions during ethanol fuel production was high HC-emissions during use of the ethanol fuel, during production of ignition improver and denaturants and during production of process heat (Tables 116, 119 and 122 and Tables A17-A22, Appendix 2). The reason for higher energy requirements during ethanol fuel production was a high requirement of process energy during production of ignition improver and denaturants and a high requirement of process heat (steam) during ethanol production (Tables 116, 119 and 122 and A17-A22, Appendix 2).

Compared with physical allocation (Table 133) the differences with allocation with expanded system (Table 138) were usually greater between the rapeseed oil, RME and ethanol fuels. The differences between plant sizes were also greater with allocation with expanded system.

The stability over time varied between the allocation methods studied. No allocation and physical allocation always gave the same outputs with the same well-defined inputs, independent of time. However the results from the two methods do not have to be same. The results from economic allocation depend on the prices of the products. Because the prices vary from day to day, the results also vary. Therefore the results from an economic allocation correspond to the price level of the products on a specific day.

When it was considered that carbon atoms of biomass origin replaced fossil carbon atoms in replaced fossil glycerine during RME production, the GWP-emissions decreased by 11.1 g CO_2-eq/MJ_{engine} for all three plant sizes studied in systems with physical, economic and no allocation (see Tables 133, 136 and 137 and Tables A6, A10 and A14, Appendix 1). With expanded systems to avoid allocation (Table 138) this replacement is already considered with the system expansion. If the replaced glycerine had been of biomass origin instead, the above described consideration would have been unnecessary.

In this example during allocation with expanded system, rapeseed oil in rapemeal replaces soyoil in feed, rapemeal replaced soymeal and glycerine replaced fossil glycerine. In the same way during the ethanol fuel production, distiller's waste replaced soymeal and soyoil in soymeal feed during allocation with expanded system. One problem was that the soybean could be cultivated in many places around the world with very varying transport distances and cultivation conditions. How much fertiliser was used during cultivation? Was the soybean cultivated in Europe or America (very large differences in requirement of transportation energy and emissions)? Was the replaced glycerine of fossil or bio origin? If the glycerine emissions from the expanded system were high (as in this study), RME production would be favoured by reduced emissions. If rapeseed oil in rapemeal after small- and medium-scale extraction (as in this study) replaced soyoil in feed, after transcontinental transport with high environmental load, small-scale extraction (with lower extraction efficiency) would be favoured by reduced emissions. This explains why allocation with expanded system found RME and small-scale oil extraction to be more favourable (Table 138) compared to the other allocation methods for many of the environmental impacts studied.

One reason, that no allocation, physical allocation and economic allocation did not give the same results was that the differences were small between the different plant sizes (requirement of three digits in the physical allocation to separate them, Tables 133, 136, 137 and 138). Therefore rather small differences between the methods were enough to produce different results. It was hard to separate the different plant sizes. When straight rapeseed oil fuel and RME were compared, the differences were greater and all these three methods gave the same results (Tables 133, 136, 137 and 138). For ethanol production the same was valid in most cases in spite of a somewhat different fuel processing system.

Another reason behind no allocation not giving the same results as physical allocation and economic allocation was that the allocation distributed the emissions and energy requirement fairly between the products (Tables 106-109). The emissions and energy requirements for main inputs (*e.g.* cultivation of rapeseed/wheat, electricity for extraction/transesterification/ethanol production, hexane/methanol/ignition improver emissions etc.) were distributed: between rapeseed oil and meal; between RME, glycerine and meal; or between ethanol fuel and distiller's waste. For example, if the oil extraction efficiency was high and/or the value of the oil (physical or economic) was high, the oil part-value of the allocation would be high. Less value would be excluded from the allocation addition as meal-value or glycerine-value and the difference would be less compared with no allocation. This means that the distance between the allocated case and the non-allocated case would be less with higher oil extraction efficiency, here equivalent to larger oil extraction plants. This corresponds well with the results in Tables 133, 136 and 137 where the values from large-scale plants changed least between allocation methods. The above-described effect was not valid for physical allocation of ethanol fuel production because the same amount of ethanol and distiller's waste (Table 108) was produced independent of the size of the production plant. The fact that rapeseed oil and RME were given a higher economic value (shares of meal, glycerine and RME in Table 107) compared to their physical value (shares of meal, glycerine and RME in Table 106) indicated that economic allocation should give values closer to no allocation compared with physical allocation. Even this fact corresponds well with the results in Tables 133, 136 and 137. For ethanol fuel production, the dried distiller's waste from large plants was more (economically) valuable than wet distiller's waste from small- and medium-scale plants (Table 109). The result was more emission and energy requirement values allocated away with the distiller's waste and lower emissions and energy requirements for the main product for large-scale plants. The differences between no allocation and economic allocation were greatest for large-scale plants as shown in Tables 136 and 137.

The inputs for transesterification (*e.g.* methanol, catalyst, electricity etc.) were distributed between RME and glycerine. The energy ratio between RME and glycerine was independent of the plant size (Tables 106 and 107) but the economic value (7.1%) was somewhat higher than the energy (physical) value (4.6%) of glycerine. This indicated that a higher glycerine value would be excluded at economic allocation than at physical allocation. This meant here that physical allocation was closer to the case with no allocation than economic allocation, the opposite to the main allocation (RME, meal and glycerine) with the main process inputs above. The main allocation (for explanation see beginning of Section 3.10.1.2) with the main process inputs had a much greater contribution than the transesterification allocation (for explanation see beginning of Section 3.10.1.2) with the transesterification inputs, (Tables 114-122 and Tables A6, A10 and A14, Appendix 1) and therefore the contribution from the transesterification inputs did not come through.

The discussion about the physical and economic allocation above explains why the differences in the results between the two methods arose.

Allocation with an expanded system may be the fairest method if the system is viewed from a horizon to study impact on emissions from a specific change in the total fuel production to end use system. However, the great drawback with this method is that a change (or changes) in the assumptions in the production of the replaced products may have a very large influence on the conclusions.

It may be that physical allocation is the most suitable allocation method when a technical system is studied, as in this study, because of more stable results and well-defined input and output values. Allocation with an expanded system maybe the most suitable allocation method when the systems are studied from a more society orientated overall view.

4.7 Economic calculations, comparison between scales and fuels

Usually fuels are sold on a volume basis [SEK/litre$_{fuel}$], an easy measure to understand when comparing fuels (Table 140). The price for diesel oil MK1 (petrol station) was 6.464 SEK/litre (8.08 SEK/litre including value-added tax) (OKQ8, 2003) in January 2003. One problem when comparing diesel fuels on a volume basis is that their energy contents are different and also their efficiency when used in an engine, therefore it is most fair to make comparisons on energy output from engine (Table 142) [SEK/MJ$_{engine}$]. Therefore that measure was used below. A comparison could also be made on a mass basis (Table 139) or on energy content in fuel (Table 141), but these comparisons still have some of the drawbacks from the first method and were therefore not used. However, these measures would work if just one fuel was being studied.

Table 139. Production costs for the fuels produced in different plant sizes, based on mass

Type of plant	Small farm [SEK/kg$_{fuel}$]		Large farm [SEK/kg$_{fuel}$]		Purchased seed [SEK/kg$_{fuel}$]
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	
Small-scale rapeseed oil	10.55	7.45	8.76	5.66	5.12
Small-scale RME	14.37	11.16	12.51	9.30	8.74
Small-scale ethanol fuel	12.87	11.74	12.07	10.95	10.69
Medium-scale rapeseed oil	9.12	6.31	7.50	4.69	4.20
Medium-scale RME	11.01	8.10	9.33	6.41	5.90
Medium-scale ethanol fuel	9.78	8.65	8.99	7.86	7.60
Large-scale rapeseed oil	7.54	5.40	6.30	4.16	3.78
Large-scale RME	8.23	6.00	6.94	4.71	4.32
Large-scale ethanol fuel	7.59	6.47	6.80	5.68	5.42

Table 140. Production costs for the fuels produced in different plant sizes, based on volume

Type of plant	Small farm [SEK/litre$_{fuel}$]		Large farm [SEK/litre$_{fuel}$]		Purchased seed [SEK/litre$_{fuel}$]
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	
Small-scale rapeseed oil	9.71	6.86	8.07	5.22	4.72
Small-scale RME	12.73	9.89	11.09	8.24	7.74
Small-scale ethanol fuel	10.68	9.74	10.02	9.09	8.87
Medium-scale rapeseed oil	8.40	5.82	6.90	4.32	3.87
Medium-scale RME	9.76	7.17	8.26	5.68	5.23
Medium-scale ethanol fuel	8.11	7.18	7.46	6.52	6.31
Large-scale rapeseed oil	6.95	4.97	5.80	3.83	3.48
Large-scale RME	7.29	5.32	6.15	4.17	3.83
Large-scale ethanol fuel	6.30	5.37	5.65	4.71	4.50

Table 141. Production costs for the fuels produced in different plant sizes, based on fuel energy

Type of plant	Small farm [SEK/MJ$_{fuel}$]		Large farm [SEK/MJ$_{fuel}$]		Purchased seed [SEK/MJ$_{fuel}$]
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	
Small-scale rapeseed oil	0.275	0.195	0.229	0.148	0.134
Small-scale RME	0.373	0.290	0.325	0.242	0.227
Small-scale ethanol fuel	0.512	0.467	0.481	0.436	0.426
Medium-scale rapeseed oil	0.238	0.165	0.196	0.123	0.110
Medium-scale RME	0.286	0.210	0.242	0.167	0.153
Medium-scale ethanol fuel	0.389	0.344	0.358	0.313	0.303
Large-scale rapeseed oil	0.197	0.141	0.165	0.108	0.099
Large-scale RME	0.214	0.156	0.180	0.122	0.112
Large-scale ethanol fuel	0.302	0.257	0.271	0.226	0.216

Table 142. Production costs for the fuels produced in different plant sizes, based on engine output energy

Type of plant	Small farm [SEK/MJ$_{engine}$]		Large farm [SEK/MJ$_{engine}$]		Purchased
	Total	EU area	Total	EU area	seed
	production	comp. incl.	production	comp. incl.	[SEK/MJ$_{engine}$]
Small-scale rapeseed oil	0.849	0.600	0.705	0.456	0.412
Small-scale RME	1.071	0.831	0.932	0.693	0.651
Small-scale ethanol fuel	1.293	1.180	1.214	1.100	1.075
Medium-scale rapeseed oil	0.734	0.508	0.603	0.378	0.338
Medium-scale RME	0.821	0.603	0.695	0.478	0.440
Medium-scale ethanol fuel	0.983	0.869	0.903	0.790	0.764
Large-scale rapeseed oil	0.607	0.434	0.507	0.334	0.304
Large-scale RME	0.613	0.447	0.517	0.351	0.322
Large-scale ethanol fuel	0.763	0.650	0.684	0.570	0.545

When the rapeseed oil was extracted in a medium-scale plant instead of a small-scale plant (Table 142), the fuel production cost based on engine energy output (incl. receipts from meal) was reduced by approx. 14% (by 15-17% if EU area compensation was included and by 18% if the seed was purchased for 2.00 SEK/kg). When the rapeseed oil was extracted in a large-scale plant instead of a small-scale plant the fuel production cost (incl. receipts from meal) was reduced by approx. 28% (by 27-28% if EU area compensation was included and by 26% if the seed was purchased for 2.00 SEK/kg).

When the RME was produced in a medium-scale plant instead of a small-scale plant (Table 142) the fuel production cost based on engine energy output (incl. receipts from meal and glycerine) was reduced by 23-25% (by 27-31% if EU area compensation was included and by 32% if the seed was purchased for 2.00 SEK/kg). If the RME was produced on a large-scale plant instead of a small-scale plant the fuel production cost (incl. receipts from meal and glycerine) was reduced by 43-45% (by 46-49% if EU area compensation was included and by approx. 51% if the seed was purchased for 2.00 SEK/kg).

When the ethanol fuel was produced in a medium-scale plant instead of a small-scale plant (Table 142) the fuel production cost based on engine energy output (incl. receipts from distiller's waste) was reduced by 24-26% (by 26-28% if EU area compensation was included and by 29% if the wheat was purchased for 0.97 SEK/kg). If the ethanol fuel was produced in a large-scale plant instead of a small-scale plant the fuel production cost (incl. receipts from distiller's waste) was reduced by 41-44% (by 45-48% if EU area compensation was included and by approx. 49% if the wheat was purchased for 0.97 SEK/kg).

When RME was produced instead of rapeseed oil (Table 142) the fuel production cost based on engine energy output (incl. receipts from meal and glycerine) was increased by 26-32; 12-15; and 1-2% for small-; medium-; and large-scale plants respectively (by 39-52; 19-26; and 3-5% for small-; medium-; and large-scale plants respectively if EU area compensation was included and by 58; 30; and 6% for small-; medium-; and large-scale plants respectively if the seed was purchased for 2.00 SEK/kg).

When ethanol fuel was produced instead of rapeseed oil (Table 142) the fuel production cost based on engine energy output (incl. receipts from distiller's waste and meal) was increased by 52-72; 34-50; and 26-35% for small-; medium-; and large-scale plants respectively (by 97-140; 71-110; and 50-71% for small-; medium-; and large-scale plants respectively if EU area compensation was included and by 160; 130; and 79% for small-; medium-; and large-scale plants respectively if the rapeseed was purchased for 2.00 SEK/kg and the wheat was purchased for 0.97 SEK/kg).

For larger farms the results for the above cases were similar (Table 142). When rapeseed oil produced from seed grown on a large farm was compared with seed grown on a smaller farm, the fuel production cost based on engine energy output (incl. receipts from meal) was reduced by 16-18% (reduced by 23-26% with EU area compensation included). When RME produced on seed grown on a large farm was compared with seed grown on a smaller farm the fuel production cost based on engine energy output (incl. receipts from meal and glycerine) was reduced by 13-16% (reduced by 17-22% with EU area compensation included). When ethanol fuel produced on wheat grown on a large farm was compared with wheat grown on a smaller farm the fuel production cost based on engine energy output (incl. receipts from distiller's waste) was reduced by 6-10% (reduced by 7-12% with EU area compensation included).

The reason behind the costs being lower with larger production systems is that labour in particular can be used more efficiently. Larger extraction plants also have higher oil extraction efficiency and therefore produce a higher yield of the more valuable rapeseed oil. For ethanol production plants in particular, larger plants utilise the energy (electricity and heat) more efficiently than smaller plants. Machines and buildings are also used more efficiently in a larger plant. The higher costs for transport to larger plants are not high enough to come through.

The more complicated transesterification process made the RME produced more expensive than rapeseed oil, especially for smaller plants. For large plants the difference was small or negligible (Table 142). The even more complicated ethanol production process made ethanol fuel produced more expensive than rapeseed oil and RME, especially for smaller plants (Table 142). The ethanol fuel also became more expensive due to the requirement for expensive ignition improver and denaturants (Tables 125, 128 and 131).

The cost for diesel oil MK1 was 6.46 SEK/litre (OKQ8, 2003: excl. value added tax) equivalent to 0.520 SEK/MJ_{engine} (density 0.813 kg/l; lower heating value 43.3 MJ/kg (SMP, 1993); engine efficiency 0.353 calculated after Aakko *et al.* (2000) and SMP (1993)). These prices would make it profitable to produce rapeseed oil and RME in large-scale plants if the EU area compensation is on the level of today (Table 142). If the seed is produced on a large farm it would also be profitable to produce rapeseed oil and RME in a medium-scale plant with the EU area compensation (Table 142). Rapeseed oil could be produced profitably in a small plant if the seed were grown on a large farm and if there was EU area compensation (Table 142). If the seed is purchased for 2.00 SEK/kg, rapeseed oil could be produced profitably in all the plant sizes studied and RME in the medium- and large-scale plants (Table 142). Ethanol as ethanol fuel could not be produced profitably in any of the cases studied, but is not far from being produced profitably if the wheat were grown on a large farm with EU area compensation and after that processed in a large-scale plant (Table 142). The same is also valid for wheat purchased for 0.97 SEK/kg.

If the cost for the diesel oil MK1 was what farmers had to pay for it in 2002 and 2003 (Henemo, 2002 and 2003): 5.70 SEK/litre (0.458 SEK/MJ_{engine}), rapeseed oil and RME could only be produced profitably, with EU area compensation, in large-scale plants (Table 142). If the seed was grown on a large farm with EU area compensation, rapeseed oil could also be produced profitably in small- and medium-scale plants (Table 142). If the seed was purchased for 2.00 SEK/kg, rapeseed oil could be produced profitably in all the plant sizes studied and RME in the medium- and large-scale plants as with the higher MK1 price above (Table 142). Ethanol fuel could not be produced profitably in any of the cases studied (Table 142).

RME was assumed to make 5.61 SEK/litre (Lindkvist, pers. comm.) equivalent to 0.472 SEK/MJ_{engine} (density 0.886 kg/l; lower heating value 38.5 MJ/kg (SMP, 1993); engine efficiency 0.349 calculated after Aakko *et al.* (2000) and SMP (1993)). At that price, RME could be produced profitably in large-scale plants if the seed were grown with the EU area compensation of today (Table 142). If the seed were purchased for 2.00 SEK/kg, RME could be produced profitably in medium- and large-scale plants (Table 142).

Ethanol fuel was assumed to make 6.30 SEK/litre (Elfving, pers. comm.) equivalent to 0.763 SEK/MJ_{engine} (density 0.830 kg/l; (Sekab, 2003) lower heating value 25.1 MJ/kg (calculated after Aylward & Findlay, 1994; Schmitz, 2003; Solomons, 1996; Lif, pers. comm.; and Sekab, 2003); engine efficiency 0.396 calculated after Haupt *et al.* (1999)). At that price, ethanol fuel could be produced profitably in large-scale plants in all the cases studied (Table 142).

The above results show that production of rapeseed oil and RME may be a way for farmers to make rapeseed production more profitable (get a higher price for the seed than 2.00 SEK/kg) and get better paid for the cultivation work. For ethanol fuel production this would be harder because the requirement of larger plants to become profitable.

4.8 Sensitivity analysis

This section deals with traditional sensitivity analysis, which is presented for each of the fuels studied at a time in Tables 143-145 with physical allocation and in Tables 146-148 with no allocation. For description of the conditions for the sensitivity analysis see Section 3.11.1. When the factors were changed, all factors except for seed harvest had practically the same change in impact categories and energy requirements, but with the opposite sign, when they were changed by +20% or –20% and therefore only the change +20% is accounted for in Tables 143-148. For example for RME production, the GWP-emissions changed by *e.g.* +15.7% when the use of fertiliser increased by 20% and changed by –15.7% when the use of fertiliser decreased by 20%.

It was shown that all impact categories studied and the energy requirements were quite sensitive to changes in seed harvest, emissions (AP, EP and POCP) when the rapeseed oil, RME or ethanol fuel produced was used, and use of fertilisers (Tables 143-145). Changes in soil emissions and tractive power also had an influence, but to a much smaller extent. For ethanol fuel production, production of ignition improver, steam (heat) production and seed drying also had some influence (Table 145). The effects of the other changes were negligible. With no allocation the results were similar (Tables 146-148) but with a somewhat lower influence for the factor ‘use of fuels produced’ (rapeseed oil, RME and ethanol fuel). After the allocation the values that were shared with the meal, glycerine or distiller's waste were lower (Tables 143-145 in comparison to Tables 146-148). The values that were not shared with the meal, glycerine or distiller's waste (values connected to the transesterification or ethanol processing and emissions when the rapeseed oil, RME or ethanol fuel produced was used) were higher.

Table 143. Changes in impact categories and energy requirements when some production factors were changed in a sensitivity analysis for small-scale production of rapeseed oil, physical allocation, [g/MJ_{engine}]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Seed harvest, +20%	-16.1	-6.2	-5.8	-5.7	-12.9
Seed harvest, -20%	+24.2	+9.3	+8.8	+8.6	+19.4
Use of fertiliser, +20%	+17.7	+6.6	+6.2	+4.5	+10.2
Soil emissions, +20%	+6.7	+5.5	+5.7	0	0
Use of pesticides, +20%	+0.045	+0.012	+0.0028	+0.0087	+0.29
Use of tractive power, +20%	+1.5	+0.77	+0.78	+2.3	+3.5
Use of machinery for cultivation, +20%	+0.035	+0.0056	+0.0027	+0.039	+1.3
Use of oil for seed drying, +20%	+0.60	+0.030	+0.022	+0.60	+1.5
Use of electricity for oil extraction, +20%	+0.074	+0.012	+0.0057	+0.083	+2.7
Emissions when driving on the rapeseed oil, +20%	+0.049	+12.4	+13.0	+12.5	0

Table 144. Changes in impact categories and energy requirements when some production factors were changed in a sensitivity analysis for small-scale production of RME, physical allocation, [g/MJ_{engine}]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Seed harvest, +20%	-14.2	-5.6	-5.3	-5.9	-9.9
Seed harvest, -20%	+21.4	+8.4	+7.9	+8.9	+14.8
Use of fertiliser, +20%	+15.7	+6.0	+5.6	+4.6	+7.7
Soil emissions, +20%	+6.0	+4.9	+5.2	0	0
Use of pesticides, +20%	+0.040	+0.011	+0.0025	+0.0090	+0.22
Use of tractive power, +20%	+1.3	+0.70	+0.71	+2.4	+2.7
Use of machinery for cultivation, +20%	+0.031	+0.0051	+0.0024	+0.040	+0.98
Use of oil for seed drying, +20%	+0.53	+0.028	+0.020	+0.62	+1.1
Use of electricity for oil extraction, +20%	+0.066	+0.011	+0.0052	+0.086	+2.1
Use of electricity for transesterification, +20%	+0.068	+0.011	+0.0054	+0.090	+2.2
Emissions during production of methanol, +20%	+0.46	+0.046	+0.047	+0.19	+2.4
Emissions when driving on the RME, +20%	+0.039	+13.1	+13.6	+11.9	0

Table 145. Changes in impact categories and energy requirements when some production factors were changed in a sensitivity analysis for small-scale production of ethanol fuel, physical allocation, [g/MJ_{engine}]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Seed harvest, +20%	-10.1	-5.8	-5.5	-0.89	-5.7
Seed harvest, -20%	+15.3	+8.8	+8.4	+1.4	+8.7
Use of fertiliser, +20%	+10.5	+5.9	+5.6	+0.65	+3.9
Soil emissions, +20%	+4.2	+4.8	+5.1	0	0
Use of pesticides, +20%	+0.048	+0.018	+0.0043	+0.0020	+0.20
Use of tractive power, +20%	+1.1	+0.80	+0.83	+0.37	+1.7
Use of machinery for cultivation, +20%	+0.032	+0.0073	+0.0036	+0.0079	+0.76
Use of oil for seed drying, +20%	+1.1	+0.077	+0.057	+0.24	+1.7
Use of electricity for ethanol production, +20%	+0.11	+0.025	+0.012	+0.026	+2.6
Use of steam for ethanol production, +20%	+0.59	+1.1	+0.94	+2.1	+0.60
Emissions during production of chemicals, enzymes etc., +20%	+0.043	+0.027	+0.0095	+0.0012	+0.079
Emissions during production of ignition improver, +20%	+1.4	+0.60	+0.33	+2.7	+5.3
Emissions during production of denaturants, +20%	+0.59	+0.077	+0.065	+0.88	+2.2
Emissions during handling of waste water, +20%	+0.012	+0.0027	+0.0013	+0.0029	+0.28
Emissions when driving on the ethanol fuel, +20%	+0.29	+11.4	+12.2	+13.0	0

Table 146. Changes in impact categories and energy requirements when some production factors were changed in a sensitivity analysis for small-scale production of rapeseed oil, no allocation, [g/MJ_{engine}]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Seed harvest, +20%	-16.1	-9.3	-8.9	-8.5	-12.9
Seed harvest, -20%	+24.2	+13.9	+13.4	+12.8	+19.4
Use of fertiliser, +20%	+17.7	+9.9	+9.5	+6.7	+10.2
Soil emissions, +20%	+6.7	+8.2	+8.7	0	0
Use of pesticides, +20%	+0.045	+0.018	+0.0043	+0.013	+0.29
Use of tractive power, +20%	+1.5	+1.2	+1.2	+3.5	+3.5
Use of machinery for cultivation, +20%	+0.035	+0.0084	+0.0041	+0.058	+1.3
Use of oil for seed drying, +20%	+0.60	+0.046	+0.033	+0.90	+1.5
Use of electricity for oil extraction, +20%	+0.074	+0.018	+0.0088	+0.12	+2.7
Emissions when driving on the rapeseed oil, +20%	+0.023	+8.7	+9.3	+8.8	0

Table 147. Changes in impact categories and energy requirements when some production factors were changed in a sensitivity analysis for small-scale production of RME, no allocation, [g/MJ_{engine}]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Seed harvest, +20%	-15.2	-8.8	-8.4	-8.9	-11.2
Seed harvest, -20%	+22.8	+13.2	+12.7	+13.4	+16.9
Use of fertiliser, +20%	+16.7	+9.4	+8.9	+7.0	+8.9
Soil emissions, +20%	+6.4	+7.8	+8.3	0	0
Use of pesticides, +20%	+0.042	+0.017	+0.0040	+0.014	+0.25
Use of tractive power, +20%	+1.4	+1.1	+1.1	+3.6	+3.1
Use of machinery for cultivation, +20%	+0.033	+0.0080	+0.0039	+0.061	+1.1
Use of oil for seed drying, +20%	+0.57	+0.043	+0.031	+0.94	+1.3
Use of electricity for oil extraction, +20%	+0.070	+0.017	+0.0083	+0.13	+2.4
Use of electricity for transesterification, +20%	+0.035	+0.0084	+0.0041	+0.064	+1.2
Emissions during production of methanol, +20%	+0.23	+0.034	+0.036	+0.13	+1.3
Emissions when driving on the RME, +20%	+0.019	+9.3	+9.8	+8.0	0

Table 148. Changes in impact categories and energy requirements when some production factors were changed in a sensitivity analysis for small-scale production of ethanol fuel, no allocation, [g/MJ_{engine}]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Seed harvest, +20%	-11.7	-7.7	-7.5	-1.4	-7.0
Seed harvest, -20%	+17.8	+11.8	+11.4	+2.1	+10.7
Use of fertiliser, +20%	+12.2	+7.9	+7.6	+1.0	+4.8
Soil emissions, +20%	+4.8	+6.4	+7.0	0	0
Use of pesticides, +20%	+0.055	+0.024	+0.0059	+0.0032	+0.24
Use of tractive power, +20%	+1.2	+1.1	+1.1	+0.59	+2.0
Use of machinery for cultivation, +20%	+0.037	+0.0098	+0.0048	+0.012	+0.93
Use of oil for seed drying, +20%	+1.3	+0.10	+0.077	+0.37	+2.1
Use of electricity for ethanol production, +20%	+0.10	+0.027	+0.013	+0.034	+2.5
Use of steam for ethanol production, +20%	+0.44	+0.95	+0.82	+2.1	+0.47
Emissions during production of chemicals, enzymes etc., +20%	+0.050	+0.036	+0.013	+0.0018	+0.096
Emissions during production of ignition improver, +20%	+1.0	+0.49	+0.27	+2.5	+4.0
Emissions during production of denaturants, +20%	+0.42	+0.063	+0.053	+0.84	+1.6
Emissions during handling of waste water, +20%	+0.013	+0.0036	+0.0018	+0.0045	+0.34
Emissions when driving on the ethanol fuel, +20%	+0.20	+9.3	+10.0	+12.4	0

The influence of increasing and decreasing the seed yield by 20%, increasing and decreasing some other factors by 20%, and increasing and decreasing the emissions when using the fuels produced by 20% on the difference between small- and large-scales was studied in Tables 149-154 (for calculations see Section 3.11.1). A negative sign in the tables indicates that the large-scale plant has lower emissions/energy requirements. A positive sign indicates the opposite. It was demonstrated that the changes in the input parameters had a small or negligible influence on the difference between the two production scales. The sign was only changed for RME production, in comparison to the original, during physical allocation, for GWP- and AP-emissions, which showed a negligible difference between large- and small-scale RME production (difference just 0.07% for the original case), and for the most important factors, seed harvest and use of fertilisers with soil emissions (Table 150). The sign was not changed in any case for production of rapeseed oil or ethanol fuel (Tables 149 and 151). A changed sign indicates that the conditions regarding which production scale gives the lowest emissions have changed because of the changed conditions for the production factors. The most sensitive factors for changes were seed harvest, use of fertilisers and soil emissions (Tables 149-151). Changes in emissions (AP, EP and POCP) when the fuels produced were used and use of electricity also had an influence, but to a smaller extent. For ethanol fuel production, production of ignition improver and steam (heat) production also had some influence (Table 151). The effects of the other changes were negligible.

Table 149. Original differences between small- and large-scale systems, and the differences when some production factors were changed, rapeseed oil, physical allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Original (no change) (from Table 134)	**+0.24**	**+0.19**	**+0.21**	**+1.21**	**-3.26**
Seed harvest, +20%	+0.45	+0.26	+0.28	+1.34	-3.60
Seed harvest, -20%	+0.02	+0.10	+0.13	+1.05	-2.90
Use of fertiliser, +20%	+0.07	+0.13	+0.15	+1.12	-3.04
Use of fertiliser, -20%	+0.48	+0.27	+0.28	+1.31	-3.53
Soil emissions, +20%	+0.17	+0.14	+0.15	+1.21	-3.26
Soil emissions, -20%	+0.32	+0.25	+0.28	+1.21	-3.26
Use of pesticides, +20%	+0.24	+0.19	+0.21	+1.21	-3.26
Use of pesticides, -20%	+0.24	+0.19	+0.21	+1.21	-3.27
Use of tractive power, +20%	+0.22	+0.18	+0.20	+1.16	-3.18
Use of tractive power, -20%	+0.26	+0.20	+0.22	+1.26	-3.35
Use of machinery for cultivation, +20%	+0.24	+0.19	+0.21	+1.21	-3.23
Use of machinery for cultivation, -20%	+0.24	+0.19	+0.21	+1.21	-3.29
Use of oil for seed drying, +20%	+0.23	+0.19	+0.21	+1.20	-3.23
Use of oil for seed drying, -20%	+0.25	+0.19	+0.21	+1.22	-3.30
Use of electricity for oil extraction, +20%	+0.21	+0.19	+0.21	+1.17	-4.32
Use of electricity for oil extraction, -20%	+0.27	+0.20	+0.22	+1.25	-2.14
Emissions when driving on the rapeseed oil, +20%	+0.24	+0.17	+0.19	+1.08	-3.26
Emissions when driving on the rapeseed oil, -20%	+0.24	+0.22	+0.24	+1.38	-3.26

Table 150. Original differences between small- and large-scale systems, and the differences when some production factors were changed, RME, physical allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Original (no change) (from Table 134)	**-0.07**	**+0.07**	**+0.10**	**+1.10**	**-3.79**
Seed harvest, +20%	+0.11	+0.15	+0.17	+1.25	-3.95
Seed harvest, -20%	-0.26	-0.02	+0.01	+0.91	-3.61
Use of fertiliser, +20%	-0.22	+0.01	+0.04	+1.00	-3.60
Use of fertiliser, -20%	+0.13	+0.15	+0.17	+1.21	-4.01
Soil emissions, +20%	-0.13	+0.02	+0.04	+1.10	-3.79
Soil emissions, -20%	0.00	+0.14	+0.17	+1.10	-3.79
Use of pesticides, +20%	-0.07	+0.07	+0.10	+1.10	-3.78
Use of pesticides, -20%	-0.07	+0.07	+0.10	+1.10	-3.80
Use of tractive power, +20%	-0.08	+0.07	+0.09	+1.05	-3.72
Use of tractive power, -20%	-0.06	+0.08	+0.11	+1.16	-3.86
Use of machinery for cultivation, +20%	-0.07	+0.07	+0.10	+1.10	-3.77
Use of machinery for cultivation, -20%	-0.07	+0.07	+0.10	+1.10	-3.82
Use of oil for seed drying, +20%	-0.08	+0.07	+0.10	+1.09	-3.76
Use of oil for seed drying, -20%	-0.06	+0.07	+0.10	+1.11	-3.82
Use of electricity for oil extraction, +20%	-0.10	+0.07	+0.10	+1.06	-4.59
Use of electricity for oil extraction, -20%	-0.04	+0.08	+0.10	+1.14	-2.96
Use of electricity for transesterification, +20%	-0.07	+0.07	+0.10	+1.10	-3.80
Use of electricity for transesterification, -20%	-0.07	+0.07	+0.10	+1.11	-3.78
Emissions during production of methanol, +20%	-0.07	+0.07	+0.10	+1.10	-3.70
Emissions during production of methanol, -20%	-0.07	+0.07	+0.10	+1.10	-3.88
Emissions when driving on the RME, +20%	-0.07	+0.07	+0.09	+0.98	-3.79
Emissions when driving on the RME, -20%	-0.07	+0.09	+0.12	+1.25	-3.79

Table 151. Original differences between small- and large-scale systems, and the differences when some production factors were changed for ethanol fuel production, physical allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Original (no change) (from Table 135)	**+1.18**	**+0.28**	**+1.04**	**-7.51**	**-1.73**
Seed harvest, +20%	+1.32	+0.30	+1.10	-7.58	-1.57
Seed harvest, -20%	+1.01	+0.25	+0.96	-7.42	-1.95
Use of fertiliser, +20%	+1.07	+0.26	+0.98	-7.46	-1.67
Use of fertiliser, -20%	+1.32	+0.29	+1.10	-7.56	-1.80
Soil emissions, +20%	+1.13	+0.26	+0.99	-7.51	-1.73
Soil emissions, -20%	+1.23	+0.29	+1.09	-7.51	-1.73
Use of pesticides, +20%	+1.18	+0.28	+1.04	-7.51	-1.73
Use of pesticides, -20%	+1.18	+0.28	+1.04	-7.51	-1.74
Use of tractive power, +20%	+1.17	+0.28	+1.03	-7.48	-1.71
Use of tractive power, -20%	+1.19	+0.28	+1.05	-7.54	-1.76
Use of machinery for cultivation, +20%	+1.18	+0.28	+1.04	-7.51	-1.72
Use of machinery for cultivation, -20%	+1.18	+0.28	+1.04	-7.51	-1.75
Use of oil for seed drying, +20%	+1.17	+0.28	+1.04	-7.49	-1.70
Use of oil for seed drying, -20%	+1.19	+0.28	+1.04	-7.53	-1.76
Use of electricity for ethanol production, +20%	+1.16	+0.27	+1.04	-7.52	-2.19
Use of electricity for ethanol production, -20%	+1.20	+0.28	+1.04	-7.51	-1.25
Use of steam for ethanol production, +20%	+1.05	+0.10	+0.99	-8.93	-1.89
Use of steam for ethanol production, -20%	+1.32	+0.46	+1.08	-6.03	-1.57
Emissions during production of chemicals, enzymes etc., +20%	+1.18	+0.28	+1.04	-7.51	-1.73
Emissions during production of chemicals, enzymes etc., -20%	+1.18	+0.28	+1.04	-7.51	-1.73
Emissions during production of ignition improver, +20%	+1.16	+0.28	+1.04	-7.32	-1.65
Emissions during production of ignition improver, -20%	+1.20	+0.28	+1.04	-7.72	-1.83
Emissions during production of denaturants, +20%	+1.17	+0.28	+1.04	-7.45	-1.70
Emissions during production of denaturants, -20%	+1.19	+0.28	+1.04	-7.58	-1.77
Emissions during handling of waste water, +20%	+1.18	+0.28	+1.04	-7.51	-1.74
Emissions during handling of waste water, -20%	+1.18	+0.28	+1.04	-7.51	-1.73
Emissions when driving on the ethanol fuel, +20%	+1.18	+0.25	+0.93	-6.65	-1.73
Emissions when driving on the ethanol fuel, -20%	+1.18	+0.31	+1.18	-8.64	-1.73

With no allocation, the results were similar (Tables 152-154) to those with physical allocation but with a somewhat higher influence from the changed factors. A great difference was that the original (no change) level was on much higher level, a few per cent to tens of per cent instead of tenths of one per cent to a few per cent. The influence of each production factor was accounted for by the difference from the original (no change) level. The most sensitive factors for changes were seed harvest, use of fertilisers, soil emissions and changes in emissions (AP, EP and POCP) when the fuels produced were used (Tables 152-154). Use of electricity and tractive power also had an influence, but to a much smaller extent. For ethanol fuel production, production of steam (heat) and ignition improver also had some influence (Table 154). The effects of the other changes were negligible. The changes from physical allocation were small.

Table 152. Original differences between small- and large-scale systems, and the differences when some production factors were changed, rapeseed oil, no allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Original (no change) (calculated after Table 136)	**-29.74**	**-16.50**	**-15.78**	**-15.51**	**-32.14**
Seed harvest, +20%	-29.58	-15.06	-14.33	-14.10	-32.35
Seed harvest, -20%	-29.91	-18.23	-17.53	-17.23	-31.91
Use of fertiliser, +20%	-29.88	-17.77	-17.06	-16.45	-32.00
Use of fertiliser, -20%	-29.56	-14.95	-14.23	-14.43	-32.31
Soil emissions, +20%	-29.80	-17.57	-16.97	-15.51	-32.14
Soil emissions, -20%	-29.68	-15.25	-14.36	-15.51	-32.14
Use of pesticides, +20%	-29.74	-16.50	-15.78	-15.51	-32.14
Use of pesticides, -20%	-29.74	-16.50	-15.78	-15.51	-32.14
Use of tractive power, +20%	-29.76	-16.66	-15.96	-16.01	-32.09
Use of tractive power, -20%	-29.73	-16.34	-15.60	-14.97	-32.20
Use of machinery for cultivation, +20%	-29.74	-16.50	-15.78	-15.52	-32.12
Use of machinery for cultivation, -20%	-29.74	-16.50	-15.78	-15.50	-32.16
Use of oil for seed drying, +20%	-29.75	-16.51	-15.79	-15.64	-32.12
Use of oil for seed drying, -20%	-29.74	-16.49	-15.78	-15.37	-32.16
Use of electricity for oil extraction, +20%	-29.77	-16.51	-15.78	-15.57	-32.89
Use of electricity for oil extraction, -20%	-29.72	-16.49	-15.78	-15.45	-31.35
Emissions when driving on the rapeseed oil, +20%	-29.74	-15.17	-14.44	-14.26	-32.14
Emissions when driving on the rapeseed oil, -20%	-29.75	-18.08	-17.40	-17.00	-32.14

Table 153. Original differences between small- and large-scale systems, and the differences when some production factors were changed, RME, no allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Original (no change) (calculated after Table 136)	**-28.08**	**-15.67**	**-14.95**	**-16.24**	**-28.48**
Seed harvest, +20%	-27.62	-14.23	-13.50	-14.83	-28.16
Seed harvest, -20%	-28.55	-17.42	-16.71	-17.94	-28.85
Use of fertiliser, +20%	-28.44	-16.96	-16.23	-17.18	-28.66
Use of fertiliser, -20%	-27.57	-14.12	-13.41	-15.17	-28.27
Soil emissions, +20%	-28.23	-16.75	-16.14	-16.24	-28.48
Soil emissions, -20%	-27.90	-14.42	-13.54	-16.24	-28.48
Use of pesticides, +20%	-28.08	-15.68	-14.95	-16.24	-28.49
Use of pesticides, -20%	-28.07	-15.67	-14.95	-16.24	-28.48
Use of tractive power, +20%	-28.11	-15.84	-15.12	-16.74	-28.55
Use of tractive power, -20%	-28.04	-15.51	-14.77	-15.70	-28.42
Use of machinery for cultivation, +20%	-28.08	-15.68	-14.95	-16.25	-28.51
Use of machinery for cultivation, -20%	-28.07	-15.67	-14.95	-16.23	-28.46
Use of oil for seed drying, +20%	-28.09	-15.68	-14.95	-16.38	-28.51
Use of oil for seed drying, -20%	-28.06	-15.67	-14.94	-16.11	-28.46
Use of electricity for oil extraction, +20%	-28.10	-15.68	-14.95	-16.30	-29.22
Use of electricity for oil extraction, -20%	-28.05	-15.67	-14.94	-16.18	-27.71
Use of electricity for transesterification, +20%	-28.07	-15.67	-14.95	-16.23	-28.20
Use of electricity for transesterification, -20%	-28.08	-15.67	-14.95	-16.25	-28.77
Emissions during production of methanol, +20%	-28.01	-15.67	-14.94	-16.22	-28.12
Emissions during production of methanol, -20%	-28.14	-15.68	-14.95	-16.26	-28.86
Emissions when driving on the RME, +20%	-28.07	-14.35	-13.61	-15.03	-28.48
Emissions when driving on the RME, -20%	-28.08	-17.27	-16.57	-17.66	-28.48

Table 154. Original differences between small- and large-scale systems, and the differences when some production factors were changed for ethanol fuel production, no allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Original (no change) (calculated after Table 136)	**+3.74**	**+4.86**	**+5.47**	**-4.63**	**+10.83**
Seed harvest, +20%	+4.24	+5.27	+5.91	-4.70	+11.99
Seed harvest, -20%	+3.15	+4.34	+4.91	-4.54	+9.36
Use of fertiliser, +20%	+3.33	+4.50	+5.08	-4.59	+10.34
Use of fertiliser, -20%	+4.26	+5.28	+5.91	-4.68	+11.38
Soil emissions, +20%	+3.56	+4.57	+5.11	-4.63	+10.83
Soil emissions, -20%	+3.93	+5.19	+5.88	-4.63	+10.83
Use of pesticides, +20%	+3.73	+4.86	+5.47	-4.63	+10.81
Use of pesticides, -20%	+3.74	+4.86	+5.47	-4.63	+10.86
Use of tractive power, +20%	+3.69	+4.81	+5.41	-4.61	+10.62
Use of tractive power, -20%	+3.78	+4.91	+5.53	-4.66	+11.06
Use of machinery for cultivation, +20%	+3.73	+4.86	+5.47	-4.63	+10.73
Use of machinery for cultivation, -20%	+3.74	+4.86	+5.47	-4.63	+10.94
Use of oil for seed drying, +20%	+3.69	+4.85	+5.46	-4.62	+10.61
Use of oil for seed drying, -20%	+3.78	+4.86	+5.47	-4.65	+11.06
Use of electricity for ethanol production, +20%	+3.79	+4.88	+5.47	-4.61	+12.10
Use of electricity for ethanol production, -20%	+3.68	+4.84	+5.46	-4.66	+9.50
Use of steam for ethanol production, +20%	+3.96	+5.45	+6.18	-5.63	+10.98
Use of steam for ethanol production, -20%	+3.50	+4.26	+4.75	-3.60	+10.68
Emissions during production of chemicals, enzymes etc., +20%	+3.73	+4.86	+5.47	-4.63	+10.82
Emissions during production of chemicals, enzymes etc., -20%	+3.74	+4.86	+5.47	-4.63	+10.84
Emissions during production of ignition improver, +20%	+3.70	+4.84	+5.45	-4.52	+10.42
Emissions during production of ignition improver, -20%	+3.77	+4.88	+5.48	-4.76	+11.29
Emissions during production of denaturants, +20%	+3.72	+4.86	+5.46	-4.60	+10.66
Emissions during production of denaturants, -20%	+3.75	+4.86	+5.47	-4.67	+11.01
Emissions during handling of waste water, +20%	+3.73	+4.86	+5.47	-4.63	+10.78
Emissions during handling of waste water, -20%	+3.74	+4.86	+5.47	-4.63	+10.88
Emissions when driving on the ethanol fuel, +20%	+3.73	+4.45	+4.97	-4.12	+10.83
Emissions when driving on the ethanol fuel, -20%	+3.74	+5.36	+6.08	-5.29	+10.83

The above sensitivity analysis shows that changes in the following factors have the greatest potential to change the final result: changes in seed harvest; use of the fuels produced (rapeseed oil, RME and ethanol fuel); and use of fertilisers. There probably exists a great potential to reduce all kind of emissions if fertilisers could be produced in a more environmentally friendly way.

4.9 Scenario analysis

The effects of some changes in production strategies were analysed. For description of the scenarios studied see Section 3.11.2.

The most important changes in the results were observed: when the straw was harvested (Tables 155-157) for all fuels; when catalysts were used (Tables 155-157); for RME production when the methanol was produced from *Salix* instead of from natural gas (Table 156); for ethanol fuel production when the ignition improver and denaturants produced were of bio-origin instead of fossil origin (Table 157); and when electricity mainly produced from fossil fuels (fossil fuel electricity) (for description see Section 3.6.1) was used instead of Swedish electricity (Tables 155-157). Use of the fuels produced for cultivation and transport also gave important changes in the results (Tables 155-157).

When the straw was harvested, approx. 42%; 42%; and 46% (Tables 106 and 108) of the environmental load for the cultivation was allocated away with the straw for rapeseed oil, RME and ethanol fuel respectively. This reduced the environmental load by 15-42%; 13-37%; and 3-29% for rapeseed oil, RME and ethanol fuel respectively (Tables 155-157). When the allocation was made according to monetary units (economic allocation) instead of physical (energy), values were 2.8-3.0%; 2.4-2.7%; and 2.3-2.5% (Tables 107 and 109) of the environmental load for the cultivation allocated away with the straw for rapeseed oil, RME and ethanol fuel respectively. This reduced the environmental load by 1-3%; 1-2%; and 0.2-2% for rapeseed oil, RME and ethanol fuel respectively (Tables 155-157).

When catalysts were used in all operations the POCP-emissions were reduced by 44-54%, AP- and EP-emissions by 0.2-4%, and GWP-emissions was almost unaffected depending on the fuel studied (Tables 155-157). Methanol produced from *Salix* increased the energy requirement by almost 32% and reduced the GWP-emissions by 9% (Table 156) during RME production. Ignition improver of bio-origin increased the energy requirement by 70% and reduced the GWP-emissions by 15% (Table 157) during ethanol fuel production. With fossil fuel electricity (for all applications together), the GWP-emissions increased by 12-18% and the energy requirement by 11-14% depending on the fuel studied (Tables 155-157). When the rapeseed oil produced was used for cultivation and transport in the system studied, GWP-emissions decreased by 5% and POCP-emissions by 8% (Table 155). However, the categories AP- and EP-emissions increased by almost 3%, and the energy requirement by 6%. When the RME produced was used for cultivation and transport in the system studied, GWP-emissions decreased by 4% and POCP-emissions by almost 10% (Table 156). However, the categories AP- and EP-emissions increased by about 2%, and the energy requirement by almost 5%. When the ethanol fuel produced was used for cultivation and transport in the system studied, GWP-emissions decreased by 3% and AP- and EP-emissions by approx. 0.5% (Table 157). However, the POCP-emissions and the energy requirement increased by approx. 1%. When ignition improver and denaturants of bio-origin (bio-optimization) were used to produce the ethanol fuel used for cultivation and transport in the system studied, GWP-emissions decreased by 28%. However, the AP-, EP- and POCP-emissions and the energy requirement increased by 28, 6, 110 and 104% respectively (Table 157). Other factors studied had only a minor influence on impact categories and energy requirement.

Table 155. Influence of using alternative production scenarios in small-scale production of rapeseed oil, physical allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Straw harvested	-42.1	-15.8	-14.9	-15.8	-36.2
Straw harvested (economic allocation)	-3.0	-1.3	-1.2	-1.3	-2.6
Ploughless tillage	-0.52	-0.57	-0.58	-0.87	-1.4
Fossil fuel electricity: extraction etc.	+8.1	+0.62	+0.29	+0.81	+7.2
Fossil fuel electricity: machinery	+4.2	+0.33	+0.15	+0.44	+4.1
Fossil fuel electricity: all	+12.3	+0.95	+0.44	+1.3	+11.3
Catalyst used in cultivation operations	-0.012	-0.22	-0.23	-4.5	0
Catalyst used in transport	0	0	0	0	0
Catalyst used in use of fuel produced	-0.20	-3.7	-3.9	-49.1	0
Catalyst used in all operations	-0.21	-3.9	-4.1	-53.6	0
Produced rapeseed oil fuel used for cultivation and transport	-5.0	+2.7	+2.7	-8.2	+6.1
All transport distances doubled	0	0	0	0	0
All transport distances halved	0	0	0	0	0
Machinery and building mass coefficient = 2/3 (area)	+0.019	+0.0031	+0.0015	+0.022	+0.72
Machinery and building mass coefficient = 1 (volume)	-0.011	-0.0018	-0.00088	-0.013	-0.42
Improved oil extraction efficiencies	+0.18	+0.061	+0.055	+0.088	+1.2
Small-scale extraction efficiency as in large-scale extraction	-0.70	-0.29	-0.29	-0.14	+5.2
Small-scale extraction as large-scale extraction	-0.95	-0.32	-0.31	-0.31	-5.4

Table 156. Influence of using alternative production scenarios in small-scale production of RME, physical allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Straw harvested	-37.1	-14.2	-13.4	-16.3	-27.2
Straw harvested (economic allocation)	-2.4	-1.0	-0.99	-1.2	-1.8
Ploughless tillage	-0.46	-0.51	-0.53	-0.90	-1.0
Methanol produced from *Salix*	-9.0	+0.64	+0.62	+5.7	+31.5
Fossil fuel electricity: extraction etc.	+13.9	+1.1	+0.51	+1.7	+10.6
Fossil fuel electricity: machinery	+4.3	+0.34	+0.16	+0.52	+3.5
Fossil fuel electricity: all	+18.2	+1.4	+0.66	+2.2	+14.1
Catalyst used in cultivation operations	-0.011	-0.20	-0.21	-4.7	0
Catalyst used in transport	-0.000089	-0.0013	-0.0014	-0.025	0
Catalyst used in use of fuel produced	-0.16	-3.9	-4.1	-46.7	0
Catalyst used in all operations	-0.17	-4.1	-4.3	-51.4	0
Produced RME fuel used for cultivation and transport	-4.1	+2.0	+2.0	-9.8	+4.7
All transport distances doubled	+0.056	+0.024	+0.024	+0.085	+0.12
All transport distances halved	-0.028	-0.012	-0.012	-0.042	-0.062
Machinery and building mass coefficient = 2/3 (area)	+0.036	+0.0059	+0.0028	+0.047	+1.1
Machinery and building mass coefficient = 1 (volume)	-0.021	-0.0034	-0.0016	-0.027	-0.65
Improved oil extraction efficiencies	+0.11	+0.038	+0.034	+0.070	+0.79
Small-scale extraction efficiency as in large-scale extraction	-0.87	-0.36	-0.35	-0.27	+3.5
Small-scale extraction as large-scale extraction	-1.1	-0.39	-0.36	-0.44	-4.4

Table 157. Influence of using alternative production scenarios in small-scale production of ethanol fuel, physical allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Straw harvested	-29.4	-15.6	-14.8	-2.9	-19.6
Straw harvested (economic allocation)	-1.8	-1.1	-1.1	-0.24	-1.3
Ploughless tillage	-0.38	-0.58	-0.61	-0.14	-0.64
Steam produced by *Salix*	+0.19	+1.2	-0.10	-0.54	+0.54
Ignition improver of bio-origin	-14.6	+24.3	+4.3	+80.8	+69.8
Denaturants of bio-origin	-7.2	+2.0	+0.85	+26.7	+28.6
Ignition improver and denaturants of bio-origin	-21.8	+26.3	+5.2	+107.5	+98.4
Fossil fuel electricity: ethanol production etc.	+13.3	+1.5	+0.69	+0.30	+7.6
Fossil fuel electricity: machinery	+5.1	+0.56	+0.26	+0.12	+3.1
Fossil fuel electricity: all	+18.4	+2.0	+0.95	+0.41	+10.7
Catalyst used in cultivation operations	-0.0093	-0.22	-0.24	-0.73	0
Catalyst used in transport	-0.00020	-0.0041	-0.0044	-0.011	0
Catalyst used in use of fuel produced	-1.3	0	0	-43.4	0
Catalyst used in all operations	-1.4	-0.23	-0.25	-44.2	0
Fuel produced used for cultivation and transports	-3.0	-0.44	-0.51	+0.98	+1.3
Fuel produced used for cultivation and transports with bio-optimization	-28.2	+28.0	+6.2	+110.5	+103.7
All transport distances doubled	+0.13	+0.075	+0.077	+0.036	+0.21
All transport distances halved	-0.063	-0.038	-0.039	-0.018	-0.10
Machinery and building mass coefficient = 2/3 (area)	+0.057	+0.013	+0.0064	+0.014	+1.4
Machinery and building mass coefficient = 1 (volume)	-0.033	-0.0076	-0.0037	-0.0082	-0.80
Small-scale production with large-scale energy efficiency	-0.73	-0.90	-0.19	-8.1	-3.0
Small-scale production as large-scale production	-0.93	-1.6	-1.4	-3.0	-3.0

With no allocation (Tables 158-160) the results were similar to physical allocation for most factors (Tables 155-157). However, the influence was much greater for the following factors during production of rapeseed oil and RME (Tables 158-159): Small-scale extraction efficiency as in large-scale extraction and small-scale extraction as large-scale extraction. The same, but on a somewhat lower degree, was also valid for the case with improved oil extraction efficiency. The reason for this was that the rapeseed oil and RME yields would be larger because of the higher oil extraction level and therefore there would be more rapeseed oil and RME to spread the emissions and energy requirement over. With no allocation, the emission values and energy requirement values decreased correspondingly (Tables 158-159). With physical allocation the emissions values and energy requirement were also distributed on the meal and the effect of the higher extraction efficiency was therefore much lower (Tables 155-156). When the straw was harvested the environmental load was not influenced by no allocation, because with no allocation no environmental load was allocated away and therefore the results could not be influenced (Tables 158-159).

Table 158. Influence of using alternative production scenarios in small-scale production of rapeseed oil, no allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Straw harvested	0	0	0	0	0
Ploughless tillage	-0.52	-0.85	-0.89	-1.3	-1.4
Fossil fuel electricity: extraction etc.	+8.1	+0.93	+0.44	+1.2	+7.2
Fossil fuel electricity: machinery	+4.2	+0.49	+0.23	+0.65	+4.1
Fossil fuel electricity: all	+12.3	+1.4	+0.67	+1.9	+11.3
Catalyst used in cultivation operations	-0.012	-0.33	-0.35	-6.7	0
Catalyst used in transport	0	0	0	0	0
Catalyst used in use of fuel produced	-0.093	-2.6	-2.8	-34.5	0
Catalyst used in all operations	-0.11	-3.0	-3.1	-41.2	0
Produced rapeseed oil fuel used for cultivation and transport	-5.0	+4.1	+4.2	-12.3	+5.9
All transport distances doubled	0	0	0	0	0
All transport distances halved	0	0	0	0	0
Machinery and building mass coefficient = 2/3 (area)	+0.019	+0.0047	+0.0023	+0.032	+0.72
Machinery and building mass coefficient = 1 (volume)	-0.011	-0.0027	-0.0013	-0.019	-0.42
Improved oil extraction efficiencies	-6.8	-3.8	-3.7	-3.8	-5.9
Small-scale extraction efficiency as in large-scale extraction	-30.5	-17.1	-16.4	-17.0	-26.4
Small-scale extraction as large-scale extraction	-30.6	-17.1	-16.4	-17.2	-33.8

Table 159. Influence of using alternative production scenarios in small-scale production of RME, no allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Straw harvested	0	0	0	0	0
Ploughless tillage	-0.49	-0.81	-0.84	-1.4	-1.2
Methanol produced from *Salix*	-4.4	+0.48	+0.47	+4.0	+17.1
Fossil fuel electricity: extraction etc.	+11.1	+1.3	+0.60	+1.8	+9.0
Fossil fuel electricity: machinery	+4.3	+0.50	+0.23	+0.73	+3.8
Fossil fuel electricity: all	+15.3	+1.8	+0.84	+2.6	+12.8
Catalyst used in cultivation operations	-0.012	-0.31	-0.33	-7.0	0
Catalyst used in transport	-0.000088	-0.0019	-0.0021	-0.034	0
Catalyst used in use of fuel produced	-0.075	-2.8	-2.9	-31.6	0
Catalyst used in all operations	-0.087	-3.1	-3.3	-38.7	0
Produced RME fuel used for cultivation and transport	-4.8	+3.9	+4.0	-12.9	+5.2
All transport distances doubled	+0.055	+0.035	+0.036	+0.12	+0.13
All transport distances halved	-0.028	-0.018	-0.018	-0.059	-0.066
Machinery and building mass coefficient = 2/3 (area)	+0.028	+0.0067	+0.0033	+0.051	+0.94
Machinery and building mass coefficient = 1 (volume)	-0.016	-0.0039	-0.0019	-0.030	-0.55
Improved oil extraction efficiencies	-6.4	-3.6	-3.5	-4.0	-5.1
Small-scale extraction efficiency as in large-scale extraction	-28.7	-16.2	-15.5	-17.8	-23.0
Small-scale extraction as large-scale extraction	-28.9	-16.2	-15.5	-18.0	-29.4

Table 160. Influence of using alternative production scenarios in small-scale production of ethanol fuel, no allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Straw harvested	0	0	0	0	0
Ploughless tillage	-0.44	-0.78	-0.83	-0.22	-0.79
Steam produced by *Salix*	+0.15	+1.0	-0.089	-0.55	+0.43
Ignition improver of bio-origin	-10.3	+19.9	+3.6	+77.1	+51.9
Denaturants of bio-origin	-5.1	+1.6	+0.70	+25.5	+21.3
Ignition improver and denaturants of bio-origin	-15.4	+21.5	+4.3	+102.5	+73.2
Fossil fuel electricity: ethanol production etc.	+13.1	+1.7	+0.79	+0.39	+7.9
Fossil fuel electricity: machinery	+5.9	+0.75	+0.36	+0.18	+3.8
Fossil fuel electricity: all	+19.0	+2.4	+1.1	+0.57	+11.7
Catalyst used in cultivation operations	-0.011	-0.30	-0.33	-1.1	0
Catalyst used in transport	-0.00015	-0.0036	-0.0039	-0.011	0
Catalyst used in use of fuel produced	-0.95	0	0	-41.4	0
Catalyst used in all operations	-0.96	-0.31	-0.33	-42.6	0
Fuel produced used for cultivation and transports	-3.4	-0.59	-0.68	+1.5	+1.5
Fuel produced used for cultivation and transports with bio-optimization	-22.8	+23.7	+5.7	+107.3	+79.6
All transport distances doubled	+0.094	+0.065	+0.067	+0.036	+0.16
All transport distances halved	-0.047	-0.032	-0.034	-0.018	-0.082
Machinery and building mass coefficient = 2/3 (area)	+0.066	+0.018	+0.0087	+0.022	+1.7
Machinery and building mass coefficient = 1 (volume)	-0.039	-0.010	-0.0051	-0.013	-0.97
Small-scale production with large-scale energy efficiency	+1.6	+3.3	+3.8	-5.5	+9.8
Small-scale production as large-scale production	-0.71	-1.4	-1.2	-3.1	-2.8

The influence of the alternative scenarios on the differences between small- and large-scales is shown in Tables 161-163 with physical allocation and in Tables 164-166 with no allocation (calculations explained in Section 3.11.2). A negative sign in the tables indicates that the large-scale plant has lower emissions/energy requirements. A positive sign indicates the opposite. Most of the studied scenarios had small effects on the difference.

For the rapeseed oil, RME and ethanol fuels (Tables 161-163): Small-scale extraction as large-scale extraction (rapeseed oil and RME); small-scale extraction efficiency as large-scale extraction (rapeseed oil and RME); small-scale production as large-scale production (ethanol fuel); small-scale production with large-scale energy efficiency (ethanol fuel); improved oil extraction efficiencies (rapeseed oil and RME); transport distances doubled or halved and choice of electricity (fossil) were the most important factors followed by: use of catalysts; fuel produced used for cultivation and transport with bio-optimization (ethanol fuel); produced rapeseed oil, RME or ethanol fuel used for cultivation and transports; use of ignition improver and/or denaturants of bio-origin (ethanol fuel); use of *Salix* methanol (RME); straw harvested; and steam produced by *Salix* (ethanol fuel).

The sign was only changed in some places, for the above-discussed factors, in comparison to the original. For GWP-, AP- and EP-emissions that showed a negligible difference between large- and small-scale production (rapeseed oil: difference 0.19-0.24% for the original case; RME: difference 0.07-0.10% for the original case; and ethanol fuel: difference 0.28-1.18% for the original case). Exceptions large enough to change the sign were (Tables 161-163): Small-scale extraction as large-scale extraction for input energy (rapeseed oil and RME (also GWP)) depending on longer transport for large plants; small-scale production as large-scale production and small-scale production with large-scale energy efficiency for input energy (ethanol fuel) depending on longer transport for large plants; all transport distances doubled (ethanol fuel) for input energy (for explanation see below); and small-scale production with large-scale energy efficiency for POCP-emissions (ethanol fuel) depending on higher HC-emissions for steam (heat) production in small plants (Table 34). The sign was also changed for straw harvested (RME: GWP); steam produced by *Salix* (ethanol fuel: AP); fossil fuel electricity (rapeseed oil: GWP and AP; RME: AP and EP; ethanol fuel: GWP and AP); fuel produced used for cultivation and transport (rapeseed oil: GWP; ethanol fuel: GWP); transport distances doubled (RME: GWP); transport distances halved (rapeseed oil: GWP, AP and EP; RME: AP and EP; ethanol fuel: AP); and small-scale extraction as in large-scale extraction (RME: GWP). A changed sign indicates that the conditions regarding which production scale gives the lowest emissions have changed because of the changed conditions for the production factors. The changed sign for doubled/halved transport distances depended on longer transport for large plants, favouring small-scale plants if doubled, the opposite if halved. The changed sign for emissions when Swedish electricity was replaced by fossil fuel electricity (for description see Section 3.6.1) was due to small plants having a higher requirement of electricity and therefore not being favoured when the electricity is produced in a less environmentally friendly way.

Table 161. Original differences between small- and large-scale systems in the basic scenario and the differences when some alternative scenarios were analysed for rapeseed oil production, physical allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Original (no change) (from Table 134)	**+0.24**	**+0.19**	**+0.21**	**+1.21**	**-3.26**
Straw harvested	+1.40	+0.48	+0.49	+1.69	-4.33
Ploughless tillage	+0.25	+0.20	+0.22	+1.23	-3.30
Fossil fuel electricity: extraction etc.	-2.53	-0.04	+0.11	+0.91	-5.21
Fossil fuel electricity: machinery	-0.05	+0.17	+0.20	+1.17	-3.41
Fossil fuel electricity: all	-2.70	-0.06	+0.10	+0.88	-5.27
Catalyst used in cultivation operations	+0.24	+0.19	+0.22	+1.31	-3.26
Catalyst used in transport	+0.24	+0.16	+0.18	+0.76	-3.26
Catalyst used in use of fuel produced	+0.24	+0.20	+0.22	+2.38	-3.26
Catalyst used in all operations	+0.24	+0.17	+0.19	+1.72	-3.26
Produced rapeseed oil fuel used for cultivation and transport	-0.32	+0.53	+0.55	+0.34	-2.53
All transport distances doubled	+1.46	+0.71	+0.73	+2.76	-0.12
All transport distances halved	-0.37	-0.07	-0.05	+0.43	-4.83
Machinery and building mass coefficient = 2/3 (area)	+0.22	+0.19	+0.21	+1.18	-4.06
Machinery and building mass coefficient = 1 (volume)	+0.26	+0.20	+0.21	+1.23	-2.65
Improved oil extraction efficiencies	+0.06	+0.13	+0.16	+1.12	-4.38
Small-scale extraction efficiency as in large-scale extraction	+0.94	+0.49	+0.50	+1.35	-8.00
Small-scale extraction as large-scale extraction	+1.20	+0.51	+0.52	+1.53	+2.22

Table 162. Original differences between small- and large-scale systems in the basic scenario and the differences when some alternative scenarios were analysed for RME production, physical allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Original (no change) (from Table 134)	**-0.07**	**+0.07**	**+0.10**	**+1.10**	**-3.79**
Straw harvested	+0.94	+0.38	+0.39	+1.67	-4.51
Ploughless tillage	-0.07	+0.08	+0.11	+1.12	-3.82
Methanol produced from *Salix*	-0.08	+0.07	+0.10	+1.04	-2.90
Fossil fuel electricity: extraction etc.	-2.37	-0.13	+0.01	+0.80	-4.62
Fossil fuel electricity: machinery	-0.73	+0.02	+0.08	+1.01	-4.21
Fossil fuel electricity: all	-2.87	-0.18	-0.02	+0.72	-4.97
Catalyst used in cultivation operations	-0.07	+0.08	+0.10	+1.21	-3.79
Catalyst used in transport	-0.07	+0.05	+0.07	+0.64	-3.79
Catalyst used in use of fuel produced	-0.07	+0.08	+0.11	+2.06	-3.79
Catalyst used in all operations	-0.07	+0.05	+0.08	+1.42	-3.79
Produced RME fuel used for cultivation and transport	-0.55	+0.39	+0.42	+0.13	-3.34
All transport distances doubled	+1.00	+0.54	+0.57	+2.71	-1.42
All transport distances halved	-0.61	-0.16	-0.13	+0.29	-4.98
Machinery and building mass coefficient = 2/3 (area)	-0.11	+0.07	+0.10	+1.05	-5.02
Machinery and building mass coefficient = 1 (volume)	-0.04	+0.08	+0.10	+1.14	-2.84
Improved oil extraction efficiencies	-0.18	+0.04	+0.07	+1.03	-4.55
Small-scale extraction efficiency as in large-scale extraction	+0.80	+0.44	+0.45	+1.37	-7.05
Small-scale extraction as large-scale extraction	+1.03	+0.46	+0.47	+1.55	+0.66

Table 163. Original differences between small- and large-scale systems in the basic scenario and the differences when some alternative scenarios were analysed for ethanol fuel production, physical allocation, [g/MJ_{engine}]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Original (no change) (from Table 135)	**+1.18**	**+0.28**	**+1.04**	**-7.51**	**-1.73**
Straw harvested	+1.67	+0.33	+1.22	-7.74	-2.15
Ploughless tillage	+1.18	+0.28	+1.04	-7.52	-1.74
Steam produced by *Salix*	+1.12	-0.53	+1.26	-7.40	-1.88
Ignition improver of bio-origin	+1.38	+0.22	+1.00	-4.16	-1.04
Denaturants of bio-origin	+1.27	+0.27	+1.03	-5.93	-1.36
Ignition improver and denaturants of bio-origin	+1.51	+0.22	+0.99	-3.62	-0.89
Fossil fuel electricity: ethanol production etc.	-0.51	+0.09	+0.94	-7.52	-2.09
Fossil fuel electricity: machinery	+0.04	+0.15	+0.98	-7.53	-2.37
Fossil fuel electricity: all	-1.45	-0.04	+0.88	-7.54	-2.67
Catalyst used in cultivation operations	+1.18	+0.28	+1.04	-7.57	-1.73
Catalyst used in transport	+1.18	+0.21	+0.97	-7.68	-1.73
Catalyst used in use of fuel produced	+1.20	+0.28	+1.04	-13.28	-1.73
Catalyst used in all operations	+1.19	+0.21	+0.97	-13.75	-1.73
Fuel produced used for cultivation and transports	+0.11	+0.21	+0.96	-7.18	-1.31
Fuel produced used for cultivation and transports with bio-optimization	-0.19	+0.38	+0.96	-2.96	-0.21
All transport distances doubled	+3.17	+1.47	+2.27	-6.94	+1.58
All transport distances halved	+0.18	-0.32	+0.42	-7.80	-3.39
Machinery and building mass coefficient = 2/3 (area)	+1.11	+0.26	+1.03	-7.53	-3.23
Machinery and building mass coefficient = 1 (volume)	+1.23	+0.29	+1.04	-7.50	-0.59
Small-scale production with large-scale energy efficiency	+1.93	+1.19	+1.23	+0.59	+1.29
Small-scale production as large-scale production	+2.13	+1.90	+2.42	-4.61	+1.29

In Tables 164-166 the scenario analysis was handled in the same way as in Tables 161-163 with the difference that the data were not allocated. A great difference was that the original (no change) level was on a much higher level, a few per cent to tens of per cent instead of tenths of one per cent to a few per cent. The influence of each production factor was accounted for by the difference from the original (no change) level. The influence of the categories studied was in most cases as above (Tables 161-163) with physical allocation (for explanation see above). For rapeseed oil and RME (Tables 164 and 165) the influence was greater for: Small-scale extraction as large-scale extraction; and small-scale extraction efficiency as in large-scale extraction. For ethanol fuel (Table 166) the influence was greater for: small-scale production with large-scale energy efficiency; and small-scale production as large-scale production. The reasons for these are that with that studied changes to small-scale plants, they become much more similar to the large-scale plants, and none of those changes were allocated away to any by-products and hidden. The result is that the differences between large-scale plants and small-scale plants become much smaller (Tables 164-166). For straw harvested, with no allocation, the differences between production scales was not influenced, because the original values were not changed since no environmental load could be allocated away to the straw.

A change in sign in Tables 164-166 shows that the statement regarding which production size gives the least emissions or has the least energy requirement or vice versa has changed in comparison to the original case. Such as change was only seen for: small-scale extraction efficiency as in large-scale extraction (rapeseed oil and RME); small-scale extraction as in large-scale extraction (rapeseed oil and RME); and small-scale production with large-scale energy efficiency (ethanol fuel).

Table 164. Original differences between small- and large-scale systems in the basic scenario and the differences when some alternative scenarios were analysed for rapeseed oil production, no allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Original (no change) (calculated after Table 136)	**-29.74**	**-16.50**	**-15.78**	**-15.51**	**-32.14**
Straw harvested	-29.74	-16.50	-15.78	-15.51	-32.14
Ploughless tillage	-29.74	-16.38	-15.65	-15.31	-32.16
Fossil fuel electricity: extraction etc.	-31.70	-16.86	-15.95	-15.98	-33.51
Fossil fuel electricity: machinery	-29.95	-16.59	-15.82	-15.64	-32.25
Fossil fuel electricity: all	-31.82	-16.95	-16.00	-16.10	-33.56
Catalyst used in cultivation operations	-29.74	-16.45	-15.73	-14.43	-32.14
Catalyst used in transport	-29.75	-16.53	-15.81	-16.00	-32.14
Catalyst used in use of fuel produced	-29.77	-16.95	-16.23	-23.67	-32.14
Catalyst used in all operations	-29.77	-16.93	-16.22	-23.71	-32.14
Produced rapeseed oil fuel used for cultivation and transport	-30.15	-16.68	-16.00	-14.65	-31.50
All transport distances doubled	-28.83	-15.92	-15.18	-13.79	-29.79
All transport distances halved	-30.20	-16.79	-16.08	-16.37	-33.32
Machinery and building mass coefficient = 2/3 (area)	-29.76	-16.51	-15.78	-15.54	-32.70
Machinery and building mass coefficient = 1 (volume)	-29.73	-16.50	-15.78	-15.49	-31.71
Improved oil extraction efficiencies	-24.61	-13.19	-12.58	-12.16	-27.88
Small-scale extraction efficiency as in large-scale extraction	+1.03	+0.67	+0.69	+1.82	-7.79
Small-scale extraction as large-scale extraction	+1.29	+0.70	+0.71	+2.04	+2.46

Table 165. Original differences between small- and large-scale systems in the base scenario and the differences when some alternative scenarios were analysed for RME production, no allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Original (no change) (calculated after Table 136)	**-28.08**	**-15.67**	**-14.95**	**-16.24**	**-28.48**
Straw harvested	-28.08	-15.67	-14.95	-16.24	-28.48
Ploughless tillage	-28.06	-15.55	-14.81	-16.04	-28.46
Methanol produced from *Salix*	-29.36	-15.60	-14.88	-15.61	-24.33
Fossil fuel electricity: extraction etc.	-29.10	-15.96	-15.09	-16.62	-28.90
Fossil fuel electricity: machinery	-28.47	-15.78	-15.00	-16.40	-28.82
Fossil fuel electricity: all	-29.42	-16.07	-15.14	-16.77	-29.20
Catalyst used in cultivation operations	-28.07	-15.63	-14.89	-15.16	-28.48
Catalyst used in transport	-28.08	-15.70	-14.98	-16.75	-28.48
Catalyst used in use of fuel produced	-28.10	-16.12	-15.40	-23.76	-28.48
Catalyst used in all operations	-28.10	-16.11	-15.38	-23.81	-28.48
Produced RME fuel used for cultivation and transport	-28.35	-15.86	-15.16	-15.54	-28.15
All transport distances doubled	-27.21	-15.12	-14.38	-14.45	-26.44
All transport distances halved	-28.51	-15.95	-15.23	-17.14	-29.51
Machinery and building mass coefficient = 2/3 (area)	-28.10	-15.68	-14.95	-16.29	-29.26
Machinery and building mass coefficient = 1 (volume)	-28.06	-15.67	-14.94	-16.21	-27.88
Improved oil extraction efficiencies	-23.13	-12.50	-11.89	-12.77	-24.61
Small-scale extraction efficiency as in large-scale extraction	+0.92	+0.61	+0.64	+1.86	-7.15
Small-scale extraction as large-scale extraction	+1.15	+0.65	+0.66	+2.09	+1.23

Table 166. Original differences between small- and large-scale systems in the base scenario and the differences when some alternative scenarios were analysed for ethanol fuel production, no allocation, [g/MJ$_{engine}$]

Changed production factors	GWP [%]	AP [%]	EP [%]	POCP [%]	Input energy [%]
Original (no change) (calculated after Table 136)	**+3.74**	**+4.86**	**+5.47**	**-4.63**	**+10.83**
Straw harvested	+3.74	+4.86	+5.47	-4.63	+10.83
Ploughless tillage	+3.75	+4.90	+5.51	-4.64	+10.92
Steam produced by *Salix*	+3.79	+4.46	+5.77	-4.90	+10.97
Ignition improver of bio-origin	+4.16	+4.05	+5.28	-2.62	+7.11
Denaturants of bio-origin	+3.93	+4.78	+5.43	-3.69	+8.92
Ignition improver and denaturants of bio-origin	+4.41	+4.00	+5.24	-2.29	+6.22
Fossil fuel electricity: ethanol production etc.	+9.51	+5.66	+5.85	-4.39	+14.82
Fossil fuel electricity: machinery	+2.26	+4.66	+5.37	-4.67	+9.58
Fossil fuel electricity: all	+7.91	+5.45	+5.75	-4.43	+13.52
Catalyst used in cultivation operations	+3.74	+4.87	+5.49	-4.69	+10.83
Catalyst used in transport	+3.73	+4.77	+5.37	-4.88	+10.83
Catalyst used in use of fuel produced	+3.77	+4.86	+5.47	-7.91	+10.83
Catalyst used in all operations	+3.77	+4.79	+5.39	-8.50	+10.83
Fuel produced used for cultivation and transports	+2.60	+4.80	+5.40	-4.18	+11.20
Fuel produced used for cultivation and transports with bio-optimization	+2.90	+4.14	+5.15	-1.28	+6.94
All transport distances doubled	+6.00	+6.43	+7.10	-3.77	+14.77
All transport distances halved	+2.60	+4.07	+4.65	-5.07	+8.86
Machinery and building mass coefficient = 2/3 (area)	+3.66	+4.84	+5.46	-4.66	+8.79
Machinery and building mass coefficient = 1 (volume)	+3.79	+4.88	+5.47	-4.62	+12.36
Small-scale production with large-scale energy efficiency	+2.12	+1.50	+1.57	+0.87	+0.95
Small-scale production as large-scale production	+4.48	+6.33	+6.73	-1.60	+13.99

The magnitude of the influence on emissions and energy requirement was about the same for the allocation methods in Tables 161-163 and in Tables 164-166. The production factors in the scenario analysis were influenced by factors that were influenced by the allocation and factors that were not. For example electricity for extraction was allocated both for RME, glycerine and meal, but electricity for transesterification was allocated only for RME and glycerine. Because of that it is more complicated to explain which values will increase and which will decrease. Some of the mentioned measures in the scenario analysis have the potential to influence which production size has the lowest emissions or energy requirement, principally depending on the small differences between the production sizes.

The above scenario analysis shows that: Catalysts were the most effective way to reduce AP-, EP- and POCP-emissions; using the fuel produced for cultivation and transport was a good way to reduce GWP-emissions. Methanol from biomass (RME) gave a considerably increased energy demand, reduced GWP-emissions and somewhat higher POCP-emissions. Ignition improver and denaturants of bio-origin (ethanol fuel) gave a considerably increased energy demand, reduced GWP-emissions, increased AP-emissions and considerably increased POCP-emissions. When Swedish electricity was replaced by fossil fuel electricity (for description see Section 3.6.1), the GWP-emissions and energy requirement increased considerably. The amount of straw harvested reduces the environmental load depending on the chosen allocation method, and because of that the proportion of the environmental load that it is possible to allocate away from the environmental heavy cultivation step.

4.10 Sensitivity analysis of economic calculations

This section deals with traditional sensitivity analysis for the economic calculations that are accounted for in Tables 167-169. When the factors were changed, all factors except for seed harvest had practically the same change in impact, but with the opposite sign, when they were changed by +20% or –20% and therefore only the change +20% was accounted for in Tables 167-169. For the small farm when RME was produced (Table 168), for example the production cost was +6.69% when the labour price increased by 20% and changed to –6.69% when the labour price decreased by 20%. In Tables 167-169 the sign is negative for prices that represent an income, *e.g.* meal price, distiller's waste price and glycerine price.

It was shown that the production costs were quite sensitive to changes in seed harvest, meal price (rapeseed oil and RME), labour price, price for machinery and buildings (investment costs), ignition improver price (ethanol fuel) and price for fertilisers (Tables 167-169). The effects of the other changes were small or negligible. As some sort of scenario analysis, production of the seed on a larger farm, production with the EU area compensation included and purchased seed were also studied. Because of lower labour costs on a larger farm for the seed production, the influence on the labour costs were decreased for that case. The relative costs for the other production factors increased correspondingly. With the EU area compensation included, the production factors become more sensitive to changes in the price for the production factors. Because of lower costs for the seed production, that made it easier for changes in prices to make an impact. The same was valid for the purchased seed, except for labour, because a large part of the labour belonged to the seed production.

Table 167. Changes in production cost when some production factors were changed in a sensitivity analysis for small-scale production of rapeseed oil, [SEK/MJ_{engine}]

Changed production factors	Small farm [%]		Large farm [%]		Purchased
	Total	EU area	Total	EU area	seed
	production	comp. incl.	production	comp. incl.	[%]
Seed harvest, +20%	-20.55	-22.16	-21.44	-24.05	not relevant
Seed harvest, -20%	+30.82	+33.23	+32.16	+36.07	not relevant
Labour price, +20%	+5.38	+7.62	+4.30	+6.64	+3.38
Fertiliser price, +20%	+4.46	+6.32	+5.38	+8.31	not relevant
Electricity price, +20%	+0.51	+0.72	+0.61	+0.95	+0.96
Meal price, +20%	-7.55	-10.68	-9.09	-14.06	-15.54
Transport price, +20%	0	0	0	0	0
Machinery and buildings price, +20%	+2.63	+3.72	+3.17	+4.90	+5.41

Table 168. Changes in production cost when some production factors were changed in a sensitivity analysis for small-scale production of RME, [SEK/MJ_{engine}]

Changed production factors	Small farm [%]		Large farm [%]		Purchased
	Total	EU area	Total	EU area	seed
	production	comp. incl.	production	comp. incl.	[%]
Seed harvest, +20%	-19.41	-20.21	-19.90	-21.01	not relevant
Seed harvest, -20%	+29.12	+30.31	+29.85	+31.52	not relevant
Labour price, +20%	+6.69	+8.62	+6.09	+8.20	+6.31
Fertiliser price, +20%	+3.40	+4.39	+3.91	+5.26	not relevant
Electricity price, +20%	+0.56	+0.72	+0.65	+0.87	+0.87
Meal price, +20%	-5.76	-7.42	-6.62	-8.90	-9.47
Methanol price, +20%	+0.58	+0.74	+0.66	+0.89	+0.95
Glycerine price, +20%	-0.68	-0.87	-0.78	-1.05	-1.11
Transport price, +20%	+0.031	+0.039	+0.035	+0.047	+0.050
Machinery and buildings price, +20%	+3.91	+5.04	+4.50	+6.05	+6.44

Table 169. Changes in production cost when some production factors were changed in a sensitivity analysis for small-scale production of ethanol fuel, [SEK/MJ$_{engine}$]

Changed production factors	Small farm [%]		Large farm [%]		Purchased
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	seed [%]
Seed harvest, +20%	-12.36	-11.95	-12.45	-12.02	not relevant
Seed harvest, -20%	+18.54	+17.92	+18.68	+18.03	not relevant
Fertiliser price, +20%	+1.16	+1.27	+1.23	+1.36	not relevant
Electricity price, +20%	+0.30	+0.33	+0.28	+0.31	+0.32
Steam price, +20%	+0.41	+0.45	+0.44	+0.49	+0.50
Chemicals price, +20%	+0.34	+0.37	+0.36	+0.39	+0.40
Ignition improver price, +20%	+2.86	+3.13	+3.04	+3.36	+3.44
Denaturants price, +20%	+0.46	+0.51	+0.49	+0.54	+0.56
Transport price, +20%	+0.025	+0.028	+0.027	+0.030	+0.030
Machinery and buildings price, +20%	+5.62	+6.16	+5.99	+6.61	+6.76
Distiller's waste price, +20%	-0.59	-0.65	-0.63	-0.69	-0.71
Labour price, +20%	+4.13	+4.52	+3.78	+4.17	+3.49

The influence of increasing and decreasing the seed yield by 20% and increasing and decreasing the price for some production factors by 20%, on the difference between small- and large-scales was also studied (Tables 170-172) (for description of calculations see Section 3.11.1). The influence of each production factor was accounted for by the difference from the original (no change) level. It was demonstrated that the changes in the input parameters had a small or negligible influence on the difference between the two production scales. For RME and ethanol fuel production, the production costs were approx. 40-50% lower for large-scale plants in all the cases with all the price changes. For rapeseed oil production the production costs were approx. 20-30% lower for large-scale plants in all the cases with all the price changes. For production of RME and ethanol fuel, the difference in production cost in favour of large plants became greater with seed production on larger farms and with production with EU area compensation. That was because lower seed production costs made the lower RME production costs on a larger plant come through more. For the purchased seed (2.00 SEK/kg rapeseed and 0.97 SEK/kg wheat) the same is valid but on a somewhat higher degree, which makes the large plant even more favoured. However, for rapeseed oil plants the above-described effects are the opposite due to the production plant being more simple and therefore *e.g.* the higher transport costs for a larger plant coming through more (Tables 123-131).

Table 170. Original differences between small- and large-scale systems, and the differences when some production factors were changed during production of rapeseed oil, [SEK/MJ$_{engine}$]

Changed production factors	Small farm [%]		Large farm [%]		Purchased seed [%]
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	
Original (no change) (calculated after Table 142)	**-28.48**	**-27.60**	**-28.04**	**-26.64**	**-26.22**
Seed harvest, +20%	-27.00	-25.40	-26.21	-23.58	not relevant
Seed harvest, -20%	-29.83	-29.52	-29.68	-29.21	not relevant
Labour price, +20%	-29.31	-28.81	-29.03	-28.22	-27.88
Labour price, -20%	-27.55	-26.18	-26.97	-24.84	-24.45
Fertiliser price, +20%	-28.57	-27.77	-28.18	-26.95	not relevant
Fertiliser price, -20%	-28.38	-27.39	-27.90	-26.28	not relevant
Electricity price, +20%	-28.65	-27.83	-28.25	-26.97	-26.58
Electricity price, -20%	-28.31	-27.35	-27.84	-26.31	-25.86
Meal price, +20%	-26.13	-24.05	-25.13	-21.64	-20.52
Meal price, -20%	-30.50	-30.45	-30.47	-30.41	-30.39
Transport price, +20%	-27.91	-26.79	-27.36	-25.58	-25.05
Transport price, -20%	-29.05	-28.40	-28.73	-27.71	-27.40
Machinery and buildings price, +20%	-29.76	-29.42	-29.59	-29.06	-28.91
Machinery and buildings price, -20%	-27.13	-25.63	-26.39	-23.97	-23.23

Table 171. Original differences between small- and large-scale systems, and the differences when some production factors were changed during production of RME, [SEK/MJ$_{engine}$]

Changed production factors	Small farm [%]		Large farm [%]		Purchased
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	seed [%]
Original (no change) (calculated after Table 142)	**-42.74**	**-46.23**	**-44.54**	**-49.36**	**-50.56**
Seed harvest, +20%	-42.25	-45.75	-44.06	-48.96	not relevant
Seed harvest, -20%	-43.20	-46.67	-44.99	-49.71	not relevant
Labour price, +20%	-44.08	-47.65	-46.16	-51.14	-52.84
Labour price, -20%	-41.21	-44.55	-42.70	-47.26	-47.97
Fertiliser price, +20%	-42.34	-45.58	-44.02	-48.42	not relevant
Fertiliser price, -20%	-43.16	-46.95	-45.11	-50.40	not relevant
Electricity price, +20%	-42.76	-46.23	-44.55	-49.33	-50.53
Electricity price, -20%	-42.72	-46.23	-44.53	-49.38	-50.59
Meal price, +20%	-41.85	-45.35	-43.64	-48.59	-49.86
Meal price, -20%	-43.53	-46.99	-45.33	-50.00	-51.13
Methanol price, +20%	-42.67	-46.12	-44.45	-49.19	-50.37
Methanol price, -20%	-42.81	-46.35	-44.63	-49.53	-50.75
Glycerine price, +20%	-43.03	-46.64	-44.89	-49.88	-51.13
Glycerine price, -20%	-42.45	-45.83	-44.20	-48.84	-50.00
Transport price, +20%	-42.29	-45.66	-44.03	-48.67	-49.83
Transport price, -20%	-43.18	-46.81	-45.05	-50.05	-51.29
Machinery and buildings price, +20%	-44.13	-47.84	-46.06	-51.09	-52.33
Machinery and buildings price, -20%	-41.23	-44.45	-42.88	-47.39	-48.55

Table 172. Original differences between small- and large-scale systems, and the differences when some production factors were changed during production of ethanol fuel, [SEK/MJ$_{engine}$]

Changed production factors	Small farm [%]		Large farm [%]		Purchased
	Total production	EU area comp. incl.	Total production	EU area comp. incl.	seed [%]
Original (no change) (calculated after Table 142)	**-40.97**	**-44.91**	**-43.66**	**-48.16**	**-49.30**
Seed harvest, +20%	-40.41	-44.08	-43.10	-47.30	not relevant
Seed harvest, -20%	-41.60	-45.84	-44.28	-49.11	not relevant
Fertiliser price, +20%	-40.51	-44.35	-43.12	-47.51	not relevant
Fertiliser price, -20%	-41.46	-45.49	-44.20	-48.82	not relevant
Electricity price, +20%	-40.75	-44.65	-43.42	-47.88	-49.02
Electricity price, -20%	-41.20	-45.18	-43.89	-48.43	-49.58
Steam price, +20%	-40.63	-44.52	-43.28	-47.71	-48.84
Steam price, -20%	-41.32	-45.31	-44.04	-48.60	-49.76
Chemicals price, +20%	-40.95	-44.87	-43.62	-48.10	-49.24
Chemicals price, -20%	-41.00	-44.95	-43.69	-48.21	-49.36
Ignition improver price, +20%	-40.95	-44.76	-43.55	-47.89	-48.99
Ignition improver price, -20%	-41.00	-45.07	-43.77	-48.44	-49.63
Denaturants price, +20%	-41.01	-44.94	-43.68	-48.16	-49.30
Denaturants price, -20%	-40.94	-44.89	-43.63	-48.15	-49.30
Transport price, +20%	-40.43	-44.31	-43.07	-47.51	-48.64
Transport price, -20%	-41.52	-45.51	-44.24	-48.80	-49.96
Machinery and buildings price, +20%	-42.58	-46.44	-45.21	-49.58	-50.69
Machinery and buildings price, -20%	-39.17	-43.19	-41.90	-46.52	-47.71
Distiller's waste price, +20%	-42.07	-46.14	-44.84	-49.49	-50.68
Distiller's waste price, -20%	-39.89	-43.70	-42.49	-46.84	-47.94
Labour price, +20%	-41.92	-45.77	-44.81	-49.24	-50.74
Labour price, -20%	-39.95	-43.98	-42.41	-46.97	-47.76

4.11 Monte Carlo simulation of error propagation

The results from the Monte Carlo simulation of error propagation are described below. The methodology is described in Section 3.11.3. First the values from the LCA are accounted for (Tables 133, 138, 175 and 181), followed by equivalent average values from the Monte Carlo simulation (Tables 173, 176 and 182), uncertainty values (Tables 174, 177 and 183), z-values for calculation of probability values from the normal distribution (Tables 178 and 184) and finally probability values (Tables 179 and 185). The probability values give the probability that case 1 is less than case 2 for the given assumptions in the LCA model and the Monte Carlo simulation. Plant sizes are compared in Tables 175-180 and fuels are compared in Tables 181-185.

Table 174 shows uncertainty values as standard deviation values from the Monte Carlo simulation for rapeseed oil, RME and ethanol fuel production. The LCA values for these values are accounted for in Table 133. For each fuel and type of emission or energy requirement the differences between the plant sizes were very small. Between rapeseed oil and RME production the differences were also small, but the differences to production of ethanol fuel were greater. Differences between types of emissions and energy requirement were greater depending on different results from the LCA (Table 133). The average emission and energy requirement values from the Monte Carlo simulation (Table 173) corresponding to the LCA-values diverged by less than one percent in all cases, indicating that the results from the Monte Carlo simulation were reliable.

Table 173. Average values for emissions and energy requirement from the Monte Carlo simulation

Type of plant	GWP $[g/MJ_{engine}]$	AP $[g/MJ_{engine}]$	EP $[g/MJ_{engine}]$	POCP $[g/MJ_{engine}]$	Input energy $[MJ/MJ_{engine}]$
Rapeseed oil production:					
Small-scale	122	1.94	0.342	0.0261	0.695
Medium-scale	120	1.93	0.340	0.0259	0.643
Large-scale	122	1.94	0.343	0.0264	0.671
RME production:					
Small-scale	128	1.98	0.351	0.0233	0.850
Medium-scale	126	1.97	0.349	0.0231	0.795
Large-scale	128	1.98	0.352	0.0235	0.817
Ethanol fuel production:					
Small-scale	103	1.16	0.200	0.1001	0.910
Medium-scale	102	1.17	0.204	0.0929	0.889
Large-scale	104	1.16	0.202	0.0923	0.895

Table 174. Uncertainty values as standard deviation values from the Monte Carlo simulation

Type of plant	GWP [g/MJ$_{engine}$]	AP [g/MJ$_{engine}$]	EP [g/MJ$_{engine}$]	POCP [g/MJ$_{engine}$]	Input energy [MJ/MJ$_{engine}$]
Rapeseed oil production:					
Small-scale	16.78	0.1641	0.02910	0.001989	0.06997
Medium-scale	16.50	0.1629	0.02889	0.001979	0.06813
Large-scale	16.64	0.1635	0.02900	0.001984	0.06798
RME production:					
Small-scale	15.71	0.1593	0.02843	0.001633	0.06602
Medium-scale	15.44	0.1581	0.02825	0.001622	0.06442
Large-scale	15.54	0.1586	0.02832	0.001626	0.06387
Ethanol fuel production:					
Small-scale	8.78	0.0888	0.01568	0.006494	0.04365
Medium-scale	8.80	0.0894	0.01579	0.006399	0.04267
Large-scale	8.79	0.0873	0.01546	0.006479	0.04242

4.11.1 Comparison between production scales

Differences from comparisons of plant sizes are accounted for in Table 175. These values are very small in comparison to the original LCA values (Table 133). The differences were about the same size independent of the fuel studied. One exception was the POCP-emissions during production of ethanol fuel, which differed between plant sizes. This could be explained by high HC-emissions during small-scale production of heat (steam) (Table 34). The reasons for the differences between production scales are further discussed in Section 4.4: Comparison between production scales.

The average emissions and energy requirement values from the Monte Carlo simulation (Table 176) corresponding to the LCA-values (Table 175) diverged by part of or a few percent in most cases, up to at most 9%, for small-scale – large-scale RME production for GWP-emissions. The cases that diverged the most were somewhat less reliable, but were assumed to be sufficiently reliable as the basis for the probability calculation in Table 179. In those probabilities, only the first digit may be reliable. The difference between the two values compared was very small (less than 0.1% of the original values).

The uncertainty values for the comparisons of plant sizes (Table 177) differed greatly (3 - almost 600% of the total). The uncertainty values were least for rapeseed oil plants and highest for ethanol fuel plants. This depended on a higher share of the factors studied originating from the cultivation (Tables 114-122), which is dependent (does not contribute to the uncertainty) on plant sizes for rapeseed oil and RME production.

The probability values in Table 179 were directly calculated from the z-values (Table 178) with a normal distribution table. When it was assumed that a difference existed between the values compared if: $P < 0.05$ or $P > 0.95$, then differences existed between:
Small-scale and medium-scale production of rapeseed oil and RME for all factors studied;

Small-scale and medium-scale production of ethanol fuel for EP- and POCP-emissions;
Small-scale and large-scale production of rapeseed oil for AP-, EP- and POCP-emissions and energy requirement;
Small-scale and large-scale production of RME for POCP-emissions;
Small-scale and large-scale production of ethanol fuel for GWP- and POCP-emissions;
Medium-scale and large-scale production of rapeseed oil for all studied factors;
Medium-scale and large-scale production of RME for GWP-, AP-, EP- and POCP-emissions;
Medium-scale and large-scale production of ethanol fuel for GWP-emissions.

Table 175. Differences during comparison of plant sizes

Type of plants compared	GWP $[g/MJ_{engine}]$	AP $[g/MJ_{engine}]$	EP $[g/MJ_{engine}]$	POCP $[g/MJ_{engine}]$	Input energy $[MJ/MJ_{engine}]$
Rapeseed oil production:					
Small-scale - medium-scale	2.17	0.0122	0.00198	0.00018	0.0507
Small-scale - large-scale	-0.29	-0.0037	-0.00073	-0.00032	0.0226
Medium-scale - large-scale	-2.46	-0.0159	-0.00271	-0.00050	-0.0281
RME production:					
Small-scale - medium-scale	2.09	0.0117	0.00190	0.00018	0.0533
Small-scale - large-scale	0.09	-0.0015	-0.00035	-0.00026	0.0321
Medium-scale- large-scale	-2.01	-0.0132	-0.00225	-0.00044	-0.0212
Ethanol fuel production:					
Small-scale - medium-scale	0.52	-0.0112	-0.00350	0.00719	0.0225
Small-scale - large-scale	-1.20	-0.0032	-0.00207	0.00751	0.0157
Medium-scale - large-scale	-1.72	0.0080	0.00143	0.00032	-0.0068

Table 176. Average values for differences during comparison of plant sizes using Monte Carlo simulation

Type of plants compared	GWP [g/MJ$_{engine}$]	AP [g/MJ$_{engine}$]	EP [g/MJ$_{engine}$]	POCP [g/MJ$_{engine}$]	Input energy [MJ/MJ$_{engine}$]
Rapeseed oil production:					
Small-scale - medium-scale	2.18	0.0122	0.00199	0.00019	0.0516
Small-scale - large-scale	-0.28	-0.0037	-0.00072	-0.00031	0.0234
Medium-scale - large-scale	-2.46	-0.0159	-0.00271	-0.00050	-0.0282
RME production:					
Small-scale - medium-scale	2.10	0.0119	0.00192	0.00018	0.0546
Small-scale - large-scale	0.10	-0.0014	-0.00035	-0.00025	0.0329
Medium-scale - large-scale	-2.01	-0.0133	-0.00227	-0.00044	-0.0216
Ethanol fuel production:					
Small-scale - medium-scale	0.52	-0.0110	-0.00345	0.00719	0.0218
Small-scale - large-scale	-1.21	-0.0031	-0.00204	0.00749	0.0152
Medium-scale - large-scale	-1.73	0.0079	0.00141	0.00030	-0.0066

Table 177. Uncertainty values as standard deviation values from the Monte Carlo simulation during comparison of plant sizes

Type of plants compared	GWP [g/MJ$_{engine}$]	AP [g/MJ$_{engine}$]	EP [g/MJ$_{engine}$]	POCP [g/MJ$_{engine}$]	Input energy [MJ/MJ$_{engine}$]
Rapeseed oil production:					
Small-scale - medium-scale	0.329	0.0021	0.00035	0.000028	0.0124
Small-scale - large-scale	0.200	0.0012	0.00020	0.000021	0.0121
Medium-scale - large-scale	0.173	0.0011	0.00019	0.000015	0.0079
RME production:					
Small-scale - medium-scale	0.311	0.0025	0.00041	0.000029	0.0204
Small-scale - large-scale	0.230	0.0023	0.00037	0.000026	0.0207
Medium-scale - large-scale	0.161	0.0021	0.00034	0.000020	0.0180
Ethanol fuel production:					
Small-scale - medium-scale	0.504	0.0104	0.00170	0.002010	0.0316
Small-scale - large-scale	0.484	0.0090	0.00145	0.001976	0.0317
Medium-scale - large-scale	0.443	0.0095	0.00165	0.001731	0.0311

Table 178. Z-values calculated from the Monte Carlo simulation for comparison of plant sizes

Type of plants compared	GWP [g/MJ_{engine}]	AP [g/MJ_{engine}]	EP [g/MJ_{engine}]	POCP [g/MJ_{engine}]	Input energy [MJ/MJ_{engine}]
Rapeseed oil production:					
Small-scale - medium-scale	6.59	5.80	5.58	6.47	4.09
Small-scale - large-scale	-1.45	-3.13	-3.68	-14.82	1.86
Medium-scale - large-scale	-14.22	-14.44	-14.50	-33.03	-3.55
RME production:					
Small-scale - medium-scale	6.73	4.78	4.67	6.17	2.62
Small-scale - large-scale	0.39	-0.64	-0.94	-9.84	1.55
Medium-scale - large-scale	-12.47	-6.22	-6.56	-22.35	-1.18
Ethanol fuel production:					
Small-scale - medium-scale	1.03	-1.08	-2.06	3.58	0.71
Small-scale - large-scale	-2.48	-0.36	-1.43	3.80	0.50
Medium-scale - large-scale	-3.88	0.84	0.87	0.18	-0.22

Table 179. Probability values calculated from the Monte Carlo simulation for comparison of plant sizes

Type of plants compared	GWP [g/MJ_{engine}]	AP [g/MJ_{engine}]	EP [g/MJ_{engine}]	POCP [g/MJ_{engine}]	Input energy [MJ/MJ_{engine}]
Rapeseed oil production:					
P(small-scale < medium-scale)	$2*10^{-11}$	$3*10^{-9}$	$1*10^{-8}$	$5*10^{-11}$	0.00002
P(small-scale < large-scale)	0.93	0.9991	0.99988	$1-5*10^{-50}$	0.03
P(medium-scale < large-scale)	$1-4*10^{-46}$	$1-2*10^{-47}$	$1-6*10^{-48}$	$1-2*10^{-239}$	0.9998
RME production:					
P(small-scale < medium-scale)	$8*10^{-12}$	$9*10^{-7}$	$2*10^{-6}$	$3*10^{-10}$	0.004
P(small-scale < large-scale)	0.35	0.74	0.83	$1-4*10^{-23}$	0.06
P(medium-scale < large-scale)	$1-6*10^{-36}$	$1-3*10^{-10}$	$1-3*10^{-11}$	$1-7*10^{-111}$	0.88
Ethanol fuel production:					
P(small-scale < medium-scale)	0.15	0.86	0.98	0.0002	0.24
P(small-scale < large-scale)	0.994	0.64	0.92	0.00007	0.31
P(medium-scale < large-scale)	0.99995	0.20	0.19	0.43	0.59

In Table 180, small-scale and large-scale ethanol fuel production are compared when different uncertainties for the input data were assumed. In this example only the ethanol plants were included, while cultivation and use of the fuel were excluded. Only the independent parts of the process were left then (see Section 3.11.3 for explanation). When the input coefficients of variation were halved (to 5%) the output uncertainty values were approximately halved (Table 180). When the input coefficients of variation were increased by 50% (to 15%) the output uncertainty values were approximately increased by 50%, perhaps somewhat less (Table 180).

The probability follows with most observed differences for the lowest input coefficients of variation (observed differences when P < 0.05 or P > 0.95). More complicated systems (with dependent variables) will behave in the same manner but with some of the effects from the change of the input variances hidden by the dependence between the variables.

Table 180. Comparison of small-scale and large-scale ethanol fuel plants at different uncertainty levels (excl. cultivation and use)

Type of plants compared	GWP [g/MJ$_{fuel}$]	AP [g/MJ$_{fuel}$]	EP [g/MJ$_{fuel}$]	POCP [g/MJ$_{fuel}$]	Input energy [MJ/MJ$_{fuel}$]
Small-scale - large-scale	-0.48	-0.0013	-0.00082	0.0030	0.0062
Uncertainty values[a]:					
Input coefficients of variation: 5%	0.21	0.0019	0.00027	0.00042	0.0072
Input coefficients of variation: 10%	0.41	0.0038	0.00056	0.00082	0.0130
Input coefficients of variation: 15%	0.60	0.0055	0.00081	0.00120	0.0216
Probability that: small-scale < large-scale[b]					
Input coefficients of variation: 5%	0.987	0.75	0.9986	$1.0*10^{-12}$	0.19
Input coefficients of variation: 10%	0.88	0.63	0.929	0.00014	0.32
Input coefficients of variation: 15%	0.79	0.59	0.84	0.0068	0.39

[a] Uncertainty value from Monte Carlo simulation equivalent to the standard deviation.
[b] Probability values calculated using assumptions of normal distribution.

4.11.2 Comparison between fuels

Differences from comparisons of fuels are accounted for in Table 181. These values are small in comparison to the original LCA values with physical allocation (Table 133) and with some exceptions also for allocation with expanded system (Table 138). In the following paragraphs, first the values for physical allocation are discussed and after that the values for allocation with expanded system are treated. The differences were considerably smaller when RME was compared with rapeseed oil in comparison to RME – ethanol fuel and rapeseed oil – ethanol fuel (for expanded system also valid for AP-, EP- and POCP-emissions). The exception was the requirement of energy, where the difference was smallest for the comparison of RME and ethanol fuel. The reasons for the differences between fuels are further discussed in Section 4.5: Comparison between fuels.

The average emissions and energy requirement values from the Monte Carlo simulation (Table 182) corresponding to the LCA-values (Table 181) diverged by part of or a few percent in most cases up to at most 12% for large-scale RME – large-scale rapeseed oil production for AP-emissions. The cases that diverged the most were probably somewhat less reliable, but were assumed to be sufficiently reliable as the basis for the probability calculations in Table 185. In that table, probabilities may only be reliable to the first digit. The difference between the two values compared was very small (approx. 2% of the original values). With expanded system the deviations were in most cases of the same size as for physical allocation, but with one exception: the EP-emissions for all three scales when RME was compared with rapeseed oil were 230-270% lower than the original (with opposite sign). The explanation for this was that the differences for these cases between the two fuels compared were negligible (less than 0.3% of the original values, see Tables 138 and 181), which made these difference values very small in comparison to the uncertainty values (Tables 183). Because of that, the values from the Monte Carlo simulations are not necessarily unreliable even for these cases.

The uncertainty values for the comparisons of plant sizes (Table 183) differed greatly (8 – more than 500% of the total). The uncertainty values were of the same size for all three fuel production comparisons. However, the relative uncertainties were much higher for the comparison of RME and rapeseed oil depending on much lower absolute values (Table 181). For the expanded system the uncertainty values were of the same size as with physical allocation with exceptions for the EP-emissions for all three scales when RME was compared with rapeseed oil and GWP-emissions when large-scale RME was compared with large-scale ethanol fuel, which were much larger (2700-3300% of the total, see above for explanation).

The probability values in Table 185 can be calculated directly from the z-values (Table 184) with a normal distribution table. When it was assumed that a difference existed between the compared values if: $P < 0.05$ or $P > 0.95$, then differences existed between (physical allocation):
RME and rapeseed oil production for GWP-emissions and energy requirement;
RME and ethanol fuel production for AP-, EP- and POCP-emissions;
Rapeseed oil and ethanol fuel production for AP-, EP- and POCP-emissions and energy requirement.
The behaviour was the same for all three production scales studied.

With expanded system, with the same assumptions, differences existed between:
RME and rapeseed oil production for GWP-and POCP-emissions and energy requirement;
RME and ethanol fuel production for AP-, EP- and POCP-emissions and energy requirement;
Rapeseed oil and ethanol fuel production for AP-, EP- and POCP-emissions.
The behaviour was almost the same for all three production scales studied. Between rapeseed oil and ethanol fuel production, differences existed for GWP-emissions for large plants and almost also for small- and medium-scale plants. The deviation for GWP-emissions when rapeseed oil and ethanol were compared could be explained by P-values almost equal to 0.05 for all three production sizes (one smaller than, two bigger than). Differences for energy need between rapeseed oil and ethanol fuel productions existed between small- and medium-scale plants but not for large-scale plants.

The reason for the differences between RME and rapeseed oil production was the requirement of inputs to transesterify the rapeseed and to produce the methanol during the RME production, which required energy with resultant GWP-emissions. However, these inputs gave small emissions of AP-, EP- and POCP-emission in comparison to the use of the rapeseed oil and RME produced (Tables 114-115, 117-118 and 120-121 and Tables A3-A14, Appendix 1), which contributed to a large part of the uncertainty in the Monte Carlo simulation. Therefore no differences could be observed.

The reason for the differences between RME and ethanol fuel production was that the differences between these two fuels were large enough to be observed. The same was also valid between rapeseed oil and ethanol fuel production.

The differences between the two allocation methods were rather large. The results regarding which fuel gave least environmental load were in some cases the opposite for the two allocation methods when rapeseed oil and RME productions were compared (GWP- and AP-emissions and energy requirement for all production scales studied) (Table 181) (for explanation see Section 4.6). However, there were rather large similarities in the pattern (which were 'significant' and which were not 'significant') between the allocation methods when studying whether $P < 0.05$ or $P > 0.95$ during comparisons of the fuels (Table 185).

Table 181. Differences during comparison of fuels

Type of fuels compared	GWP [g/MJ$_{engine}$]	AP [g/MJ$_{engine}$]	EP [g/MJ$_{engine}$]	POCP [g/MJ$_{engine}$]	Input energy [MJ/MJ$_{engine}$]
Physical allocation:					
Small-scale production:					
RME - rapeseed oil	5.60	0.0406	0.0084	-0.0029	0.155
RME - ethanol fuel	24.88	0.8242	0.1517	-0.0767	-0.061
Rapeseed oil - ethanol fuel	19.28	0.7836	0.1433	-0.0738	-0.215
Medium-scale production:					
RME - rapeseed oil	5.67	0.0411	0.0085	-0.0029	0.152
RME - ethanol fuel	23.30	0.8012	0.1463	-0.0697	-0.091
Rapeseed oil - ethanol fuel	17.63	0.7602	0.1378	-0.0668	-0.243
Large-scale production:					
RME - rapeseed oil	5.22	0.0383	0.0080	-0.0030	0.145
RME - ethanol fuel	23.58	0.8224	0.1500	-0.0689	-0.077
Rapeseed oil - ethanol fuel	18.37	0.7841	0.1419	-0.0660	-0.222
Expanded system:					
Small-scale production:					
RME - rapeseed oil	-47.54	-0.069	0.0007	-0.0116	-0.806
RME - ethanol fuel	16.39	0.617	0.1833	-0.0930	-1.397
Rapeseed oil - ethanol fuel	63.93	0.686	0.1826	-0.0813	-0.592
Medium-scale production:					
RME - rapeseed oil	-47.30	-0.072	0.0009	-0.0117	-0.815
RME - ethanol fuel	9.19	0.680	0.1738	-0.0829	-1.321
Rapeseed oil - ethanol fuel	56.49	0.752	0.1729	-0.0712	-0.505
Large-scale production:					
RME - rapeseed oil	-47.21	-0.086	0.0008	-0.0121	-0.841
RME - ethanol fuel	0.59	0.958	0.1672	-0.0758	-0.900
Rapeseed oil - ethanol fuel	47.80	1.043	0.1665	-0.0637	-0.059

Table 182. Average values for differences during comparison of fuels using Monte Carlo simulation

Type of fuels compared	GWP [g/MJ$_{engine}$]	AP [g/MJ$_{engine}$]	EP [g/MJ$_{engine}$]	POCP [g/MJ$_{engine}$]	Input energy [MJ/MJ$_{engine}$]
Physical allocation:					
Small-scale production:					
RME - rapeseed oil	5.47	0.0361	0.0076	-0.0029	0.155
RME - ethanol fuel	24.92	0.8249	0.1518	-0.0768	-0.062
Rapeseed oil - ethanol fuel	19.30	0.7837	0.1433	-0.0738	-0.216
Medium-scale production:					
RME - rapeseed oil	5.55	0.0366	0.0077	-0.0029	0.152
RME - ethanol fuel	23.34	0.8021	0.1465	-0.0698	-0.090
Rapeseed oil - ethanol fuel	17.63	0.7602	0.1378	-0.0668	-0.243
Large-scale production:					
RME - rapeseed oil	5.09	0.0338	0.0072	-0.0030	0.145
RME - ethanol fuel	23.59	0.8256	0.1505	-0.0689	-0.075
Rapeseed oil - ethanol fuel	18.39	0.7844	0.1420	-0.0660	-0.221
Expanded system:					
Small-scale production:					
RME - rapeseed oil	-47.52	-0.079	-0.0012	-0.0117	-0.804
RME - ethanol fuel	18.34	0.613	0.1833	-0.0933	-1.388
Rapeseed oil - ethanol fuel	65.31	0.688	0.1837	-0.0817	-0.585
Medium-scale production:					
RME - rapeseed oil	-47.25	-0.084	-0.0011	-0.0119	-0.813
RME - ethanol fuel	10.61	0.681	0.1736	-0.0832	-1.316
Rapeseed oil - ethanol fuel	57.60	0.759	0.1739	-0.0714	-0.503
Large-scale production:					
RME - rapeseed oil	-47.59	-0.095	-0.0010	-0.0122	-0.849
RME - ethanol fuel	0.85	0.955	0.1665	-0.0761	-0.908
Rapeseed oil - ethanol fuel	48.39	1.048	0.1670	-0.0639	-0.059

Table 183. Uncertainty values as standard deviation values from the Monte Carlo simulation during comparison of fuels

Type of fuels compared	GWP [g/MJ$_{engine}$]	AP [g/MJ$_{engine}$]	EP [g/MJ$_{engine}$]	POCP [g/MJ$_{engine}$]	Input energy [MJ/MJ$_{engine}$]
Physical allocation:					
Small-scale production:					
RME - rapeseed oil	1.26	0.1791	0.0327	0.00213	0.0132
RME - ethanol fuel	17.01	0.1782	0.0317	0.00670	0.0767
Rapeseed oil - ethanol fuel	18.22	0.1787	0.0315	0.00685	0.0794
Medium-scale production:					
RME - rapeseed oil	1.24	0.1791	0.0327	0.00213	0.0125
RME - ethanol fuel	16.78	0.1771	0.0315	0.00665	0.0753
Rapeseed oil - ethanol fuel	17.96	0.1775	0.0313	0.00663	0.0781
Large-scale production:					
RME - rapeseed oil	1.30	0.1792	0.0327	0.00213	0.0123
RME - ethanol fuel	16.92	0.1827	0.0325	0.00676	0.0744
Rapeseed oil - ethanol fuel	18.06	0.1778	0.0313	0.00674	0.0771
Expanded system:					
Small-scale production:					
RME - rapeseed oil	6.16	0.1801	0.0327	0.00252	0.1334
RME - ethanol fuel	38.36	0.3160	0.0489	0.00824	0.3013
Rapeseed oil - ethanol fuel	39.08	0.3240	0.0500	0.00833	0.2846
Medium-scale production:					
RME - rapeseed oil	6.48	0.1813	0.0328	0.00259	0.1419
RME - ethanol fuel	35.19	0.2909	0.0458	0.00795	0.2782
Rapeseed oil - ethanol fuel	35.54	0.2986	0.0466	0.00796	0.2403
Large-scale production:					
RME - rapeseed oil	6.54	0.1795	0.0327	0.00247	0.1436
RME - ethanol fuel	28.05	0.2413	0.0400	0.00750	0.2147
Rapeseed oil - ethanol fuel	28.43	0.2424	0.0399	0.00750	0.1617

Table 184. Z-values calculated from the Monte Carlo simulation for comparison of fuels

Type of fuels compared	GWP [g/MJ$_{engine}$]	AP [g/MJ$_{engine}$]	EP [g/MJ$_{engine}$]	POCP [g/MJ$_{engine}$]	Input energy [MJ/MJ$_{engine}$]
Physical allocation:					
Small-scale production:					
RME - rapeseed oil	4.46	0.23	0.26	-1.36	11.71
RME - ethanol fuel	1.46	4.62	4.78	-11.45	-0.79
Rapeseed oil - ethanol fuel	1.06	4.38	4.55	-10.77	-2.71
Medium-scale production:					
RME - rapeseed oil	4.58	0.23	0.26	-1.36	12.22
RME - ethanol fuel	1.39	4.52	4.64	-10.48	-1.21
Rapeseed oil - ethanol fuel	0.98	4.28	4.40	-10.07	-3.12
Large-scale production:					
RME - rapeseed oil	4.02	0.21	0.24	-1.39	11.85
RME - ethanol fuel	1.39	4.50	4.61	-10.19	-1.03
Rapeseed oil - ethanol fuel	1.02	4.41	4.53	-9.80	-2.88
Expanded system:					
Small-scale production:					
RME - rapeseed oil	-7.71	-0.38	0.02	-4.61	-6.04
RME - ethanol fuel	0.43	1.95	3.74	-11.28	-4.64
Rapeseed oil - ethanol fuel	1.64	2.12	3.65	-9.76	-2.08
Medium-scale production:					
RME - rapeseed oil	-7.30	-0.40	0.03	-4.54	-5.74
RME - ethanol fuel	0.26	2.34	3.80	-10.43	-4.75
Rapeseed oil - ethanol fuel	1.59	2.52	3.71	-8.95	-2.10
Large-scale production:					
RME - rapeseed oil	-7.21	-0.48	0.02	-4.91	-5.86
RME - ethanol fuel	0.02	3.97	4.18	-10.11	-4.19
Rapeseed oil - ethanol fuel	1.68	4.30	4.17	-8.49	-0.36

Table 185. Probability values calculated from the Monte Carlo simulation for comparison of fuels

Type of fuels compared	GWP [g/MJ_{engine}]	AP [g/MJ_{engine}]	EP [g/MJ_{engine}]	POCP [g/MJ_{engine}]	Input energy [MJ/MJ_{engine}]
Physical allocation:					
Small-scale production:					
P(RME < rapeseed oil)	$4*10^{-6}$	0.41	0.40	0.91	$5*10^{-32}$
P(RME < ethanol fuel)	0.07	$2*10^{-6}$	$9*10^{-7}$	$1-1*10^{-30}$	0.79
P(rapeseed oil < ethanol fuel)	0.15	$6*10^{-6}$	$3*10^{-6}$	$1-2*10^{-27}$	0.997
Medium-scale production:					
P(RME < rapeseed oil)	$2*10^{-6}$	0.41	0.40	0.91	$1*10^{-34}$
P(RME < ethanol fuel)	0.08	$3*10^{-6}$	$2*10^{-6}$	$1-5*10^{-26}$	0.89
P(rapeseed oil < ethanol fuel)	0.16	$9*10^{-6}$	$5*10^{-6}$	$1-4*10^{-24}$	0.9991
Large-scale production:					
P(RME < rapeseed oil)	$3*10^{-5}$	0.42	0.40	0.92	$1*10^{-32}$
P(RME < ethanol fuel)	0.08	$3*10^{-6}$	$2*10^{-6}$	$1-1*10^{-24}$	0.85
P(rapeseed oil < ethanol fuel)	0.15	$5*10^{-6}$	$3*10^{-6}$	$1-6*10^{-23}$	0.998
Expanded system:					
Small-scale production:					
P(RME < rapeseed oil)	$1-6*10^{-15}$	0.65	0.49	$1-2*10^{-6}$	$1-8*10^{-10}$
P(RME < ethanol fuel)	0.33	0.03	$9*10^{-5}$	$1-8*10^{-30}$	$1-2*10^{-6}$
P(rapeseed oil < ethanol fuel)	0.051	0.02	$1*10^{-4}$	$1-8*10^{-23}$	0.98
Medium-scale production:					
P(RME < rapeseed oil)	$1-1*10^{-13}$	0.66	0.49	$1-3*10^{-6}$	$1-5*10^{-9}$
P(RME < ethanol fuel)	0.40	0.010	$7*10^{-5}$	$1-9*10^{-26}$	$1-1*10^{-6}$
P(rapeseed oil < ethanol fuel)	0.056	0.006	$1*10^{-4}$	$1-2*10^{-19}$	0.98
Large-scale production:					
P(RME < rapeseed oil)	$1-3*10^{-13}$	0.68	0.49	$1-5*10^{-7}$	$1-2*10^{-9}$
P(RME < ethanol fuel)	0.49	$4*10^{-5}$	$1*10^{-5}$	$1-2*10^{-24}$	$1-1*10^{-5}$
P(rapeseed oil < ethanol fuel)	0.046	$8*10^{-6}$	$2*10^{-5}$	$1-1*10^{-17}$	0.64

4.12 Comparison to results from other studies

4.12.1 Rapeseed oil and RME

Two main LCAs on RME have been performed in Sweden. The first of these was by Ragnarsson (1994) and the second by Blinge *et al.* (1997) and Blinge (1998) (Table 186). Blinge *et al.* (1997) give two variants, the second with lower emissions of CO, HC, NO_x and particle emissions depending on the fuel produced fuel being used in vehicles with better equipment to reduce these emissions (Table 186). The values in Uppenberg *et al.* (2001) are in principle the values from Blinge *et al.* (1997).

Table 186. Literature study, large-scale production of RME (engine emissions included)

Study/ Emissions	CO_2[c]	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	HCl	Particles	Input energy
	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[MJ/MJ_{fuel}]
This study	17.98	0.049	0.015	0.010	0.702	0.028	0.091	0.087	0.00054	0.0059	0.28
Blinge *et al.*, 1997[b]	8.98	0.031	0.042	0.031	0.914	0.017		0.066		0.0132	0.29
Blinge *et al.*, 1997[a] and Blinge, 1998, production	9.00	0.020	0.031	0.031	0.081	0.018		0.067		0.0020	0.30
Uppenberg *et al.*, 2001	9.00	0.031	0.042	0.031	0.911	0.018		0.067		0.0130	0.30
Ragnarsson, 1994	29.90	0.135	0.034	0.054	1.100	0.010	0.005	0.064		0.0240	0.47

[a] Heavy vehicles without particle filter. Emissions measured after ECE R49. That value Blinge *et al.* (1997) recommends.
[b] Engine efficiency 40%. Diesel oil fuel for transports. Products allocated.
[c] If, for this study, it is considered that carbon atoms of biomass origin replace fossil carbon atoms in replaced fossil glycerine, the CO_2-emissions would be 14.11 g/MJ_{fuel}.

The main reason that the emissions are higher in Ragnarsson (1994) is that the seed harvest was assumed to be lower (less RME to spread out the emissions on) in that report (1847 kg/ha for Ragnarsson (1994); 2647 kg/ha for Blinge *et al.* (1997) and Blinge (1998); and 2470 kg/ha in this study, all with a water content (wet basis) of 8%). A lower harvest gives higher emission values after division by the functional unit (*e.g.* 1.0 MJ energy in the produced fuel). Other explanations for differences between the studies are differences in system boundaries etc. *e.g.* more details were included in this study. In both LCAs physical allocation (with 1 MJ of energy in the RME fuel was delivered to the final consumer chosen as functional unit, *i.e.* 1.0 MJ_{fuel}) used. In this study physical allocation was also the main type of allocation.

There is also a German LCA where production of rapeseed oil and RME in small- and large-scale plants have been compared (Gärtner & Reinhardt, 2001; Reinhardt & Gärtner, 2002; Jungk *et al.*, 2000). That study was similar to the present study but it was conducted under German or Central European conditions (Table 187).

Table 187. Comparison with a German study, large-scale production, expanded system

	Energy requirement [GJ/ha]	CO_2-equivalents [kg/ha]	SO_2-equivalents [kg/ha]	PO_4^{3-}-equivalents [kg/ha]	C_2H_4-equivalents [kg/ha]	N_2O [kg/ha]
Rapeseed production:						
This study	11.78	2405	14.41	2.40	0.19	5.47
Reinhardt & Gärtner (2002)	10.43	2228	16.76	2.85	0.13	5.05
Total, large-scale rapeseed oil:						
This study	5.66	1992	25.08	4.95	0.30	5.33
Reinhardt & Gärtner (2002)	9.81	2166	39.52	7.19	2.66	5.09
Total, large-scale RME:						
This study	-5.95	1406	24.86	5.15	0.14	5.31
Reinhardt & Gärtner (2002)	-5.30	1522	16.15	3.76	0.99	5.60

The values obtained by Gärtner & Reinhardt (2001) and Reinhardt & Gärtner (2002) for the rapeseed production are very similar to the values from this study (Table 187). Energy requirement, CO_2- (GWP-) and C_2H_4- (POCP-) equivalents are somewhat lower than in this study and SO_2- (AP-) and PO_4^{3-}- (EP-) equivalents somewhat higher. Total energy requirement and emissions are calculated using an expanded system where the by-product rapemeal is used as an animal feed in substitution of soymeal imported from the USA. Glycerine from the transesterification replaces conventional petroleum based glycerine. The rapeseed-fuel life cycles are credited for this use. In the present study, allocation with expanded system was studied as an alternative allocation method, see Section 4.6. The differences between the German study and this study (Table 187) are probably due to the fact that Gärtner & Reinhardt (2001), Reinhardt & Gärtner (2002) and Jungk *et al.* (2000) carried out their study under somewhat different assumptions (*e.g.* German conditions).

Gärtner & Reinhardt (2001) and Reinhardt & Gärtner (2002) found that RME had significantly better environmental advantages over straight rapeseed oil fuel. The same results were obtained with expanded system in this study (Tables 138 and 187) but all the other allocation methods gave the opposite result (Tables 133, 136 and 137). Advantages for RME in these studies depend on replaced high environmental load for replaced glycerine of petroleum origin and lower emissions (except for NO_x) and better efficiency when the RME produced was used in engines in comparison to straight rapeseed oil (Table 102) (calculations after Aakko *et al.* (2000); Thuneke (1999); SMP (1993); SMP (1994); Bernesson (1993)). Gärtner & Reinhardt (2001) and Reinhardt & Gärtner (2002) also found that large-scale plants had a lower energy requirement and emissions of GWP in this study for expanded system confirmed this result for GWP-emissions but not for energy requirements (Table 138). Small-scale plants gave somewhat lower AP- and EP-emissions and lower POCP-emissions (mainly from hexane extraction), in this study confirmed for AP- and POCP-emissions but not for EP-emissions (Table 138). In this study the differences were very small between plant sizes for EP-emissions.

4.12.2 Ethanol fuel

Two main LCAs on ethanol fuel have been performed in Sweden. The first of these was by Almemark (1996) and the second by Blinge *et al.* (1997) and Blinge (1998) (Table 188). The values in Uppenberg *et al.* (2001) are in principle the values from Almemark (1996).

Table 188. Literature study, large-scale production of ethanol fuel (engine emissions included)

Study/ Emissions	CO_2[c]	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	HCl	Particles	Input energy
	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[g/MJ_{fuel}]	[MJ/MJ_{fuel}]
This study	23.67	0.31	0.060	0.0073	0.46	0.027	0.059	0.055	0.0010	0.0074	0.35
excl. Beraid etc.[a]	12.04	0.31	0.043	0.0077	0.45	0.021	0.063	0.059	0.0011	0.0060	0.23
Uppenberg *et al.*, 2001	7.70	0.028	0.0256	0.0057	0.528	0.0067		0.033		0.0612	0.52
Almemark, 1996[b]	7.73	0.02165	0.00876	0.00567	0.6106	0.0067		0.033		0.06138	0.52
Almemark, 1996[c]	43.30	0.02215	0.00979	0.0067	0.670	0.17				0.01698	0.82
Blinge *et al.*, 1997[d] and											
Blinge, 1998, production	6.61	0.018	0.024	0	0.49	0.0013		0.057		0.0033	1.11

[a] Ignition improver, denaturant and corrosion inhibitor with transport excluded; allocation made with ethanol produced (as E95 with 6.5 weight% water: Sekab, 2003) 46557 MJ/ha; no CO_2-emissions during ethanol combustion assumed.
[b] Project Agroetanol, conventional continuous ethanol production process.
[c] Alternative process that gives more valuable feedstuffs that can be utilized separately.
[d] Heavy vehicles without particle filter. Emissions measured after ECE R49. That value is recommended by Blinge *et al.*, 1997.

The main reason for the higher GWP-emissions and energy requirement in the second process by Almemark (1996) (Table 188) is that this process was not designed to get as much ethanol as possible but instead as much valuable feedstuffs as possible. In both Blinge *et al.* (1997) and Almemark (1996) physical allocation (with 1 MJ of energy in the ethanol delivered to the final consumer as functional unit, *i.e.* 1.0 $MJ_{ethanol}$) was used. In this study physical allocation (with 1 MJ of energy delivered on the engine shaft the functional unit, *i.e.* 1.0 MJ_{engine} that is easy to recalculate to the functional unit of 1 MJ of energy in the ethanol fuel delivered to the final consumer, *i.e.* 1.0 MJ_{fuel}) was also the main type of allocation.

4.13 Comparison to fossil fuel

The production and use of the rapeseed oil, RME and ethanol fuels may also be compared with the production and use of fossil MK1 diesel fuel (Swedish environmental class 1 diesel fuel oil). Table 189 accounts for MK1 fuel produced (Table 13) and used under Swedish conditions according to IVL recommendations (Uppenberg *et al.*, 2001) after a study made by Blinge *et al.* (1997). Engine emission values were from Aakko *et al.* (2000), as were the emission values for RME used in this study (Table 102). Engine efficiency when running on MK1 fuel (Table 102) was calculated from the efficiency when running on MK3 fuel (Aakko *et al.*, 2000) with assumptions of the same relationship between engine efficiencies when running on MK1 fuel and MK3 fuel as in SMP (1993). Sulphur dioxide emissions were calculated from the sulphur content in MK1 (10 ppm according to Aakko *et al.*, 2000). Carbon dioxide emissions (73 g/MJ_{fuel}) were given in Uppenberg *et al.* (2001) for use of MK1 fuel in heavy diesel engines.

Table 189. Environmental impact from production and use of MK1 diesel oil fuel (calculated after Uppenberg et al., 2001; Aakko et al., 2000; SMP, 1993)

Production factor/ Type of environmental impact	GWP [g/MJ_{engine}]	AP [g/MJ_{engine}]	EP [g/MJ_{engine}]	POCP [g/MJ_{engine}]	Input energy [MJ/MJ_{engine}]
Total environmental load MK1	217	1.11	0.194	0.0675	0.170

Rapeseed oil fuels (physical allocation) reduced GWP-emissions by 42-45% compared to MK1 fuel (Tables 189 and 133). POCP-emissions were reduced by 61-66%. However, AP-emissions were increased by 74-79% and EP-emissions by 75-81% compared to MK1 fuel (Tables 189 and 133). The energy requirements for production of rapeseed oil fuels were 3.8-5.0 times higher than for fossil MK1 fuel (Tables 189 and 133).

Ethanol fuel (physical allocation) reduced GWP-emissions by 52-53% compared to MK1 fuel (Tables 189 and 133). However, AP-emissions were increased by 4-5%, EP-emissions by 2-4% and POCP-emissions by 37-48% compared to MK1 fuel (Tables 189 and 133). The energy requirements for production of ethanol fuel were 5.2-5.3 times higher than for fossil MK1 fuel (Tables 189 and 133).

Other allocation methods gave similar results with some variations (Tables 133, 136, 137 and 138). With no allocation, during production of rapeseed oil and RME, the GWP-emissions could be increased for small- and medium-scale plants depending on a smaller amount of fuel over which to spread out the greater unallocated emissions.

Gärtner & Reinhardt (2001) and Reinhardt & Gärtner (2002) found that compared to diesel oil fuel the rapeseed oil fuels had a lower requirement of fossil energy and lower emissions of greenhouse gases. Other emissions were higher.

5 GENERAL DISCUSSION

The results of this study demonstrate that the differences in environmental impacts and energy requirements (with physical allocation) between small-, medium- and large-scale systems for the production and use of rapeseed oil, RME and ethanol fuel were small or even negligible in most cases. However in spite of their size, these differences were in many cases significant according to the Monte Carlo simulation, especially for rapeseed oil and RME. This was because the differences were swallowed up in comparison to the dominating cultivation emissions etc. that did not directly contribute to differences between production scales. The differences between rapeseed oil and RME were somewhat bigger, and for GWP-emissions and energy requirement they were significant according to the Monte Carlo simulation. During production and use of ethanol fuel the GWP-, AP- and EP-emissions were lower than during production of rapeseed oil or RME. However, the POCP-emissions and energy requirement were higher. According to the results from the Monte Carlo simulation, these differences were close to significance or significant.

The dominating production step regarding environmental impact and energy requirement was the cultivation, and as this step was identical for all production scales, the total difference might also be small. Furthermore, in the large-scale system, the more efficient use of machinery and buildings, for rapeseed oil and RME production the higher oil extraction efficiency and for ethanol fuel production the more efficient use of energy were, to a certain degree, outweighed by the longer transport distances. All these factors were, however, very small in comparison to cultivation.

The straw from rapeseed or wheat cultivation was not considered in this study because it is seldom or never harvested as a fuel in Sweden today. The main reasons for this are combustion problems and difficulties in harvesting the straw with sufficiently low moisture contents due to poor weather conditions during the harvest season. Therefore, the straw is used in the crop rotation to increase the humus content in the soil instead. Because of a lower yield per hectare from rape straw, it is more expensive to harvest than wheat straw and therefore more seldom harvested.

The results show that the choice of allocation method has a great effect on the absolute levels of the environmental load figures calculated. The figures calculated without allocation were in many cases twice as high during production of rapeseed oil and RME, and 1.5 times as high during production of ethanol fuel, as the figures calculated using physical calculation. The differences between physical and economic allocation were also quite large. This indicates that when different biofuels or production strategies are to be compared against each other, it is very important that the results are calculated using the same allocation strategies and system limitations.

The great effect on the results caused by allocation strategy used may be seen as a weakness of the LCA method but is more a result of the environmental load problem having many different aspects and seldom simple answers. This study focused mostly on physical allocation because of well-defined inputs, the value of which does not change over time. Physical allocation is also recommended before economic allocation in ISO 14041 (ISO, 1998). A drawback with physical and economic allocations is, however, that they often do not consider the environmental impact when different by-products replace other products in later processes. In such cases, it is often better to use the expanded system allocation procedure. For example, from the expanded system calculations in this study it was shown that in a situation where there is a requirement of glycerine and a meal with a high fat and protein content, RME can be produced at the same time as energy is saved and the POCP-emissions reduced. Thus, allocation with an expanded system may be the fairest method if the system is studied on a higher system level and the impact from a specific change in the total fuel production to end-use system is of interest. However the drawback with this method is that a change in the assumptions in the production of the replaced products may have very significant effects on the results.

In systems with physical, economic or no allocation, straight rapeseed oil fuel gives lower emissions and has a lower energy requirement compared to RME. The reason is that when the rapeseed oil is used straight, there is no requirement of resources for the transesterification and production of methanol, etc. However, in systems with expanded system, RME gives lower emissions and has a lower energy requirement compared to straight rapeseed fuel. The reason is that the by-product glycerine from the production of RME replaces glycerine of petroleum origin and a high environmental load. That environmental load is credited to the RME production process. The drawback with this procedure is that the result depends on how the by-product glycerine is used: does it replace glycerine of fossil or of biologic origin?; or is it used at all? The RME system is also favoured by lower emissions (except for NO_x) and better efficiency when the RME produced is used in engines in comparison to straight rapeseed oil.

For large-scale systems, the results from this work differed somewhat from previous LCA studies carried out by Ragnarsson (1994) (only RME), Almemark (1996) (only ethanol), Blinge *et al.* (1997), Blinge (1998) and Uppenberg *et al.* (2001). All these studies were based on data for Swedish conditions and physical allocation. The differences can, however, be explained by different assumptions and system delimitations. The results (rapeseed oil and RME) by Gärtner & Reinhardt (2001) and Reinhardt & Gärtner (2002) for German conditions with expanded system allocation were similar to the results in this study.

It is clear that the production and use of rapeseed oil and RME reduce the GWP- and POCP-emissions in comparison to the production and use of diesel oil (MK1). Based on data from the studies by SMP (1993), Aakko *et al.* (2000) and Uppenberg *et al.* (2001), the GWP- and POCP-emissions for the production and use of MK1 are 217 g CO_2-eq/MJ_{engine} and 68 mg C_2H_4-eq/MJ_{engine}, whereas the corresponding values in this study were 122 g CO_2-eq/MJ_{engine} and 26 mg C_2H_4-eq/MJ_{engine}, respectively for rapeseed oil and 127 g CO_2-eq/MJ_{engine} and 23 mg C_2H_4-eq/MJ_{engine}, respectively for RME (large-scale system with physical allocation). However, the categories of AP and EP were increased by 75% and 77% respectively for rapeseed oil and by 79% and 81% respectively for RME, in comparison to MK1. The energy requirement for the production and use of rapeseed oil was 3.9 times higher than for MK1 (Uppenberg *et al.*, 2001) and for RME 4.8 times higher than for MK1 (Uppenberg *et al.*, 2001). The results from the scenario analysis in which the rapeseed oil and RME produced replaced MK1 confirmed these relationships.

It is clear that the production and use of ethanol fuel in heavy diesel engines reduce the GWP in comparison to the production and use of diesel oil (MK1). However, the POCP is increased. When the same comparison with MK1 as above is conducted, the GWP and POCP for the production and use of the ethanol fuel in this study were 103 g CO_2-eq/MJ_{engine} and 92 mg C_2H_4-eq/MJ_{engine}, respectively (large-scale system with physical allocation). The differences for the categories of AP and EP were much smaller, they increased by 5% and 4% respectively, in comparison to MK1. The energy requirement for the production and use of ethanol fuel was 5.2 times higher than for MK1 (Uppenberg *et al.*, 2001). The results from the scenario analysis in which the ethanol fuel produced replaced MK1 confirmed these relationships.

When ethanol fuel production was compared with RME production (large-scale with physical allocation in this study) the GWP, AP and EP decreased by 19%, 41% and 43% respectively. However, the POCP and energy requirement increased by 294% and 9% respectively. According to the results from the Monte Carlo simulation, these differences were close to significance or significant.

To decrease the environmental impact of rapeseed oil, RME and ethanol fuel production in general, several strategies may be useful, but the results presented clearly show that increased seed harvest and decreased use of artificial fertilisers decrease the impact considerably. While the potential for increased seed harvest is constrained by biological factors and weather conditions, the potential for a decrease in the use of energy-demanding artificial fertilisers is much higher. Organic waste and sewage water can be used to fulfil the nutrient demands with a very limited energy cost at the same time as high costs for water sanitation plants are avoided. Since the rapeseed and wheat will not be used as food, the hygiene demands on the fertilisers can be decreased and waste products normally not allowed in agriculture can be used. These principles have been extensively studied in *Salix* production (Hansson *et al.*, 1999) and can also be applied in rapeseed or wheat cultivation. However, there is a risk that organic waste and sewage water may contain heavy metals, pesticide residuals or other undesired organic substances.

To reduce the environmental load during production of ethanol fuel for diesel engines, something must be done about the ignition improver and denaturants. As shown in this study, the denaturants can be produced from biomass or eliminated from the fuel with *e.g.* another type of ignition system in the diesel engines (STU, 1986) or the amount required can be decreased by a higher compression ratio in the engines (STU, 1986).

The results of the economic part of this study demonstrate that the differences in production costs between small-, medium- and large-scale systems for the production of rapeseed oil, RME, or ethanol fuel are significant. This is especially because of labour, but also machines being used more efficiently in larger plants. The differences between the plant sizes are so important that they have an impact even if the costs for production of the seed or wheat dominate. The differences in production costs between rapeseed oil and RME were significant for small plants in favour of rapeseed oil but small or negligible for large plants. For small-scale plants the additional process cost for the transesterification has a greater impact. For large plants the extra costs for the transesterification are almost swamped in comparison to the seed production cost. The differences in production costs between rapeseed oil fuels and ethanol fuel were significant for all plant sizes in favour of rapeseed oil fuels. The reasons for that are the more complicated and expensive process for ethanol production, which has a much higher requirement of energy especially as heat and a requirement of expensive ignition improver.

The production costs of rapeseed oil and RME could be reduced to almost the same size as between medium- and small-scale plants if they were produced on a larger farm. The influence on the costs of ethanol production is lower if the wheat is produced on a larger farm. The production cost would be reduced even more with EU area compensation as received by farmers in the EU today. However such compensation can be changed from one day to another and is therefore not trustworthy in the long run. The fuels could also be produced more cheaply if the seed or wheat were purchased on the market. Today, farmers do not get reimbursed for all their costs when rapeseed or wheat is grown in Central Sweden. A solution to get a greater profit could be for the farmers to join together and start a medium-scale plant and sell the RME or the rapeseed oil instead of the seed. However, the ethanol would probably be too expensive to produce in medium-scale plants.

When the price paid for RME at the plant (Lindkvist, pers. comm.) is 5.61 SEK/litre (0.47 SEK/MJ_{engine}) excluding value added tax, it is profitable to produce rapeseed oil and RME in large-scale plants with EU area compensation independent of the size of farm on which the seed is grown. If the farm is large, the production would also be profitable in medium-scale plants. When the seed is purchased for 2.00 SEK/kg, rapeseed oil and RME can be produced profitably in medium- and large-scale plants.

When the price paid for ethanol fuel at the plant (Elfving, pers. comm.) is 6.30 SEK/litre (0.76 SEK/MJ_{engine}) excluding value added tax, it is only profitable to produce ethanol fuel in large-scale plants with or without EU area compensation, independent of the size of farm on which the seed is grown. When the wheat is purchased for 0.97 SEK/kg, production of ethanol fuel is also very close to being profitable in medium-scale plants.

6 CONCLUSIONS

This study demonstrated that the differences in environmental impacts and energy requirements (with physical allocation) between small-, medium- and large-scale systems for the production of rapeseed oil, RME and ethanol for heavy diesel engines were small or even negligible (Figure 6). The dominating step was the cultivation, and as this step was the same for all scales, the differences between the scales were levelled out. Furthermore, in the large-scale system, the more efficient use of machinery and buildings, the higher oil extraction efficiency in the production of rapeseed oil and RME, and the more efficient use of energy in the production of ethanol were, to a certain degree, outweighed by the longer transport distances.

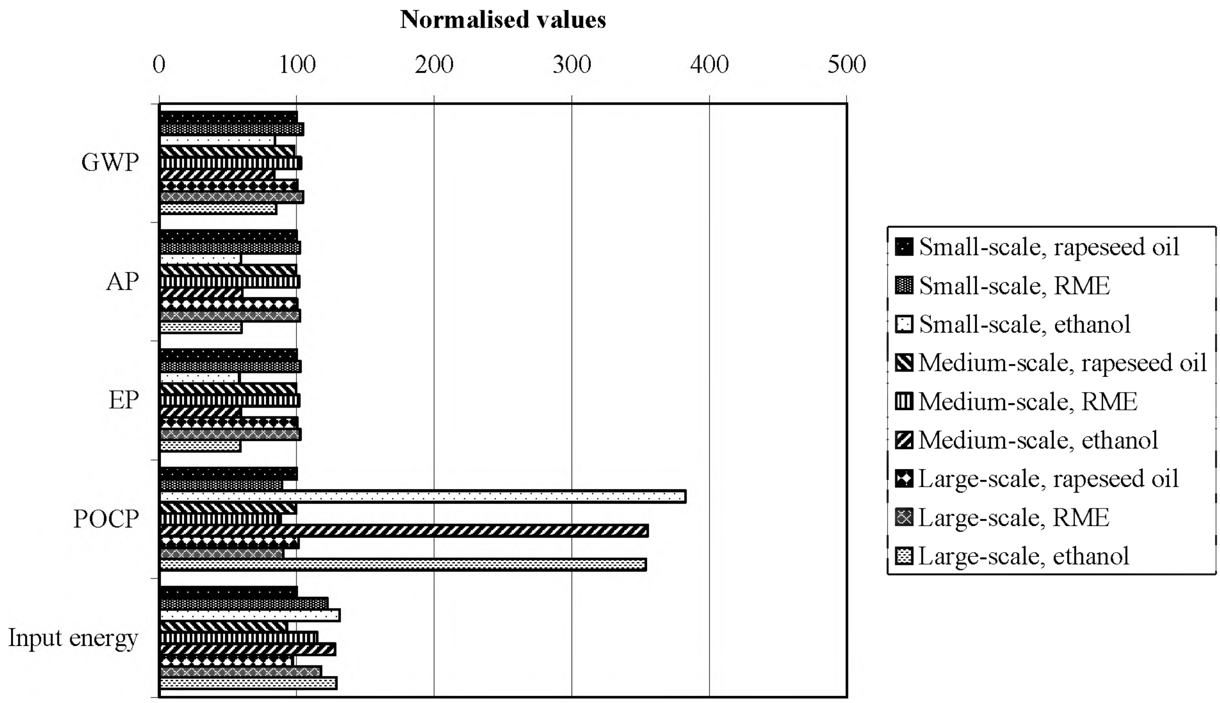

Figure 6. Normalised (small-scale rapeseed oil = 100) emission category and input energy values for production of the three fuels studied on three different scales with physical allocation and 1.0 MJ on the engine shaft (MJ_{engine}) as functional unit.

The results were largely dependent on the method used for allocation of the environmental burden between the rapeseed oil, RME and ethanol fuel and the by-products meal, distiller's waste and/or glycerine (see Figures 6 and 7). This indicates that when different biofuel production strategies are to be compared, it is important that the calculations are based on the same allocation strategies. For example, when physical, economic and no allocation were used, rapeseed oil would be preferred, whereas RME would be preferred according to the calculations with the expanded system allocation method.

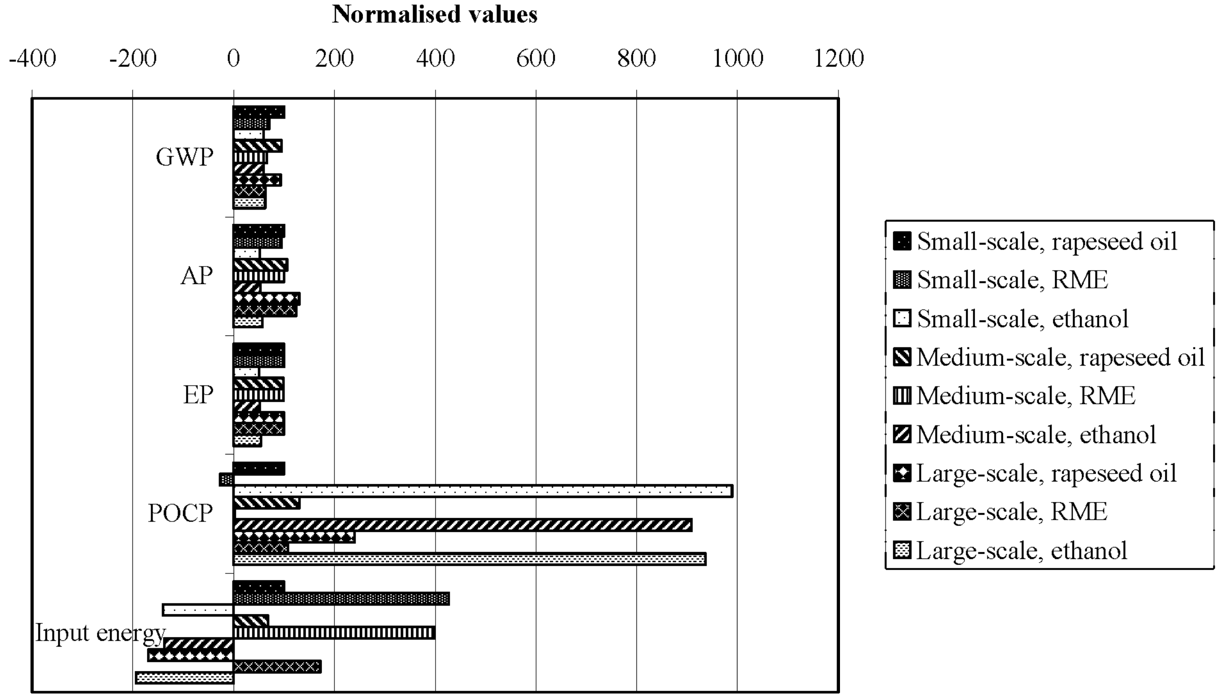

Figure 7. Normalised (small-scale rapeseed oil = 100) emission category and input energy values for production of the three fuels studied on three different scales with allocation with expanded system and 1.0 MJ on the engine shaft (MJ_{engine}) as functional unit.

The production of rapeseed oil generally had a lower environmental impact than the production of RME, and the differences between these fuels were greater than those between the plant scales (Figures 6 and 7). For the production and use of ethanol, the GWP-, AP- and EP-emissions were lower than for the production of rapeseed oil and RME (Figures 6 and 7). However, the energy requirement, and especially the POCP-emissions, were significantly higher.

For all fuels, the dominating production step was the cultivation, in which the production of fertilisers, soil emissions and tractive power made major contributions. For the production process of the RME fuel, the production of methanol and electricity for oil extraction and transesterification were the dominant steps, whereas for the production process of ethanol, the production of ignition improver, denaturants, heat and electricity were the dominant steps.

Irrespective of production scale, the use of rapeseed oil, RME and ethanol fuel reduces the global warming potential (GWP) in comparison to diesel fuel. The photochemical ozone creation potential (POCP) is reduced by rapeseed oil and RME but is increased by ethanol production and use in comparison to diesel oil. The acidification potential (AP), eutrophication potential (EP) and energy requirement (physical allocation) were increased in this comparison for all three fuels studied.

The economic calculations in this study demonstrated that the production costs were significantly lower for large plants than for small plants for all fuels. Regarding the differences in production costs between the rapeseed oil and RME, the costs of production in small plants were lower for rapeseed oil, whereas the difference was small for large plants. The ethanol fuel was more expensive to produce than rapeseed oil and RME, independent of the plant size.

Rapeseed oil and RME could be produced profitably on large-scale plants with EU area compensation independent of the size of the farm on which the seed/cereal is grown. If the farm is large, the production would also be profitable in medium-scale plants. Ethanol fuel could only be produced profitably in large-scale plants.

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APPENDIX 1. PRODUCTION OF RAPESEED OIL AND RME

Table A1. Emissions, cultivation of rapeseed

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Seed	2497	1.09	1.43	1.75	10.16	4.61	18.54	17.73	0.11	0.0002	0.58
Production of fertilisers	509509	103.23	269.80	498.43	970.40	1329.20	103.73	2709.90	33.63	0.055	147.06
Soil emissions							5600.80	2744.39			
Production of pesticides	4958	2.68	0.29	0.18	6.97	17.53	0.16	1.52	0.21		0.043
Tractive power	176145	186.58	131.78	4.64	2068.36	45.10		0			27.64
Heat for seed drying	72204	30.20	35.87	8.49	57.57	18.37		0.94			1.89
Electricity for drying and cleaning of the seed	692	1.59	0.26	4.32	1.32	1.15	0.019	0.063	0		0.22
Machinery inputs (Swedish electricity)	3567	8.19	1.32	22.29	6.82	5.91	0.10	0.32	0		1.14
Transport of fertiliser	1371	2.71	1.26	0.036	14.16	0.35		0			0.22
Machinery inputs, transport of fertiliser, (Sw. el.)	89	0.20	0.033	0.56	0.17	0.15	0.0025	0.0081	0		0.028
Total emissions	771031	336.47	442.04	540.69	3135.94	1422.37	5723.35	5474.88	33.95	0.056	178.81

Table A2. Emissions categories and energy requirements, cultivation of rapeseed

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Seed	7789	0.32	46.66	0.32	7.77	0.32	0.63	0.32	38.17	0.32
Production of fertilisers	1323309	55.03	2233.08	15.50	161.49	6.73	115.54	59.54	7005.96	59.45
Soil emissions	812340	33.78	10529.50	73.08	1950.90	81.33	0	0	0	0
Production of pesticides	5418	0.23	22.90	0.16	0.96	0.040	0.23	0.12	199.58	1.69
Tractive power	176624	7.34	1492.96	10.36	267.20	11.14	60.21	31.03	2440.88	20.71
Heat for seed drying	72739	3.02	58.67	0.41	7.44	0.31	15.61	8.05	1000.47	8.49
Electricity for drying and cleaning of the seed	813	0.034	2.11	0.015	0.18	0.0074	0.20	0.10	171.82	1.46
Machinery inputs (Swedish electricity)	4191	0.17	10.88	0.075	0.92	0.038	1.01	0.52	885.82	7.52
Transport of fertiliser	1377	0.057	10.26	0.071	1.83	0.076	0.61	0.32	19.00	0.16
Machinery inputs, transport of fertiliser, (Sw. el.)	105	0.0044	0.27	0.0019	0.023	0.00095	0.025	0.013	22.14	0.19
Total emissions	2404705	100	14407.29	100	2398.71	100	194.06	100	11783.83	100

Table A3. Emissions, small-scale production of rapeseed oil

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Cultivation of rapeseed *	771031	336.47	442.04	540.69	3135.94	1422.37	5723.35	5474.88	33.95	0.056	178.81
Emissions, electricity, small-scale oil extraction *	7645	17.55	2.83	47.77	14.62	12.67	0.21	0.69	0		2.44
Total machinery, oil extraction, Swedish el. *	380	0.87	0.14	2.37	0.73	0.63	0.011	0.034	0		0.12
Building material, Swedish el. *	121	0.28	0.045	0.75	0.23	0.20	0.0034	0.011	0		0.038
Emissions when driving on the rapeseed oil **	0	1382.64	243.92	0	16161.22	119.23		0			136.96
Total; cultivation, - driving	779177	1737.80	688.97	591.59	19312.74	1555.10	5723.57	5475.62	33.95	0.056	318.37
Total; cultivation, - driving [g/MJ_{engine}]	82.97	0.185	0.0734	0.0630	2.056	0.166	0.609	0.583	0.00362	0.0000059	0.0339
Total; cultivation, - driving [g/MJ_{fuel}]	26.92	0.0123	0.0154	0.0204	0.109	0.0496	0.198	0.189	0.00117	0.0000019	0.00627
Allocation (MJ)	366500	1549.70	453.26	278.27	17643.59	794.62	2692.19	2575.56	15.97	0.026	222.29
cultivation, - driving [g/MJ_{engine}]	39.02	0.165	0.0483	0.0296	1.879	0.0846	0.287	0.274	0.00170	0.0000028	0.0237
cultivation, - driving [g/MJ_{fuel}]	12.66	0.00577	0.00723	0.00961	0.0512	0.0233	0.0930	0.0890	0.000552	0.0000009	0.00295
Allocation (SEK)	445649	1585.77	498.47	338.36	17963.73	940.48	3273.59	3131.77	19.42	0.032	240.71
cultivation, - driving [g/MJ_{engine}]	47.45	0.169	0.0531	0.0360	1.913	0.100	0.349	0.333	0.00207	0.0000034	0.0256
cultivation, - driving [g/MJ_{fuel}]	15.39	0.00702	0.00879	0.0117	0.0623	0.0284	0.113	0.108	0.000671	0.0000011	0.00358

* Oil and meal included

** Oil included

Allocation (soymeal, soyoil, fossil glycerine)

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Total; cultivation, - driving (0)	779177	1737.80	688.97	591.59	19312.74	1555.10	5723.57	5475.62	33.95	0.056	318.37
Production, soymeal with eq. amount soyoil (1)	784112	1949.41	421.74	1918.48	7043.64	6837.31	303.73	304.97	48.64		547.03
Transport of soymeal with eq. amount soyoil (2)	11427	11.63	6.89	0.30	107.02	2.93		0			1.08
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	22.65	0.0520	0.0084	0.14	0.043	0.038	0.00064	0.0021	0		0.0072
Total [(0) - [(1) + (2) + (3)]]	-16385	-223.29	260.33	-1327.34	12162.04	-5285.17	5419.84	5170.64	-14.69	0.056	-229.75
cultivation, - driving [g/MJ_{engine}]	-1.745	-0.0238	0.0277	-0.1413	1.295	-0.563	0.577	0.551	-0.001564	0.0000059	-0.0245
cultivation, - driving [g/MJ_{fuel}]	-0.566	-0.0555	0.000567	-0.0459	-0.138	-0.187	0.187	0.179	-0.000507	0.0000019	-0.0127

Table A4. Emissions categories and energy requirements, small-scale production of rapeseed oil

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Cultivation of rapeseed *	2404705	99.49	14407.29	55.70	2398.71	53.44	194.06	55.57	11783.83	85.35
Emissions, electricity, small-scale oil extraction *	8984	0.37	23.31	0.090	1.96	0.044	2.17	0.62	1898.72	13.75
Total machinery, oil extraction, Swedish el. *	446	0.018	1.16	0.0045	0.098	0.0022	0.11	0.031	94.32	0.68
Building material, Swedish el. *	142	0.0059	0.37	0.0014	0.031	0.00069	0.034	0.010	29.96	0.22
Emissions when driving on the rapeseed oil **	2765	0.11	11432.09	44.20	2087.81	46.51	152.87	43.77		0
Total; cultivation, - driving	2417043	100	25864.22	100	4488.61	100	349.24	100	13806.83	100
Total; cultivation, - driving [g/MJ_{engine}]	257.36		2.754		0.4779		0.03719		1.470	
Total; cultivation, - driving [g/MJ_{fuel}]	83.40		0.499		0.0829		0.00678		0.477	
Allocation (MJ)	1138365	47.10	18220.50	70.45	3217.07	71.67	245.24	70.22	6494.29	47.04
cultivation, - driving [g/MJ_{engine}]	121.21		1.940		0.3426		0.02611		0.692	
cultivation, - driving [g/MJ_{fuel}]	39.23		0.235		0.0390		0.00319		0.224	
Allocation (SEK)	1383608	57.24	19686.52	76.11	3460.95	77.11	265.19	75.93	7896.79	57.19
cultivation, - driving [g/MJ_{engine}]	147.33		2.096		0.3685		0.02824		0.841	
cultivation, - driving [g/MJ_{fuel}]	47.70		0.285		0.0474		0.00388		0.273	
* Oil and meal included										
** Oil included										
Allocation (soymeal, soyoil, fossil glycerine)										
Total; cultivation, - driving (0)	2417043	100	25864.22	100	4488.61	100	349.24	100	13806.83	100
Production, soymeal with eq. amount soyoil (1)	922408	38.16	12381.68	47.87	1015.74	22.63	260.10	74.48	15957.27	115.58
Transport of soymeal with eq. amount soyoil (2)	11457	0.47	77.84	0.30	13.83	0.31	3.22	0.92	158.35	1.15
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	26.61	0.0011	0.069	0.00027	0.0058	0.00013	0.0064	0.0018	5.62	0.041
Total [(0) - [(1) + (2) + (3)]]	1483151	61.36	13404.63	51.83	3459.04	77.06	85.91	24.60	-2314.41	-16.76
cultivation, - driving [g/MJ_{engine}]	157.92		1.427		0.3683		0.00915		-0.2464	
cultivation, - driving [g/MJ_{fuel}]	51.14		0.0681		0.0474		-0.00231		-0.0800	

Table A5. Emissions, small-scale production of RME

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Cultivation of rapeseed *	771031	336.47	442.04	540.69	3135.94	1422.37	5723.35	5474.88	33.95	0.056	178.81
Emissions, electricity, small-scale oil extraction *	7645	17.55	2.83	47.77	14.62	12.67	0.21	0.69	0		2.44
Total machinery, oil extraction, Swedish el. *	380	0.87	0.14	2.37	0.73	0.63	0.011	0.034	0		0.12
Building material, Swedish el. *	121	0.28	0.045	0.75	0.23	0.20	0.0034	0.011	0		0.038
Methanol, natural gas, best case **	29782	8.21	4.66	3.80	65.97	0.61		0.48			0
Transport of methanol **	718	0.73	0.43	0.019	6.74	0.18		0			0.068
Transport of methanol, machinery, Swedish el. **	3.2	0.0075	0.0012	0.020	0.0062	0.0054	0.000091	0.00029	0		0.0010
Catalyst, KOH **	2130	0.65	0.025	0.0038	8.84	7.55					0.0027
Electricity, transesterification **	3763	8.64	1.39	23.51	7.20	6.24	0.11	0.34	0		1.20
Machinery, transesterification, Swedish el. **	220	0.50	0.081	1.37	0.42	0.36	0.0062	0.020	0		0.070
Building material, transesterification, Swedish el. **	56	0.13	0.021	0.35	0.11	0.092	0.0016	0.0050	0		0.018
Transport of glycerine ***	687	0.70	0.41	0.018	6.45	0.18		0			0.065
Transport of glycerine, machinery, Swedish el. ***	3.1	0.0071	0.0012	0.019	0.0059	0.0052	0.000087	0.00028	0		0.0010
Emissions when driving on the RME, fossil meth ****	108300	1192.73	216.86		18026.43	114.70					81.32
Compensation for bio-carbon in glycerine replacing fossil carbon	-108300										
Total; cultivation, - driving	924839	1567.47	668.92	620.71	21273.69	1565.80	5723.69	5476.46	33.95	0.056	264.15
Total; cultivation, - driving [g/MJ_{engine}]	94.77	0.161	0.0685	0.0636	2.180	0.160	0.587	0.561	0.00348	0.0000057	0.0271
Total; cultivation, - driving [g/MJ_{fuel}]	29.17	0.0134	0.0161	0.0222	0.116	0.0518	0.204	0.196	0.00121	0.0000020	0.00653
Total; cultivation, - driving[a]	816539										
Total; cultivation, - driving [g/MJ_{engine}][a]	83.67										
Total; cultivation, - driving [g/MJ_{fuel}][a]	25.30										
Allocation (MJ)	495353	1371.20	424.26	295.05	19535.63	777.87	2586.39	2475.05	15.34	0.025	164.59
cultivation, - driving [g/MJ_{engine}]	50.76	0.141	0.0435	0.0302	2.002	0.0797	0.265	0.254	0.00157	0.0000026	0.0169
cultivation, - driving [g/MJ_{fuel}]	13.83	0.00638	0.00741	0.01054	0.0539	0.0237	0.0924	0.0884	0.000548	0.0000009	0.00297
Allocation (MJ)[a]	387052										
cultivation, - driving [g/MJ_{engine}][a]	39.66										
cultivation, - driving [g/MJ_{fuel}][a]	9.96										
Allocation (SEK)	592624	1415.49	480.18	368.87	19930.53	958.43	3307.63	3165.02	19.62	0.032	187.41
cultivation, - driving [g/MJ_{engine}]	60.73	0.145	0.0492	0.0378	2.042	0.098	0.339	0.324	0.00201	0.0000033	0.0192
cultivation, - driving [g/MJ_{fuel}]	17.30	0.00796	0.00941	0.0132	0.0680	0.0301	0.118	0.113	0.000701	0.0000011	0.00379
Allocation (SEK)[a]	484324										
cultivation, - driving [g/MJ_{engine}][a]	49.63										
cultivation, - driving [g/MJ_{fuel}][a]	13.43										

Production factor	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	HCl	PAH	Particles
	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]
* RME, meal and glycerine included											
** RME and glycerine included											
*** Glycerine included											
**** RME included											
Allocation (soymeal, soyoil, fossil glycerine)											
Total; cultivation, - driving (0)[a]	816539	1567.47	668.92	620.71	21273.69	1565.80	5723.69	5476.46	33.95	0.056	264.15
Production, soymeal with eq. amount soyoil (1)	784112	1949.41	421.74	1918.48	7043.64	6837.31	303.73	304.97	48.64		547.03
Transport of soymeal with eq. amount soyoil (2)	11427	11.63	6.89	0.30	107.02	2.93		0			1.08
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	22.65	0.0520	0.0084	0.14	0.043	0.038	0.00064	0.0021	0		0.0072
Production of fossil glycerine (4)	421420	263.77	199.16	752.32	861.61	904.30	0.31	15.64	30.40		55.12
Total [(0) - [(1) + (2) + (3) + (4)]][a]	-400443	-657.39	41.12	-2050.54	13261.38	-6178.78	5419.65	5155.85	-45.09	0.056	-339.09
cultivation, - driving [g/MJ_{engine}][a]	-41.03	-0.0674	0.00421	-0.2101	1.359	-0.633	0.555	0.528	-0.00462	0.0000057	-0.0347
cultivation, - driving [g/MJ_{fuel}][a]	-18.17	-0.0661	-0.00628	-0.0733	-0.170	-0.225	0.194	0.184	-0.00161	0.0000020	-0.0150

[a] With compensation for bio-carbon in glycerine replacing fossil carbon.

Table A6. Emissions categories and energy requirements, small-scale production of RME

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Cultivation of rapeseed *	2404705	93.81	14407.29	52.88	2398.71	50.58	194.06	58.00	11783.83	73.95
Emissions, electricity, small-scale oil extraction *	8984	0.35	23.31	0.086	1.96	0.041	2.17	0.65	1898.72	11.91
Total machinery, oil extraction, Swedish el. *	446	0.017	1.16	0.0043	0.098	0.0021	0.11	0.032	94.32	0.59
Building material, Swedish el. *	142	0.0055	0.37	0.0014	0.031	0.00065	0.034	0.010	29.96	0.19
Methanol, natural gas, best case **	30027	1.17	46.79	0.17	8.52	0.18	2.22	0.66	1043.93	6.55
Transport of methanol **	719	0.028	4.90	0.018	0.87	0.018	0.20	0.060	9.94	0.062
Transport of methanol, machinery, Swedish el. **	3.8	0.00015	0.0099	0.000036	0.00083	0.000018	0.00092	0.00028	0.81	0.0051
Catalyst, KOH **	2131	0.083	13.73	0.050	1.14	0.024	0.036	0.011	60.91	0.38
Electricity, transesterification **	4422	0.17	11.48	0.042	0.97	0.020	1.07	0.32	934.59	5.86
Machinery, transesterification, Swedish el. **	258	0.010	0.67	0.0025	0.056	0.0012	0.062	0.019	54.58	0.34
Building material, transesterification, Swedish el. **	65	0.0025	0.17	0.00062	0.014	0.00030	0.016	0.0047	13.81	0.087
Transport of glycerine ***	689	0.027	4.69	0.017	0.83	0.018	0.19	0.057	9.53	0.060
Transport of glycerine, machinery, Swedish el. ***	3.7	0.00014	0.0095	0.000035	0.00080	0.000017	0.00088	0.00026	0.77	0.0048
Emissions when driving on the RME, fossil meth ****	110686	4.32	12733.20	46.73	2328.77	49.11	134.45	40.18		0
Compensation for bio-carbon in glycerine replacing fossil carbon	-108300									
Total; cultivation, - driving	2563284	100	27247.79	100	4741.98	100	334.61	100	15935.69	100
Total; cultivation, - driving [g/MJ_{engine}]	262.67		2.792		0.4859		0.03429		1.633	
Total; cultivation, - driving [g/MJ_{fuel}]	87.61		0.519		0.0862		0.00715		0.569	
Total; cultivation, - driving[a]	2454983									
Total; cultivation, - driving [g/MJ_{engine}][a]	251.57									
Total; cultivation, - driving [g/MJ_{fuel}][a]	83.75									
Allocation (MJ)	1237495	48.28	19328.72	70.94	3424.65	72.22	226.62	67.73	8259.09	51.83
cultivation, - driving [g/MJ_{engine}]	126.81		1.981		0.3509		0.02322		0.846	
cultivation, - driving [g/MJ_{fuel}]	40.25		0.236		0.0391		0.00329		0.295	
Allocation (MJ)[a]	1129194									
cultivation, - driving [g/MJ_{engine}][a]	115.71									
cultivation, - driving [g/MJ_{fuel}][a]	36.38									
Allocation (SEK)	1540785	60.11	21145.41	77.60	3726.89	78.59	251.27	75.09	9946.08	62.41
cultivation, - driving [g/MJ_{engine}]	157.89		2.167		0.3819		0.02575		1.019	
cultivation, - driving [g/MJ_{fuel}]	51.09		0.301		0.0499		0.00417		0.355	
Allocation (SEK)[a]	1432485									
cultivation, - driving [g/MJ_{engine}][a]	146.79									
cultivation, - driving [g/MJ_{fuel}][a]	47.22									

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
* RME, meal and glycerine included										
** RME and glycerine included										
*** Glycerine included										
**** RME included										
Allocation (soymeal, soyoil, fossil glycerine)										
Total; cultivation, - driving (0)[a]	2454983	95.77	27247.79	100	4741.98	100	334.61	100	15935.69	100
Production, soymeal with eq. amount soyoil (1)	922408	35.99	12381.68	45.44	1015.74	21.42	260.10	77.73	15957.27	100.14
Transport of soymeal with eq. amount soyoil (2)	11457	0.45	77.84	0.29	13.83	0.29	3.22	0.96	158.35	0.99
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	26.61	0.0010	0.069	0.00025	0.0058	0.00012	0.0064	0.0019	5.62	0.035
Production of fossil glycerine (4)	443879	17.32	1534.76	5.63	111.42	2.35	95.48	28.54	10083.45	63.28
Total [(0) - [(1) + (2) + (3) + (4)]][a]	1077213	42.02	13253.45	48.64	3600.99	75.94	-24.20	-7.23	-10269.00	-64.44
cultivation, - driving [g/MJ_{engine}][a]	110.39		1.358		0.3690		-0.00248		-1.052	
cultivation, - driving [g/MJ_{fuel}][a]	34.53		0.0186		0.0454		-0.00567		-0.367	

[a] With compensation for bio-carbon in glycerine replacing fossil carbon.

Table A7. Emissions, medium-scale production of rapeseed oil

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Cultivation of rapeseed *	771031	336.47	442.04	540.69	3135.94	1422.37	5723.35	5474.88	33.95	0.056	178.81
Transport seed to extraction, fuel *	1196	1.12	0.90	0.031	12.54	0.31		0			0.10
Transport seed to extraction, machinery *	116	0.27	0.043	0.72	0.22	0.19	0.0032	0.010	0		0.037
Emissions, electricity, medium-scale oil extraction *	4498	10.32	1.66	28.10	8.60	7.46	0.13	0.41	0		1.43
Total machinery, oil extraction, Swedish el. *	171	0.39	0.063	1.07	0.33	0.28	0.0048	0.016	0		0.055
Building material, Swedish el. *	71	0.16	0.026	0.44	0.13	0.12	0.0020	0.0064	0		0.022
Transport meal from extraction, fuel **	622	0.51	0.44	0.016	6.81	0.16		0			0.055
Transport meal from extraction, machinery **	55	0.13	0.020	0.34	0.10	0.091	0.0015	0.0050	0		0.017
Transport oil from extraction, fuel ***	458	0.47	0.27	0.012	4.30	0.12		0			0.043
Transport oil from extraction, machinery ***	2.1	0.0048	0.00077	0.013	0.0040	0.0034	0.000058	0.00019	0		0.00066
Emissions when driving on the rapeseed oil ***	0	1524.97	269.03	0	17824.87	131.51					151.06
Total; cultivation, - driving	778220	1874.80	714.49	571.45	20993.85	1562.60	5723.48	5475.33	33.95	0.056	331.64
Total; cultivation, - driving [g/MJ_{engine}]	75.13	0.181	0.0690	0.0552	2.027	0.151	0.553	0.529	0.00328	0.0000054	0.0320
Total; cultivation, - driving [g/MJ_{fuel}]	24.37	0.0110	0.0140	0.0179	0.099	0.0448	0.179	0.171	0.00106	0.0000017	0.00566
Allocation (MJ)	396659	1703.24	496.05	291.18	19439.18	861.09	2918.14	2791.62	17.31	0.028	243.11
cultivation, - driving [g/MJ_{engine}]	38.29	0.164	0.0479	0.0281	1.877	0.0831	0.282	0.270	0.00167	0.0000027	0.0235
cultivation, - driving [g/MJ_{fuel}]	12.42	0.00558	0.00711	0.00912	0.0506	0.0229	0.0914	0.0874	0.000542	0.0000009	0.00288
Allocation (SEK)	474992	1738.40	540.88	348.75	19757.49	1005.31	3495.09	3343.55	20.73	0.034	261.30
cultivation, - driving [g/MJ_{engine}]	45.86	0.168	0.0522	0.0337	1.907	0.097	0.337	0.323	0.00200	0.0000033	0.0252
cultivation, - driving [g/MJ_{fuel}]	14.88	0.00668	0.00851	0.0109	0.0605	0.0274	0.109	0.105	0.000649	0.0000011	0.00345

* Oil and meal included

** Meal included

*** Oil included

Allocation (soymeal, soyoil, fossil glycerine)	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Total; cultivation, - driving (0)	778220	1874.80	714.49	571.45	20993.85	1562.60	5723.48	5475.33	33.95	0.056	331.64
Production, soymeal with eq. amount soyoil (1)	717706	1784.30	386.01	1755.97	6447.08	6258.08	277.99	279.14	44.53		500.70
Transport of soymeal with eq. amount soyoil (2)	11123	11.32	6.70	0.29	104.17	2.85		0			1.05
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	22.04	0.0506	0.0082	0.14	0.042	0.037	0.00062	0.0020	0		0.0070
Total [(0) - [(1) + (2) + (3)]]	49370	79.13	321.77	-1184.95	14442.56	-4698.36	5445.49	5196.18	-10.57	0.056	-170.13
cultivation, - driving [g/MJ_{engine}]	4.766	0.0076	0.0311	-0.1144	1.394	-0.454	0.526	0.502	-0.001021	0.0000054	-0.0164
cultivation, - driving [g/MJ_{fuel}]	1.546	-0.0453	0.00165	-0.0371	-0.106	-0.151	0.171	0.163	-0.000331	0.0000017	-0.0101

Table A8. Emissions categories and energy requirements, medium-scale production of rapeseed oil

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Cultivation of rapeseed *	2404705	99.54	14407.29	53.27	2398.71	50.97	194.06	53.20	11783.83	90.40
Transport seed to extraction, fuel *	1199	0.050	9.08	0.034	1.62	0.034	0.40	0.11	16.58	0.13
Transport seed to extraction, machinery *	136	0.0056	0.35	0.0013	0.030	0.00063	0.033	0.0090	28.76	0.22
Emissions, electricity, medium-scale oil extraction *	5285	0.22	13.72	0.051	1.16	0.025	1.27	0.35	1116.98	8.57
Total machinery, oil extraction, Swedish el. *	201	0.0083	0.52	0.0019	0.044	0.00094	0.049	0.013	42.56	0.33
Building material, Swedish el. *	83	0.0034	0.22	0.00080	0.018	0.00039	0.020	0.0055	17.52	0.13
Transport meal from extraction, fuel **	624	0.026	4.93	0.018	0.88	0.019	0.20	0.054	8.62	0.066
Transport meal from extraction, machinery **	64	0.0027	0.17	0.00062	0.014	0.00030	0.016	0.0043	13.61	0.10
Transport oil from extraction, fuel ***	459	0.019	3.13	0.012	0.56	0.012	0.13	0.035	6.34	0.049
Transport oil from extraction, machinery ***	2.4	0.00010	0.0063	0.000023	0.00053	0.000011	0.00059	0.00016	0.51	0.0039
Emissions when driving on the rapeseed oil ***	3050	0.13	12608.92	46.62	2302.73	48.93	168.61	46.22		0
Total; cultivation, - driving	2415810	100	27048.32	100	4705.76	100	364.79	100	13035.32	100
Total; cultivation, - driving [g/MJ_{engine}]	233.23		2.611		0.4543		0.03522		1.258	
Total; cultivation, - driving [g/MJ_{fuel}]	75.57		0.452		0.0753		0.00614		0.408	
Allocation (MJ)	1233082	51.04	19969.86	73.83	3527.74	74.97	268.59	73.63	6638.14	50.92
cultivation, - driving [g/MJ_{engine}]	119.04		1.928		0.3406		0.02593		0.641	
cultivation, - driving [g/MJ_{fuel}]	38.53		0.231		0.0384		0.00313		0.208	
Allocation (SEK)	1476181	61.11	21424.57	79.21	3769.83	80.11	288.33	79.04	7949.22	60.98
cultivation, - driving [g/MJ_{engine}]	142.51		2.068		0.3639		0.02784		0.767	
cultivation, - driving [g/MJ_{fuel}]	46.14		0.276		0.0460		0.00375		0.249	

* Oil and meal included

** Meal included

*** Oil included

Allocation (soymeal, soyoil, fossil glycerine)										
Total; cultivation, - driving (0)	2415810	100	27048.32	100	4705.76	100	364.79	100	13035.32	100
Production, soymeal with eq. amount soyoil (1)	844288	34.95	11332.84	41.90	929.71	19.76	238.07	65.26	14605.58	112.05
Transport of soymeal with eq. amount soyoil (2)	11152	0.46	75.76	0.28	13.46	0.29	3.14	0.86	154.13	1.18
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	25.90	0.0011	0.067	0.00025	0.0057	0.00012	0.0062	0.0017	5.47	0.042
Total [(0) - [(1) + (2) + (3)]]	1560344	64.59	15639.65	57.82	3762.59	79.96	123.58	33.88	-1729.87	-13.27
cultivation, - driving [g/MJ_{engine}]	150.64		1.510		0.3632		0.01193		-0.1670	
cultivation, - driving [g/MJ_{fuel}]	48.78		0.0949		0.0457		-0.00141		-0.0542	

Table A9. Emissions, medium-scale production of RME

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Cultivation of rapeseed *	771031	336.47	442.04	540.69	3135.94	1422.37	5723.35	5474.88	33.95	0.056	178.81
Transport seed to extraction, fuel *	1196	1.12	0.90	0.031	12.54	0.31			0		0.10
Transport seed to extraction, machinery *	116	0.27	0.043	0.72	0.22	0.19	0.0032	0.010	0		0.037
Emissions, electricity, medium-scale oil extraction *	4498	10.32	1.66	28.10	8.60	7.46	0.13	0.41	0		1.43
Total machinery, oil extraction, Swedish el. *	171	0.39	0.063	1.07	0.33	0.28	0.0048	0.016	0		0.055
Building material, Swedish el. *	71	0.16	0.026	0.44	0.13	0.12	0.0020	0.0064	0		0.022
Methanol, natural gas, best case **	32848	9.05	5.13	4.19	72.76	0.68		0.53			0
Transport of methanol **	791	0.81	0.47	0.021	7.43	0.20		0			0.075
Transport of methanol, machinery, Swedish el. **	3.6	0.0082	0.0013	0.022	0.0068	0.0059	0.00010	0.00032	0		0.0011
Catalyst, KOH **	2349	0.72	0.028	0.0042	9.75	8.33					0.0030
Electricity, transesterification **	4056	9.31	1.50	25.35	7.76	6.72	0.11	0.37	0		1.29
Machinery, transesterification, Swedish el. **	84	0.19	0.031	0.52	0.16	0.14	0.0023	0.0076	0		0.027
Building material, transesterification, Swedish el. **	35	0.081	0.013	0.22	0.067	0.058	0.00099	0.0032	0		0.011
Transport meal from extraction, fuel ***	622	0.51	0.44	0.016	6.81	0.16		0			0.055
Transport meal from extraction, machinery ***	55	0.13	0.020	0.34	0.10	0.091	0.0015	0.0050	0		0.017
Transport RME from transesterification, fuel ****	440	0.45	0.26	0.012	4.14	0.11		0			0.042
Transport RME from transesterification, machinery ****	2.0	0.0046	0.00074	0.012	0.0038	0.0033	0.000056	0.00018	0		0.00064
Transport of glycerine *****	758	0.77	0.45	0.020	7.12	0.19		0			0.072
Transport of glycerine, machinery, Swedish el. *****	3.4	0.0079	0.0013	0.021	0.0066	0.0057	0.000096	0.00031	0		0.0011
Emissions when driving on the RME, fossil meth ****	119449	1315.51	239.18		19882.09	126.51					89.69
Compensation for bio-carbon in glycerine replacing fossil carbon	-119449										
Total; cultivation, - driving	938580	1686.27	692.27	601.81	23155.97	1573.93	5723.60	5476.23	33.95	0.056	271.75
Total; cultivation, - driving [g/MJ$_{engine}$]	87.20	0.157	0.0643	0.0559	2.151	0.146	0.532	0.509	0.00315	0.0000052	0.0252
Total; cultivation, - driving [g/MJ$_{fuel}$]	26.53	0.0120	0.0147	0.0195	0.106	0.0469	0.185	0.177	0.00110	0.0000018	0.00590
Total; cultivation, - driving[a]	819131										
Total; cultivation, - driving [g/MJ$_{engine}$][a]	76.10										
Total; cultivation, - driving [g/MJ$_{fuel}$][a]	22.66										
Allocation (MJ)	538599	1505.91	464.00	308.50	21525.43	842.39	2801.92	2681.19	16.62	0.027	179.42
cultivation, - driving [g/MJ$_{engine}$]	50.04	0.140	0.0431	0.0287	2.000	0.0783	0.260	0.249	0.00154	0.0000025	0.0167
cultivation, - driving [g/MJ$_{fuel}$]	13.58	0.00617	0.00728	0.00999	0.0532	0.0232	0.0908	0.0868	0.000538	0.0000009	0.00291
Allocation (MJ)[a]	419149										
cultivation, - driving [g/MJ$_{engine}$][a]	38.94										
cultivation, - driving [g/MJ$_{fuel}$][a]	9.71										

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Allocation (SEK)	632860	1548.16	518.34	377.75	21910.10	1017.38	3503.55	3352.38	20.78	0.034	201.51
cultivation, - driving [g/MJ_{engine}]	58.80	0.144	0.0482	0.0351	2.036	0.0945	0.326	0.311	0.00193	0.0000032	0.0187
cultivation, - driving [g/MJ_{fuel}]	16.63	0.00754	0.00904	0.0122	0.0657	0.0289	0.113	0.109	0.000673	0.0000011	0.00362
Allocation (SEK)[a]	513411										
cultivation, - driving [g/MJ_{engine}][a]	47.70										
cultivation, - driving [g/MJ_{fuel}][a]	12.76										
* RME, meal and glycerine included											
** RME and glycerine included											
*** Meal included											
**** RME included											
***** Glycerine included											
Allocation (soymeal, soyoil, fossil glycerine)											
Total; cultivation, - driving (0)[a]	819131	1686.27	692.27	601.81	23155.97	1573.93	5723.60	5476.23	33.95	0.056	271.75
Production, soymeal with eq. amount soyoil (1)	717706	1784.30	386.01	1755.97	6447.08	6258.08	277.99	279.14	44.53		500.70
Transport of soymeal with eq. amount soyoil (2)	11123	11.32	6.70	0.29	104.17	2.85		0			1.05
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	22.04	0.051	0.0082	0.14	0.042	0.037	0.00062	0.0020	0		0.0070
Production of fossil glycerine (4)	464801	290.92	219.67	829.77	950.30	997.39	0.34	17.25	33.53		60.79
Total [(0) - [(1) + (2) + (3) + (4)]][a]	-374520	-400.32	79.88	-1984.35	15654.37	-5684.42	5445.27	5179.84	-44.11	0.056	-290.80
cultivation, - driving [g/MJ_{engine}][a]	-34.80	-0.0372	0.00742	-0.1844	1.454	-0.528	0.506	0.481	-0.00410	0.0000052	-0.0270
cultivation, - driving [g/MJ_{fuel}][a]	-16.00	-0.0556	-0.00516	-0.0643	-0.137	-0.188	0.176	0.168	-0.00143	0.0000018	-0.0123

[a] With compensation for bio-carbon in glycerine replacing fossil carbon.

Table A10. Emissions categories and energy requirements, medium-scale production of RME

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Cultivation of rapeseed *	2404705	93.32	14407.29	50.42	2398.71	48.12	194.06	55.67	11783.83	76.95
Transport seed to extraction, fuel *	1199	0.047	9.08	0.032	1.62	0.032	0.40	0.12	16.58	0.11
Transport seed to extraction, machinery *	136	0.0053	0.35	0.0012	0.030	0.00060	0.033	0.0094	28.76	0.19
Emissions, electricity, medium-scale oil extraction *	5285	0.21	13.72	0.048	1.16	0.023	1.27	0.37	1116.98	7.29
Total machinery, oil extraction, Swedish el. *	201	0.0078	0.52	0.0018	0.044	0.00088	0.049	0.014	42.56	0.28
Building material, Swedish el. *	83	0.0032	0.22	0.00075	0.018	0.00036	0.020	0.0057	17.52	0.11
Methanol, natural gas, best case **	33118	1.29	51.61	0.18	9.40	0.19	2.45	0.70	1151.39	7.52
Transport of methanol **	793	0.031	5.40	0.019	0.96	0.019	0.22	0.063	10.97	0.072
Transport of methanol, machinery, Swedish el. **	4.2	0.00016	0.011	0.000038	0.00092	0.000018	0.0010	0.00029	0.89	0.0058
Catalyst, KOH **	2351	0.091	15.15	0.053	1.26	0.025	0.040	0.011	67.18	0.44
Electricity, transesterification **	4767	0.18	12.37	0.043	1.04	0.021	1.15	0.33	1007.37	6.58
Machinery, transesterification, Swedish el. **	98	0.0038	0.26	0.00089	0.021	0.00043	0.024	0.0068	20.78	0.14
Building material, transesterification, Swedish el. **	41	0.0016	0.11	0.00038	0.0091	0.00018	0.0100	0.0029	8.76	0.057
Transport meal from extraction, fuel ***	624	0.024	4.93	0.017	0.88	0.018	0.20	0.057	8.62	0.056
Transport meal from extraction, machinery ***	64	0.0025	0.17	0.00058	0.014	0.00028	0.016	0.0045	13.61	0.089
Transport RME from transesterification, fuel ****	442	0.017	3.01	0.011	0.53	0.011	0.12	0.035	6.10	0.040
Transport RME from transesterification, machinery ****	2.3	0.000091	0.0061	0.000021	0.00051	0.000010	0.00056	0.00016	0.49	0.0032
Transport of glycerine *****	760	0.030	5.18	0.018	0.92	0.018	0.21	0.061	10.51	0.069
Transport of glycerine, machinery, Swedish el. *****	4.0	0.00016	0.010	0.000037	0.00088	0.000018	0.00097	0.00028	0.85	0.0056
Emissions when driving on the RME, fossil meth ****	122080	4.74	14043.98	49.15	2568.50	51.52	148.29	42.54		0
Compensation for bio-carbon in glycerine replacing fossil carbon	-119449									
Total; cultivation, - driving	2576760	100	28573.35	100	4985.12	100	348.57	100	15313.76	100
Total; cultivation, - driving [g/MJ_{engine}]	239.40		2.655		0.4632		0.03239		1.423	
Total; cultivation, - driving [g/MJ_{fuel}]	79.50		0.471		0.0783		0.00649		0.496	
Total; cultivation, - driving[a]	2457311									
Total; cultivation, - driving [g/MJ_{engine}][a]	228.31									
Total; cultivation, - driving [g/MJ_{fuel}][a]	75.64									
Allocation (MJ)	1342337	52.09	21192.42	74.17	3756.78	75.36	248.00	71.15	8535.65	55.74
cultivation, - driving [g/MJ_{engine}]	124.71		1.969		0.3490		0.02304		0.793	
cultivation, - driving [g/MJ_{fuel}]	39.52		0.232		0.0385		0.00323		0.276	
Allocation (MJ)[a]	1222888									
cultivation, - driving [g/MJ_{engine}][a]	113.62									
cultivation, - driving [g/MJ_{fuel}][a]	35.65									

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Allocation (SEK)	1636950	63.53	22959.42	80.35	4050.87	81.26	271.91	78.01	10073.54	65.78
cultivation, - driving [g/MJ_{engine}]	152.09		2.133		0.3764		0.02526		0.936	
cultivation, - driving [g/MJ_{fuel}]	49.06		0.289		0.0480		0.00400		0.326	
Allocation (SEK)[a]	1517501									
cultivation, - driving [g/MJ_{engine}][a]	140.99									
cultivation, - driving [g/MJ_{fuel}][a]	45.20									
* RME, meal and glycerine included										
** RME and glycerine included										
*** Meal included										
**** RME included										
***** Glycerine included										
Allocation (soymeal, soyoil, fossil glycerine)										
Total; cultivation, - driving (0)[a]	2457311	95.36	28573.35	100	4985.12	100	348.57	100	15313.76	100
Production, soymeal with eq. amount soyoil (1)	844288	32.77	11332.84	39.66	929.71	18.65	238.07	68.30	14605.58	95.38
Transport of soymeal with eq. amount soyoil (2)	11152	0.43	75.76	0.27	13.46	0.27	3.14	0.90	154.13	1.01
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	26	0.0010	0.067	0.00024	0.0057	0.00011	0.0062	0.0018	5.47	0.036
Production of fossil glycerine (4)	489572	19.00	1692.75	5.92	122.89	2.47	105.31	30.21	11121.45	72.62
Total [(0) - [(1) + (2) + (3) + (4)]][a]	1112273	43.17	15471.93	54.15	3919.06	78.62	2.05	0.59	-10572.88	-69.04
cultivation, - driving [g/MJ_{engine}][a]	103.34		1.437		0.3641		0.000190		-0.982	
cultivation, - driving [g/MJ_{fuel}][a]	32.07		0.0462		0.0437		-0.00474		-0.342	

[a] With compensation for bio-carbon in glycerine replacing fossil carbon.

Table A11. Emissions, large-scale production of rapeseed oil

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Cultivation of rapeseed *	771031	336.47	442.04	540.69	3135.94	1422.37	5723.35	5474.88	33.95	0.056	178.81
Transport seed to extraction, fuel *	15487	15.19	9.07	0.41	146.33	3.97		0			1.47
Transport seed to extraction, machinery *	55	0.13	0.020	0.34	0.10	0.091	0.0015	0.0050	0		0.017
Emissions, electricity, large-scale oil extraction *	4393	10.08	1.62	27.45	8.40	7.28	0.12	0.40	0		1.40
Total machinery, oil extraction, Swedish el. *	89	0.20	0.033	0.56	0.17	0.15	0.0025	0.0081	0		0.028
Building material, Swedish el. *	37	0.084	0.014	0.23	0.070	0.061	0.0010	0.0033	0		0.012
Emissions, hexane *	1341	0.84	2.19	1.62	4.54	6.18	0.0049	0.032	0.0089		0.21
Transport meal from extraction, fuel **	6776	6.33	3.82	0.18	64.75	1.74		0			0.65
Transport meal from extraction, machinery **	20	0.046	0.0075	0.13	0.039	0.033	0.00057	0.0018	0		0.0064
Transport oil from extraction, fuel ***	9401	9.60	5.59	0.25	88.27	2.41		0			0.89
Transport oil from extraction, machinery ***	43	0.098	0.016	0.27	0.081	0.071	0.0012	0.0039	0		0.014
Emissions when driving on the rapeseed oil ***	0	1992.63	351.53		23291.17	171.84					197.38
Total; cultivation, - driving	808673	2371.70	815.96	572.12	26739.87	1616.17	5723.48	5475.34	33.96	0.056	380.89
Total; cultivation, - driving [g/MJ_{engine}]	59.75	0.175	0.0603	0.0423	1.976	0.119	0.423	0.405	0.00251	0.0000041	0.0281
Total; cultivation, - driving [g/MJ_{fuel}]	19.38	0.00909	0.0111	0.0137	0.0827	0.0346	0.137	0.131	0.00081	0.0000013	0.00440
Allocation (MJ)	541994	2246.28	662.91	384.45	25594.28	1142.12	3846.43	3679.67	22.82	0.037	320.56
cultivation, - driving [g/MJ_{engine}]	40.04	0.166	0.0490	0.0284	1.891	0.0844	0.284	0.272	0.00169	0.0000028	0.0237
cultivation, - driving [g/MJ_{fuel}]	12.99	0.00608	0.00746	0.00922	0.0552	0.0233	0.0922	0.0882	0.000547	0.0000009	0.00295
Allocation (SEK)	609634	2277.26	701.75	433.22	25875.58	1265.04	4334.97	4147.03	25.72	0.042	336.10
cultivation, - driving [g/MJ_{engine}]	45.04	0.168	0.0518	0.0320	1.912	0.093	0.320	0.306	0.00190	0.0000031	0.0248
cultivation, - driving [g/MJ_{fuel}]	14.61	0.00682	0.00839	0.0104	0.0619	0.0262	0.104	0.099	0.000617	0.0000010	0.00332

* Oil and meal included

** Meal included

*** Oil included

Allocation (soymeal, soyoil, fossil glycerine)

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Total; cultivation, - driving (0)	808673	2371.70	815.96	572.12	26739.87	1616.17	5723.48	5475.34	33.96	0.056	380.89
Production, soymeal with eq. amount soyoil (1)	378981	942.16	203.75	927.01	3404.19	3303.62	146.72	147.38	23.52		264.39
Transport of soymeal with eq. amount soyoil (2)	9167	9.33	5.53	0.24	85.85	2.35		0			0.87
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	18.17	0.0417	0.0067	0.11	0.035	0.030	0.00051	0.0016	0		0.0058
Total [(0) - [(1) + (2) + (3)]]	420507	1420.18	606.68	-355.25	23249.79	-1689.82	5576.76	5327.95	10.44	0.056	115.63
cultivation, - driving [g/MJ_{engine}]	31.07	0.1049	0.0448	-0.0262	1.718	-0.125	0.412	0.394	0.000771	0.0000041	0.0085
cultivation, - driving [g/MJ_{fuel}]	10.08	-0.0137	0.00612	-0.0085	-0.00099	-0.045	0.134	0.128	0.000250	0.0000013	-0.0020

Table A12. Emissions categories and energy requirements, large-scale production of rapeseed oil

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Cultivation of rapeseed *	2404705	98.26	14407.29	46.29	2398.71	44.03	194.06	45.63	11783.83	87.27
Transport seed to extraction, fuel *	15527	0.63	106.40	0.34	18.90	0.35	4.24	1.00	214.61	1.59
Transport seed to extraction, machinery *	64	0.0026	0.17	0.00054	0.014	0.00026	0.016	0.0036	13.59	0.10
Emissions, electricity, large-scale oil extraction *	5162	0.21	13.40	0.043	1.13	0.021	1.25	0.29	1091.00	8.08
Total machinery, oil extraction, Swedish el. *	105	0.0043	0.27	0.00087	0.023	0.00042	0.025	0.0060	22.18	0.16
Building material, Swedish el. *	43	0.0018	0.11	0.00036	0.0094	0.00017	0.010	0.0025	9.13	0.068
Emissions, hexane *	1390	0.057	9.37	0.030	0.59	0.011	0.92	0.22	128.56	0.95
Transport meal from extraction, fuel **	6793	0.28	47.06	0.15	8.36	0.15	1.78	0.42	93.89	0.70
Transport meal from extraction, machinery **	24	0.00097	0.062	0.00020	0.0052	0.000095	0.0057	0.0013	5.01	0.037
Transport oil from extraction, fuel ***	9426	0.39	64.19	0.21	11.40	0.21	2.62	0.62	130.27	0.96
Transport oil from extraction, machinery ***	50	0.0020	0.13	0.00042	0.011	0.00020	0.012	0.0028	10.56	0.078
Emissions when driving on the rapeseed oil ***	3985	0.16	16475.65	52.94	3008.91	55.23	220.32	51.81		0
Total; cultivation, - driving	2447274	100	31124.11	100	5448.07	100	425.26	100	13502.63	100
Total; cultivation, - driving [g/MJ_{engine}]	180.81		2.300		0.4025		0.03142		0.998	
Total; cultivation, - driving [g/MJ_{fuel}]	58.57		0.351		0.0585		0.00491		0.324	
Allocation (MJ)	1644510	67.20	26309.49	84.53	4646.25	85.28	357.71	84.12	9054.08	67.05
cultivation, - driving [g/MJ_{engine}]	121.50		1.944		0.3433		0.02643		0.669	
cultivation, - driving [g/MJ_{fuel}]	39.32		0.236		0.0392		0.00329		0.217	
Allocation (SEK)	1851672	75.66	27550.33	88.52	4852.76	89.07	374.82	88.14	10186.17	75.44
cultivation, - driving [g/MJ_{engine}]	136.81		2.036		0.3585		0.02769		0.753	
cultivation, - driving [g/MJ_{fuel}]	44.29		0.265		0.0442		0.00370		0.244	

* Oil and meal included

** Meal included

*** Oil included

Allocation (soymeal, soyoil, fossil glycerine)										
Total; cultivation, - driving (0)	2447274	100	31124.11	100	5448.07	100	425.26	100	13502.63	100
Production, soymeal with eq. amount soyoil (1)	445812	18.22	5983.08	19.22	490.88	9.01	125.67	29.55	7711.09	57.11
Transport of soymeal with eq. amount soyoil (2)	9191	0.38	62.44	0.20	11.09	0.20	2.59	0.61	127.03	0.94
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	21.35	0.0009	0.055	0.00018	0.0047	0.000086	0.0051	0.0012	4.51	0.033
Total [(0) - [(1) + (2) + (3)]]	1992250	81.41	25078.54	80.58	4946.09	90.79	296.99	69.84	5660.01	41.92
cultivation, - driving [g/MJ_{engine}]	147.19		1.853		0.3654		0.02194		0.4182	
cultivation, - driving [g/MJ_{fuel}]	47.66		0.2062		0.0464		0.00184		0.1357	

Table A13. Emissions, large-scale production of RME

Production factor	CO_2	CO	HC	CH_4	NO_x	SO_x	NH_3	N_2O	HCl	PAH	Particles
	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]	[g/ha]
Cultivation of rapeseed *	771031	336.47	442.04	540.69	3135.94	1422.37	5723.35	5474.88	33.95	0.056	178.81
Transport seed to extraction, fuel *	15487	15.19	9.07	0.41	146.33	3.97		0			1.47
Transport seed to extraction, machinery *	55	0.13	0.020	0.34	0.10	0.091	0.0015	0.0050	0		0.017
Emissions, electricity, large-scale oil extraction *	4393	10.08	1.62	27.45	8.40	7.28	0.12	0.40	0		1.40
Total machinery, oil extraction, Swedish el. *	89	0.20	0.033	0.56	0.17	0.15	0.0025	0.0081	0		0.028
Building material, Swedish el. *	37	0.084	0.014	0.23	0.070	0.061	0.0010	0.0033	0		0.012
Emissions, hexane *	1341	0.84	2.19	1.62	4.54	6.18	0.0049	0.032	0.0089		0.21
Methanol, natural gas, best case **	42921	11.83	6.71	5.48	95.08	0.88		0.69			0
Transport of methanol **	1034	1.06	0.62	0.027	9.71	0.26		0			0.098
Transport of methanol, machinery, Swedish el. **	4.7	0.011	0.0017	0.029	0.0089	0.0078	0.00013	0.00042	0		0.0015
Catalyst, KOH **	3070	0.94	0.036	0.0055	12.73	10.88					0.0039
Electricity, transesterification **	5177	11.88	1.91	32.35	9.90	8.58	0.15	0.47	0		1.65
Machinery, transesterification, Swedish el. **	54	0.13	0.020	0.34	0.10	0.090	0.0015	0.0049	0		0.017
Building material, transesterification, Swedish el. **	23	0.053	0.0085	0.14	0.044	0.038	0.00064	0.0021	0		0.0073
Transport meal from extraction, fuel ***	6776	6.33	3.82	0.18	64.75	1.74		0			0.65
Transport meal from extraction, machinery ***	20	0.046	0.0075	0.13	0.039	0.033	0.00057	0.0018	0		0.0064
Transport RME from transesterification, fuel ****	9043	9.24	5.38	0.24	84.91	2.32		0			0.86
Transport RME from transesterification, machinery ****	41	0.094	0.015	0.26	0.078	0.068	0.0011	0.0037	0		0.013
Transport of glycerine *****	991	1.01	0.59	0.026	9.30	0.25		0			0.094
Transport of glycerine, machinery, Swedish el. *****	4.5	0.010	0.0017	0.028	0.0086	0.0074	0.00013	0.00041	0		0.0014
Emissions when driving on the RME, fossil meth ****	156080	1718.93	312.53		25979.27	165.31					117.20
Compensation for bio-carbon in glycerine replacing fossil carbon	-156080										
Total; cultivation, - driving	1017673	2124.55	786.64	610.52	29561.50	1630.55	5723.63	5476.50	33.96	0.056	302.55
Total; cultivation, - driving [g/MJ_{engine}]	72.36	0.151	0.0559	0.0434	2.102	0.116	0.407	0.389	0.00241	0.0000040	0.0215
Total; cultivation, - driving [g/MJ_{fuel}]	21.36	0.0101	0.0118	0.0151	0.0888	0.0363	0.142	0.136	0.00084	0.0000014	0.00459
Total; cultivation, - driving[a]	861593										
Total; cultivation, - driving [g/MJ_{engine}][a]	61.26										
Total; cultivation, - driving [g/MJ_{fuel}][a]	17.49										
Allocation (MJ)	725185	1986.65	619.72	404.88	28307.58	1114.59	3684.87	3526.09	21.86	0.036	236.90
cultivation, - driving [g/MJ_{engine}]	51.56	0.141	0.0441	0.0288	2.013	0.0793	0.262	0.251	0.00155	0.0000025	0.0168
cultivation, - driving [g/MJ_{fuel}]	14.11	0.00664	0.00761	0.0100	0.0577	0.0235	0.0913	0.0874	0.000542	0.0000009	0.00297
Allocation (MJ)[a]	569105										
cultivation, - driving [g/MJ_{engine}][a]	40.47										
cultivation, - driving [g/MJ_{fuel}][a]	10.24										

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Allocation (SEK)	797864	2019.89	661.97	457.26	28612.08	1248.52	4219.23	4037.25	25.04	0.041	253.85
cultivation, - driving [g/MJ_{engine}]	56.73	0.144	0.0471	0.0325	2.034	0.0888	0.300	0.287	0.00178	0.0000029	0.0180
cultivation, - driving [g/MJ_{fuel}]	15.91	0.00746	0.00866	0.0113	0.0653	0.0269	0.105	0.100	0.000621	0.0000010	0.00339
Allocation (SEK)[a]	641784										
cultivation, - driving [g/MJ_{engine}][a]	45.63										
cultivation, - driving [g/MJ_{fuel}][a]	12.04										
* RME, meal and glycerine included											
** RME and glycerine included											
*** Meal included											
**** RME included											
***** Glycerine included											
Allocation (soymeal, soyoil, fossil glycerine)											
Total; cultivation, - driving (0)[a]	861593	2124.55	786.64	610.52	29561.50	1630.55	5723.63	5476.50	33.96	0.056	302.55
Production, soymeal with eq. amount soyoil (1)	378981	942.16	203.75	927.01	3404.19	3303.62	146.72	147.38	23.52		264.39
Transport of soymeal with eq. amount soyoil (2)	9167	9.33	5.53	0.24	85.85	2.35		0			0.87
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	18.17	0.042	0.0067	0.11	0.035	0.030	0.00051	0.0016	0		0.0058
Production of fossil glycerine (4)	607340	380.14	287.03	1084.23	1241.73	1303.25	0.45	22.53	43.82		79.44
Total [(0) - [(1) + (2) + (3) + (4)]][a]	-133913	792.88	290.33	-1401.07	24829.70	-2978.70	5576.46	5306.58	-33.38	0.056	-42.15
cultivation, - driving [g/MJ_{engine}][a]	-9.52	0.0564	0.02064	-0.0996	1.765	-0.212	0.397	0.377	-0.00237	0.0000040	-0.00300
cultivation, - driving [g/MJ_{fuel}][a]	-7.19	-0.0230	-0.00055	-0.0347	-0.0285	-0.0779	0.138	0.132	-0.00083	0.0000014	-0.00395

[a] With compensation for bio-carbon in glycerine replacing fossil carbon.

Table A14. Emissions categories and energy requirements, large-scale production of RME

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Cultivation of rapeseed *	2404705	90.50	14407.29	43.51	2398.71	41.27	194.06	48.04	11783.83	71.74
Transport seed to extraction, fuel *	15527	0.58	106.40	0.32	18.90	0.33	4.24	1.05	214.61	1.31
Transport seed to extraction, machinery *	64	0.0024	0.17	0.00050	0.014	0.00024	0.016	0.0038	13.59	0.083
Emissions, electricity, large-scale oil extraction *	5162	0.19	13.40	0.040	1.13	0.019	1.25	0.31	1091.00	6.64
Total machinery, oil extraction, Swedish el. *	105	0.0039	0.27	0.00082	0.023	0.00039	0.025	0.0063	22.18	0.14
Building material, Swedish el. *	43	0.0016	0.11	0.00034	0.0094	0.00016	0.010	0.0026	9.13	0.056
Emissions, hexane *	1390	0.052	9.37	0.028	0.59	0.010	0.92	0.23	128.56	0.78
Methanol, natural gas, best case **	43274	1.63	67.44	0.20	12.28	0.21	3.20	0.79	1504.48	9.16
Transport of methanol **	1037	0.039	7.06	0.021	1.25	0.022	0.29	0.071	14.33	0.087
Transport of methanol, machinery, Swedish el. **	5.5	0.00021	0.014	0.000043	0.0012	0.000021	0.0013	0.00033	1.16	0.0071
Catalyst, KOH **	3072	0.12	19.79	0.060	1.65	0.028	0.052	0.013	87.79	0.53
Electricity, transesterification **	6083	0.23	15.79	0.048	1.33	0.023	1.47	0.36	1285.69	7.83
Machinery, transesterification, Swedish el. **	64	0.0024	0.17	0.00050	0.014	0.00024	0.015	0.0038	13.53	0.082
Building material, transesterification, Swedish el. **	27	0.0010	0.070	0.00021	0.0059	0.00010	0.0065	0.0016	5.70	0.035
Transport meal from extraction, fuel ***	6793	0.26	47.06	0.14	8.36	0.14	1.78	0.44	93.89	0.57
Transport meal from extraction, machinery ***	24	0.00089	0.062	0.00019	0.0052	0.000089	0.0057	0.0014	5.01	0.031
Transport RME from transesterification, fuel ****	9067	0.34	61.75	0.19	10.97	0.19	2.52	0.62	125.32	0.76
Transport RME from transesterification, machinery ****	48.1	0.0018	0.12	0.00038	0.011	0.00018	0.012	0.0029	10.16	0.062
Transport of glycerine *****	993	0.037	6.77	0.020	1.20	0.021	0.28	0.068	13.73	0.084
Transport of glycerine, machinery, Swedish el. *****	5.3	0.00020	0.014	0.000041	0.0012	0.000020	0.0013	0.00031	1.11	0.0068
Emissions when driving on the RME, fossil meth ****	159518	6.00	18350.79	55.42	3356.17	57.74	193.77	47.97		0
Compensation for bio-carbon in glycerine replacing fossil carbon	-156080									
Total; cultivation, - driving	2657008	100	33113.91	100	5812.63	100	403.91	100	16424.80	100
Total; cultivation, - driving [g/MJ_{engine}]	188.92		2.355		0.4133		0.02872		1.168	
Total; cultivation, - driving [g/MJ_{fuel}]	61.91		0.366		0.0609		0.00521		0.407	
Total; cultivation, - driving[a]	2500928									
Total; cultivation, - driving [g/MJ_{engine}][a]	177.83									
Total; cultivation, - driving [g/MJ_{fuel}][a]	58.04									
Allocation (MJ)	1782192	67.08	27876.70	84.18	4940.49	85.00	330.19	81.75	11451.56	69.72
cultivation, - driving [g/MJ_{engine}]	126.72		1.982		0.3513		0.02348		0.814	
cultivation, - driving [g/MJ_{fuel}]	40.22		0.236		0.0393		0.00338		0.284	
Allocation (MJ)[a]	1626112									
cultivation, - driving [g/MJ_{engine}][a]	115.62									
cultivation, - driving [g/MJ_{fuel}][a]	36.35									

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Allocation (SEK)	2007447	75.55	29231.15	88.27	5165.96	88.87	348.78	86.35	12617.18	76.82
cultivation, - driving [g/MJ_{engine}]	142.74		2.078		0.3673		0.02480		0.897	
cultivation, - driving [g/MJ_{fuel}]	45.81		0.270		0.0449		0.00384		0.313	
Allocation (SEK)[a]	1851366									
cultivation, - driving [g/MJ_{engine}][a]	131.64									
cultivation, - driving [g/MJ_{fuel}][a]	41.94									
* RME, meal and glycerine included										
** RME and glycerine included										
*** Meal included										
**** RME included										
***** Glycerine included										
Allocation (soymeal, soyoil, fossil glycerine)										
Total; cultivation, - driving (0)[a]	2500928	94.13	33113.91	100	5812.63	100	403.91	100	16424.80	100
Production, soymeal with eq. amount soyoil (1)	445812	16.78	5983.08	18.07	490.88	8.45	125.67	31.11	7711.09	46.95
Transport of soymeal with eq. amount soyoil (2)	9191	0.35	62.44	0.19	11.09	0.19	2.59	0.64	127.03	0.77
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	21	0.00080	0.055	0.00017	0.0047	0.000080	0.0051	0.0013	4.51	0.027
Production of fossil glycerine (4)	639708	24.08	2211.86	6.68	160.57	2.76	137.61	34.07	14532.03	88.48
Total [(0) - [(1) + (2) + (3) + (4)]][a]	1406196	52.92	24856.48	75.06	5150.09	88.60	138.04	34.18	-5949.85	-36.22
cultivation, - driving [g/MJ_{engine}][a]	99.99		1.767		0.3662		0.00982		-0.423	
cultivation, - driving [g/MJ_{fuel}][a]	30.90		0.161		0.0445		-0.00138		-0.147	

[a] With compensation for bio-carbon in glycerine replacing fossil carbon.

APPENDIX 2. PRODUCTION OF ETHANOL FUEL

Table A15. Emissions, cultivation of wheat

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Seed	30685	15.02	18.35	18.89	120.06	56.40	189.29	173.22	1.07	0.0017	6.43
Production of fertilisers	420396	98.60	247.42	419.94	838.40	1328.11	89.10	2116.30	27.31	0.044	131.22
Soil emissions							4797.60	2350.82			
Production of pesticides	7267	3.93	0.43	0.27	10.22	25.70	0.24	2.23	0.31		0.06
Tractive power	177240	192.74	133.35	4.66	2083.56	45.38		0			27.81
Heat for seed drying	179510	75.09	89.17	21.12	143.14	45.67		2.35			4.69
Electricity for drying and cleaning of the seed	2079	4.77	0.77	12.99	3.98	3.45	0.058	0.19	0		0.66
Machinery inputs (Swedish electricity)	4520	10.38	1.67	28.24	8.65	7.49	0.13	0.41	0		1.44
Transport of fertiliser	1137	2.24	1.04	0.030	11.74	0.29		0			0.18
Machinery inputs, transport of fertiliser, (Sw. el.)	74	0.17	0.027	0.46	0.14	0.12	0.0021	0.0067	0		0.024
Total emissions	822909	402.94	492.24	506.60	3219.89	1512.62	5076.41	4645.53	28.69	0.046	172.53

Table A16. Emissions categories and energy requirements, cultivation of wheat

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Seed	82423	3.73	497.25	3.73	81.45	3.73	8.08	3.73	489.93	3.73
Production of fertilisers	1056676	47.80	2106.52	15.80	139.34	6.38	105.85	48.88	5740.19	43.69
Soil emissions	695844	31.48	9019.49	67.64	1671.13	76.51	0	0	0	0
Production of pesticides	7941	0.36	33.57	0.25	1.40	0.064	0.33	0.15	292.54	2.23
Tractive power	177733	8.04	1503.88	11.28	269.17	12.32	61.08	28.21	2456.07	18.69
Heat for seed drying	180841	8.18	145.86	1.09	18.49	0.85	38.82	17.93	2487.33	18.93
Electricity for drying and cleaning of the seed	2443	0.11	6.34	0.048	0.53	0.024	0.59	0.27	516.32	3.93
Machinery inputs (Swedish electricity)	5312	0.24	13.78	0.103	1.16	0.053	1.28	0.59	1122.58	8.54
Transport of fertiliser	1142	0.052	8.51	0.064	1.52	0.069	0.51	0.23	15.76	0.12
Machinery inputs, transport of fertiliser, (Sw. el.)	87	0.0039	0.23	0.0017	0.019	0.00087	0.021	0.0097	18.36	0.14
Total emissions	2210443	100	13335.43	100	2184.21	100	216.56	100	13139.09	100

Table A17. Emissions, small-scale production of ethanol fuel

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Cultivation of wheat *	822909	402.94	492.24	506.60	3219.89	1512.62	5076.41	4645.53	28.69	0.046	172.53
Emissions, electricity, small-scale ethanol fermentation *	7965	18.28	2.95	49.77	15.24	13.20	0.22	0.72	0		2.54
Emissions, steam (heat), small-scale ethanol fermentation *	6463	148.66	68.73	20.68	230.53	29.52	0	7.76	12.50		52.35
Emissions, electricity, small-scale ethanol distillation **	4762	10.93	1.76	29.75	9.11	7.89	0.13	0.43	0		1.52
Emissions, steam (heat), small-scale ethanol distillation **	37959	873.07	403.64	121.47	1353.89	173.35	0	45.55	73.39		307.47
Emissions, electricity, handling of distiller's waste ***	59	0.13	0.022	0.37	0.11	0.097	0.0016	0.0053	0		0.019
Emissions, steam (heat), handling of distiller's waste ***	0	0	0	0	0	0	0	0	0		0
Total machinery, ethanol production, Swedish el. *	2003	4.60	0.74	12.52	3.83	3.32	0.056	0.18	0		0.64
Building material, Swedish el. *	362	0.83	0.13	2.26	0.69	0.60	0.010	0.033	0		0.12
Emissions, handling of waste water, Swedish el. *	1710	3.93	0.63	10.69	3.27	2.83	0.048	0.15	0		0.55
Emissions production of chemicals for ethanol production *	7482	2.22	0.27	0.0032	24.50	34.90	0.10	0	0	0	2.37
Transport of chemicals for ethanol production *	379	0.39	0.23	0.0100	3.55	0.097		0			0.036
Transport of chemicals for ethanol production, machinery, Swedish el. *	1.5	0.0034	0.00056	0.0094	0.0029	0.0025	0.000042	0.00014	0		0.00048
Emissions production of ignition improver and corrosion inhibitor **	148590	51.44	679.63	5.75	520.86	346.02	0	0	0	0	84.63
Emissions production of denaturants **	62404	3.56	226.14	0.70	103.00	20.09	0	0	0	0	6.42
Transport of chemicals for ethanol fuel production **	2393	2.43	1.44	0.063	22.41	0.61		0			0.23
Transport of chemicals for ethanol fuel production, machinery, Swedish el. **	9.5	0.022	0.0035	0.059	0.018	0.016	0.00027	0.00086	0		0.0030
Emissions when driving on the ethanol fuel, fossil chemicals added **	433447	15155.75	1839.42		19344.17	0					114.54
Total; cultivation, - driving	1538899	16679.18	3717.97	760.70	24855.07	2145.17	5076.98	4700.36	114.57	0.046	745.95
Total; cultivation, - driving [g/MJ_{engine}]	74.64	0.809	0.180	0.0369	1.21	0.104	0.246	0.228	0.00556	0.0000022	0.0362
Total; cultivation, - driving [g/MJ_{fuel}]	21.23	0.0293	0.0361	0.0146	0.106	0.0412	0.098	0.090	0.00220	0.0000009	0.0121
Total; cultivation, - driving[a]	282543	1120.49	1386.31	254.10	2291.01	632.56	0.58	54.83	85.88	0	458.89
Total; cultivation, - driving [g/MJ_{fuel}][a]	5.43	0.0215	0.0266	0.00488	0.0440	0.0122	0.000011	0.00105	0.00165	0	0.00881
Allocation (MJ)	1205691	16450.81	3495.95	523.98	23481.41	1518.58	3085.47	2874.57	98.42	0.028	655.27
cultivation, - driving [g/MJ_{engine}]	58.48	0.798	0.170	0.0254	1.14	0.0737	0.150	0.139	0.00477	0.0000014	0.0318
cultivation, - driving [g/MJ_{fuel}]	14.83	0.0249	0.0318	0.0101	0.0795	0.0292	0.0593	0.0552	0.00189	0.0000005	0.0104
Allocation (MJ)[a]	272141	1050.18	1357.39	216.10	2180.43	599.32	0.40	51.36	80.98	0	435.88
cultivation, - driving [g/MJ_{fuel}][a]	5.23	0.0202	0.0261	0.00415	0.0419	0.0115	0.000008	0.00099	0.00156	0	0.00837
Allocation (SEK)	1490650	16646.03	3685.84	726.15	24656.28	2054.45	4788.91	4436.26	112.23	0.043	732.81
cultivation, - driving [g/MJ_{engine}]	72.30	0.807	0.179	0.0352	1.196	0.100	0.232	0.215	0.00544	0.0000021	0.0355
cultivation, - driving [g/MJ_{fuel}]	20.31	0.0286	0.0355	0.0139	0.102	0.0395	0.092	0.085	0.00216	0.0000008	0.0119
Allocation (SEK)[a]	280988	1110.20	1382.11	248.29	2274.91	627.66	0.55	54.33	85.18	0	455.54
cultivation, - driving [g/MJ_{fuel}][a]	5.40	0.0213	0.0265	0.00477	0.0437	0.0121	0.000011	0.00104	0.00164	0	0.00875

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
* Ethanol fuel and distiller's waste included											
** Ethanol fuel included											
*** Distiller's waste included											
Allocation (soymeal, soyoil)											
Total; cultivation, - driving (0)	1538899	16679.18	3717.97	760.70	24855.07	2145.17	5076.98	4700.36	114.57	0.046	745.95
Total; cultivation, - driving (0)[a]	282543	1120.49	1386.31	254.10	2291.01	632.56	0.58	54.83	85.88	0	458.89
Production, soymeal with eq. amount soyoil (1)	875545	2176.72	470.91	2142.17	7864.97	7634.50	339.14	340.53	54.32	0	610.82
Transport of soymeal with eq. amount soyoil (2)	13095	13.33	7.89	0.34	122.63	3.35		0			1.24
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	25.95	0.060	0.0096	0.16	0.050	0.043	0.00073	0.0023	0		0.0083
Total [(0) - [(1) + (2) + (3)]]	650233	14489.08	3239.15	-1381.97	16867.42	-5492.73	4737.85	4359.83	60.25	0.046	133.88
cultivation, - driving [g/MJ_{engine}]	31.54	0.703	0.157	-0.0670	0.818	-0.266	0.230	0.211	0.00292	0.0000022	0.0065
cultivation, - driving [g/MJ_{fuel}]	4.16	-0.0128	0.0269	-0.0265	-0.0476	-0.106	0.091	0.084	0.00116	0.0000009	0.00037
Total [(0) - [(1) + (2) + (3)]][a]	-606123	-1069.62	907.50	-1888.58	-5696.64	-7005.34	-338.56	-285.70	31.57	0	-153.18
cultivation, - driving [g/MJ_{fuel}][a]	-11.64	-0.0205	0.0174	-0.0363	-0.1094	-0.135	-0.00650	-0.00549	0.000606	0	-0.00294

[a] Cultivation and use of the fuel produced excluded.

Table A18. Emissions categories and energy requirements, small-scale production of ethanol fuel

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Cultivation of wheat *	2210443	74.15	13335.43	45.69	2184.21	43.87	216.56	10.03	13139.09	52.30
Emissions, electricity, small-scale ethanol fermentation *	9360	0.31	24.29	0.083	2.05	0.041	2.26	0.10	1978.06	7.87
Emissions, steam (heat), small-scale ethanol fermentation *	9532	0.32	201.88	0.69	29.78	0.60	33.58	1.55	86.18	0.34
Emissions, electricity, small-scale ethanol distillation **	5596	0.19	14.52	0.050	1.22	0.025	1.35	0.063	1182.61	4.71
Emissions, steam (heat), small-scale ethanol distillation **	55983	1.88	1185.65	4.06	174.90	3.51	197.23	9.13	506.13	2.01
Emissions, electricity, handling of distiller's waste ***	69	0.0023	0.18	0.00061	0.015	0.00030	0.017	0.00077	14.60	0.058
Emissions, steam (heat), handling of distiller's waste ***	0	0	0	0	0	0	0	0	0	0
Total machinery, ethanol production, Swedish el. *	2354	0.079	6.11	0.021	0.51	0.010	0.57	0.026	497.49	1.98
Building material, Swedish el. *	425	0.014	1.10	0.0038	0.093	0.0019	0.10	0.0048	89.88	0.36
Emissions, handling of waste water, Swedish el. *	2010	0.067	5.21	0.018	0.44	0.0088	0.48	0.022	424.70	1.69
Emissions production of chemicals for ethanol production *	7487	0.25	52.24	0.18	3.20	0.064	0.20	0.0091	121.07	0.48
Transport of chemicals for ethanol production *	380	0.013	2.58	0.0088	0.46	0.0092	0.11	0.0050	5.25	0.021
Transport of chemicals for ethanol production, machinery, Swedish el. *	1.8	0.000059	0.0046	0.000016	0.00039	0.0000078	0.00043	0.000020	0.37	0.0015
Emissions production of ignition improver and corrosion inhibittor **	148826	4.99	710.63	2.43	67.29	1.35	273.95	12.68	4994.97	19.88
Emissions production of denaturants **	62427	2.09	92.19	0.32	13.31	0.27	90.60	4.20	2045.93	8.14
Transport of chemicals for ethanol fuel production **	2399	0.080	16.30	0.056	2.89	0.058	0.67	0.031	33.15	0.13
Transport of chemicals for ethanol fuel production, machinery, Swedish el. **	11	0.00037	0.029	0.000099	0.0024	0.000049	0.0027	0.00012	2.36	0.0094
Emissions when driving on the ethanol fuel, fossil chemicals added **	463758	15.56	13540.92	46.39	2499.01	50.19	1342.00	62.14		0
Total; cultivation, - driving	2981061	100	29189.27	100	4979.38	100	2159.68	100	25121.83	100
Total; cultivation, - driving [g/MJ_{engine}]	144.59		1.416		0.2415		0.1048		1.219	
Total; cultivation, - driving [g/MJ_{fuel}]	48.35		0.301		0.0476		0.0157		0.483	
Total; cultivation, - driving[a]	306860	100	2312.92	100	296.17	100	601.12	100	11982.74	100
Total; cultivation, - driving [g/MJ_{fuel}][a]	5.89		0.0444		0.00569		0.0115		0.230	
Allocation (MJ)	2101516	70.50	23842.84	81.68	4108.23	82.50	2060.08	95.39	18696.66	74.42
cultivation, - driving [g/MJ_{engine}]	101.93		1.156		0.1993		0.0999		0.907	
cultivation, - driving [g/MJ_{fuel}]	31.46		0.198		0.0309		0.0138		0.359	
Allocation (MJ)[a]	294415	95.94	2197.64	95.02	281.82	95.16	586.48	97.56	10711.69	89.39
cultivation, - driving [g/MJ_{fuel}][a]	5.66		0.0422		0.00541		0.0113		0.206	
Allocation (SEK)	2853776	95.73	28415.76	97.35	4853.36	97.47	2145.26	99.33	24179.95	96.25
cultivation, - driving [g/MJ_{engine}]	138.42		1.378		0.2354		0.1041		1.173	
cultivation, - driving [g/MJ_{fuel}]	45.91		0.286		0.0452		0.0154		0.464	
Allocation (SEK)[a]	305000	99.39	2296.09	99.27	294.08	99.29	598.99	99.65	11786.40	98.36
cultivation, - driving [g/MJ_{fuel}][a]	5.86		0.0441		0.00565		0.0115		0.226	

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
* Ethanol fuel and distiller's waste included										
** Ethanol fuel included										
*** Distiller's waste included										
Allocation (soymeal, soyoil)										
Total; cultivation, - driving (0)	2981061	100	29189.27	100	4979.38	100	2159.68	100	25121.83	100
Total; cultivation, - driving (0)[a]	306860	100	2312.92	100	296.17	100	601.12	100	11982.74	100
Production, soymeal with eq. amount soyoil (1)	1029967	34.55	13825.35	47.36	1134.18	22.78	290.43	13.45	17817.87	70.93
Transport of soymeal with eq. amount soyoil (2)	13129	0.44	89.20	0.31	15.84	0.32	3.69	0.17	181.46	0.72
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	30.50	0.0010	0.079	0.00027	0.0067	0.00013	0.0074	0.00034	6.45	0.026
Total [(0) - [(1) + (2) + (3)]]	1937934	65.01	15274.64	52.33	3829.36	76.90	1865.55	86.38	7116.06	28.33
cultivation, - driving [g/MJ_{engine}]	94.00		0.741		0.1857		0.0905		0.3452	
cultivation, - driving [g/MJ_{fuel}]	28.32		0.0333		0.0256		0.0101		0.1367	
Total [(0) - [(1) + (2) + (3)]][a]	-736267	-239.94	-11601.71	-501.60	-853.86	-288.30	306.99	51.07	-6023.03	-50.26
cultivation, - driving [g/MJ_{fuel}][a]	-14.1		-0.223		-0.0164		0.00590		-0.116	

[a] Cultivation and use of the fuel produced excluded.

Table A19. Emissions, medium-scale production of ethanol fuel

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Cultivation of wheat *	822909	402.94	492.24	506.60	3219.89	1512.62	5076.41	4645.53	28.69	0.046	172.53
Emissions, electricity, medium-scale ethanol fermentation *	7135	16.38	2.64	44.58	13.65	11.83	0.20	0.65	0		2.27
Emissions, steam (heat), medium-scale ethanol fermentation *	5290	100.51	16.40	3.53	312.11	11.11	0	7.05	5.82		11.99
Emissions, electricity, medium-scale ethanol distillation **	4266	9.79	1.58	26.66	8.16	7.07	0.12	0.39	0		1.36
Emissions, steam (heat), medium-scale ethanol distillation **	31068	590.29	96.31	20.71	1833.01	65.24	0	41.42	34.17		70.42
Emissions, electricity, handling of distiller's waste ***	57	0.13	0.021	0.36	0.11	0.095	0.0016	0.0052	0		0.018
Emissions, steam (heat), handling of distiller's waste ***	0	0	0	0	0	0	0	0	0		0
Total machinery, ethanol production, Swedish el. *	703	1.61	0.26	4.39	1.34	1.17	0.020	0.06	0		0.22
Building material, Swedish el. *	212	0.49	0.078	1.32	0.40	0.35	0.0059	0.019	0		0.067
Emissions, handling of waste water, Swedish el. *	1671	3.84	0.62	10.44	3.20	2.77	0.047	0.15	0		0.53
Emissions production of chemicals for ethanol production *	7482	2.22	0.27	0.0032	24.50	34.90	0.10	0	0	0	2.37
Transport of chemicals for ethanol production *	329	0.33	0.20	0.0086	3.08	0.084		0			0.031
Transport of chemicals for ethanol production, machinery, Swedish el. *	1.3	0.0030	0.00048	0.0081	0.0025	0.0022	0.000037	0.00012	0		0.00042
Emissions production of ignition improver and corrosion inhibitor **	148590	51.44	679.63	5.75	520.86	346.02	0	0	0	0	84.63
Emissions production of denaturants **	62404	3.56	226.14	0.70	103.00	20.09	0	0	0	0	6.42
Transport of chemicals for ethanol fuel production **	2339	2.39	1.39	0.062	21.96	0.60		0			0.22
Transport of chemicals for ethanol fuel production, machinery, Swedish el. **	11	0.024	0.0039	0.066	0.020	0.018	0.00030	0.00096	0		0.0034
Transport of wheat to ethanol production *	3836	4.11	3.03	0.10	38.28	0.98		0			0.32
Transport of wheat to ethanol production, machinery, Swedish el. *	407.5	0.94	0.15	2.55	0.78	0.68	0.011	0.037	0		0.13
Transport of distiller's waste from ethanol production ***	12305	13.17	9.72	0.32	122.79	3.15		0			1.03
Transport of distiller's waste from ethanol production, machinery, Swedish el. ***	1307	3.00	0.48	8.17	2.50	2.17	0.037	0.12	0		0.42
Transport of produced ethanol fuel **	1138	1.16	0.68	0.030	10.69	0.29		0			0.11
Transport of produced ethanol fuel, machinery, Swedish el. **	5.1	0.012	0.0019	0.032	0.010	0.0085	0.00014	0.00047	0		0.0016
Emissions when driving on the ethanol fuel, fossil chemicals added **	433447	15155.75	1839.42		19344.17	0					114.54
Total; cultivation, - driving	1546913	16364.09	3371.25	636.40	25584.52	2021.24	5076.95	4695.43	68.68	0.046	469.64
Total; cultivation, - driving [g/MJ_{engine}]	75.03	0.794	0.164	0.0309	1.24	0.098	0.246	0.228	0.00333	0.0000022	0.0228
Total; cultivation, - driving [g/MJ_{fuel}]	21.39	0.0232	0.0294	0.0122	0.120	0.0388	0.098	0.090	0.00132	0.0000009	0.00682
Total; cultivation, - driving[a]	290558	805.40	1039.59	129.79	3020.45	508.62	0.54	49.91	39.99	0	182.58
Total; cultivation, - driving [g/MJ_{fuel}][a]	5.58	0.0155	0.0200	0.00249	0.0580	0.0098	0.000010	0.00096	0.00077	0	0.00351

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Allocation (MJ)	1199820	16138.56	3158.67	402.56	24040.17	1397.41	3085.42	2869.86	55.14	0.028	393.45
cultivation, - driving [g/MJ_{engine}]	58.20	0.783	0.153	0.0195	1.17	0.0678	0.150	0.139	0.00267	0.0000014	0.0191
cultivation, - driving [g/MJ_{fuel}]	14.72	0.0189	0.0253	0.0077	0.0902	0.0268	0.0593	0.0551	0.00106	0.0000005	0.00536
Allocation (MJ)[a]	266271	737.93	1020.10	94.69	2739.19	478.16	0.36	46.66	37.71	0	174.07
cultivation, - driving [g/MJ_{fuel}][a]	5.11	0.0142	0.0196	0.00182	0.0526	0.0092	0.0000068	0.00090	0.00072	0	0.00334
Allocation (SEK)	1485014	16317.52	3331.76	595.00	25253.87	1926.37	4788.85	4431.26	66.72	0.043	457.36
cultivation, - driving [g/MJ_{engine}]	72.03	0.791	0.162	0.0289	1.225	0.093	0.232	0.215	0.00324	0.0000021	0.0222
cultivation, - driving [g/MJ_{fuel}]	20.20	0.0223	0.0287	0.0114	0.114	0.0370	0.092	0.085	0.00128	0.0000008	0.00659
Allocation (SEK)[a]	275352	781.69	1028.03	117.15	2872.51	499.59	0.48	49.33	39.66	0	180.09
cultivation, - driving [g/MJ_{fuel}][a]	5.29	0.0150	0.0197	0.00225	0.0552	0.0096	0.0000093	0.00095	0.00076	0	0.00346
* Ethanol fuel and distiller's waste included											
** Ethanol fuel included											
*** Distiller's waste included											
Allocation (soymeal, soyoil)											
Total; cultivation, - driving (0)	1546913	16364.09	3371.25	636.40	25584.52	2021.24	5076.95	4695.43	68.68	0.046	469.64
Total; cultivation, - driving (0)[a]	290558	805.40	1039.59	129.79	3020.45	508.62	0.54	49.91	39.99	0	182.58
Production, soymeal with eq. amount soyoil (1)	875545	2176.72	470.91	2142.17	7864.97	7634.50	339.14	340.53	54.32	0	610.82
Transport of soymeal with eq. amount soyoil (2)	13095	13.33	7.89	0.34	122.63	3.35		0			1.24
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	25.95	0.060	0.0096	0.16	0.050	0.043	0.00073	0.0023	0		0.0083
Total [(0) - [(1) + (2) + (3)]]	658247	14173.99	2892.44	-1506.28	17596.87	-5616.66	4737.81	4354.90	14.36	0.046	-142.43
cultivation, - driving [g/MJ_{engine}]	31.93	0.688	0.140	-0.0731	0.854	-0.272	0.230	0.211	0.00070	0.0000022	-0.00691
cultivation, - driving [g/MJ_{fuel}]	4.32	-0.0189	0.0202	-0.0289	-0.0336	-0.108	0.091	0.084	0.00028	0.0000009	-0.00494
Total [(0) - [(1) + (2) + (3)]][a]	-598108	-1384.71	560.78	-2012.89	-4967.20	-7129.27	-338.59	-290.63	-14.32	0	-429.49
cultivation, - driving [g/MJ_{fuel}][a]	-11.49	-0.0266	0.0108	-0.0387	-0.0954	-0.137	-0.0065	-0.0056	-0.00028	0	-0.00825

[a] Cultivation and use of the fuel produced excluded.

Table A20. Emissions categories and energy requirements, medium-scale production of ethanol fuel

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Cultivation of wheat *	2210443	74.07	13335.43	45.15	2184.21	43.05	216.56	10.79	13139.09	52.60
Emissions, electricity, medium-scale ethanol fermentation *	8385	0.28	21.76	0.074	1.83	0.036	2.02	0.10	1772.01	7.09
Emissions, steam (heat), medium-scale ethanol fermentation *	7660	0.26	234.71	0.79	40.32	0.79	10.60	0.53	70.53	0.28
Emissions, electricity, medium-scale ethanol distillation **	5013	0.17	13.01	0.044	1.10	0.022	1.21	0.060	1059.42	4.24
Emissions, steam (heat), medium-scale ethanol distillation **	44987	1.51	1378.43	4.67	236.80	4.67	62.28	3.10	414.24	1.66
Emissions, electricity, handling of distiller's waste ***	67	0.0023	0.18	0.00059	0.015	0.00029	0.016	0.00081	14.26	0.057
Emissions, steam (heat), handling of distiller's waste ***	0	0	0	0	0	0	0	0	0	0
Total machinery, ethanol production, Swedish el. *	826	0.028	2.14	0.0073	0.18	0.0036	0.20	0.0099	174.56	0.70
Building material, Swedish el. *	249	0.0083	0.65	0.0022	0.054	0.0011	0.060	0.0030	52.56	0.21
Emissions, handling of waste water, Swedish el. *	1964	0.066	5.10	0.017	0.43	0.0085	0.47	0.024	415.04	1.66
Emissions production of chemicals for ethanol production *	7487	0.25	52.24	0.18	3.20	0.063	0.20	0.0098	121.07	0.48
Transport of chemicals for ethanol production *	329	0.011	2.24	0.0076	0.40	0.0078	0.093	0.0046	4.55	0.018
Transport of chemicals for ethanol production, machinery, Swedish el. *	1.5	0.000051	0.0040	0.000013	0.00033	0.0000066	0.00037	0.000018	0.32	0.0013
Emissions production of ignition improver and corrosion inhibittor **	148826	4.99	710.63	2.41	67.29	1.33	273.95	13.65	4994.97	20.00
Emissions production of denaturants **	62427	2.09	92.19	0.31	13.31	0.26	90.60	4.51	2045.93	8.19
Transport of chemicals for ethanol fuel production **	2345	0.079	15.97	0.054	2.84	0.056	0.65	0.033	32.41	0.13
Transport of chemicals for ethanol fuel production, machinery, Swedish el. **	12	0.00042	0.032	0.00011	0.0027	0.000054	0.0030	0.00015	2.63	0.011
Transport of wheat to ethanol production *	3847	0.13	27.78	0.094	4.95	0.097	1.38	0.069	53.16	0.21
Transport of wheat to ethanol production, machinery, Swedish el. *	479	0.016	1.24	0.0042	0.10	0.0021	0.12	0.0058	101.21	0.41
Transport of distiller's waste from ethanol production ***	12339	0.41	89.10	0.30	15.86	0.31	4.42	0.22	170.51	0.68
Transport of distiller's waste from ethanol production, machinery, Swedish el. ***	1536	0.051	3.99	0.013	0.34	0.0066	0.37	0.018	324.64	1.30
Transport of produced ethanol fuel **	1141	0.038	7.77	0.026	1.38	0.027	0.32	0.016	15.77	0.063
Transport of produced ethanol fuel, machinery, Swedish el. **	6.1	0.00020	0.016	0.000053	0.0013	0.000026	0.0015	0.000073	1.28	0.0051
Emissions when driving on the ethanol fuel, fossil chemicals added **	463758	15.54	13540.92	45.85	2499.01	49.26	1342.00	66.85		0
Total; cultivation, - driving	2984127	100	29535.51	100	5073.61	100	2007.52	100	24980.18	100
Total; cultivation, - driving [g/MJ_{engine}]	144.74		1.433		0.2461		0.0974		1.212	
Total; cultivation, - driving [g/MJ_{fuel}]	48.41		0.307		0.0495		0.0128		0.480	
Total; cultivation, - driving[a]	309926	100	2659.16	100	390.39	100	448.96	100	11841.09	100
Total; cultivation, - driving [g/MJ_{fuel}][a]	5.95		0.0511		0.00750		0.00862		0.227	

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Allocation (MJ)	2090835	70.07	24074.65	81.51	4180.40	82.39	1911.83	95.23	18232.00	72.99
cultivation, - driving [g/MJ_{engine}]	101.41		1.168		0.2028		0.0927		0.884	
cultivation, - driving [g/MJ_{fuel}]	31.25		0.202		0.0323		0.0109		0.350	
Allocation (MJ)[a]	283734	91.55	2429.44	91.36	353.99	90.68	438.22	97.61	10247.03	86.54
cultivation, - driving [g/MJ_{fuel}][a]	5.45		0.0467		0.00680		0.00842		0.197	
Allocation (SEK)	2842988	95.27	28665.83	97.06	4930.54	97.18	1989.57	99.11	23568.34	94.35
cultivation, - driving [g/MJ_{engine}]	137.90		1.390		0.2392		0.0965		1.143	
cultivation, - driving [g/MJ_{fuel}]	45.70		0.291		0.0467		0.0124		0.453	
Allocation (SEK)[a]	294212	94.93	2546.16	95.75	371.26	95.10	443.30	98.74	11174.79	94.37
cultivation, - driving [g/MJ_{fuel}][a]	5.65		0.0489		0.00713		0.00851		0.215	
* Ethanol fuel and distiller's waste included										
** Ethanol fuel included										
*** Distiller's waste included										
Allocation (soymeal, soyoil)										
Total; cultivation, - driving (0)	2984127	100	29535.51	100	5073.61	100	2007.52	100	24980.18	100
Total; cultivation, - driving (0)[a]	309926	100	2659.16	100	390.39	100	448.96	100	11841.09	100
Production, soymeal with eq. amount soyoil (1)	1029967	34.51	13825.35	46.81	1134.18	22.35	290.43	14.47	17817.87	71.33
Transport of soymeal with eq. amount soyoil (2)	13129	0.44	89.20	0.30	15.84	0.31	3.69	0.18	181.46	0.73
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	30.50	0.0010	0.079	0.00027	0.0067	0.00013	0.0074	0.00037	6.45	0.026
Total [(0) - [(1) + (2) + (3)]]	1941000	65.04	15620.88	52.89	3923.58	77.33	1713.39	85.35	6974.41	27.92
cultivation, - driving [g/MJ_{engine}]	94.15		0.758		0.1903		0.0831		0.3383	
cultivation, - driving [g/MJ_{fuel}]	28.37		0.0400		0.0274		0.00713		0.1340	
Total [(0) - [(1) + (2) + (3)]][a]	-733201	-236.57	-11255.47	-423.27	-759.64	-194.58	154.83	34.49	-6164.68	-52.06
cultivation, - driving [g/MJ_{fuel}][a]	-14.08		-0.216		-0.0146		0.00297		-0.118	

[a] Cultivation and use of the fuel produced excluded.

Table A21. Emissions, large-scale production of ethanol fuel

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Cultivation of wheat *	822909	402.94	492.24	506.60	3219.89	1512.62	5076.41	4645.53	28.69	0.046	172.53
Emissions, electricity, large-scale ethanol fermentation *	6336	14.54	2.34	39.59	12.12	10.50	0.18	0.57	0		2.02
Emissions, steam (heat), large-scale ethanol fermentation *	4617	108.65	9.23	0.92	221.91	9.70	0	8.77	5.08		10.46
Emissions, electricity, large-scale ethanol distillation **	3788	8.69	1.40	23.67	7.25	6.28	0.11	0.34	0		1.21
Emissions, steam (heat), large-scale ethanol distillation **	27114	638.08	54.23	5.42	1303.28	56.94	0	51.52	29.83		61.46
Emissions, electricity, drying of distiller's waste ***	10560	24.24	3.90	65.98	20.20	17.50	0.30	0.96	0		3.37
Emissions, steam (heat), drying of distiller's waste ***	31657	745.00	63.31	6.33	1521.66	66.48	0	60.15	34.82		71.76
Total machinery, ethanol production, Swedish el. *	366	0.84	0.14	2.29	0.70	0.61	0.010	0.033	0		0.12
Building material, Swedish el. *	110	0.25	0.041	0.69	0.21	0.18	0.0031	0.0100	0		0.035
Emissions, handling of waste water, Swedish el. *	1632	3.75	0.60	10.20	3.12	2.71	0.046	0.15	0		0.52
Emissions production of chemicals for ethanol production *	7482	2.22	0.27	0.0032	24.50	34.90	0.10				2.37
Transport of chemicals for ethanol production *	309	0.32	0.18	0.0081	2.90	0.079		0			0.029
Transport of chemicals for ethanol production, machinery, Swedish el. *	1.4	0.0032	0.00052	0.0087	0.0027	0.0023	0.000039	0.00013	0		0.00045
Emissions production of ignition improver and corrosion inhibitor **	148590	51.44	679.63	5.75	520.86	346.02	0	0	0	0	84.63
Emissions production of denaturants **	62404	3.56	226.14	0.70	103.00	20.09	0	0	0	0	6.42
Transport of chemicals for ethanol fuel production **	1754	1.79	1.04	0.046	16.47	0.45		0			0.17
Transport of chemicals for ethanol fuel production, machinery, Swedish el. **	7.9	0.018	0.0029	0.050	0.015	0.013	0.00022	0.00072	0		0.0025
Transport of wheat to ethanol production *	40292	40.20	23.91	1.06	379.18	10.32		0			3.82
Transport of wheat to ethanol production, machinery, Swedish el. *	150	0.34	0.056	0.94	0.29	0.25	0.0042	0.014	0		0.048
Transport of distiller's waste from ethanol production ***	9632	9.00	5.43	0.25	92.04	2.47		0			0.92
Transport of distiller's waste from ethanol production, machinery, Swedish el. ***	29	0.066	0.011	0.18	0.055	0.048	0.00080	0.0026	0		0.0091
Transport of produced ethanol fuel **	17885	18.27	10.64	0.47	167.93	4.58		0			1.69
Transport of produced ethanol fuel, machinery, Swedish el. **	81	0.19	0.030	0.51	0.15	0.13	0.0023	0.0073	0		0.026
Emissions when driving on the ethanol fuel, fossil chemicals added **	433447	15155.75	1839.42		19344.17	0					114.54
Total; cultivation, - driving	1631153	17230.15	3414.21	671.67	26961.90	2102.86	5077.16	4768.05	98.41	0.046	538.14
Total; cultivation, - driving [g/MJ_{engine}]	79.12	0.836	0.166	0.0326	1.31	0.102	0.246	0.231	0.00477	0.0000022	0.0261
Total; cultivation, - driving [g/MJ_{fuel}]	23.01	0.0398	0.0302	0.0129	0.146	0.0404	0.098	0.092	0.00189	0.0000009	0.00814
Total; cultivation, - driving[a]	374797	1671.45	1082.55	165.07	4397.83	590.25	0.75	122.53	69.73	0	251.08
Total; cultivation, - driving [g/MJ_{fuel}][a]	7.20	0.0321	0.0208	0.00317	0.0845	0.0113	0.0000144	0.00235	0.00134	0	0.00482

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NO_x [g/ha]	SO_x [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	PAH [g/ha]	Particles [g/ha]
Allocation (MJ)	1232425	16226.66	3134.03	378.34	23811.87	1395.84	3085.38	2880.88	50.34	0.028	386.79
cultivation, - driving [g/MJ$_{engine}$]	59.78	0.787	0.152	0.0184	1.15	0.0677	0.150	0.140	0.00244	0.0000014	0.0188
cultivation, - driving [g/MJ$_{fuel}$]	15.35	0.0206	0.0249	0.0073	0.0858	0.0268	0.0593	0.0553	0.00097	0.0000005	0.00523
Allocation (MJ)[a]	298875	826.03	995.47	70.47	2510.89	476.59	0.32	57.67	32.91	0	167.41
cultivation, - driving [g/MJ$_{fuel}$][a]	5.74	0.0159	0.0191	0.00135	0.0482	0.0092	0.0000061	0.00111	0.00063	0	0.00322
Allocation (SEK)	1466249	16378.46	3273.93	527.04	24833.91	1814.16	4427.91	4111.89	59.27	0.040	437.55
cultivation, - driving [g/MJ$_{engine}$]	71.12	0.794	0.159	0.0256	1.205	0.088	0.215	0.199	0.00288	0.0000019	0.0212
cultivation, - driving [g/MJ$_{fuel}$]	19.84	0.0235	0.0276	0.0101	0.105	0.0348	0.085	0.079	0.00114	0.0000008	0.00620
Allocation (SEK)[a]	315085	871.28	1005.19	85.20	2681.44	494.90	0.41	60.20	34.25	0	172.54
cultivation, - driving [g/MJ$_{fuel}$][a]	6.05	0.0167	0.0193	0.00164	0.0515	0.0095	0.0000078	0.00116	0.00066	0	0.00331
* Ethanol fuel and distiller's waste included											
** Ethanol fuel included											
*** Distiller's waste included											
Allocation (soymeal, soyoil)											
Total; cultivation, - driving (0)	1631153	17230.15	3414.21	671.67	26961.90	2102.86	5077.16	4768.05	98.41	0.046	538.14
Total; cultivation, - driving (0)[a]	374797	1671.45	1082.55	165.07	4397.83	590.25	0.75	122.53	69.73	0	251.08
Production, soymeal with eq. amount soyoil (1)	875545	2176.72	470.91	2142.17	7864.97	7634.50	339.14	340.53	54.32	0	610.82
Transport of soymeal with eq. amount soyoil (2)	13095	13.33	7.89	0.34	122.63	3.35		0			1.24
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	25.95	0.060	0.0096	0.16	0.050	0.043	0.00073	0.0023	0		0.0083
Total [(0) - [(1) + (2) + (3)]]	742487	15040.04	2935.40	-1471.01	18974.25	-5535.03	4738.02	4427.52	44.10	0.046	-73.92
cultivation, - driving [g/MJ$_{engine}$]	36.01	0.730	0.142	-0.0714	0.920	-0.268	0.230	0.215	0.00214	0.0000022	-0.00359
cultivation, - driving [g/MJ$_{fuel}$]	5.94	-0.0022	0.0211	-0.0283	-0.0071	-0.106	0.091	0.085	0.00085	0.0000009	-0.00362
Total [(0) - [(1) + (2) + (3)]][a]	-513869	-518.65	603.74	-1977.61	-3589.82	-7047.65	-338.39	-218.01	15.41	0	-360.98
cultivation, - driving [g/MJ$_{fuel}$][a]	-9.87	-0.00996	0.0116	-0.0380	-0.0690	-0.135	-0.00650	-0.00419	0.000296	0	-0.00693

[a] Cultivation and use of the fuel produced excluded.

Table A22. Emissions categories and energy requirements, large-scale production of ethanol fuel

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Cultivation of wheat *	2210443	71.48	13335.43	43.57	2184.21	41.59	216.56	10.51	13139.09	47.19
Emissions, electricity, large-scale ethanol fermentation *	7445	0.24	19.32	0.063	1.63	0.031	1.80	0.087	1573.45	5.65
Emissions, steam (heat), large-scale ethanol fermentation *	7452	0.24	169.50	0.55	28.67	0.55	8.05	0.39	61.56	0.22
Emissions, electricity, large-scale ethanol distillation **	4451	0.14	11.55	0.038	0.97	0.019	1.07	0.052	940.71	3.38
Emissions, steam (heat), large-scale ethanol distillation **	43764	1.42	995.48	3.25	168.37	3.21	47.25	2.29	361.52	1.30
Emissions, electricity, drying of distiller's waste ***	12409	0.40	32.20	0.11	2.71	0.052	2.99	0.15	2622.42	9.42
Emissions, steam (heat), drying of distiller's waste ***	51097	1.65	1162.29	3.80	196.58	3.74	55.17	2.68	422.10	1.52
Total machinery, ethanol production, Swedish el. *	430	0.014	1.12	0.0036	0.094	0.0018	0.10	0.0050	90.95	0.33
Building material, Swedish el. *	130	0.0042	0.34	0.0011	0.028	0.00054	0.031	0.0015	27.39	0.098
Emissions, handling of waste water, Swedish el. *	1918	0.062	4.98	0.016	0.42	0.0080	0.46	0.022	405.39	1.46
Emissions production of chemicals for ethanol production *	7487	0.24	52.24	0.17	3.20	0.061	0.20	0.0095	121.07	0.43
Transport of chemicals for ethanol production *	310	0.010	2.11	0.0069	0.37	0.0071	0.086	0.0042	4.28	0.015
Transport of chemicals for ethanol production, machinery, Swedish el. *	1.6	0.000053	0.0043	0.000014	0.00036	0.0000068	0.00040	0.000019	0.35	0.0012
Emissions production of ignition improver and corrosion inhibittor **	148826	4.81	710.63	2.32	67.29	1.28	273.95	13.30	4994.97	17.94
Emissions production of denaturants **	62427	2.02	92.19	0.30	13.31	0.25	90.60	4.40	2045.93	7.35
Transport of chemicals for ethanol fuel production **	1759	0.057	11.98	0.039	2.13	0.041	0.49	0.024	24.31	0.087
Transport of chemicals for ethanol fuel production, machinery, Swedish el. **	9.3	0.00030	0.024	0.000079	0.0020	0.000039	0.0023	0.00011	1.97	0.0071
Transport of wheat to ethanol production *	40396	1.31	275.74	0.90	48.98	0.93	11.18	0.54	558.33	2.01
Transport of wheat to ethanol production, machinery, Swedish el. *	177	0.0057	0.46	0.0015	0.039	0.00073	0.043	0.0021	37.31	0.13
Transport of distiller's waste from ethanol production ***	9655	0.31	66.89	0.22	11.89	0.23	2.53	0.12	133.47	0.48
Transport of distiller's waste from ethanol production, machinery, Swedish el. ***	34	0.0011	0.087	0.00029	0.0074	0.00014	0.0081	0.00039	7.13	0.026
Transport of produced ethanol fuel **	17932	0.58	122.13	0.40	21.69	0.41	4.99	0.24	247.83	0.89
Transport of produced ethanol fuel, machinery, Swedish el. **	95	0.0031	0.25	0.00081	0.021	0.00040	0.023	0.0011	20.10	0.072
Emissions when driving on the ethanol fuel, fossil chemicals added **	463758	15.00	13540.92	44.24	2499.01	47.59	1342.00	65.16		0
Total; cultivation, - driving	3092405	100	30607.85	100	5251.62	100	2059.59	100	27841.62	100
Total; cultivation, - driving [g/MJ_{engine}]	150.00		1.485		0.2547		0.0999		1.350	
Total; cultivation, - driving [g/MJ_{fuel}]	50.49		0.328		0.0529		0.0138		0.535	
Total; cultivation, - driving[a]	418204	100	3731.50	100	568.40	100	501.04	100	14702.53	100
Total; cultivation, - driving [g/MJ_{fuel}][a]	8.03		0.0717		0.0109		0.00962		0.282	

Production factor	GWP		AP		EP		POCP		Input energy	
	[g CO_2-eq/ha]	[%]	[g SO_2-eq/ha]	[%]	[g PO_4^{3-}-eq/ha]	[%]	[g C_2H_4-eq/ha]	[%]	[MJ/ha]	[%]
Allocation (MJ)	2126320	68.76	23908.98	78.11	4150.89	79.04	1905.33	92.51	18372.60	65.99
cultivation, - driving [g/MJ_{engine}]	103.14		1.160		0.2013		0.0924		0.891	
cultivation, - driving [g/MJ_{fuel}]	31.93		0.199		0.0317		0.0108		0.353	
Allocation (MJ)[a]	319219	76.33	2263.77	60.67	324.48	57.09	431.72	86.17	10387.64	70.65
cultivation, - driving [g/MJ_{fuel}][a]	6.13		0.0435		0.00623		0.00829		0.200	
Allocation (SEK)	2728248	88.22	27574.52	90.09	4750.56	90.46	1968.40	95.57	22608.80	81.21
cultivation, - driving [g/MJ_{engine}]	132.33		1.337		0.2304		0.0955		1.097	
cultivation, - driving [g/MJ_{fuel}]	43.50		0.270		0.0432		0.0120		0.434	
Allocation (SEK)[a]	336605	80.49	2402.82	64.39	346.55	60.97	437.52	87.32	11149.26	75.83
cultivation, - driving [g/MJ_{fuel}][a]	6.47		0.0462		0.00666		0.00840		0.214	
* Ethanol fuel and distiller's waste included										
** Ethanol fuel included										
*** Distiller's waste included										
Allocation (soymeal, soyoil)										
Total; cultivation, - driving (0)	3092405	100	30607.85	100	5251.62	100	2059.59	100	27841.62	100
Total; cultivation, - driving (0)[a]	418204	100	3731.50	100	568.40	100	501.04	100	14702.53	100
Production, soymeal with eq. amount soyoil (1)	1029967	33.31	13825.35	45.17	1134.18	21.60	290.43	14.10	17817.87	64.00
Transport of soymeal with eq. amount soyoil (2)	13129	0.42	89.20	0.29	15.84	0.30	3.69	0.18	181.46	0.65
Transport, machinery (Sw. el.) of soymeal with eq. amount soyoil (3)	30.50	0.00099	0.079	0.00026	0.0067	0.00013	0.0074	0.00036	6.45	0.023
Total [(0) - [(1) + (2) + (3)]]	2049278	66.27	16693.22	54.54	4101.59	78.10	1765.46	85.72	9835.85	35.33
cultivation, - driving [g/MJ_{engine}]	99.40		0.810		0.1989		0.0856		0.4771	
cultivation, - driving [g/MJ_{fuel}]	30.45		0.0605		0.0308		0.00813		0.1889	
Total [(0) - [(1) + (2) + (3)]][a]	-624923	-149.43	-10183.13	-272.90	-581.63	-102.33	206.91	41.30	-3303.24	-22.47
cultivation, - driving [g/MJ_{fuel}][a]	-12.0		-0.196		-0.0112		0.00397		-0.0634	

[a] Cultivation and use of the fuel produced excluded.

Institutionerna för biometri och informatik respektive lantbruksteknik gick samman 2003-07-01 och blev Institutionen för biometri och teknik.

Tidigare utgåvor från Institutionen för biometri och teknik

Examensarbeten

04:01 Ericsson, Niclas. Uthållig sanitet i Peru – En förstudie i staden Picota.
04:02 Ekvall, Cecilia. LCA av dricksvattendesinfektion – en jämförelse av klor och UV-ljus.
04:03 Wertsberg, Karin. Behandling av lakvatten med kemiska oxidationsmedel för att delvis bryta ned oönskade organiska föreningar – En studie utförd vid Hovgårdens avfallsanläggning i Uppsala.

Licentiatavhandlingar

001 Sundberg, Cecilia. Food waste composting – effects of heat, acids and size.

Tidigare utgåvor från Institutionen för biometri och informatik

Institutionsrapporter

2003

80 Edlund, T. Pluripolar Completeness of Graphs and Pseudocontinuation. Licentiatavhandling.
79 Nilsson, K. Macrolide antibiotics – mode of action and resistance mechanisms. Licentiatavhandling.
78 Sahlin, U. Analysis of forest field data with a spatial approach. Examensarbete.
77 Seeger, P. Nested t by 2 Row-Column-Designs suitable for bridge competitions.

2002

76 Wörman, A. Low-Velocity Flows in Constructed Wetlands: Physico-Mathematical Model and Computer Codes in Matlab-Environment.
75 Huber, K.T., Moulton, V. & Steel, M. Four characters suffice to convexly define a phylogenetic tree.
74 Ekbohm, G. Induktion, biometri, vetenskap.
73 Huber, K.T:, Moulton, V. & Semple, C. Replacing cliques by stars in quasi-median graphs.
72 Huber, K.T. Recovering trees from well-separated multi-state characters.
71 Holland, B.R., Huber, K.T., Dress, A. & Moulton, V. δ-plots: A tool for analyzing phylogenetic distance data.
70 Huber, K.T., Koolen, J.H. & Moulton, V. The Tight Span of an Antipodal Metric Space: Part II – Geometrical Properties.
69 Huber, K.T., Langton, M., Penny, D., Moulton, V. & Hendy, Michael. Spectronet: A package for computing spectra and median networks.
68 Åsenblad, N. Multivariate Linear Normal Models for the Analysis of Cross-Over Designs. Filosofie Licentiatavhandling i biometri med inriktning mot matematisk statistik.

Tidigare utgåvor från Institutionen för lantbruksteknik

Institutionsmeddelanden

248 2002 Lundh, J-E., Huisman, M. En jämförande studie av några maskinella och motormanuella röjningsmetoder utmed järnväg – uppföljning av skottutveckling efter röjning samt utvärdering av selektiv röjning.
249 2002 Ljungberg, D Gebresenbet, G Eriksson, H SAMTRA - samordning av godstransporter: Undersökning av möjligheter och hinder för samordnad varudistribution i centrala Uppsala.
250 2002 Larsolle, A., Wretblad, P. & Westberg, C. A comparison of biological effect and spray liquid distribution and deposition for different spray application techniques in different crops.
251 2003 Tidåker, P. Life Cycle Assessment of Grain Production Using Source-Separated Human Urine and Mineral Fertiliser.
252 2003 Perez Porras, J., Gebresenbet, G. Biogas development in developing countries.
253 2003 Wikner, I. Environmental conditions in typical cattle transport vehicles in Scandinavia.
254 2003 Sundberg, C. Food waste composting – effects of heat, acids and size.
255 2003 Nilsson, D. Harvesting and handling of flax for the production of short fibres under Swedish conditions. A literature review.

Institutionsmeddelanden

02:01 Fredriksson, H. Storskalig sommarskörd av vass - energiåtgång, kostnader och flöden av växtnäring för system med skörd och efterföljande behandling.
02:02 Björklund, A. Latrin och matavfall i kretslopp i Stockholms skärgård.
02:03 Jannes, S. Hantering av slaggvatten på högdalenverket – ett helhetsgrepp på hanteringen av förorenade vattenströmmar till och från slaggvattensystemet.
02:04 Flodman, M. Emissioner av metan, lustgas och ammoniak vid lagring av avvattnat rötslam.
02:05 Andersson, A. & Jensen, A. Flöden och sammansättning på BDT-vatten, urin, fekalier och fast organiskt avfall i Gebers.
02:06 Hammar, M. Organiskt avfall för biogas produktion i Götene, Lidköping, Skara och Vara kommuner
02:07 Nilsson, D. Småskalig uppvärmning med biobränslen. Kurskompendium.
03:01 Sjöberg, C. Lokalt omhändertagande av restprodukter från enskilda avlopp i Oxundaåns avrinningsområde.
03:02 Nilsson, D. Production and use of flax and hemp fibres. A report from study tours to some European countries.
03:03 Rogstrand, G. Beneficial Management for Composting of Poultry Litter and Yard-Trimmings- Environmental Impacts, Compost Product Quality and Food Safety.
03:04 Lundborg, M. Inverkan av hastighet och vägförhållande på bränsleförbrukning vid körning med traktor.
03:05 Ahlgren, S. Environmental impact of chemical and mechanical weed control in agriculture. A comparing study.
03:06 Kihlström, M. Possibilities for intermodal grain transports in the Mälardalen region – environmental and economical aspects.