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Self-sufficiency of motor fuels on organic farms – evaluation of systems based on fuels produced in industrial-scale plants

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Abstract

The aim of the present work was to evaluate systems for making organic farms self-sufficient in bio-based fuels. The energy efficiency and environmental load for systems based on rape methyl ester (RME), ethanol and biogas produced by processing raw material from the farm in industrial-scale plants were evaluated using a life cycle perspective. Eventual constraints when implementing the systems in practice were also identified and the farmer's costs for the systems estimated.

The RME scenario showed some good characteristics; the energy efficiency and potential effects on global warming were favourable, the technology well known and no engine modifications were necessary. However, the high price of the organically produced rapeseed made the fuel expensive. The ethanol scenario provided fuel at a comparatively low cost, but the energy efficiency was low and existing engines would have to be modified. The biogas scenario was not as economically advantageous, due to high costs for storage and transport of the biogas and the extensive tractor modifications needed.

The calculations further showed that systems based on so-called exchange of fuels, i.e. when the farm produces raw material for one type of biofuel, but instead uses another type of biofuel more suitable for its own tractors, were an economically favourable way of supplying the organic farms with 'self-produced' bio-based fuels. The exchange scenario based on delivery of organic wheat to a large-scale plant and use of RME at the farm was somewhat more expensive than scenarios based on production of biogas raw material at the farm. However, the wheat/RME system has the advantage of being possible to put into practice immediately, since industrial-scale wheat ethanol plants are in operation and RME fuel is available on the market.

Keywords: Organic farming; RME; Ethanol; Biogas; Biofuel; Life cycle perspective

1. Introduction

In organic farming, there is an ambition of production to be based on the use of natural, biological, and renewable resources (IFOAM, 2006). However, estimations show that the organic farms in Sweden annually consume approx. 36 000 m^3 diesel oil (Baky et al., 2002), and this consumption will gradually increase as the scale of organic farming increases. A change to bio-based fuels is supported by the Swedish authorities (SJV, 2001) and will be a logical step towards a sustainable food production system. There is also major work going on in the EU to increase the use of bio-based fuels. The goal of the Commission is for 5.75% of the total volume of fuels to be of renewable origin by the year 2010 (EC, 2003).

In a study by Baky et al. (2002), rape methyl ester (RME), ethanol and biogas were identified as possible fuels for self-sufficiency in motor fuel on organic farms. These three fuels have also been identified as having the potential to meet the EU goals on the Swedish market, with respect to systems of production, distribution and utilisation (SOU, 2004).

RME, ethanol and biogas are based on renewable sources. However, being of renewable origin does not necessarily mean environmentally friendly or sustainable. If the purpose of changing to a renewable motor fuel is to reduce the environmental load, it is important that the production system is designed in a way that minimises the total environmental burden. In order to also be sustainable in economic terms, it is of course important that the fuels can be produced and used to a reasonable cost and that the systems implemented are robust to possible system variations.

Different solutions are possible for making organic farms self-sufficient in bio-based fuels. One possibility is that the fuels are produced from the biomass in smaller-scale plants at the organic farm itself. Such systems are described and analysed by Fredriksson et al. (2006). The study shows that the total fuel costs for the farm will be substantially higher compared to diesel fuel. In particular, the costs will be so high for the small-scale ethanol and biogas systems that they are probably not reasonable to implement at the moment.

Another possibility is that biomass from the organic farms is transported to large-scale fuel production plants and the fuels and useful by-products are then transported back and used at the farm. The characteristics of such systems have not been analysed but studies comparing small- and large-scale plants in general indicate that the fuel costs can be decreased due to use of more efficient techniques and other large-scale benefits. However, the transport element then becomes more extensive (Bernesson, 2004a, 2004b; Bernesson et al., 2004, 2006), affecting the environmental load.

The bio-based fuel easiest for an organic farmer to use at the moment is RME. The existing fuel storage facilities at the farm can be used and little or no changes to tractors are needed. The fuel raw material easiest to produce for many organic farms is ley, since their crop rotation normally has to include years with nitrogen fixing crops used as green manure, in order to manage the nitrogen balance of the soils. This ley may instead be harvested for biogas production and the sludge returned to the soil, with positive effects on the nutrient balance. However, systems for use of biogas as tractor fuel are quite complicated and expensive (Finsterwalder & Maurer, 1986) in most cases. Systems based on ‘exchange of fuels’, i.e. that the farm produces raw material for one type of biofuel, but instead uses another type of fuel for its own tractors, may be a favourable way to make organic farms self-sufficient in bio-based fuels, if the principle of exchange is accepted by the organic farming regulations.

Life Cycle Assessment (LCA) is a useful tool for analysing the whole life cycle of a product such as motor fuel (Lindfors et al., 1995; Wenzel et al., 1997; Rydh et al., 2002). The environmental impact of systems producing and utilising RME, ethanol and biogas from agricultural raw materials have been analysed using LCA methodology in several studies (Johansson et al., 1992; Ragnarsson, 1994; Almemark & Lindfors, 1996; Kaltschmitt & Reinhardt, 1997; Blinge et al., 1997; Blinge, 1998; Patyk & Reinhardt, 2000; Gärtner & Reinhardt, 2001; Bernesson, 2004a, 2004b; Bernesson et al., 2004, 2006). However, in these studies conventional methods of cultivation, including mineral fertilisers and pesticides, were used and the fuel was utilised outside the agricultural system. Organic production is very different to conventional production, which affects the costs and the environmental load to a certain degree (Mattsson, 1999). Fredriksson et al. (2006) studied the energy balance and environmental load in the previously mentioned study of farm scale organic production of RME, ethanol and biogas. One result was that the total global warming potential was decreased by 58-72% compared to diesel when the biofuel systems were used.

The aim of the present work was to evaluate systems for making organic farms self-sufficient in bio-based fuels. The energy efficiency and environmental load for systems based on RME, ethanol and biogas produced by processing raw material from the farm in industrial-scale plants were evaluated using a life cycle perspective. Eventual constraints when implementing the systems in practice were also identified and the farmer's costs for the systems estimated. The farmer's cost for producing biomass for fuel production, which is exchanged for another type of fuel more suitable for tractors, was also calculated.

2. Methodology

2.1. System description, basic scenarios

In order to enable comparisons between different scenarios, the common basis for the calculations was defined as the amount of motor fuel that would meet the fuel demand for cultivation of 1 000 ha with a given crop rotation during one year. The reason for including a whole crop rotation in the study was to define the amount of fuel needed in order to achieve self-sufficiency and to take crop rotation effects into consideration. The cultivated area can be a large farm or a cooperation of several farms.

The three basic fuel production and utilisation scenarios studied are described in Table 1 and shown schematically in

Fig. 1. The agricultural raw materials produced were processed into motor fuel in large-scale plants. The transport distance between farm and plant was assumed to be 25 km in all scenarios. The biofuel produced was then transported back to the farm and utilised in field operations.

The production capacity of plants was assumed to be 800 tonnes year^{-1}, 2 100 tonnes year^{-1} and 1 500 000 nm^{3} year^{-1} purified vehicle gas (97% CH_4) for the RME, ethanol fuel and biogas, respectively. The raw material from the hypothetical farm was therefore only part of the raw materials processed in the plant.

Table 1. Description of scenarios studied

	Fuel raw material produced at the farm	Fuel used
Basic scenarios		
1	Rapeseed	RME
2	Wheat	Ethanol
3	Ley	Biogas
Exchange scenarios		
4	Ley	RME
5	Ley	Ethanol
6	Wheat	RME

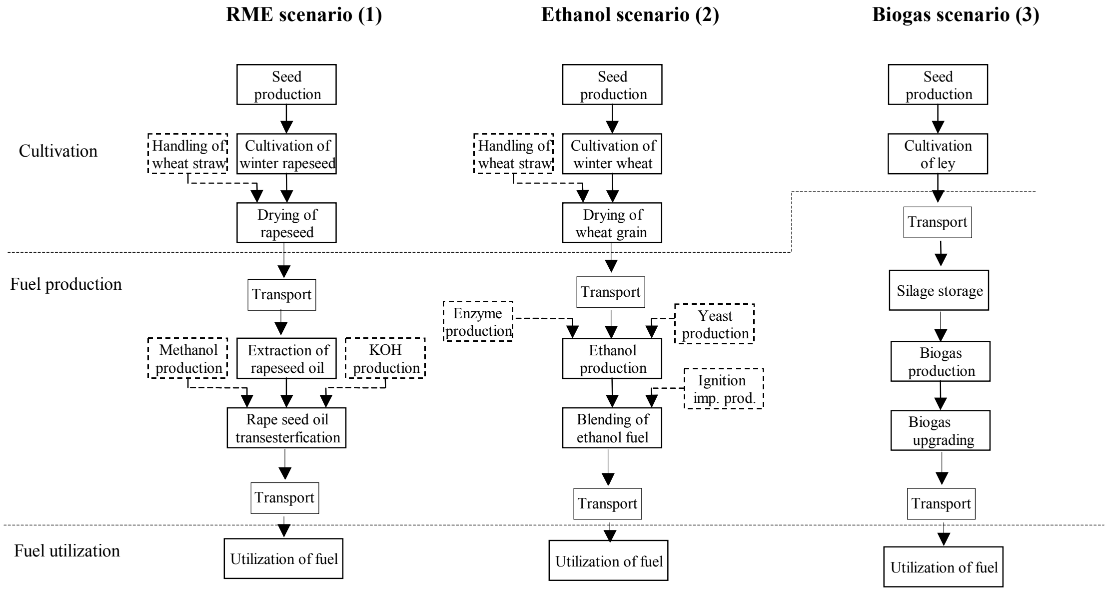

Fig. 1. Schematic description of scenarios studied.

2.2. Calculations of energy balances and environmental loads

The environmental performance of the studied scenarios was calculated using a LCA based methodology. A few simplifications were made compared to the LCA methodology described in the ISO 14000 series standards (ISO, 1997; ISO, 1998), i.e. only a limited amount of impact categories were studied and only economic allocation of environmental load was used. The energy requirements and emissions in all processes from raw material acquisition through distribution and processing to end use were quantified. The potential environmental load, categorised in different impact categories, was then calculated using characterisation factors. Different substances have different relative contribution to the impact categories. For example, nitrous oxide has a factor of 296 for global warming, i.e. 1 kg of nitrous oxide corresponds to 296 kg carbon dioxide equivalents. The categories calculated in this study were use of primary energy, global warming potential (GWP) for 100 years time horizon, acidification potential (AP) and eutrophication potential (EP) using characterisation factors from IPCC (2001) and Lindfors et al. (1995).

The calculations were performed in a computer model in Matlab-Simulink created for the purpose of the study. More details on the calculation model are presented in Baky et al. (2006). Production of capital goods such as machinery and buildings for cultivation and fuel production was not included in the calculations, as Bernesson et al. (2004) and Bernesson et al. (2006) showed that production of capital goods is of minor importance for the overall result.

The production systems studied produced more than one output and the environmental load of the systems therefore had to be allocated between the main product and the by-products. Allocation due to the economic value of the products was used (economic allocation). The methods developed by van Zeijts et al. (1999) for allocation of processes affecting other crops in the cropping plan were used. According to those methods, the environmental impact of green manure should be allocated to all crops according to land use per crop in the cropping plan, as organic matter benefits all crops. For leguminous cash crops, it was assumed that only the specific crop profited from the nitrogen fixation. For more discussion on the choice of allocation principles, see Fredriksson et al. (2006).

2.3. Economic calculations

The costs related to fuel use for the 1 000 ha in the three different basic scenarios were calculated. The costs were divided into:

1. Raw material costs, calculated as the lost market value of the products delivered to the fuel plant. For ley otherwise used as green manure and not sold at the market, the value of the soil nutrients removed with the harvested biomass and the harvesting costs were included.

2. Costs for transportation of the raw material to the plant.

3. Fuel production costs at the plant.

4. Costs for transportation of the fuel back to the farm.

5. Costs for storage of the fuel at the farm.

6. Costs for adjustments to diesel-engined tractors for the new fuel (or the difference in price between market-available tractors aimed for new fuels and traditional diesel tractors).

2.4. Input data and calculation assumptions

A brief description of the data used for the scenarios studied follows. A more detailed description can be found in Baky et al. (2006).

2.4.1. Crop production and transport to the plant

In order to enable comparisons between the different scenarios, a common organic crop rotation was defined. A proven crop rotation from the Logården research farm in south-western Sweden (58°20´N, 12°38´E) was chosen (Helander, 1997). The seven-year crop rotation for stockless organic farming presented in Table 2 is designed to prevent problems with pests and weeds, to require a minimum of cultivation and to be favourable from an economic perspective. Nitrogen is supplied by nitrogen-fixing crops grown twice in the rotation. For the study it was assumed that each crop was grown on 143 ha each year and that the crops were evenly distributed over the total area.

The crop rotation includes cultivation of all the crops needed to produce the motor fuels included in the study. The numbers of field operations and yields presented in Table 2 are average data from the Logården research farm (Baky et al., 2006).

Wheat and oilseed were dried at the farm using wheat straw as fuel, and then transported to the plant by diesel-fuelled trucks. In the biogas scenario, ley was assumed to be harvested and then directly transported in containers to the plant by diesel-fuelled trucks.

Table 2. Crop rotation, average number of field operations (year^{-1}) and yields for the farm studied

Crop rotation	Disc harrowing	Stubble cultivation	Ploughing	Harrowing	Sowing	Rolling	Weed harrowing	Inter-row cultivation	Mowing	Harvesting	Yield (kg ha^{-1} year^{-1})
Field beans	0.5	0.875	1	3.5	1	1	0.4	0.6	0	1	2400
Oats	0.125	0.25	1	2.5	1	0.5	0.5	0.2	0	1	3200
Green manure	0	0	0	0	1	0	0	0	2	0	6000[c]
Winter rapeseed	0.375	1.375	1	3.8	1	1.8	0	0	0	1	2000
Winter wheat	0	1	1	3.6	1	0.6	0.75	0.6	0	1	3500
Green manure/ley	0	0	0	0	1/1	0	0	0	2/0	0/3[b]	(6000)[a,c]
Rye	0.375	0.75	1	3.6	1	0.5	0	0	0	1	3200

[a] In the biogas scenario green manure is harvested as ley.

[b] The ley is harvested.

[c] Measured as dry matter.

2.4.2. Rape methyl ester production, transport and storage (scenario 1)

Rapeseed oil was extracted using a strainer oil expeller with an oil extraction efficiency of 75% (Bernesson, 2004a). The consumption of electricity during oil extraction was set to 0.22 MJ kg^{-1} seed (Bernesson et al., 2004).

In the transesterification process, 110 kg methanol per 1 000 kg oil (Norén, 1990) was used, with 10 kg KOH per m^3 rapeseed oil (Norén et al., 1993) as the catalyst. The consumption of electricity in the transesterification process was 0.60 MJ kg^{-1}

RME (Kaltschmitt & Reinhardt, 1997) and the emissions to air during oil extraction and transesterification were assumed to be negligible. Data on production of renewable methanol from biomass and KOH were taken from Furnander (1996) and Finnveden et al. (1994) respectively. The RME was assumed to be transported to the farm by diesel-fuelled tankers and stored in ordinary fuel tanks on the farm. Further details on RME production can be found in Bernesson (2004a) and Bernesson et al. (2004).

2.4.3. Ethanol production, transport and storage (scenario 2)

Ethanol was assumed to be produced in a conventional fermentation process. Wheat grain was ground using a hammer mill and the flour was mixed with water and enzymes and heated in order to convert the starch into sugar. The mash was fermented using yeast, after which distillation to 95% was performed. Based on Bernesson (2004a), the ethanol yield was set to 296 kg tonne^{-1} wheat, with an input of thermal energy and electricity of 1 725 MJ tonne^{-1} wheat and 230 MJ tonne^{-1} wheat respectively. Thermal energy was assumed to be supplied from wood biomass. For production of ethanol, 3.2 tonnes of distillers waste (9.1% dry matter), used as animal feed, was produced per tonne wheat. It was assumed that there were no emissions from the ethanol production process, except for carbon dioxide of biological origin.

Due to the fuel properties of ethanol (95%), some ignition improver has to be added in order for the fuel to be utilised in diesel engines. For this purpose Beraid 3540, an ignition improver commonly used in ethanol for buses, was assumed to be used together with a denaturant (MTBE and isobutanol). Data on production of Beraid 3540 and denaturants were taken from Ericson & Odéhn (1999). Further details on ethanol production can be found in Bernesson (2004a) and in Bernesson et al. (2006). The ethanol fuel was transported with diesel-fuelled tankers to the farm. Ethanol fuel can be stored in diesel tanks on the farm, even though the safety regulations in Sweden are stricter and comparable to those for petrol storage.

2.4.4. Biogas production, transport and storage (scenario 3)

The ley was packed into large plastic silo bags and stored close to the biogas plant. For the production of biogas, a continuous, single-stage mixed tank reactor operating at a mesophilic temperature was assumed. For the calculations, the submodel of anaerobic digestion from the ORWARE model was used (Dalemo, 1996; Eriksson et al., 2002). The submodel calculates net gas production, use of heat and electricity and estimates the emissions from storage of digestion residue. Based on data from Nordberg & Edström (1997) and Nordberg et al. (1997), the methane yield and the electricity use were set to 300 litres methane kg^{-1} volatile solids and 3% of the energy in the biogas respectively.

To utilise biogas as a motor fuel, carbon dioxide and corrosive substances have to be removed. This was assumed to be done by use of a water scrubber with a flash-tank for re-circulation of methane. The use of electricity was set to 6% of the energy in the incoming gas and the loss of methane was assumed to be 3% based on Persson (2003).

It was assumed that the gas was transported in small high-pressure (200 bar) gas bottles combined to bottle sets containing 0.5 m^3 compressed gas. Each set provides an easily exchangeable unit allowing effective handling at the farm and at the vehicles. Empty gas bottle sets are transported back to the biogas plant and refilled.

2.4.5. Fuel utilisation

RME can be used in normal diesel engines, while for ethanol fuels the injection system and normally also the compression ratio have to be adjusted to compensate for the lower energy content etc. Use of biogas demands mounting of spark plug ignition systems or other quite extensive changes to the engines. Furthermore, large gas tanks have to be mounted on the tractors, in order to achieve reasonable driving distances between fuel refills. It was assumed that each tractor carries an exchangeable 0.5 m^3 compressed gas bottle set. When used for heavy operations 10 h a day, the bottle sets have to be exchanged 2 times per day. By use of exchangeable bottles, no other expensive equipment for storage or refuelling is needed at the farm.

No data on fuel consumption and emissions in agricultural field work were available for the fuels studied. Instead, fuel consumption and emissions when using diesel were calculated from figures presented by Lindgren et al. (2002), and then compensated for the characteristics of the different fuels. Factors for recalculation of fuel consumption and emissions from the diesel figures were based on emission figures for heavy vehicles presented by Lingsten et al. (1997), Hansson et al. (1998) and Haupt et al. (1999). The calculated factors are presented in Table 3. Emissions of CO_2 from utilisation of the fuels were not accounted for, as the CO_2 is of renewable origin. However, the ignition improver added in the ethanol scenario was made from fossil raw material and its utilisation resulted in emissions of 8.33 g CO_2 per MJ energy in the fuel (Bernesson, 2004a). When biogas is used in engines, there is an emission of methane of 0.125 g per MJ energy in fuel that will contribute to global warming (Nilsson et al., 2001).

Table 3. Fuel consumption and emissions relative to diesel when using rape methyl ester (RME), ethanol and biogas

	Diesel	RME	Ethanol	Biogas
NO_X (g g_{diesel}^{-1})	1.00	1.20	0.61	0.56
CO_2	1.00	0	0.11	0.035[a]
SO_X	1.00	0	0	0
Fuel consumption (MJ MJ_{diesel}^{-1})	1.00	1.04	0.89	1.34

[a] Calculated as CO_2-equivalents from emissions of non-combusted methane from engine, 1 g CH_4 = 21 g CO_2.

2.4.6. Economic calculations

The market prices for the organic rapeseed and wheat delivered to the fuel plant were estimated to be 0.42 € kg^{-1} and 0.15 € kg^{-1}, respectively (1 € = 9.2 SEK, Swedish krona) (Lantmannen, 2006). For ley the harvesting costs were 0.0077 € kg^{-1} and the value of nutrients calculated to 0.0091 € kg^{-1} assuming values of 0.75 € kg^{-1} N, 1.15 € kg^{-1} P and 0.39 € kg^{-1} K (Baky et al., 2006).

The costs for transportation of rapeseed and wheat to the processing plant with open-sided lorries have been calculated as: transport cost (SEK kg^{-1} material) = 0.02 + 0.0005 distance (km) (Bernesson, 2004a). The costs for transportation of ley with container lorries have been calculated to be 30% higher on a mass basis compared to transportation with open-sided lorries (an open-sided lorry carries 40.0 tonnes (Bernesson, 2004a) and a container lorry carries 32.5 tonnes (Hansson et al., 2003)).

According to Bernesson (2004a), the production prices for RME and ethanol fuel in the plant sizes studied (processing: excl. cultivation and by-products, incl. ignition improver and denaturants) are 0.40 € kg^{-1} and 0.57 € kg^{-1}, respectively. The production costs for biogas were assumed to be 0.65 € nm^{-3}. The costs for transportation of RME and ethanol fuel back to the farm with tank lorries were assumed to be 15% higher on a mass basis compared to transportation with open-sided lorries (a tanker carries 36.5 tonnes (Bernesson, 2004a)).

The rental charge for a 10 m^3 farm tank used to store RME was 890 € $year^{-1}$ (ABG, 2004), while the cost for the corresponding equipment for ethanol fuel was 1 330 € $year^{-1}$.

The rental charge for a gas bottle set in the exchange system was assumed to be 1 100 € $year^{-1}$ based on Baky et al. (2006). To limit the amount of gas transport to the farm to a maximum one journey per day, three bottle sets were needed for each tractor. The total yearly amount of filled bottle sets transported to the farm was thus 610. The transport cost for each bottle set was difficult to estimate since they depend on how many other gas users are involved, the design of the logistic system, etc. An average of 10 bottle sets per transport were assumed to be delivered to the farm. The time for transport (50 km round trip), loading and off-loading of filled bottle sets and loading and off-loading of empty bottle sets at the fuel production plant and at the farm, was estimated to two hours. The cost for truck and driver was set to 75 € $hour^{-1}$, adding up to a cost of 150 € $transport^{-1}$.

It was estimated that 8 tractors of 100 kW each were used to cultivate the 1 000 ha studied. The diesel tractors were assumed to be driven by RME without any conversion. The cost for conversion to ethanol use was assumed to be 10 900 € per tractor and the tractor's economic lifetime 15 years. The conversion of a diesel tractor to use of gas is quite complicated and calculations based on the rebuild of smaller trucks show that the total costs of the vehicle increase by 30%, which is 26 000 € per tractor. More details on the economic calculations can be found in Baky et al. (2006).

2.5. Exchange of fuels

Three scenarios based on exchange of fuels were studied (Table 1). Scenario 4 was motivated by the fact that raw material for biogas production is very easy available at an organic farm with green manure in its crop rotation, while RME is a lot less complicated to use as tractor fuel for the farmer. The scenario therefore included a system where the farm delivers ley to an industrial-scale biogas plant in an amount sufficient to produce all fuel used at the farm's tractor operations. However, the gas fuel is instead used for city buses or other vehicles more suited to gas use, and the tractors are fuelled by an equivalent amount of non-organically produced RME from the market.

In scenario 5 too, ley is produced at the organic farm and used for biogas production, but the tractors are instead fuelled by ethanol fuel from the market. The amount of RME available on the market may be limited and use of ethanol may be an alternative. Conversion of diesel engines to ethanol is not so complicated and the same systems for handling and storage of the fuels can be used.

Scenario 4 and 5 assume that a biogas plant is located reasonably close to the farm, which is not always the case. Dry products such as wheat are not so sensitive to transport distances and in scenario 6, the farm produces wheat for ethanol production but uses RME to fuel the tractors. Since large-scale ethanol plants already exist in Sweden, this scenario can be directly implemented by organic farmers.

It is likely that the fuel production facilities will use both conventional and organic raw material and that they are not willing to pay a higher price for organically produced biomass. The farmer will have to sell his crops to the same price as conventional crops, resulting in a decrease of revenue.

The costs to the farmer in these scenarios, calculated to enable comparisons with the costs described in section 2.3, can then be assumed to be:

1. The decrease in revenue when the crop is sold as raw material to the fuel plant instead of as a higher valued organically produced product on the food market.

2. The farmer's costs for buying the fuel used from the fuel company.

3. The costs for storage of the fuel at the farm.

4. The costs for conversion of the tractors to the fuel used.

The wheat for the fuel production has a value of 0.105 € kg^{-1} when produced in conventional farming (Bernesson, 2004a) compared to 0.154 € for organic products. It is difficult to value ley delivered to the biogas plant, since normally no market exists for organic ley. Instead it was assumed that the farmer was reimbursed for the value of the nutrients removed and for the harvesting costs, i.e. that no loss of revenue was present.

The market prices for RME and ethanol fuel delivered to the farm were assumed to be 891 € m^{-3} (Andersson, 2005) and 568 € m^{-3} (Elfving, 2005) respectively. The costs for fuel storage and conversion of the tractors are the same as described in section 2.4.6.

3. Results of basic scenarios

3.1. Land use

In production of motor fuel for self-sufficiency, the different scenarios required different amounts of land. In the RME scenario, 8.5% of the 1 000 ha was used on average for fuel production. For production of ethanol, 5.5% of the area was used on average and for production of biogas 3.8%. In the assumed seven-year crop rotation, the maximum available amount of land was 14.3% for cultivation of rapeseed and winter wheat and 28.6% for cultivation of green manure that could be harvested as a ley crop, which more than enough satisfy the need for fuel raw material.

3.2. Energy use

The input of primary energy (including both fossil and renewable energy) for the basic scenarios is presented in Table 4. The cultivation figures included energy for cultivation and harvest of the area needed to produce raw material for the amount of fuel produced. The effects of drying of the grain and oil-seed were also included. In fuel production, the energy used mainly consisted of electricity and heat for the processes and energy for production of input materials such as methanol and ignition improver. The energy inputs were allocated between the fuels produced and the by-products in each scenario. However, the non-allocated figures are also presented (Table 4). Furthermore, the energy content in all fuel produced (and used) is also presented for each scenario (Table 4). The amount of fuel produced was 52 732 kg RME, 67 599 kg ethanol or 70 004 nm^3 biogas (97% methane).

The RME scenario showed the lowest total energy input when the non-allocated values were compared. When the allocated values were compared, the more valuable by-products of the RME scenario resulted in the RME value being even more favourable. The total energy efficiency, calculated as the energy in the fuel produced divided by the total allocated energy use, was 8.3 for RME, 2.6 for ethanol and 4.4 for biogas.

In ethanol production, large amounts of heat were used for the distillation. In the biogas scenario, production and cleaning of the gas required a lot of energy, mainly as electricity and heat. The use of energy for transport was highest for the biogas scenario, but in general quite low for all scenarios.

The amount of energy in the fuel produced (and used) differed between the scenarios studied. This was due to the difference in assumed engine efficiency for the fuels. In the biogas scenario extra fuel was also needed to collect the ley that otherwise would have been incorporated in the soil.

Table 4. Primary energy use and energy in the fuel produced for the basic scenarios (GJ)

Scenario	Cultivation	Fuel prod.	Transports raw mat. and fuel	Total allocated[a]	Total not allocated[b]	Energy in fuel produced
1 (RME)	162	72	4	238	468	1 983
2 (Ethanol)	194	444	13	651	678	1 697
3 (Biogas)	52	527	30	609	716	2 676

[a] Total allocated is the sum of primary energy inputs when economic allocation has been done between main products and by-products.

[b] Total not allocated is the sum of primary inputs when no allocation has been done.

3.3. Environmental impacts

The potential environmental impacts of the basic scenarios studied are presented in Table 5. As for energy use, the calculated potential environmental impacts were allocated between the fuels produced and the by-products. The values for fuel utilisation were not allocated. Included in Table 5 are also the corresponding results from the study based on small-scale plants (Fredriksson et al., 2006) and for a case with use of fossil diesel oil.

The results show that the soil emissions in general had the most severe effects on the GWP and EP. The AP was mainly affected by the engine emissions when utilising the fuels. The RME scenario showed the lowest total GWP effects but the highest AP effects. The AP effects from RME were mainly due to the fuel utilisation emissions.

The results for the large-scale systems did not differ much from the small-scale system results described by Fredriksson et al. (2006). No emissions from transport of crops and fuels between farm and plant were present in the small-scale solutions. These figures were, however, comparatively small even in the large-scale systems and had small effects on the total values.

Table 5. Potential environmental impacts for the basic scenarios when producing and using fuel for 1 000 ha

Scenario	1	2	3	
Fuel	RME	Ethanol	Biogas	Diesel
Global warming potential (kg CO_2-equivalents)				
Cultivation	21	1 007	150	
Soil emissions	42 637	37 616	28 090	
Transport to plant	257	858	1 724	
Fuel production	305	5 758	31 343	14 718
Fuel transport	91	117	681	
Fuel utilisation	0	14 878	8 107	142 984
Total	*43 311*	*60 234*	*70 095*	*157 702*
Total (small-scale, Fredriksson et al., 2006)	43 757	63 090	66 937	157 702
Acidification potential (kg SO_2-equivalents)				
Cultivation	82	47	13	
Soil emissions	157	179	154	
Transport to plant	2	6	12	
Fuel production	1.4	53	17	141
Fuel transport	0.6	1	4	
Fuel utilisation	1 398	707	688	1 110
Total	*1 639*	*993*	*888*	*1 251*
Total (small-scale, Fredriksson et al., 2006)	1 646	707	859	1 251
Eutrophication potential (kg O_2-equivalents)				
Cultivation	715	405	112	
Soil emissions	37 593	40 266	14 156	
Transport to plant	15	52	100	
Fuel production	4	333	107	893
Fuel transport	5	7	39	
Fuel utilisation	12 155	6 151	5 981	9 649
Total	*50 487*	*47 214*	*20 495*	*10 542*
Total (small-scale, Fredriksson et al., 2006)	51 083	50 328	20 267	10 542

3.4. Economy

All costs in Table 6 were calculated for the total amount of fuel used at the 1 000 ha farm. The costs were calculated as defined in section 2.3. As a comparison, the cost for using fossil diesel would be 33 545 € year^{-1}, based on a diesel price of 0.60 € litre^{-1} (Bernesson 2004a).

The ethanol scenario was the least expensive for the farmer, even though the fuel production costs were quite high. The high costs for the organic rapeseed resulted in the RME scenario not being so competitive. The raw material costs for the biogas production were low, but the high costs for fuel transport, storage and tractor conversion made the biogas scenario expensive.

Per MJ, the costs were 0.047 € for RME, 0.043 € for ethanol fuel and 0.041 € for biogas. The biogas scenario required more fuel, resulting in a higher total cost.

Table 6. Costs related to fuel use for 1 000 ha in the basic scenarios (€ year^{-1})

Scenario Raw material produced Fuel used	1 Rapeseed RME	2 Wheat Ethanol	3 Ley Biogas
Raw material	71 400	26 400	12 800
Raw material transports	600	620	3 490
Fuel production	21 100	38 500	45 500
Fuel transports	210	280	9 150
Fuel storage	890	1 330	26 400
Tractor conversion	0	5 810	13 900
Total	*94 200*	*72 940*	*111 240*

4. Results of scenarios based on exchange of fuels

All costs in Table 7 were calculated for the total amount of fuel used at the 1 000 ha farm. The costs are defined in section 2.5.

The most economically favourable scenario was to deliver biogas raw material to a plant and fuel the tractors with RME bought on the market. In general, the scenarios based on exchange of fuels were cheaper than the scenarios reported in section 3.4.

Table 7. Costs related to fuel use for 1 000 ha in the exchange scenarios (€ year^{-1})

Scenario Raw material produced Fuel used	4 Ley RME	5 Ley Ethanol	6 Wheat RME
Decrease of revenue	0	0	8 610
Fuel costs	53 390	48 600	53 400
Fuel storage costs	890	1 330	890
Tractor conversion costs	0	5 810	0
Total	*54 280*	*55 740*	*62 900*

5. Discussion

When choosing a system for large-scale implementation in organic farming, the economic aspects will be an important issue. All the scenarios were calculated to be more expensive than using fossil diesel, based on today's oil price. The difference among the scenarios were however large. For the systems studied here without exchange of fuels, the ethanol scenario showed the lowest costs. The ethanol fuel production plant studied had a capacity of 2 100 tonnes (ethanol with ignition improver and denaturants) year^{-1}. One large part of the costs in the ethanol scenario was the production costs. These costs can be decreased by use of an even larger plant. Bernesson (2004a) showed that the production costs were reduced by 31% when the size of the plant was increased to 100 000 tonnes year^{-1}.

The RME scenario showed some good characteristics; the energy balance and GWP effects were favourable, the technology well known and no engine modifications were needed. However, the main problem at the moment with this scenario is the high price of the organically produced rapeseed, making the fuel expensive. In general, increased organic cultivation may lead to increased supply and because of that a lower price for organic rapeseed.

Raw material for biogas production was available in large amounts when the strategy with green manure was applied. However, the large costs for storing and transport of the gas and the extensive tractor modifications required resulted in this scenario not being so economically advantageous. For farms situated close to a biogas plant, tractors may be fuelled directly at the plant and most of the costs for transport and tank exchange system thereby avoided. However, such a situation is probably quite rare. One way to decrease the costs for the biogas scenario may be to adopt another engine technology, based on using a liquid fuel (e.g. RME) as an ignition fuel for the gas. In this case two fuel injection systems are needed, but the use of spark plugs is avoided.

The small differences in environmental load when comparing small- and large-scale systems implies that the choice of plant size can be decided by other factors, such as for example economy. Quite small effects of plant size on environmental impact are also presented by Bernesson (2004a), Bernesson (2004b), Bernesson et al. (2004) and Bernesson et al. (2006) for RME- and ethanol-based systems.

The fuel production facilities were calculated to be industrial-scale, and that the amount of raw material delivered by the studied 1 000 ha only was a small share of the fuel production capacity. It is likely that the fuel production plants will process both organic and conventional biomass, which could make it difficult to recycle the residues to organic cropping. However, in the Swedish regulations of organic production (KRAV, 2006), it is not stated that manure or digestate have to originate from organic products. It is for example allowed to use manure from conventional dairy farms. Another example is the biogas plant in the city Västerås with household waste and ley as raw material, where the digestate have been approved for organic production.

The calculations clearly showed that systems based on exchange of fuels were an economically favourable way to make the organic farms self-sufficient in bio-based fuels compared to no exchange. Scenario 4 and 5, in which the farmer produces ley, require a biogas plant to be located within a reasonable distance to the farm, which may be a more normal situation if the current increase in biogas plants continues. In the calculations, it was assumed that the farmer was paid by the plant for the value of the nutrients in the ley removed and for the harvesting costs. If the costs for transport of the material to the plant are also added, the total costs for the plant will be 0.018 € kg^{-1}ley.

The exchange scenario based on delivery of organic wheat to a large-scale plant and use of RME at the farm (scenario 6) will be somewhat more expensive than the delivery of ley alternatives, since it is not reasonable to assume that the ethanol plant will be willing to pay the farmer more than the price for conventionally produced wheat. This system, however, has the great advantage of being possible to put into practice directly, since wheat ethanol plants are in operation and RME fuel is available at the market. The existing ethanol plants are bigger than that one modelled, but as mentioned, increasing transport costs will be counteracted by improved system efficiency. If the transport distances are increased from 25 to 250 km, and the production system efficiency not changed, a sensitivity analysis shows that the total GWP-emissions will increase by 13% and the costs by 12%.

The environmental load caused by the scenarios based on exchange of fuels is not so clearly defined. It may be argued that the total amounts of fuels produced and used are not affected by the fuel exchange, and the environmental load will thereby be the same as for system not based on exchange. On the other hand, if ethanol is produced from farm products, but RME used at the farm (scenario 6), the ethanol can be used in Otto engines, substituting for petrol instead of diesel, and the total environmental load will thereby be changed.

In order to apply the exchange system on a large scale, the exchange strategy has to be accepted in the regulations for organic farming. This is more of a question regarding the policy for organic farming and beyond the focus of the present work.

6. Conclusions

The RME scenario shows some good characteristics; the energy efficiency (8.3) and GWP effects are favourable, the technology is well known and no engine modifications are needed. However, the high price of the organically produced rapeseed makes the fuel expensive. The ethanol scenario provides fuel at a comparatively low cost, but the energy efficiency is low (2.6) and existing engines have to be modified. The high costs for storing and transport of the gas and the extensive tractor modifications result in the biogas scenario being least economically advantageous, even though the energy balance (4.4), acidification effects and eutrophication effects are quite favourable.

The calculations clearly show that systems based on so-called exchange of fuels are economically a very favourable way to supply organic farms with self-produced bio-based fuels. The exchange scenario based on delivery of organic wheat to a large-scale plant and use of RME at the farm is somewhat more expensive than the alternatives based on biogas production. This system, however, has the advantage of being possible to put into practice very soon, since wheat ethanol plants are already running and RME fuel is available on the market.

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