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Energy efficiency for rapeseed biodiesel production in different farming systems

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Abstract Due to mounting concerns related to fossil fuel use and problems with their supply, the use of alternative sources of energy is increasing. One of the alternative sources is biomass and the European Union has adopted a biofuel directive that describes targets for the use of biofuels in the transport sector. The majority of biofuels produced in Europe comes from rapeseed. In this study, we focused on analyzing the efficiency of rapeseed biodiesel production. Energy efficiency in terms of Energy Return On Energy Invested (EROEI) was analyzed for two EU countries (Poland and The Netherlands) with different agro-ecological systems. Life Cycle Inventory (LCI) accounted for inputs, processes and outputs of energy in the biodiesel production system. Input parameters were derived from literature as well as from farmer's interviews. The use of the outputs—straw, meal, and glycerin—were included in the LCI system boundary. The EROEI values ranged from 1.73 to 2.36 in Poland and from 2.18 to 2.60 in the Netherlands. The low number of respondents makes it risky to draw hard conclusions about these values but the patterns observed show that intensifying the production process and increasing yield bears very little or no benefit in terms of energy produced. Due to a higher amount of organic manure and consequently lower amount of artificial fertilizers used in crop growth in the Netherlands, the rapeseed biodiesel production system in the Netherlands is more efficient than in Poland. In both cases, the EROEI is quite low. More detailed spatial energy efficiency assessments are required to determine if and where sustainable production may be possible.

Keywords Biofuel · Energy efficiency · EROEI · LCA · LCI · RME

Introduction

Humans are using energy in many ways to improve their living standards. The world energy demand is increasing because of growing consumption by a growing population. The International Energy Outlook 2010 (EIA U.S. Energy Information Administration 2010) foresees a growth in the global energy consumption of 49% from 2007 to 2035. Fossil fuels are the main energy source that drives the world economy, however, for a number of reasons it is becoming increasingly unlikely that fossil fuel supply will be able to meet this growth in demand. Reserves of fossil fuels are non-renewable and their extraction becomes

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increasingly expensive and risky. Besides, they are the main source of already unsafe levels of green house gases (GHG) in the atmosphere (Cherubini and Strømman 2011) and, therefore, the main driver of climate change. Alternative sources of energy, solar, wind, hydro-power, are most promising in terms of environmental impacts, energy security and socio-economic externalities (Bomb et al. 2007; Cherubini et al. 2009; European Biodiesel Board 2011; Mc Alister and Horne 2009; Nanaki and Koroneos 2009). Bioenergy is yet another important alternative source of energy. In this case, energy is derived from plants and can be used directly for heating, or electricity production, but most importantly, biomass can be converted into liquid fuel (Davis et al. 2009; Halleux et al. 2008) and directly used in the existing transportation infrastructure, which is almost entirely run on fossil fuels (cars, buses, airplanes). This substitutability makes biofuels especially attractive and results in much attention and, in many cases, governmental support and economic subsidies that encourage biofuel production (Kutas et al. 2007).

Cherubini et al. (2009) estimated that currently bioenergy supplies 10 % of the total world primary energy, which in most cases is used in residential areas for domestic purposes such as heating and cooking. The majority of biofuels worldwide is produced from corn, wheat, barley, sugarcane, rapeseed, oil palm, soybean, sugar beet, potato and sunflower (Ajanovic 2011; Davis et al. 2009; Demirbas 2008). This creates a major concern that biofuel production is largely derived from the same crops that are also used for food production (Baka and Roland-Holst 2009; Kavalov 2004), which inevitably pushes food prices up. Increased interest in biofuel production due to subsidies and growing demand has an indirect impact on land use and biodiversity (Arvidsson et al. 2011; Crutzen et al. 2008; Mc Alister and Horne 2009; Nanaki and Koroneos 2009; Netherlands Environmental Assessment Agency 2010).

Biofuels, however, are and at least in the short term are likely to remain, the main alternative to liquid fossil fuels (Murphy et al. 2011; Hammond et al. 2008). The chemical compounds produced from these crops are: biodiesel, ethanol, methane, and methanol (Ajanovic 2011; Börjesson and Tufvesson 2011; Brecha 2008). In contrast to North and South America where the focus is on ethanol, in Europe biodiesel is the main type of biofuel produced for the transport sector. Not surprisingly, the European Union was the world leader in biodiesel production in 2005 (Baka and Roland-Holst 2009). Out of the total of 10.2 billion liters of biodiesel production worldwide in 2007, 60 % was produced within the European Union.

Rapeseed is the main oil crop grown in Europe (Baka and Roland-Holst 2009; VROM 2010) accounting for more than half of the biofuel production (Bureau et al. 2010). In 2008 in Europe, rapeseed accounted for 79 % of all feedstock crops used for biodiesel production (Ajanovic 2011). It is cultivated in almost all European countries (Thamsiriroj and Murphy 2010). However the true costs and benefits of biofuels, their efficiency in terms of net energy production and the magnitude of associated environmental and social impacts need further analysis.

To assess sustainability of biofuel production, all potential environmental impacts over the entire lifespan (i.e., cradle-to-grave) from raw material acquisition through production, use and disposal need to be considered. This can be achieved by applying a Life Cycle Assessment (LCA). The first step in this calculation is a Life Cycle Inventory (LCI), which is basically "the result of compiling all environmental flows, including resource use inputs and waste or pollution outputs" (Horne et al. 2009). Energy efficiency is one of the most important elements of sustainability analysis (Börjesson 2009). One simple indicator of energy efficiency is the measure of Energy Return On Energy Investment (EROI or EROEI) (Cleveland 2008; Hall et al. 2009; Mulder and Hagens 2008), which is calculated as:

$$\mathrm{EROEI} = \mathrm{E_{out}}/\mathrm{E_{in}}$$

where E_{out} is the amount of energy produced, and E_{in} is the amount of energy used in production.

Energy production with EROEI of less than or even close to one is meaningless as in this case it would require as much or even more energy than what is produced (The Offshore Valuation Group 2010). Hall et al. (2009) claimed that a minimum EROEI of 3 should be achieved in order to support continuing economic activity and social function. Murphy and Hall (2010) produced an overview of EROEI values in a comparison of different energy sources.

The EROEI index has been criticized (Wu and Sardo 2010) for inappropriately favoring energy production with low input values. Indeed as energy input approaches zero EROEI tends to infinity. As an alternative, it is suggested to look at net energy (NE) produced:

$$\mathrm{NE} = \mathrm{E}_{\mathrm{in}} - \mathrm{E}_{\mathrm{out}}$$

EROEI is more about efficiency of energy production and tells us how much energy is produced per unit of energy used. NE would favor energy production at higher costs as long as the net output of energy is higher. While both indices are worth considering, we prefer EROEI because in most cases there are many other factors in the energy production process that may be hard to account for in only energetic terms. Such externalities include land use conversion, impacts on water quality, soil loss, biodiversity impacts and other environmental effects, as well as possible esthetic, cultural and other aspects, which are difficult to account for in terms of energy and which are always higher when the operations are more energy intensive. In this case, EROEI indirectly favors the production that is less energy intensive even if the net energy produces may be somewhat lower.

One other important caveat relates to energy quality, which is not directly included in the EROEI equation. For example, if we have abundant electric energy, but are badly in need of liquid fuels, it may still make sense to produce such liquid fuels even if the energetic value of electricity input is higher than the energy produced. In this case, we need to distinguish between the various types of energy that we are considering. Besides, EROEI analysis is “highly sensitive to assumptions about both system boundaries and key parameter values” (Hall et al. 2009; Farrell et al. 2006). Nevertheless, the EROEI approach is based on solid thermodynamic principles and is, therefore, a good first step into understanding the efficiency of energy production.

Mulder and Hagens (2008) classify the level of EROEI analysis into three orders. In the context of rapeseed biofuel production and in line with the different EROEI accounting methods, first-order EROEI includes energy input from cultivation, transportation and energy for conversion of the feedstock at refinery. The direct energy output is in Rapeseed Methyl Ester (RME). Second-order EROEI calculation includes indirect energy inputs and energy costs of by- and waste products in addition to what is included in the first-order EROEI. The third order EROEI adds up all the social and environmental externalities associated with the whole production system (e.g. mitigating health problems or erosion or other forms of environmental deterioration). It then allocates energy values to them in addition to what is included in the second-order EROEI calculation.

A key parameter in the EROEI calculation is crop yield. Crop yield and consequently the energy efficiency of biofuel production are affected by various agricultural technologies that may be applied (Börjesson 2009; Johnston et al. 2009). The yield can be increased by applying manure, mineral fertilizers, herbicides, pesticides or fungicides, as well as by improving agricultural practices through cultivation, irrigation, etc. But since production and application of chemicals and advanced farming techniques always require additional energy, the energy input in crop growth also increases. It is not always obvious whether the energy output will be a net benefit or loss if we do apply these advanced technologies. The processes relevant for a second-order EROEI calculation are presented in a causal loop diagram in Fig. 1.

In this paper, we focus on analyses of energy efficiency of rapeseed biofuel production for different agro-ecological systems: Poland and the Netherlands who are on the same latitude but have somewhat different climate and soils, and a more substantial difference in farming practices. Most LCA studies depend entirely on literature (Batchelor et al. 1995). In our study, we also interviewed farmers engaged in rapeseed production to validate inputs and outputs. The engagement of farmers in our study was not intended as a comprehensive survey of practitioners to cover all the range of growing conditions and practices. Instead we saw it mostly as a “reality check” for the LCA that we were performing, as a way to discuss and validate the various steps of the production process with those who knew most about it.

In both countries, rapeseed is grown both as summer and as winter crop and in both cases it is part of a crop rotation system. Winter rapeseed is more abundant due to a higher achievable crop yield compared to summer rapeseed and because having a crop on the land during winter reduces soil erosion. Therefore, in this paper, we compare the energy efficiency of biofuel production from winter rapeseed.

Our objective is to improve the quantification of the energy production estimates for rapeseed and to

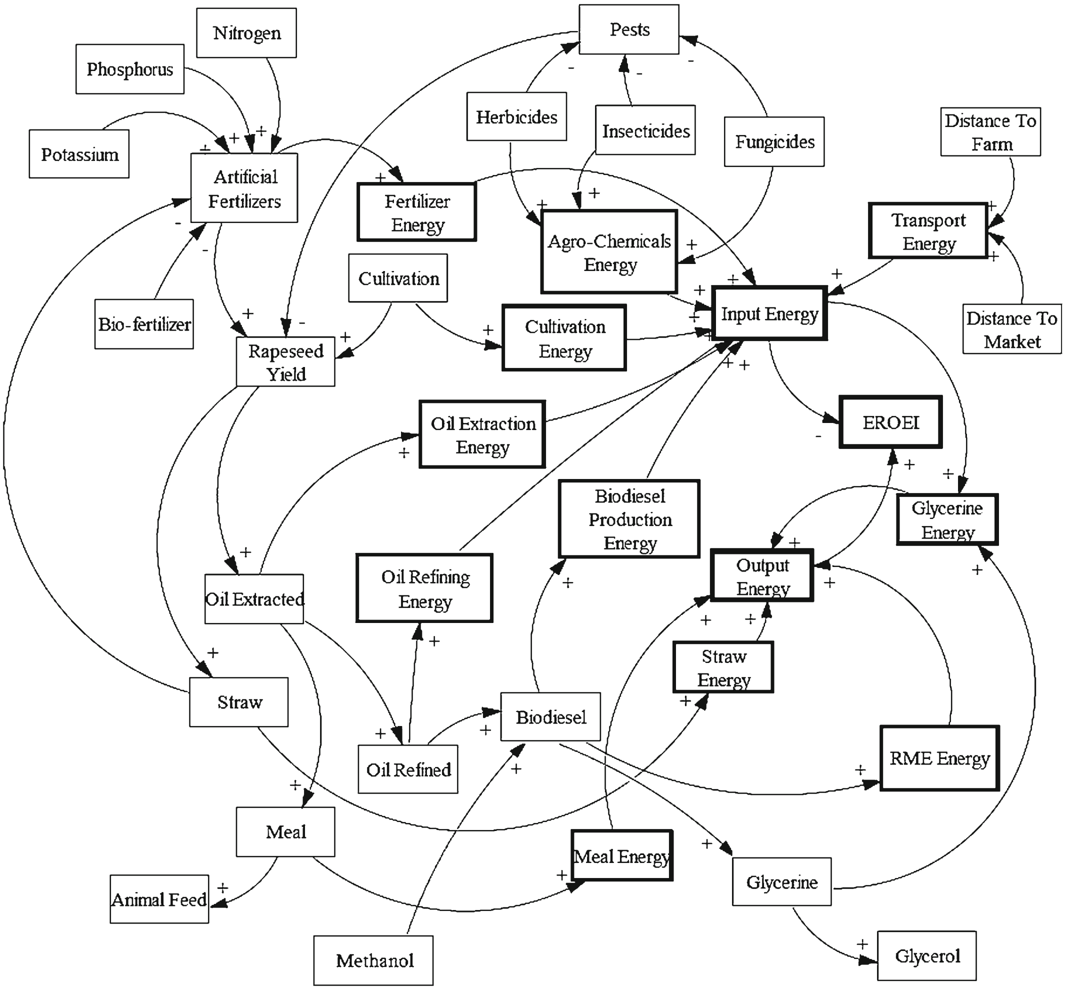

Fig. 1 Causal loop diagram of Energy Return on Energy Input (EROEI) for the rapeseed biodiesel production system. All processes that require or produce energy (*boxes with bold lines*) are connected via positive or negative cause-effect relationships

demonstrate that higher yields (agricultural goal) do not necessarily translate into higher bioenergy potential. We also aim at providing information to policy and decision makers for optimizing biofuel energy production efficiency.

Materials and methods

Study area description

Poland and the Netherlands are found on the same latitude (52° N) but differ somewhat in climate with Poland having lower temperatures in winter and overall less rainfall, especially in summer. The International Institute for Applied Systems Analysis calculated a rapeseed crop suitability map based on various climatic, topographic, soil, and crop requirement parameters (Fischer et al. 2002). We used this map in Fig. 2 to show the European rapeseed suitability with enlargements of Poland and the Netherlands on which the locations are plotted of the farmers who were interviewed. According to the FAO statistics Poland used on average 830,817 ha land over the period 2007–2011 to grow rapeseed while in the Netherlands only 2,606 ha of land was used to grow this crop. In Poland, this means more than 2.5 % of the land is used to grow rapeseed while in the Netherlands this is less than 1 %

Based on the suitability map, it appears that Poland has a better potential to grow rapeseed compared to the Netherlands. On the other hand, the farming

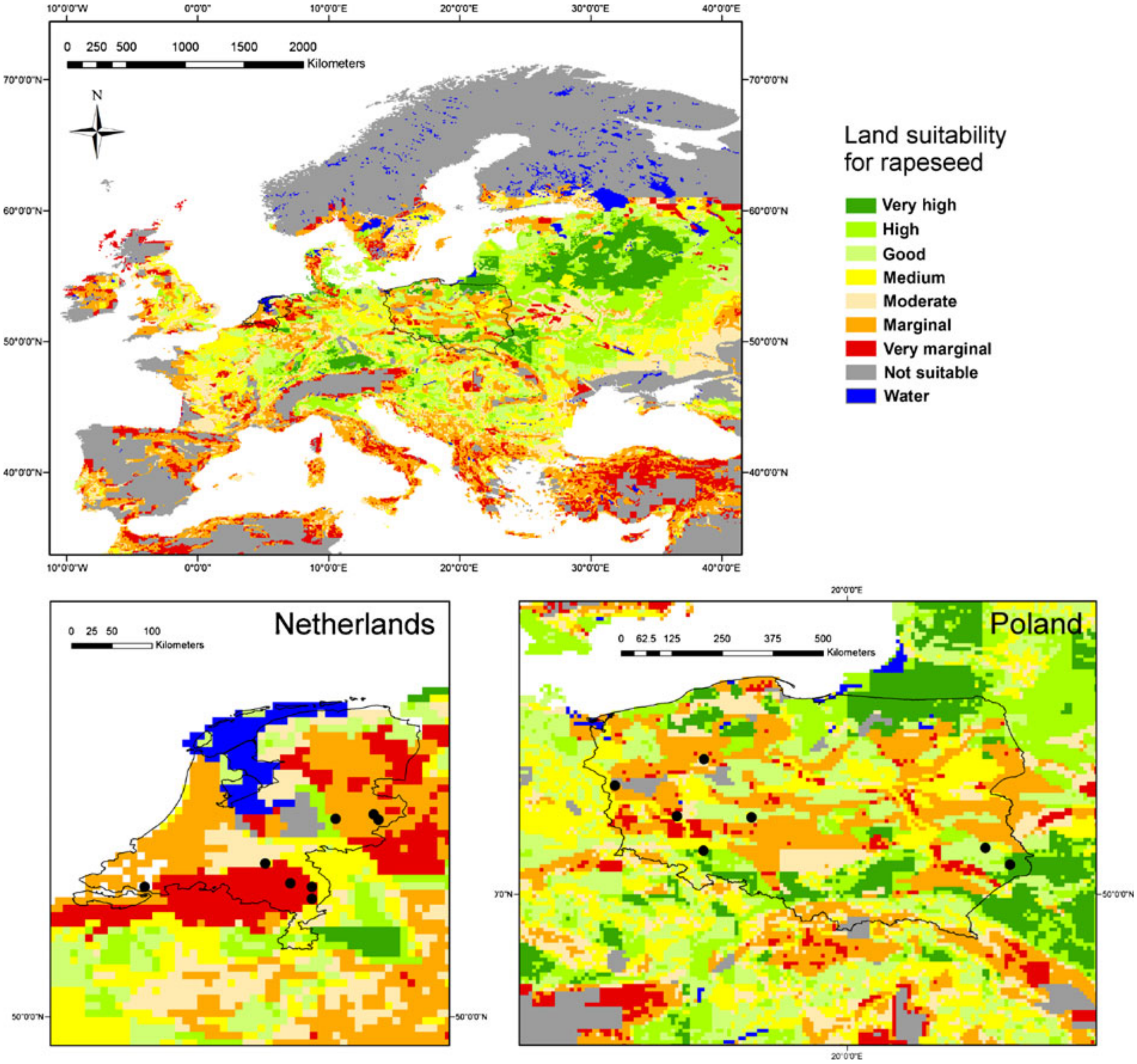

Fig. 2 GAEZ (Global Agro-Ecological Zones) suitability maps for rain fed rapeseed cropping in Europe (Fischer et al. 2002) overlaid by location maps of Polish and Dutch rapeseed farmers contributing to this study

system in the Netherlands is more advanced than in Poland. The Dutch are widely using precision farming, in particular GPS and other hi-tech methods; there are agro businesses offering services such as site specific sampling for detailed soil fertility maps and yield maps (Molenaar 2007). Agriculture in Poland is characterized by fragmentation of land ownership and a relatively low level of modernization. After World War II, lands where divided into small holdings, which were given to private farmers. Application of precision farming is rare. For example, the use of GPS is not common because of difficulties with precise identification of parcel borders. Stimulated by the Government, however, this seems to be changing now (Molenaar 2007).

Life cycle assessment for energy efficiency

LCA was conducted to estimate energy efficiency only. The general framework and principles for LCA are described in the ISO 14040 and 14044 standards (ISO 14040 2006 and ISO 14044 2006). After defining the goal and the scope, a Life Cycle Inventory was performed. Based on literature and interview data, amounts of energy were allocated to the various processes and products in the biofuel production chain. Ultimately, energy efficiency in terms of EROEI was calculated to compare the efficiency of energy production from rapeseed in the two countries.

The goal of the LCA analysis was a comparative energy efficiency assessment for two countries with different rapeseed crop production systems. The energy outputs of RME and by-products were related to all energy inputs required during crop production, transport and biomass conversion for energy production (EROEI) in Poland and the Netherlands.

The energy inputs and outputs at farm level were expressed as energy (in megajoule) per hectare (ha). The second-order EROEI calculation performed in this study included the energy inputs to produce rapeseed and the amount of fertilizers and chemicals for crop protection provided during rapeseed crop growth as well as the energy required for transport and the conversion of biomass to RME. Figure 3 shows all inputs, processes and outputs of the rapeseed biofuel system. In the calculation, only the 2009 and 2010 production seasons were taken into account.

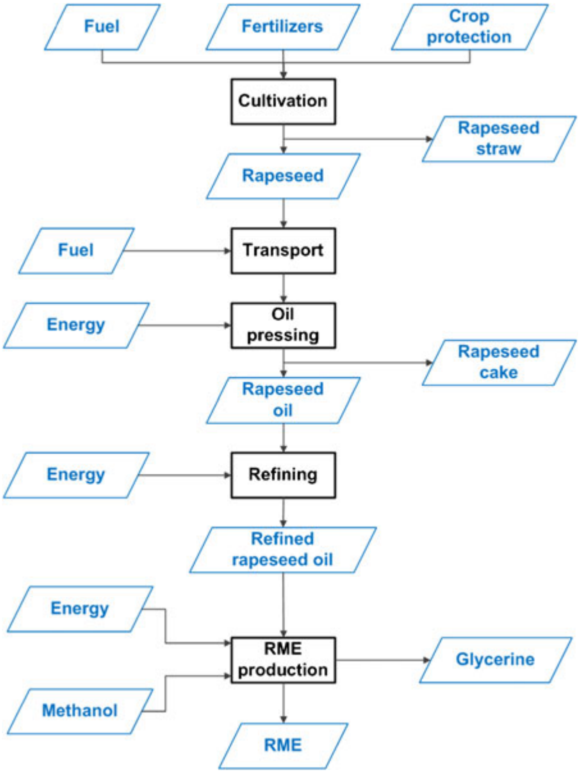

Fig. 3 System diagram for rapeseed biodiesel production

Life cycle inventory

The LCI determined the baseline for the EROEI calculation for the entire rapeseed biofuel production process. In addition to reviewing literature, we interviewed practicing farmers to compile and refine the list of all inputs and outputs within the boundaries of the rapeseed biofuel production system.

The next step was calculating the energy requirements for each process for both Poland and the Netherlands. Ideally, here we would want to have as many respondents as possible distributed across different agro-ecological regions, and covering a diverse range of farming practices. First, farmers were contacted by telephone to explain the purpose of the research and to ask if they were willing to spend about 15–20 min to fill in a questionnaire composed of 30 questions. When they indicated their willingness to cooperate, they received a questionnaire (translated into their own language). The questionnaire included questions on the location of the farm, the distance to the fields where rapeseed was grown and the distance to the biofuel production plant. Furthermore, questions were included on the types and quantity of fertilizers and crop protection chemicals used.

In the Netherlands, we received a list of farmers growing rapeseed in 2009 and 2010 via LTO Netherlands (the Dutch farmers' organization). Because the response rate of the farmers was low we tried unsuccessfully to increase the sample by contacting the local farmer cooperatives or beekeepers who advertised that their honey was from rapeseed. A practical solution to increase the number of respondents was by contacting farmers of fields where rapeseed was visually observed. This resulted in two more on-farm interviews. Based on the recommendation and contact addresses provided by the Rapeseed Farmers Association, Polish farmers were also contacted face to face, over the phone and by mail.

Unfortunately the response rate was low. We have ended up with eight farmers in each country responding to our survey. Farmers were reluctant to discuss numbers that were somehow associated with the productivity of their farms or their profits and losses. In other cases, they were probably too busy or did not connect the research with their needs or interests. Nevertheless, they have provided important information about their farming practices, were instrumental in validating the processes in our computational model, and gave us valuable estimates for energy inputs and outputs in terms of fertilizers, crop protection, transportation, yield, straw production, etc. (see the systems diagram in Fig. 3).

Computational model

The EROEI calculations were performed on a per-hectare basis using the following formulas:

Energy inputs

Cultivation Energy (CE) The amount of energy in the form of diesel fuel used, called here cultivation fuel (CF in liter per hectare) for driving the tractor and operating the machinery to cultivate the land. This includes running the tractor to distribute fertilizers, chemicals or manure. There were large discrepancies in the numbers derived from the interviews, and we ended up using estimates from literature (Downs and Hansen 1998; Grisso et al. 2010) for the operations identified in the interviews. The energy content of 35.9 MJ/l for diesel was adopted from the report by the European Commission (2005).

$$\mathrm{CE(MJ/ha)} = 35.9\mathrm{(MJ/l)} \times \mathrm{CF(l/ha)}$$

Fertilizer Production Energy (FE) The energy required for the production of the three major mineral fertilizers: nitrogen, phosphorus and potassium. The quantities of fertilizers (N, P, and K, respectively, in kilogram per hectare) used for rapeseed production were derived from the interviews. The energy conversion factors (in megajoule per kilogram) were based on Lewis (1997) with a more recent conversion factor for N-fertilization based on Jenssen and Kongshaug (2003).

$$\begin{aligned}\mathrm{FE(MJ/ha)} = {} & 40.3\mathrm{(MJ/kg)} \times \mathrm{N(kg/ha)} \\ & + 8.6\mathrm{(MJ/kg)} \times \mathrm{P(kg/ha)} \\ & + 6.4\mathrm{(MJ/kg)} \times \mathrm{K(kg/ha)}\end{aligned}$$

When raw manure was used as a substitute for mineral fertilizers, we assumed its energy production costs to be zero. Manure can be seen as waste or side product from milk and meat production, and Dutch farmers, for example, pay additional costs to get rid of it. Janulis (2004) uses, however, 1993.5 MJ/ha energy costs for the production of bio-fertilizer, which is an order of magnitude less than the cost of mineral fertilizers, but not zero. The sensitivity of the EROEI value for our assumption was tested.

Crop Protection Energy (CPE): The energy required for production of insecticides, herbicides and fungicides. The application quantities (I, H, F, respectively, in liter per hectare) were provided by the farmers. The energy conversion factor of 274.1 MJ/kg for all three types of crop protection chemicals was based on Mortimer et al. (2003) and converted from l/ha in kg/ha assuming that the density of the chemicals is equal to that of water.

$$\begin{aligned}\mathrm{CPE(MJ/ha)} = {} & 274.1\mathrm{(MJ/kg)} \\ & \times [\mathrm{I(kg/ha)} + \mathrm{H(kg/ha)} + \mathrm{F(kg/ha)}]\end{aligned}$$

Transportation Energy (TE): The energy required for round trips between the farm house and field (TF) and from the field to the market (TM) (in most cases this was the RME production plant). The average total distances (in kilometer) over the cultivation period were calculated from the interviews and doubled to account for the return trips. Fuel consumption rate for a tractor was assumed at 32.8 l diesel/100 km as suggested by Lewis (1997)[1] and the energy content for diesel was 35.9 MJ/l diesel (European Commission 2005).

$$\begin{aligned}\mathrm{TE(MJ/ha)} = {} & 2 \times 0.328\mathrm{(l/km)} \times 35.9\mathrm{(MJ/l)} \\ & \times [\mathrm{TF(km)}+\mathrm{TM(km)})/(\mathrm{field\ area(ha)}]\end{aligned}$$

Feedstock Production Energy (FPE): The total energy (MJ) required to produce the per-hectare feedstock and deliver it to the biofuel processing plant. It is the

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[1] It would make sense to assume that trucks instead of tractors would be used to deliver the yield to markets, especially over longer distances. This may be the case but it hardly changes our results, because fuel consumption of heavy trucks is almost the same as for tractors. Natural Resources Canada reports in a 2000 survey that the average fuel consumption of its fleet was 39.5 l/100 km (http://oee.nrcan.gc.ca/transportation/business/documents/case-studies/fuel-effic-benchm.cfm?attr=16). Even assuming that this has improved over the past 12 years, we get results similar to what we have for tractors.

summation of the energy inputs above:

$$\mathrm{FPE(MJ/ha)} = \mathrm{CE(MJ/ha)} + \mathrm{FE(MJ/ha)} + \mathrm{CPE(MJ/ha)} + \mathrm{TE(MJ/ha)}$$

The next step was calculating the energy input to convert the feedstock into biofuel.

Conversion energy (CoE): The energy for extraction, refining and RME production is dependent on the rapeseed yield and amount of biodiesel produced from it. Campbell and McCurdy (2008) described the different conversion products. They expressed energy input per kilogram of biodiesel produced. Their energy allocation factors were 3.38 MJ/kg biodiesel for extraction of crude rapeseed oil from the rapeseed yield (EE), 0.34 MJ/kg biodiesel for refining the crude oil into refined rapeseed oil (RE) and 7.7 MJ/kg biodiesel for the conversion of refined rapeseed oil into biofuel (BPE). From their mass balance, it was derived that 1 kg of biodiesel requires 2.66 kg of rapeseed, which means 1 kg of rapeseed produces 0.376 kg biofuel. This results in energy allocations per kilogram of rapeseed, which can be further multiplied by *Y*, yield (in kilogram per hectare) to recalculate on a per-hectare basis:

$$\mathrm{EE(MJ/ha)} = 3.38(\mathrm{MJ/kg\ biofuel}) \times 0.376(\mathrm{kg\ rapeseed/kg\ biofuel}) \times \mathrm{Y(kg\ rapeseed/ha)} = 1.27(\mathrm{MJ/kg}) \times \mathrm{Y(kg/ha)}$$

$$\mathrm{RE(MJ/ha)} = 0.34(\mathrm{MJ/kg\ biofuel}) \times 0.376(\mathrm{kg\ rapeseed/kg\ biofuel}) \times \mathrm{Y(kg\ rapeseed/ha)} = 0.13(\mathrm{MJ/kg\ rapeseed}) \times Y(\mathrm{kg\ rapeseed/ha})$$

$$\mathrm{BPE(MJ/ha)} = 7.7(\mathrm{MJ/kg\ biofuel}) \times 0.376(\mathrm{kg\ rapeseed/kg\ biofuel}) \times \mathrm{Y(kg\ rapeseed/ha)} = 2.89(\mathrm{MJ/kg\ rapeseed}) \times \mathrm{Y(kg\ rapeseed/ha)}$$

The total amount of energy necessary for the conversion of rapeseed biomass in biofuel (RME) is:

$$\mathrm{CoE(MJ/ha)} = \mathrm{EE(MJ/ha)} + \mathrm{RE(MJ/ha)} + \mathrm{BPE(MJ/ha)}$$

Total energy invested (TEI): The summation of all the energy required for cultivation, fertilizer production, crop protection chemicals production, transport and the conversion energy.

$$\mathrm{TEI(MJ/ha)} = \mathrm{FPE(MJ/ha)} + \mathrm{CoE(MJ/ha)}$$

Energy outputs

All energy outputs are converted to values that are expressed in the amount of energy produced per unit farm area (MJ/ha). Since most output energy conversion factors and values found in literature were related to the weight of biofuel produced, we converted those values to energy per kilogram rapeseed feedstock and then multiplied it by yield (*Y*) in kilogram per hectare.

Energy output in the form of biodiesel or RME (ERME): This was calculated as follows: According to Campbell and McCurdy (2008), 1.08 kg of biodiesel has the same energy content as 1.00 kg of fossil diesel. This means that 1.00 kg of biodiesel has the same energy content as 0.926 kg of fossil diesel, which gives us the energy conversion factor of 0.926× 35.9=33.2 MJ/kg biofuel based on the fossil fuel diesel energy content 35.9 MJ/kg (European Commission 2005) and 1 kg of rapeseed produces 0.376 kg biofuel (Campbell and McCurdy 2008):

$$\mathrm{ERME(MJ/ha)} = 33.2\ (\mathrm{MJ/kg\ biofuel}) \times 0.376(\mathrm{kg\ biofuel/kg\ rapeseed}) \times \mathrm{Y(kg\ rapeseed/ha)}$$

The by- and waste products considered in the calculation were rapeseed straw, meal (cake), and glycerin.

Energy from Straw (ES): Rapeseed is mainly grown for its seeds but leaving straw, roots and empty pods after harvesting the seeds on the land causes an assumed reduction of 32.5 kg of N/ha fertilization to grow the next crop. This energy reduction is called the "preceding crop effect" (ES) and is equivalent to 2122.5 MJ/ha (Gärtner and Reinhardt 2003). This is an average value used in many LCAs and it assumes that the amount of straw that becomes available as fertilizer is not dependent upon yield.

$$\mathrm{ES(MJ/ha)} = 2122.5\mathrm{(MJ/ha)}$$

Energy from Meal (EM): The mass balance of Campbell and McCurdy (2008) shows that per 2.66 kg rapeseed feedstock, there is 1.6 kg rapeseed meal and 0.1 kg glycerin produced while producing 1 kg RME. The real energy content of rapeseed meal is unknown and, therefore, Campbell and McCurdy (2008) used economic values to allocate the energy content value of 5.08 MJ/kg biodiesel or 1.91 MJ/kg rapeseed feedstock. In this case, their calculations were based on substituting rapeseed meal with another animal feedstock with a known energy value and an equal price.

$$\mathrm{EM(MJ/ha)} = 1.91\mathrm{(MJ/kg\ rapeseed)} \times \mathrm{Y(kg\ rapeseed/ha)}$$

The energy production in the form of glycerin was according Campbell and McCurdy (2008) 13 % of the total energy requirements to produce biodiesel.

$$\mathrm{EG(MJ/ha)} = 0.13 \times \mathrm{TEI(MJ/ha)}$$

The total energy return (TER) from the rapeseed biofuel production chain is the summation of all the individual output processes.

$$\mathrm{TER(MJ/ha)} = \mathrm{ERME(MJ/ha)} + \mathrm{ES(MJ/ha)} + \mathrm{EM(MJ/ha)} + \mathrm{EG(MJ/ha)}$$

Now the final step, the calculation of the energy efficiency in the form of energy return on energy investment (EROEI) can be made.

$$\mathrm{EROEI} = \mathrm{TER(MJ/ha)}\ /\mathrm{TEI(MJ/ha)}$$

The calculation of EROEI was performed for every farmer. In case a farmer had not filled in all questions, we assumed that this farmer used the average of the other farmers. This resulted in an average EROEI value as well as estimates of EROEI with minimum or maximum energy input.

Results

Survey outcomes

The interviews with farmers showed that rapeseed cultivation practices varied between farmers within a country as well as between farmers in the different countries, Poland and the Netherlands.

All energy inputs were quantified per hectare rapeseed cropland. Table 1 shows the summary of the different inputs in the two countries, including the minimum, average and maximum input per country. Although the figures are based on a low number of farmer's responses, the pattern that can be observed is clear and consistent. Fertilizer (NPK) input appears to be higher in Poland compared to the Netherlands while the crop yield is lower. This is in spite of the

Table 1 Inputs and outputs in rapeseed cropping based on farmers interviews in Poland and the Netherlands. Cultivation includes running tractors, machineries and land operations carried out in the field. The numbers for cultivation fuel use (in liter per hectare) derived from the interviews appeared to be inconsistent. Estimates from literature (Downs and Hansen 1998; Grisso et al. 2010) were used instead

Inputs and outputs	Poland (*n*=8)			Netherlands (*n*=8)		
	Minimum	Average	Maximum	Minimum	Average	Maximum
Nitrogen (kg/ha)	90	183	342	55	135	200
Phosphorus (kg/ha)	12	69	102	0	29	80
Potassium (kg/ha)	16	110	160	0	73	150
Insecticide (l/ha)	0.3	1.1	2.0	0	0.2	0.8
Herbicide (l/ha)	2.0	2.3	3.0	1.5	2.1	4.0
Fungicide (l/ha)	0.8	1.4	2.0	0	0.5	1.5
Distance to field (km)	1	2	5	0.5	4	10
Distance to market (km)	10	84	300	2	61	100
Yield (Mg/ha)	2.9	3.4	4.0	3.0	4.0	5.0

fact that Poland enjoys relatively large areas with better agro-ecological conditions for rapeseed production (Fig. 2). Average herbicide use in both countries seems to be quite similar. But it looks like more insecticide is applied in Poland than in Netherlands whereas fungicide application is lower in the Dutch farming system. The farm to market transport distances are longer in Poland compared to the Netherland. But it seems Polish farmers travel less from their farm to the field and vice versa compared to the Dutch farmers. We should be careful, however, with making hard claims based on these figures as the number of respondents was too low to consider our two farmers' surveys fully representative for the entire country. Nevertheless, these numbers are sufficient to analyze how on-farm practices influence the energy efficiency of the energy production process in both countries.

Rapeseed crop production

Polish farmers plough and sow rapeseed in August. They apply fertilizers two to four times and depending on the appearance of weeds, pests, and fungi they apply crop protection chemicals three to four times (0.3 to 3 l/ha) during the growing season. In rotation with rapeseed, other crops are grown by farmers, of which the most common ones are wheat, barley, maize, and legumes. The average yield of rapeseed is 3.4 Mg/ha. Almost all farmers sell the yield produced to temporary storage companies, oil producing factories, and biofuel producing refineries by themselves or through farmer cooperatives.

Dutch farmers also sow in August after plowing and fertilizing the land. Due to precision farming techniques they can use less fertilizers compared to Polish farmers. Dutch farmers apply organic manure during land preparation and rapeseed sowing. This was not common practice in Poland (personal communication with Szymon Kuczyński 2011, and inferred from the survey outcome). The tractors and combine harvesters are comparable in the two countries. Agrochemicals (0 to 4 l/ha) are used depending on the infestation threat. Farmers commonly grow wheat, barley, and maize in rotation with rapeseed. The average yield for rapeseed is 4.0 Mg/ha. Rapeseed produced was sold to biodiesel factories in the Netherlands or in some cases exported to Germany.

EROEI calculation based on LCI

The EROEI values in Poland ranged from 1.73 to 2.36 and in the Netherlands from 2.18 to 2.60 (Fig. 4a and c). To help to understand and interpret the results, the calculations are broken into relatively small steps. It should be noted that the "lowest EROEI value" is different from "the EROEI value resulting from the lowest input". In Table 2, first all energy inputs are presented followed by the calculated and summed energy outputs. The last row shows the resulting EROEI value. In this table, a comparison is made between the average inputs, outputs and resulting EROEI of all interviewed farmers per country and the EROEI calculations for the farmer with the lowest energy input and the one with the highest energy input in crop growth.

In terms of energy investment, farmers in Poland have on the average a higher energy input compared to their Dutch colleagues. This is mainly due to application of larger amounts of mineral fertilizers, which contribute 33.1 and 22.2 % of the total energy invested in Poland and Netherlands, respectively. Higher fertilizer application does not result in a higher yield: the average Polish rapeseed yield was 3.4 Mg/ha, while the Dutch farmers produced an average 4.0 Mg/ha (Table 1). The energy required for the conversion of rapeseed biomass to energy is the same when calculated per kg rapeseed but since the yields are larger in the Netherlands the conversion energy per hectare is larger in the Netherlands compared to Poland.

The fertilizers considered for the energy calculations are mineral fertilizers (NPK) and bio-fertilizer (manure, as common in the Netherlands). We assumed the energy production costs of bio-fertilizers to be zero, since manure in many cases is considered as a nuisance and farmers actually have to pay to get rid of it. If we need to factor in the energy costs of bio-fertilizers, we can assume the number provided by Janulis (2004), in which case the EROEI value of the Dutch rapeseed farmers will drop by 0.16. The difference in the type of fertilizers applied in the two countries results in different energy costs for rapeseed production. Out of the three commercial fertilizers, nitrogen has the highest energy production cost (40.3 MJ/kg). In Poland, average nitrogen application was 183 kg/ha, which translates into 7,375 MJ/ha spent on N-fertilizer. Compared to the total energy investment of 26,183 MJ/ha this is 28.1 %. For the Netherlands, N-fertilizer energy requirements are 19.1 % of the total energy investment.

Nitrogen fertilizers are most energy demanding and take over 85 % of energy required for production of mineral fertilizers in Poland and the Netherlands (Table 2). Note that the EROEI values that result from the lowest, average and highest energy input are different from the highest, average and lowest EROEI values, respectively.

The distances from the farm to the refinery are somewhat larger in Poland, resulting in a higher energy investment for transport. The conversion processes from biomass to energy are assumed to be the same for Poland and the Netherlands but due to higher yields in the Netherlands the per-hectare energy gain is higher there.

In both countries, a larger energy investment does not result in higher energy production efficiency although a higher crop yield is produced (Fig. 4a and b). The highest energy efficiency is generally achieved when crops are produced with the least energy invested. In the Netherlands, the interviewed farmer with the lowest energy investment produced the lowest yield resulting in a relatively low EROEI. However, it was almost the same as for the farmer with the highest energy investment. When comparing energy return on energy invested it shows that in general Dutch farmers produce rapeseed more efficiently than Polish farmers and the downward trend in Fig. 4a is more pronounced in Poland than in the Netherlands. Obviously, in both countries, additional energy investments in the form of N-fertilization do produce higher yields (Fig. 4d). However, the additional energy needed to grow and process this higher yield is not “worth” the investment as shown in Fig. 4c.

The comparison in Fig. 4d between Polish and Dutch farmers regarding the effect of nitrogen input on the yield shows that energy investments in nitrogen hardly improve the yields of Polish farmers while it does have an effect for the Dutch farmers. The slope of

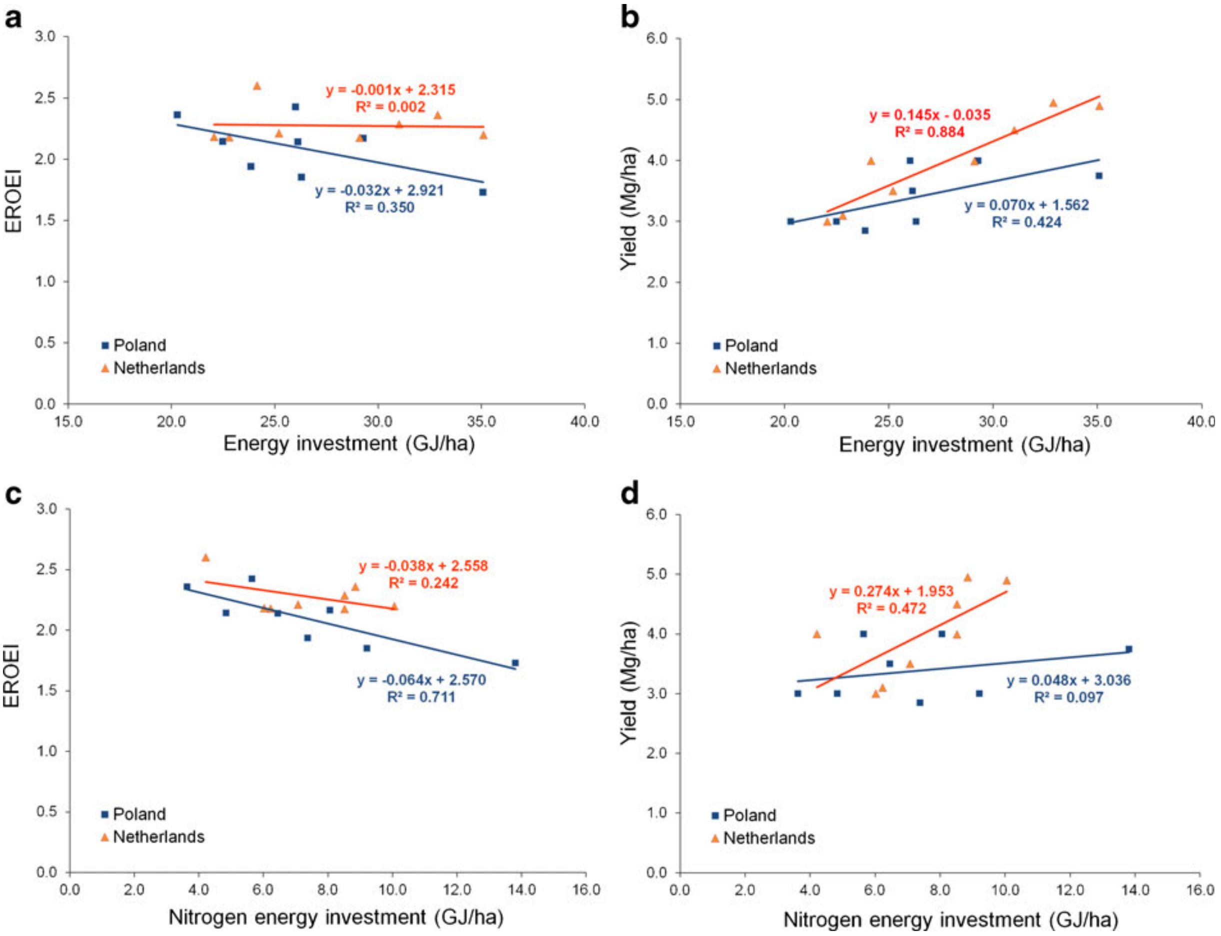

Fig. 4 EROEI and yield graphs based on farmers interviews in Poland and the Netherlands (*n*=8 for both countries)

Table 2 Energy input, output and EROEI values for Poland and the Netherlands with average, minimum and maximum total energy investment. Energy investment for operating machinery to cultivate the land (CE) was not derived from interview data but estimated based on literature (Downs and Hansen 1998; Grisso et al. 2010)

	Poland			Netherlands		
	Minimum	Average	Maximum	Minimum	Average	Maximum
Energy investment (in MJ/ha)						
CE (Cultivation Energy)=35.9×CF	1,615.50	1,615.50	1,615.50	1,615.50	1,615.50	1,615.50
FE (Fertilization Energy)=40.3×(N)+8.6×(P)+6.4×(K)	4,671.00	8,668.96	15,679.27	4,667.25	6,158.44	9,388.00
Organic manure				1,993.50	1,993.50	1,993.50
CPE (Crop Protection Energy)=274.1 (I+H+F)	1,123.81	1,333.95	1,644.60	853.14	763.63	1,014.17
TE (Transportation Energy)=2×0.328×35.9×(TF+TM)/(field area)	18.25	32.54	51.81	56.52	35.26	71.47
PTE (Production and Transport Energy)=CE+FE+CPE+TE	7,428.56	11,650.95	18,991.18	9,185.91	10,566.33	14,082.64
EE=1.27×Y	3,810.00	4,302.13	4,762.50	3,810.00	5,070.93	6,223.00
RE=0.13×Y	390.00	440.38	487.50	390.00	519.07	637.00
BPE=2.89×Y	8,670.00	9,789.88	10,837.50	8,670.00	11,539.36	14,161.00
CoE (conversion energy)=CoE×Y	12,870.00	14,532.38	16,087.50	12,870.00	17,129.36	21,021.00
TEI (Total energy investment) PTE+CoE	20,298.56	26,183.33	35,078.68	22,055.91	27,695.68	35,103.64
Energy return (in MJ/ha)						
ERME (Energy in RME)=33.2×0.376×Y	37,449.60	42,286.84	46,812.00	37,449.60	49,843.63	61,167.68
EM (Energy in meal)=1.907×Y	5,721.00	6,459.96	7,151.25	5,721.00	7,614.38	9,344.30
ES (Energy in straw)=2122.5	2,122.50	2,122.50	2,122.50	2,122.50	2,122.50	2,122.50
EG (Energy in glycerin)=0.13×TEI	2,638.81	3,403.83	4,560.23	2,867.27	3,600.44	4,563.47
TER (Total Energy Return)=ERME+EM+ES+EG	47,931.91	54,273.13	60,645.98	48,160.37	63,180.95	77,197.95
EROEI=TER/TEI	2.36	2.07	1.73	2.18	2.28	2.20

the trend lines for energy and nitrogen investment in relation to yield (Fig. 4b and d) of Dutch farmers is relatively more similar than respective slopes of trend lines for the Polish farmers. In terms of energy gains, these investments are not useful for them. It appears that fertilizer input, especially nitrogen fertilizer, can dramatically reduce efficiency of biodiesel production (Fig. 4c). Still we should be careful with these observations, because in all cases we are looking at results from different farms with potentially different agro-climatic conditions. This means that we do not really know what would be the yield if fertilizers were not applied or alternative agricultural practices would be implemented.

The energy allocation for straw was in both countries the same as it was not based on the energy content of straw but on a standard estimated preceding crop effect (Gärtner and Reinhardt 2003). Running the calculation again, using the estimated amount of straw indicated by the farmers did not result in substantially different EROEI values. In both countries, this resulted in EROEI values going down by 0.03. This means that producing bioenergy from straw seems to provide less energy than the energy saved when straw is left on the land to reduce the input energy in the form of fertilization for the next crop.

Discussion

Rapeseed biofuel production is seen as an opportunity to reduce greenhouse gas emissions and societal dependency on non-renewable fossil fuels (European Biodiesel Board 2011). Since yield is one of the variables for calculation of EROEI, every unit change in yield changes the EROEI value. Lewis (1997) indicated that energy inputs and yield per hectare depend on the different cultural practices and agro-climatic conditions. This is clearly shown in the two case study countries, which have different agricultural practices and agro-ecologies as indicated from the interview results. Both Lewis (1997) and Janulis (2004) described that energy efficiency depends on "agro-climatic conditions" and practices and technology used for the production of biofuel crops. Looking at the rapeseed suitability map in Fig. 2, it seems that in terms of agro-ecology, Poland would be a more efficient place to produce rapeseed biofuels than the Netherlands but our calculations show that currently the situation is the opposite. The main difference between farming practices in the two countries is in the use of high-tech precision farming techniques (use of manure and targeted application of fertilizers) in the Netherlands as described by Molenaar (2007). It appears that this may be influencing crop yields more than climate or ecological conditions. Growing rapeseed crops in best agro-ecological conditions, considering soils, elevation, slope, and climate, will also boost the efficiency. However, in this case, biofuels become especially dangerous by encroaching into prime agricultural lands and directly competing and displacing food production. This is exactly what may be happening if biofuels are further subsidized, and market preferences are distorted.

In this study, much time and effort was spent to prepare and execute the interviews with farmers. Searching for names and contact details of rapeseed farmers, and contacting the farmers before we could interview them was time consuming. The law on the protection and preservation of privacy rights of individuals does not allow easy access to this type of information via Governmental offices or large farmers organizations. Therefore, we had to directly contact farmers' cooperatives, local farmers' organizations and track farmers based on personal observations of them growing rapeseed. This certainly could result in some bias in the farmer's distribution over the countries. In the Netherlands, we were able to contact more farmers in the East and South of the country than in the West and North of the country.

After identifying rapeseed farmers, it remained a challenge to contact them and convince them to participate in our research. The time slot when farmers could be reached by telephone to explain the purpose of the research or to make an appointment for sending a questionnaire or to plan a visit is very limited. Several farmers who said that they were willing to fill in a questionnaire eventually never responded. The benefits of their participation are unclear and it was based on their good will only. Although the number of responding farmers was lower than planned, they showed sufficient differentiation in rapeseed cropping activities. This makes us believe that the calculations on energy inputs and outputs provide useful insight on energy efficiency of rapeseed biodiesel production. Also quite fortunately, the farmers' responses came from quite variable agro-ecological conditions (see Fig. 2), covering all the predominant suitability classes in both countries, including marginal, very marginal and suitable areas in the Netherlands, as well as highly suitable, very highly suitable and good areas in Poland.

From other studies (Bernesson et al. 2004; Börjesson et al. 2010; Lewis 1997) it was already known that mineral fertilizers, and nitrogen in particular, have a relatively large impact on the energy efficiency of rapeseed biofuel production. This research, based on interviewing farmers validated this. The fact that it is still profitable for the farmers to apply large amounts of fertilizers in attempt to increase the yield can mean only that the current market prices for fertilizers do not reflect their true energy cost. Again subsidies and failure to account for true environmental and social costs of energy blur the picture and lead to distorted efficiencies. This is yet another reason why objective measures of energy efficiency, such as EROEI, are important to understand the true picture.

Additionally our study also showed that there is substantial variation in the amounts of fertilizers used. The entire package of farming activities, and consequently the total energy input affects the yield. However, in Poland, nitrogen fertilization had a relatively weak relationship with the yield. In the Netherlands, the link between energy investment in nitrogen and an increase in crop yield is obviously stronger. In both cases, however, there was a negative relationship between total energy investment and EROEI. The trend line for Poland went down steeper compared to the one of the Netherlands. This is again contributed to a fairly large investment in N fertilization with hardly any effect on the yield. We conceptualized this relationship in Fig. 5. In case of low energy input (a), an increase in input leads to higher yields and higher EROEI values. In point (b), the maximum EROEI value is reached in the stage where an increase in input energy balances the increase in output energy. Further increasing the input energy increases the yield but not the net energy that can be produced from it (c). It should be noted that this application of manure could

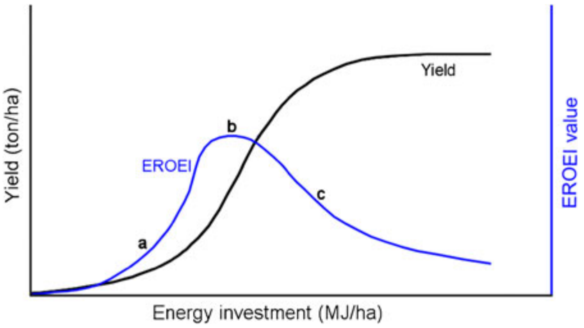

Fig. 5 Conceptual diagram of energy investment related to yield and EROEI

be also considered as waste disposal and treatment, and therefore does not have to come as an energy cost. Manure disposal is a very hot issue in farming and in most cases farmers have to pay additional fees and spend additional energies to get rid of the manure. In case we do not treat manure as a side product from another production process and do allocate energy costs to its application, the EROEI value for Dutch farmers goes down by 0.18.

Checking the FAO statistics database reveals that over the last 10 years reported in the database (2000–2009) Poland and the Netherlands achieved average countrywide yields of 2.5 and 3.4 Mg/ha, respectively, (FAOSTAT 2011). This is substantially less compared to the average yields reported by the farmers in our study for 2010. We hypothesize that farmers with relatively high yields were more likely to participate, being proud of their results and not afraid to show them to researchers. If we take the average FAO yield over the last 10 years for both countries as a basis of our calculations and assume the average energy input the same as reported by the farmers participating in our study, then the EROEI values would drop 0.24 in Poland and 0.12 in the Netherlands. However, if these yields were obtained with lower energy inputs and if we take these inputs from the trend lines in Fig. 4b, then the corresponding input investments would be 15 GJ/ha for Poland (for a yield of 2.5 Mg/ha) and around 24 GJ/ha in Netherlands (for a yield of 3.4 Mg/ha). Feeding these figures into our computational model (explained in the "Computational model" section) results in an EROEI of 2.67 for Poland and 2.26 for the Netherlands, which would confirm the better potential for efficient rapeseed biofuel production in Poland compared to the Netherlands as suggested by the suitability map of the IIASA (Fischer et al. 2002).

We should remember that there are a lot of uncertainties in doing these kinds of substitutions and generalizations. After all for each individual farm we have a unique combination of ecological (soil quality, terrain, etc.), climatic (temperature, wind, soil moisture, etc.) and agricultural (sowing practice, application schedules for fertilizers and pesticides, harvesting, storage, etc.) conditions, which also translate into unique energy performance results. We can only observe a general trend that more energy investment does not seem to result in more net energy produced. However, locally, this conclusion may not hold.

If we take into account the energy quality issue, the use of energies of other quality (say wind and solar electricity) as input energy may make rapeseed biofuel still an attractive product. For instance, assuming that all energy conversion (CoE) expenses, as well as fertilizer (FE) and pesticide (PTE) production can all be covered by electricity derived from renewable sources (wind, solar, etc.) and limiting our EROEI estimates only to the liquid phase (biodiesel), we can get substantially higher values of 31.3 in Poland and 16.2 in the Netherlands. Optimizing the use of by- and waste products can also contribute to a higher efficiency of biofuel production. All this can potentially make biodiesel a viable alternative to fossil fuels.

Also, alternative uses of by- and waste products as energy sources can produce savings on the energy input side and boost the overall efficiency of the process in terms of a specific energy type (liquid fuels). There are a number of stages in the process where energy of a different type of quality can be used, which can make biofuels still a viable substitute at least for the transition period. However, without those improvements and adjustments the future of biodiesel looks quite bleak.

Other important aspects that may determine the attractiveness of rapeseed biofuel is variability in crop yields (Fig. 4 and FAOSTAT 2011) and fluctuations in market prices (FAOSTAT 2011) for farmers as these may cause undesired fluctuations in the feedstock availability. This is more or less related to the current issues of indirect effects of biofuel productions on food crops such as rapeseed.

Life cycle analyses are relaying on literature referring to quantities of inputs and outputs including by- and waste products as well as conversion factors.

Some of these references are already quite old, not taking into account recent developments in production techniques or energy use. In this research, we have conducted farmers' interviews to extend and double check the data available from literature in attempt to improve the quantification of different energy inputs and outputs in rapeseed production. The relatively low number of responses of farmers was, however, a factor that had to be taken into account while interpreting the absolute EROEI figures but the patterns observed are clear.

Like other researchers involved in EROEI assessments, we ran into the difficulty of unclear reporting on boundary conditions or methodologies in various reports, which made comparison with other studies tricky.

Validation of energy efficiency in refining plants was not possible as none of the contacted refineries wanted to cooperate in this study. It seems they feel that outcomes of studies like this one are not beneficial for their business.

Conclusions

Our analysis has confirmed that, currently, EROEI of biodiesel production is quite low. Improving the energy efficiency of rapeseed biodiesel is certainly crucial if we want it to become a viable substitute for fossil fuels such as oil and gas, which still have much higher EROEIs. It has been depicted that different inputs and processes have different impacts on overall energy efficiency. The study concluded that fertilizer input, especially nitrogen fertilizer, could dramatically reduce efficiency of biodiesel production. The fact that it is still profitable for the farmers to apply large amounts of fertilizers in attempt to increase the yield can mean only that the current market prices for fertilizers do not reflect their true energy cost. Again subsidies and failure to account for true environmental and social costs of energy blur the picture and lead to distorted efficiencies. This is yet another reason why objective measures of energy efficiency, such as EROEI, are important to understand the true picture.

Generally, we show that investing more energy to boost rapeseed yields in most cases results in lower EROEI values. Of course, since output of biofuels depends on the yield of the feedstock, increasing yields without substantial additional inputs of energy, for example by using manure instead of mineral fertilizers, can improve the EROEI of the process.

The fact that it is still profitable for the farmers to apply large amounts of fertilizers in attempt to increase the yield can only mean that the current market prices for fertilizers do not reflect their true energy cost—another reason to evaluate sustainability of biofuels with objective measures of energy efficiency, such as EROEI.

Searching for possibilities to use renewable energy sources as input in rapeseed biofuel production and optimizing the use of by- and waste products can result in substantial savings on the energy input side and boost the overall efficiency of the process.

Collecting data about actual on-farm practices and resulting crop yields is a challenge. Farmers do not often respond to on-line questionnaires as they are too busy or they do not see any benefit for themselves. However, updating conversion factors by including information on what farmers actually do on their land and to which crop yield this leads, will definitely contribute to more realistic bioenergy production efficiency figures.

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