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Biomass and Bioenergy 26 (2004) 545–559
BIOMASS & BIOENERGY
www.elsevier.com/locate/biombioe

A limited LCA comparing large- and small-scale production of rape methyl ester (RME) under Swedish conditions

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Received 3 June 2003; received in revised form 29 September 2003; accepted 24 October 2003

Abstract

Production of rape methyl ester (RME) can be carried out with different systems solutions, in which the choice of system is usually related to the scale of the production. The purpose of this study was to analyse whether the use of a small-scale RME 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 plant sizes. For small plants and physical allocation, the global warming potential was 40.3 g CO_2-eq/MJ_{fuel}, the acidification potential 236 mg SO_2-eq/MJ_{fuel}, the eutrophication potential 39.1 mg PO_4^{3-}-eq/MJ_{fuel}, the photochemical oxidant creation potential 3.29 mg C_2H_4-eq/MJ_{fuel} and the energy requirement 295 kJ/MJ_{fuel}. It was shown that the differences in environmental impact and energy requirement between small-, medium- and large-scale systems were small or even negligible. The higher oil extraction efficiency and the more efficient use of machinery and buildings in the large-scale system were, to a certain degree, outweighed by the longer transport distances. The dominating production step was the cultivation, in which production of fertilisers, soil emissions and tractive power made major contributions to the environmental load. The results were, however, largely dependent on the method used for allocation of the environmental burden between the RME and the by-products meal and glycerine. This indicates that when different biofuels or production strategies are to be compared, it is important that the results are calculated with the same allocation strategies and system limitations.

Keywords: Rape methyl ester (RME); Bioenergy; Fuel production; Life cycle assessment (LCA); Small-scale; Large-scale

1. Introduction

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 [1]. A changeover to bio-based fuels is therefore an important step towards a more sustainable society. Rape methyl ester (RME) is a possible bio-based fuel that can be used in diesel engines with no or minor adjustments. The production of biodiesel (vegetable oil esters) has increased and was 1.06 million tonnes in the EU in 2002 [2], of which 3500 t were produced in Sweden [3].

The production of RME can be carried out on many different system scales. In large-scale systems, processing technologies have high extraction efficiencies, but the transport of raw materials to the

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doi:10.1016/j.biombioe.2003.10.003

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 and the possibility to increase rural employment. Furthermore, the transport of raw materials and residual products is decreased or eliminated. However, the extraction efficiency is lower in comparison to large-scale systems [4–6].

A main argument for the production and use of RME is its 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" [7,8]. The production of RME has been analysed by LCA methodology previously [9–11], but these studies have focused on large-scale systems. Gärtner and Reinhardt [12,13] carried out an LCA study for small-scale RME production, but their results are valid for German conditions.

When RME is produced, the by-products are meal and glycerine. The meal is 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 [7,8]. 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.

The purpose of this work was to analyse whether the use of small-scale RME production systems reduces the environmental load in comparison to medium- and large-scale systems. To fulfil this purpose, a limited LCA, including air-emissions and energy requirements, was carried out for an example of each plant size. 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 influence of uncertainty in input data was also included in the study. Furthermore, the environmental load was also analysed for alternative scenarios for the production of RME, such as using electricity mainly produced from fossil fuels and using RME instead of diesel oil in the cultivation operations and transport.

2. Methodology

2.1. System description

The RME production was assumed to take place at plants that service 40 ha (small-scale), 1000 ha (medium-scale) and 50 000 ha (large-scale) of winter rape (*Brassica napus*) cultivated in the flatlands of Svealand in Central Sweden. Assuming that 10% of the total area around small-scale plants was cultivated with rapeseed, and 5% and 1% of the area around medium- and large-scale plants, respectively, the transport distances were calculated with equations developed by Overend [14]. The collection areas were assumed to be circular. The reduction in share of total area with rapeseed for larger plants was a result of the increased share of non-farm area as the territory included was enlarged. On farm level, however, one-seventh of the cultivated area was rapeseed.

It was assumed that the annual yield was 2670 kg rapeseed per hectare with a moisture content of 15% (wet basis, w.b.) at harvest. The seeds were then dried to a moisture content of 8% (w.b.). The dried seeds had an oil content of 45%, estimated after Svenskraps [15] and Engström et al. [16].

All transport between the fields and the farms was included in the cultivation for all plant sizes studied. For the medium- and large-scale systems, the seed, RME and meal were transported to and from the plants. No such transport was needed in the small-scale system, because the seed was processed on the farms.

In all plants, the oil was extracted mechanically and then transesterified. The extraction in the small-scale plant was carried out with a hole cylinder oil expeller, and in the medium- and large-scale plants with strainer oil expellers. The extraction capacity of an oil expeller decreases with higher oil extraction efficiency and vice versa [4,17–20]. In extraction of rapeseed, oil extraction efficiencies of 58–82% [4,17–20] have been attained with hole cylinder expellers, and

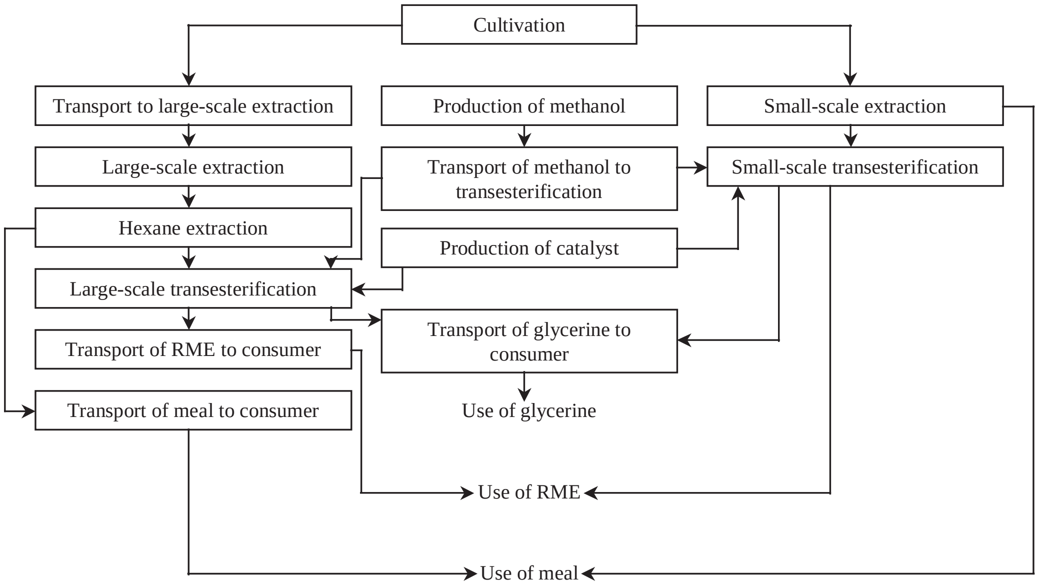

Fig. 1. Flow-chart showing the operations (in boxes) that were included for small- and large-scale production of RME. For the medium-scale system, the same operations as for the large-scale were used, with the exception of hexane extraction. The operations "cultivation", "production of methanol" and "production of catalyst" were identical for all scales.

extraction efficiencies of 70–88% [5,17,18,21] with strainer oil expellers. The lower value in the range represents the normal oil presses used in practice and the upper range the oil presses used in laboratory conditions. In this study, the oil extraction efficiencies were assumed to be 68% in the small-scale plant [4,20], 75% in the medium-scale plant [5] and 98% in the large-scale plant [6,18,19]. The extraction efficiencies chosen correspond to oil extraction capacities that are realistic for each type of expeller in practice. In the large-scale plant, the extraction took 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 the transesterification process, three methanol molecules replace a glycerine molecule in the presence of a catalyst. The need for methanol in the transesterification was assumed to be 0.11 kg/kg rapeseed oil for all plants [22]. The catalyst used was potassium hydroxide (KOH). KOH was preferred instead of NaOH, because KOH can be used as fertiliser after the transesterification. The need for KOH was set at 10 kg/m^3 rapeseed oil [23]. Production and transport of methanol and catalyst, as well as transport of glycerine to the final consumer, were included in the study.

Because plants of various sizes with different process technologies were to be compared, the energy required for manufacturing and maintenance of machines and buildings for the whole production chains was considered. For the same reason, the final use of RME, meal and glycerine was not included in the study. However, the replacement of fossil carbon atoms in glycerine with biomass carbon atoms in glycerine from the transesterification process, as well as the replacement of imported soymeal with rapemeal, was considered in an expanded system allocation procedure (see below). The systems analysed are described schematically in Fig. 1.

2.2. LCA assumptions

2.2.1. Functional unit and impact categories

The functional unit, to which the total environmental load was related, was 1.0 MJ of energy in the RME fuel delivered to the final consumer, i.e. 1.0 MJ_{fuel}.

Table 1
Impact category indicators used in this study [24]

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 [25].

The energy content was expressed in the lower heating value (38.5 MJ/kg).

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 oxidant creation potential (POCP). The category indicators used are presented in Table 1.

The energy needed in the operations was also included in the LCA. For all fuels used in the system, the energy contents were expressed in lower heating values. The electricity used was recalculated to primary energy for an average Swedish electricity production system, which was based on 48% hydropower, 44% nuclear power, 4% fossil fuels and 3% biofuels [26]. It was assumed that the grid losses were 5% for large-scale systems, 7.5% for medium-scale systems and 10% for small-scale systems [27]. In an alternative scenario, it was assumed that the electricity consumed was replaced by electricity mainly produced from fossil fuels, based on 56% coal, 34% nuclear power, 5% natural gas, 4% hydropower and 1% oil [6].

2.2.2. Allocation procedures

For the physical and economic allocations, the environmental load was shared between RME, meal and glycerine. The total energy and economic values of the products were calculated from the yield of each product and its lower heating value and price, respectively (Table 2). The lower heating value and the price for the meal were calculated from its content of oil and water to consider the differences between small- and large-scale production [28]. With no allocation, all emissions and energy used solely burdened the RME.

In the fourth allocation method, the system was expanded (see Fig. 2) so that the rapemeal produced in the large-scale plant could replace imported (overseas) soymeal, and so that the rapemeal with higher oil content produced in the medium- and small-scale plants could replace soymeal mixed with soyoil. The soymeal and the soyoil were mixed until the original protein and oil contents were reached. It was assumed that the soymeal products were transported from the harbour with an open-sided lorry to the farm for consumption (110 km). The glycerine from the transesterification process was assumed to replace glycerine produced from fossil propane gas. The emissions and energy needed for the production of soymeal, soyoil and fossil glycerine [33] were subtracted from the emissions and energy needed to produce the RME in this allocation procedure.

2.3. Calculation assumptions and input data

The assumptions made and data used in the calculations are briefly described below. A more complete description of the assumptions and calculations is presented by Bernesson [28].

Table 2
Data for the physical and economic allocations

Type of product	Product (kg/ha)	Physical allocation			Economic allocation		
		Heating value[a] (MJ/kg)	Production (MJ/ha)	Share (%)	Price[b] (SEK/kg)	Production (SEK/ha)	Share (%)
Small-scale production							
RME	727	38.50	27993	45.2	6.33	4604	57.8
Glycerine	80	17.10	1362	2.2	4.44	354	4.4
Meal	1625	20.06	32595	52.6	1.85	3009	37.8
Total			61950	100.0		7967	100.0
Medium-scale production							
RME	802	38.50	30875	49.0	6.33	5078	61.2
Glycerine	88	17.10	1502	2.4	4.44	390	4.7
Meal	1587	19.34	30694	48.7	1.78	2828	34.1
Total			63071	100.0		8295	100.0
Large-scale production							
RME	1048	38.50	40343	64.4	6.33	6635	73.7
Glycerine	115	17.10	1963	3.1	4.44	510	5.7
Meal	1331	15.29	20359	32.5	1.39	1856	20.6
Total			62665	100.0		9001	100.0

[a]Lower heating value: RME [29]; glycerine [6]; and meal calculated after Bernesson [4,28].
[b]Prices: RME [30]; glycerine [31] and meal calculated after Herland [32] and Bernesson [28].

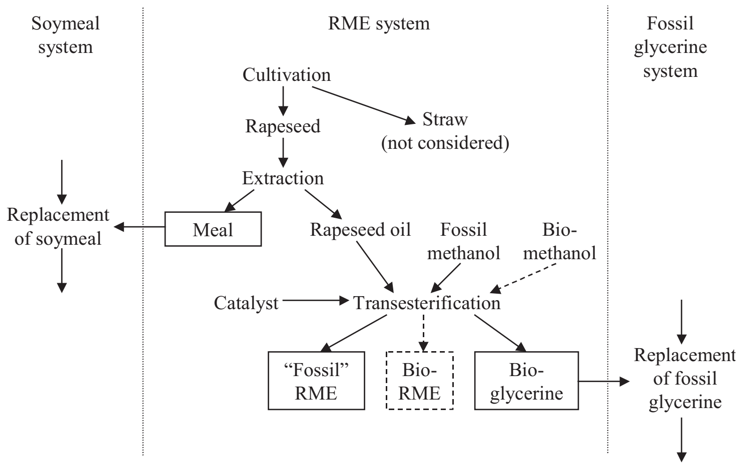

Fig. 2. Flow-chart showing the RME production system studied and the soymeal- and fossil glycerine systems, which were included in the expanded system. The alternative process denoted by a dashed line was studied in a scenario analysis.

2.3.1. *Rapeseed production*

It was assumed that seed from the previous year was used for sowing at a rate of 8 kg per hectare. Out-wintering (resowing) of winter rape was assumed to be 10%. The crop was fertilised with 140 kg N/ha, 15 kg P/ha and 25 kg K/ha. As a result of chemical and microbiological processes in the soil during cultivation, it was assumed that the air emissions of NH_3

and N_2O were 40 g and 19.6 g per kg nitrogen supplied, respectively [33]. Regarding pesticides, 2 l/ha of the herbicide Butisan S was used to control weeds, and 0.3 l/ha of the insecticide Sumi-alpha 5 FW, on average once every 2 years, to control blossom beetles. The emissions from the production of fertilisers were calculated after Davis and Haglund [34] and the emissions from the production of pesticides were calculated after Kaltschmitt and Reinhardt [6] and Green [35].

For the cultivation operations, the total fuel consumption was estimated at 65.9 l Swedish environmental class 1 diesel oil (MK1) per hectare, calculated with data presented by SLU [36], Bernesson [4], Norén et al. [37] and Hansson and Mattsson [38]. The air emissions and energy required for manufacturing of diesel oil were calculated with data presented by Uppenberg et al. [26], and the air emissions from the cultivation operations with data presented by Hansson et al. [39] and Uppenberg et al. [26]. The emissions of CO_2 were 73 g/MJ_{fuel} for MK1 [26], and the emissions of SO_x were based on the sulphur content in MK1, i.e. 10 ppm, according to Aakko et al. [40].

It was also assumed that the fertilisers were transported 10 km to the farm by a tractor with two wagons carrying 16 t. Fuel consumption and emissions from this transport were calculated with data from Berggren [41].

The quantity of lubrication oil consumed was assumed to be 0.7% of the diesel fuel used, based on data from ASAE [42], including oil used for transmissions and hydraulics. Furthermore, it was assumed that manufacturing of lubrication oil results in the same amount of emissions as manufacturing of diesel oil.

For drying of the seeds, 0.132 litres of oil (MK1) per litre water removed were used [28].

In an alternative scenario, ploughing was replaced by three disc harrowings according to Norén et al. [37]. The seed yield was assumed not to be influenced by this operation.

2.3.2. RME production

For the oil extraction, the consumption of electricity was 0.36 MJ/kg seed in the small-scale plant [4,20] and 0.22 MJ/kg seed in the medium- and large-scale plants [6]. All process energy was assumed to be electricity.

Hexane was used for oil extraction in the large-scale plant. The average losses of hexane during the extraction phase were 1.0 kg/t rapeseed [6], of which 0.375 kg/t rapeseed was lost as hydrocarbons (HC). Emissions from hexane production [6] were included in the calculations.

The transesterification process was performed in the same way for all plants, and methanol was the alcohol used in the presence of KOH as a catalyst. According to Kaltschmitt and Reinhardt [6], the consumption of electricity in the transesterification process is 0.60 MJ/kg RME (incl. heating of the oil). This figure was used for all plant sizes in this study. The emissions to air during the transesterification process were assumed to be negligible. Emissions from the production of methanol and KOH were calculated after Furnander [43] and Finnveden et al. [44], respectively. In these calculations, it was assumed that the emissions from the production of the KOH were the same, on a mole basis, as for NaOH. This is plausible as the heat of formation is the same (−425 kJ/mole) for both substances [45].

2.3.3. Transport of raw materials and products

In the small-scale system, there was no transport of raw materials and products outside the farm. In the medium-scale system, it was assumed that a tractor with two wagons, carrying 20 t totally, transported seed and meal to and from the plant located 7 km away. This transport distance was calculated with a model constructed after Overend [14] and presented by Bernesson [28]. In the large-scale system, an open sided lorry with a load weight of 40 t transported seed and meal to and from the plant, which was located 110 km away [14,28]. The meal was transported back to the farm on the return trip. The RME was transported back to the farm from both the medium- and large-scale plants by a tank lorry carrying 36.5 t. The methanol and the glycerine were transported 110 km by a similar tank lorry in all three systems. Emissions and fuel consumption for lorries are accounted for in Berggren [41] with MK1 fuel. The consumption of lubrication oil was assumed to be 0.7% of volumetric fuel consumption for both lorries and tractors.

For an analysis of a scenario in which the RME replaced diesel oil in the cultivation operations and transport, results from a study by Statens Maskinprovningar (SMP) [29] were used. In that study, the engine efficiencies were given for an engine running at its best operating point with MK1 and RME. When the relationship between these two fuels, in fuel efficiency, was assumed to be the same as the fuel needed in the lorries and tractors, the need for RME for transport was calculated. The emissions of fossil carbon dioxide were 3.9 g/MJ_{fuel} for RME, provided that one carbon atom in the empirical formula for RME ($C_{19}H_{35}O_2$) [6] has its origin in fossil methanol. Regarding emissions of SO_x, Aakko et al. [40] showed that the sulphur content in RME is 79 ppm. This figure was used in this study. The relationships between the other emissions for MK1 and RME were assumed to be as was measured by Aakko et al. [40] on a 210 kW, Volvo DH10A-285 engine with turbo-charger and intercooler.

In another analysis of a scenario, it was assumed that a catalyst was used for the reduction of emissions from diesel engines. Calculations after tests by Aakko et al. [40] showed that CO could be reduced by 81%, HC by 77.5% and NO_x by 6%.

2.3.4. Machinery and buildings

Energy and materials used for the manufacturing of agricultural machines, transport lorries, and process machines for oil extraction and transesterification, including spare parts, were calculated after data from Pimentel [46] and Bowers [47], revised by Börjesson [48]. Energy used for construction of buildings was calculated after data from Spugnoli et al. [49]. Further calculation assumptions are described by Bernesson [28].

3. Results

3.1. Rapeseed production

The environmental impacts and the energy required for cultivation of the rapeseed are presented in Fig. 3. The total environmental impact for the production of winter rapeseed was 2405 kg CO_2-eq/ha, 14.4 kg SO_2-eq/ha, 2.40 kg PO_4^{3-}-eq/ha and 0.194 kg C_2H_4-eq/ha. The impact from production of fertilisers, as well as the impact from soil emissions of N_2O and NH_3, was significant, especially on the GWP, AP and EP. The tractive power was also important, whereas seed drying and machinery inputs (energy requirement and emissions for the production of machines and buildings) made minor contributions. The influence of the other factors was negligible. The total energy requirement was 11.8 GJ/ha, and the total energy content in the rapeseed produced 63.9 GJ. This resulted in an energy ratio (lower heating value in rapeseed/requirement of process energy) of 5.4.

3.2. Comparison of different production scales

The results for the small-scale system are described in Table 3. As can be seen, the environmental

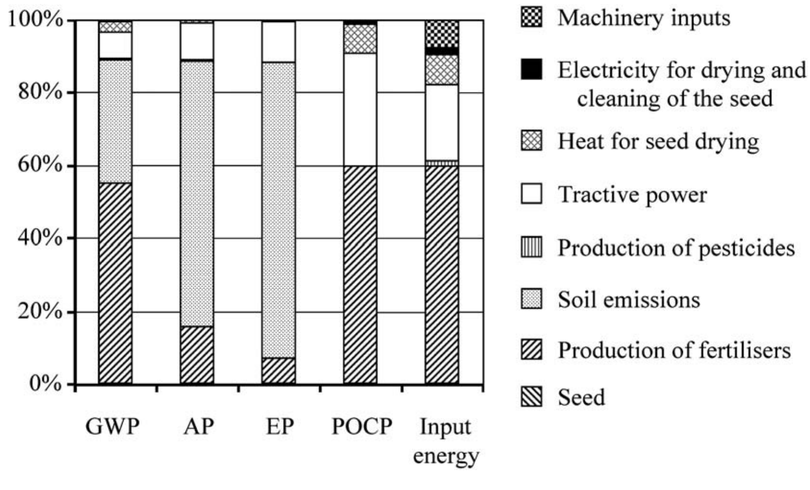

Fig. 3. Environmental impacts and energy requirements for the production of winter rapeseed.

Table 3
Environmental impacts and energy use in small-scale production of RME

Production factors	GWP (g CO_2-eq/MJ_{fuel})	AP (mg SO_2-eq/MJ_{fuel})	EP (mg PO_4^{3-}-eq/MJ_{fuel})	POCP (mg C_2H_4-eq/MJ_{fuel})	Input energy (kJ/MJ_{fuel})
Production of rapeseed	38.8	233	38.7	3.13	190
Electricity, oil extraction	0.1	0	0.0	0.03	31
Methanol	1.0	2	0.3	0.08	36
Catalyst, KOH	0.1	0	0.0	0.00	2
Electricity, transesterification	0.2	0	0.0	0.04	32
Machinery and buildings	0.0	0	0.0	0.00	4
Transport	0.0	0	0.0	0.01	0
Total	40.3	236	39.1	3.29	295

Table 4
Change of environmental impacts and energy requirements for medium- and large-scale production of RME in comparison to small-scale production

Production factors	Change to medium-scale (%)					Change to large-scale (%)				
	GWP	AP	EP	POCP	Input energy	GWP	AP	EP	POCP	Input energy
Production of rapeseed	−1.8	−1.8	−1.8	−1.8	−1.8	−1.1	−1.1	−1.1	−1.1	−1.1
Electricity, oil extraction	−42.2	−42.2	−42.2	−42.2	−41.8	−43.2	−43.2	−43.2	−43.2	−43.0
Hexane	—	—	—	—	—	0.02[a]	0.1[a]	0.01[a]	0.015[a]	2.1[a]
Methanol	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Catalyst, KOH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electricity, transesterification	−2.3	−2.3	−2.3	−2.3	−1.6	−4.6	−4.6	−4.6	−4.6	−4.2
Machinery and buildings	−57.0	−57.0	−57.0	−57.0	−57.0	−78.0	−78.0	−78.0	−78.0	−78.0
Transport	+144	+148	+146	+159	+255	+1927	+1934	+1934	+1908	+1912
Total change	−1.8	−1.7	−1.7	−1.9	−6.2	−0.1	+0.2	+0.3	+2.7	−3.7

[a]Hexane was used only in large-scale production. Therefore, these figures are expressed in g CO_2-eq/MJ_{fuel}; mg SO_2-eq/MJ_{fuel}; mg PO_4^{3-}-eq/MJ_{fuel}; mg C_2H_4-eq/MJ_{fuel} and kJ/MJ_{fuel}.

impact from production of the rapeseed accounted for more than 95% of the total impact for all emission categories. Production of methanol was responsible for 0.7–2.5% of the environmental impact, whereas the electricity was responsible for a few per cent. The other sources had influences less than 1%.

The energy required for the production of rapeseed was almost 65% of the total energy used (Table 3). Production of methanol was responsible for more than 12% of the total energy requirement, and the electricity used for extraction and transesterification for 10% and 11%, respectively. The energy embodied in machinery and buildings accounted for 1.4%, while the energy use in other production processes was negligible. When it was considered that carbon atoms, with biomass origin, replaced fossil carbon atoms in the glycerine, the value of GWP in Table 3 decreased by 3.9 g CO_2-eq/MJ_{fuel}. This reduction was the same for all three plant sizes.

The change in environmental impact and energy use for medium- and large-scale production of RME in comparison to small-scale is shown in Table 4. The results showed, for instance, that the impact categories for electricity used in oil extraction decreased by approximately 43% per MJ_{fuel} for large-scale production in comparison to small-scale production. The difference in environmental impact and energy requirement for machinery and buildings was also

Table 5
Comparison of different allocation methods for the three production scales studied

	GWP (g CO_2-eq/MJ_{fuel})	AP (mg SO_2-eq/MJ_{fuel})	EP (mg PO_4^{3-}-eq/MJ_{fuel})	POCP (mg C_2H_4-eq/MJ_{fuel})	Input energy (kJ/MJ_{fuel})
Physical allocation					
Small-scale	40.3	236	39.1	3.29	295
Medium-scale	39.5	232	38.5	3.23	277
Large-scale	40.2	236	39.3	3.38	284
Economic allocation					
Small-scale	51.1	301	49.9	4.17	355
Medium-scale	49.1	289	48.0	4.00	327
Large-scale	45.8	270	44.9	3.84	313
No allocation					
Small-scale	87.6	519	86.2	7.15	569
Medium-scale	79.5	471	78.3	6.49	497
Large-scale	61.9	366	60.9	5.21	407
Expanded system					
Small-scale	34.5	19	45.4	−5.67	−367
Medium-scale	32.1	46	43.7	−4.74	−342
Large-scale	30.9	161	44.5	−1.38	−147

large. For large-scale plants, the energy requirement for transport increased by almost a factor of 20 in comparison to small-scale plants. However, when expressed in absolute terms, this change was rather small in relation to the total energy requirement of the production system. In general, the medium-scale system had lower total values of environmental impacts and energy demand than the small-scale system, but the difference was small. The total difference between the small- and large-scale plants was even smaller.

3.3. Influence of allocation method

The results when various allocation methods were used are shown in Table 5. As can be seen, the figures for no allocation are in many cases more than twice as high as the figures for physical allocation. It can also be noted that with no allocation and economic allocation of the environmental load, both environmental impacts and energy requirements were lowest for large-scale production. With physical allocation, the medium-scale alternative was the most favourable, but the differences were small.

Allocation with expanded systems resulted in the lowest energy requirement and AP and POCP emissions for small-scale plants. GWP emissions were lowest for large-scale plants and EP emissions were lowest for medium-scale plants. Negative values, e.g. for the energy requirement, indicate that the system was a net supplier of energy. This was possible because the energy subtracted for replaced by-products exceeded the total energy needed for the production of RME.

3.4. Sensitivity analysis

The purpose of the sensitivity analysis was to analyse to what extent uncertainty in input data affected the results. Therefore, the influence of increasing and decreasing some production factors by 20%, one at a time, was studied (Table 6). All factors changed, 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% and −20%. The GWP changed, for example, +17.2% when the use of fertiliser increased by 20%, and changed −17.2% when the use of fertiliser decreased by 20%.

Table 6
Changes in impact categories and energy requirements when some production factors were changed in a sensitivity analysis for small-scale production of RME

Changed production factors	GWP (%)	AP (%)	EP (%)	POCP (%)	Input energy (%)
Seed harvest, +20%	−15.6	−16.4	−16.5	−14.6	−9.9
Seed harvest, −20%	+23.5	+24.7	+24.8	+22.0	+14.8
Use of fertiliser, +20%	+17.2	+17.6	+17.5	+11.4	+7.7
Soil emissions, +20%	+6.5	+14.5	+16.1	0.0	0.0
Use of tractive power, +20%	+1.4	+2.1	+2.2	+5.9	+2.7
Use of machinery for cultivation, +20%	0.0	0.0	0.0	+0.1	+1.0
Use of electricity for oil extraction, +20%	+0.1	0.0	0.0	+0.2	+2.1
Use of electricity for transesterification, +20%	+0.1	0.0	0.0	+0.2	+2.2
Emissions during production of methanol, +20%	+0.5	+0.1	+0.1	+0.5	+2.4

Table 7
The original difference (from Table 4) between small- and large-scale systems, and the difference when some production factors were changed

Changed production factors	GWP (%)	AP (%)	EP (%)	POCP (%)	Input energy (%)
Original (no change)	**−0.1**	**+0.2**	**+0.3**	**+2.7**	**−3.7**
Seed harvest, +20%	+0.1	+0.5	+0.6	+3.4	−3.9
Seed harvest, −20%	−0.3	−0.1	0.0	+2.0	−3.5
Use of fertiliser, +20%	−0.2	0.0	+0.1	+2.3	−3.5
Soil emissions, +20%	−0.1	0.0	+0.1	+2.7	−3.7
Use of tractive power, +20%	−0.1	+0.2	+0.3	+2.5	−3.7
Use of machinery for cultivation, +20%	−0.1	+0.2	+0.3	+2.7	−3.7
Use of electricity for oil extraction, +20%	−0.1	+0.2	+0.3	+2.6	−4.5
Use of electricity for transesterification, +20%	−0.1	+0.2	+0.3	+2.7	−3.7
Emissions during production of methanol, +20%	−0.1	+0.2	+0.3	+2.7	−3.6

It was shown that all impact categories studied and the energy requirements were quite sensitive to changes in seed harvest and use of fertilisers (Table 6). Changes in soil emissions and use of tractive power also had an influence, but to a much smaller extent. The effects of the other changes were negligible.

The influence of increasing and decreasing the seed yield by 20% and increasing some other factors by 20% on the difference between small- and large-scales was also studied (Table 7). It was demonstrated that the changes in the input parameters had a small or negligible influence on the difference between the two production scales.

3.5. Scenario analysis

The purpose of the scenario analysis was to analyse to what extent some alternative realistic scenarios affected the results. The following scenarios were studied: ploughless tillage; 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, see Fig. 2); use of electricity mainly produced from fossil fuels (fossil fuel electricity), instead of Swedish electricity; use of catalysts for reduction of the CO, HC and NO_x emissions (by 81%, 77.5% and 6%, respectively) from diesel engines in cultivation and transport; use of the RME fuel produced for

Table 8
Influence of using alternative production scenarios in small-scale production of RME

Changed production factors	GWP (%)	AP (%)	EP (%)	POCP (%)	Input energy (%)
Ploughless tillage	−0.5	−1.5	−1.6	−2.2	−1.0
Methanol produced from *Salix*	−0.3	+1.9	+2.0	+13.9	+31.5
Fossil fuel electricity	+20.0	+4.2	+2.1	+5.3	+14.1
Catalyst used in cultivation operations	0.0	−0.6	−0.6	−11.5	0.0
Catalyst used in transport	0.0	0.0	0.0	−0.1	0.0
Produced RME fuel used for cultivation and transport	−4.5	+5.8	+6.2	−24.0	+4.7
All transport distances doubled	+0.1	+0.1	+0.1	+0.2	+0.1
Improved oil extraction efficiencies	+0.1	+0.1	+0.1	+0.2	+0.8

Table 9
The original difference (from Table 4) between small- and large-scale systems in the base scenario, and the difference when some alternative scenarios were analysed

Changed production factors	GWP (%)	AP (%)	EP (%)	POCP (%)	Input energy (%)
Original (no change)	**−0.1**	**+0.2**	**+0.3**	**+2.7**	**−3.7**
Ploughless tillage	−0.1	+0.2	+0.3	+2.8	−3.8
Methanol produced from *Salix*	−0.1	+0.2	+0.3	+2.4	−2.8
Fossil fuel electricity	−3.1	−0.5	−0.1	+1.7	−4.9
Catalyst used in cultivation operations	−0.1	+0.2	+0.3	+3.2	−3.7
Catalyst used in transport	−0.1	+0.1	+0.2	+1.6	−3.7
Produced RME fuel used for cultivation and transport	−0.6	+1.1	+1.3	+0.4	−3.3
All transport distances doubled	+1.1	+1.6	+1.8	+6.7	−1.4
Improved oil extraction efficiencies	−0.2	+0.1	+0.2	+2.5	−4.5

cultivation and transport; use of plants at locations where all transport distances are doubled; and improved oil extraction efficiencies for the small- and medium-scale plants, from 68% to 73%, and from 75% to 80%, respectively.

The most important changes in the results were observed when the methanol was produced from *Salix* instead of from natural gas, and when fossil fuel electricity was used instead of Swedish electricity (Table 8). Methanol produced from *Salix* increased the energy requirement by almost 32%, but the GWP was almost unchanged. However, if the system boundary was expanded to include CO_2-emissions from the use of the RME in an engine, GWP decreased by 9.7%, because the carbon atom in the RME that originated from the fossil (natural gas) methanol was replaced by a carbon atom originating from the biofuel *Salix*. With fossil fuel electricity, the GWP increased by 20% and the energy requirement by 14%.

When the RME produced was used for cultivation and transport in the system studied, GWP decreased by almost 5% and POCP by 24%. However, the categories AP and EP increased by about 6%, and the energy requirement by almost 5%. For ploughless tillage AP, EP, POCP and energy requirement decreased by 1–2%. Other factors studied had only a minor influence on impact categories and energy requirement.

The influence of the alternative scenarios on the difference between small- and large-scales is shown in Table 9. Most of the studied scenarios had small effects on the difference. Transport distances and choice of electricity were the most important factors.

4. Discussion

The results of this study demonstrate that the differences in environmental impacts and energy requirements between small-, medium- and large-scale systems for the production of RME are small or even negligible. 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, the higher oil extraction efficiency and the more efficient use of machinery and buildings in the large-scale system were, to a certain degree, outweighed by the longer transport distances. All these factors were, however, very small in comparison with cultivation.

The straw from the rapeseed cultivation was not considered in this study because it is seldom harvested as a fuel in Sweden today. The main reasons for this are burning problems with the new varieties, and the fact that the yield per hectare is lower than, for e.g. winter wheat straw, which makes rape straw more expensive to harvest. Therefore, the straw is used in the crop rotation to increase the humus content in the soil, and cereal straw harvested instead.

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 as the figures calculated with physical allocation. 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 with 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 [50]. 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. From the expanded system calculations in this study, it was shown that in a situation where there is a need for 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. But 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.

For large-scale systems, the results from this work differed somewhat from previous LCA studies carried out by Ragnarsson [9], Blinge et al. [10], Blinge [11] and Uppenberg et al. [26]. 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 by Gärtner and Reinhardt [12,13] for German conditions with expanded system allocation were similar to the results in this study.

It is clear that the production and use of RME reduce the GWP and POCP in comparison to the production and use of diesel oil (MK1). Based on data from the studies by SMP [29], Aakko et al. [40] and Uppenberg et al. [26], the GWP and POCP 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 127 g CO_2-eq/MJ_{engine} and 23 mg C_2H_4-eq/MJ_{engine}, respectively (large-scale system with physical allocation). However, the categories of AP and EP were increased by 79% and 81%, respectively, in comparison to MK1. The energy requirement for the production and use of RME was 4.8 times higher than for MK1 [26]. The results from the scenario analysis in which the RME produced replaced MK1 confirmed these relationships.

To decrease the environmental impact of RME 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 the 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 cleaning plants are avoided. Since the rapeseed 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* [51] and can also be applied in rapeseed cultivation. It should be noted, however, that there is a risk that organic waste and sewage water may supply heavy metals, pesticide residuals or other undesired organic substances.

Whereas the LCA showed that the differences between the systems are negligible, economic calculations have demonstrated that the differences in production costs for RME are significant between small-, medium- and large-scale plants [28]. The production cost, if the seed is assumed to be purchased for 2.0 SEK/kg [52], is 7.3 SEK/l fuel (1 Euro = 9.2 SEK [53]) for small-scale production, and is reduced by 36% and 50% for medium- and large-scale production, respectively. Because of the facts that the costs are lower for larger plants and that the environmental load is almost the same for all scales, larger plants should be preferred for these reasons.

5. Conclusions

The results of this study demonstrate that the differences in environmental impacts and energy requirements between small-, medium- and large-scale systems for the production of RME are small or even negligible. The higher oil extraction efficiency and the more efficient use of machinery and buildings in the large-scale system were, to a certain degree, outweighed by the longer transport distances.

The dominating production step regarding environmental impact and energy requirement was the cultivation, in which the production of fertilisers, soil emissions and tractive power made major contributions.

The results were largely dependent on the method used for allocation of the environmental burden between the RME and the by-products meal and glycerine. 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.

Irrespective of production scale, the use of RME reduces the GWP and POCP in comparison to the use of diesel oil, whereas the AP, EP and energy requirement are increased.

Acknowledgements

The Swedish Energy Agency is gratefully acknowledged for financial support.

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