Energy efficiency of fossil and renewable fuels

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Abstract

Assessment results of renewable energy supply in agriculture and forestry are often questionable because 1. the methodology does not describe the nature dependent conditions of agricultural production, 2. there is no standard system boundary, 3. thermodynamic laws are violated and/or ignored, 4. direct and embodied energy is mixed, 5. the mainstream life cycle analysis (LCA) takes downstream and upstream inputs arbitrarily into consideration, depending on the research objectives and the research-funding agency. Thus, the calculation results neglect a wide range of specific energy input figures of upstream and downstream factors outside farm level resulting in non-comparable figures.

The EROI describes the ratio between energy output and input. The advantage of this measure is that energy input and output of fuel supply as well as the resulting CO_2 emissions are comparable. There are no standards to calculate the indirect energy input of commodities and services hidden in monetary inputs (insurances, rent for land, subsidies and fees etc.). They are usually excluded because procedures to handle them as energy input are rare. The easiest way to quantify the indirect energy is the use of the energy intensity (EI). Multiplying the price of any good or service with the energy intensity results in a rough estimation of energy embodied in the good or service. Applying the EROI and the EI to compare the efficiency of fossil and renewable energy supply released the following results:

Substitution of fossil fuels by renewable ones causes always additional costs. Most known renewable energy supply techniques need more energy than fossil fuel exploitation. Polluting the environment is - for the time being – the most competitive alternative. Renewable engine fuel, produced from biomass, is not competitive with fossil fuels in terms of EROI. The energy of one ha biomass may substitute gasoline to drive a car 40 000 km with biogas. Electric power harnessed from one ha solar panels enables to drive an electric vehicle 5 000 000 km applying the same calculation method. The most efficient way to mitigate CO_2 emissions is to include the entropy of agricultural products in energy policy decision making. Albeit wood has a high EROI, processing fuels from wood of low entropy makes no sense: Producing a table from a tree and burning the residues and the table at the end of its lifetime renders the same energy gain as using the tree for fuel only. The EROI of fossil fuels remains probably on high level during the next 50 to 100 years. Oil and gas will be replaced by coal, in Finland also by nuclear power, peat and wood. Although biomass is more renewable than fossil fuels, its EROI is lower and substitution will not reduce CO_2 emissions.

Climate change may force humankind to reduce fossil fuel consumption. The only sustainable way to achieve this is reduction of fossil fuel exploitation.

Key words

Energy return on investment, energy intensity, CO_2 emission, renewable energy, fossil energy

Introduction

The Crafoord price laureate Howard Odum stated 1996: "Because global consumption of fuels is occurring faster than their production by the environment, carbon dioxide has been increasing, affecting the climate.... Although biomass is more renewable, its EMERGY yield ratio is less than that of fossil fuels, and substitution would not reduce carbon dioxide release"

This statement and the fact that every year CO_2 content of the atmosphere increases (IPCC 2014), leads to the question: are all our efforts to replace fossil fuels by renewable ones in vain despite more than 40 years research after the "oil crisis"? To answer this question, this paper focuses rather on the energy efficiency of fossil and renewable fuels than on economic or environmental scales.

Methodology

The methodology to measure the competitiveness of renewable fuels bases on 1) calculation of the energy return on investment (EROI) of a fuel, (ii) calculating the energy balance of farms using a holistic farm model where the farm boundary = system boundary. This approach may also consider the agricultural production of a country as one big farm, and (iii) fossil energy input calculation.

The EROI

The energy return on investment is the ratio between energy output and input and describes how much energy is necessary to supply a fuel in relation to its energy content (Hall et al., 2008, Mulder & Hagens 2008, Hagens & Mulder 2008):

$$\mathrm{EROI} = \frac{\text{energy content of a fuel}}{\text{energy input to supply a fuel}} - 1$$

The advantage of this measure is that energy input and output as well as resulting CO_2 emissions are comparable The following example may clarify this statement:

A car consumes 100 gasoline units supplied with an EROI of 4.25. Then the overall fossil energy consumption is 100+100/4.25=124 fossil energy units. If we replace gasoline by ethanol produced from sugar cane with an EROI of 0.2 (Farrel et al. 2006) like we do in E95 gasoline, then the overall energy consumption of renewable energy is 100+100/0.2=600 renewable energy units. If the energy input is limited to 124 to maintain the same CO_2 emission level, only about 21 (124≈20.7+20.7/0.2) renewable energy units - that is about 1/5th - remain at the car owner's disposal.

The farm model

To apply the EROI as a measure in the farm energy analysis we may consider Finnish agriculture as a big farm embracing several production processes, storages and consumers. The model used in this paper uses the physical farm boundary as system boundary (Schäfer 2015). Thus the impact of replacing fossil fuel by renewable ones on the different processes and on the farm output like food, feed, fibre, and fuel as well as losses and emissions can be calculated.

The Energy intensity

Because reliable figures for the input of indirect fossil fuels are hardly available, two methods to assess indirect energy input are used: first multiplying mass with a mass to energy conversion factors (LCA-approach) and second multiplying cost of farm input with the energy intensity (EI), **table 1**. The world energy intensity is the energy consumed worldwide divided by the gross domestic product (GDP) of the world. Because many input items of agriculture come from the global market, the energy intensity of Finland alone does not include sufficiently goods produced outside the country. Therefore the world EI describes the reality better. The EI of primary energy includes both, fossil and renewable energy sources. The EI of fossil energy is useful estimating the fossil energy embodied in a service or good. Both energy intensity figures cover a realistic range to assess the EROI of Finnish agriculture.

Results and discussion

Presently the energy intensity of the world economy is about 3 kWh fossil energy per € and that of primary energy about 3.3 kWh/€. The imagination that the value of a10€ note was created consuming 3 litre fossil fuel may illustrate this fact. Thus only 10% of the world GDP is powered by renewable energy.

Table 1: World energy intensities of primary and fossil energy in 2010. Exchange rate 1.35$/€, unit conversion 3.6MJ/kWh, GDP = world gross domestic product

World energy intensity kWh/€	MJ/€	GDP €	Fossil energy kWh	Source
Fossil Energy				
3,38	12,16	3,77E+13	1,27E+14	EIA 2014
3,18	11,44	3,77E+13	1,20E+14	OECD/IEA 2012
2,48	8,92	4,76E+13	1,18E+14	World Bank 2014
Average 3,01	**10,84**			
Primary Energy				
3,95	14,23	3,77E+13	1,49E+14	EIA 2014
2,90	10,45	5,09E+13	1,48E+14	OECD/IEA 2012
3,06	11,00	4,76E+13	1,46E+14	World Bank 2014
Average 3,30	**11,89**			

Figure 1 shows the energy input of Finnish agriculture calculated on mass basis. The red labels mark the direct energy input, the black ones embodied energy input. The output of Finnish agriculture in terms of food is presented in **table 2** (Energiateollisuus 2014, IEA 2014, Motiva 2010, Nyholm et al. 2005, OECD/IEA, Risku-Norja 2002, Soimakallio & Saikku 2012, Suomen Biokaasuyhdistys 2014, TEM 2013, Tiike 2011a & 2011b, Statistics Finland 2004 & 2012a & 2012b, World Bank 2014). Thus the EROI of Finnish agriculture is about 0.7 (12769/19718=0.65 on mass to energy basis and 12769/18111=0.71 on EI basis). As long as the energy balance of Finnish agriculture is negative, biomass from agriculture will not contribute to replace fossil fuels outside the agricultural sector.

Table 2: Output of Finnish agriculture in 2010

Direct energy input	Quantity	unit	GJ	GWh
Total crops for human nutrition	3.19	10^9 g	36 483 184	10 134.22
Total animal products for human nutrition	2.58	10^{12} g	9 415 613	2 615.45
Honey	1.70	10^6 g	23 494	6.53
Reindeer meat	2.40	10^6 g	12 792	3.55
Mink and fitch	1 327 404	units	1 654	0.46
Fox and racoon dog	2 115 824	units	30 859	8.57
Total human nutrition and fur			**45 967 595**	**12 768.78**

There are some weaknesses or possibilities for abuse of the model. E.g. inputs rendered from external contractors like tillage or combined harvesting may bias the real energy consumption if the energy analysis will not take into account the fuel consumed by the contractor's machinery during the work inside the farm boundary. As a following the farm energy balance favours outsourcing services. The same problem pertain renewable fuels from tropical countries. These fuels are considered to be CO_2 neutral and thus improve the CO_2 balance of the importing country based on the assumption that fossil fuel is replaced by renewable fuel. However, there is no scientific proof that this is the fact. Such a balance calculation does not take into account the fossil energy input used up in the country of origin as well as the local emissions. While the energy of fossil fuel is easy to quantify via the calorific value and the mass of the fuel, the energy content embodied in goods and services is not easy to determine. Introducing the energy intensity may make this work much easier.

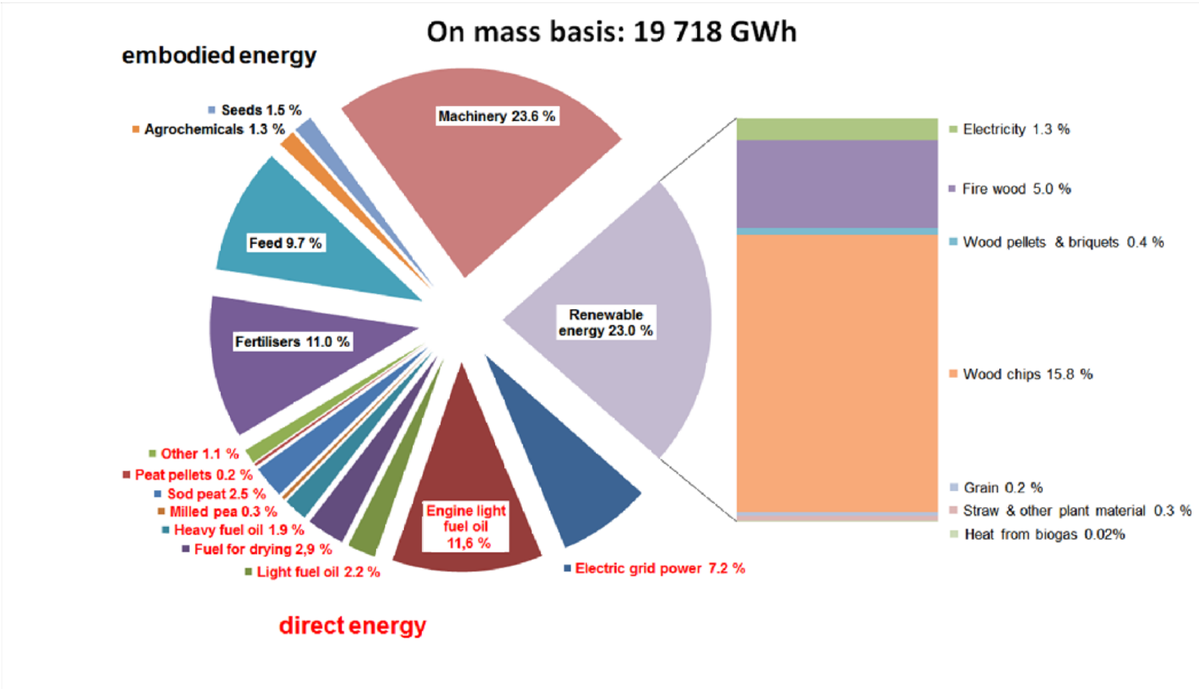

Figure 1: Energy input of Finnish agriculture in 2010 based on mass and mass to energy conversion

Figure 1 shows that most important direct energy inputs are engine fuel, electricity, and heating oil for drying. Fuel oil input makes only 19% of the total energy input. Thus replacing diesel fuels by renewable fuels has a very little impact on CO2 mitigation in the agricultural sector. The embodied fossil energy in-

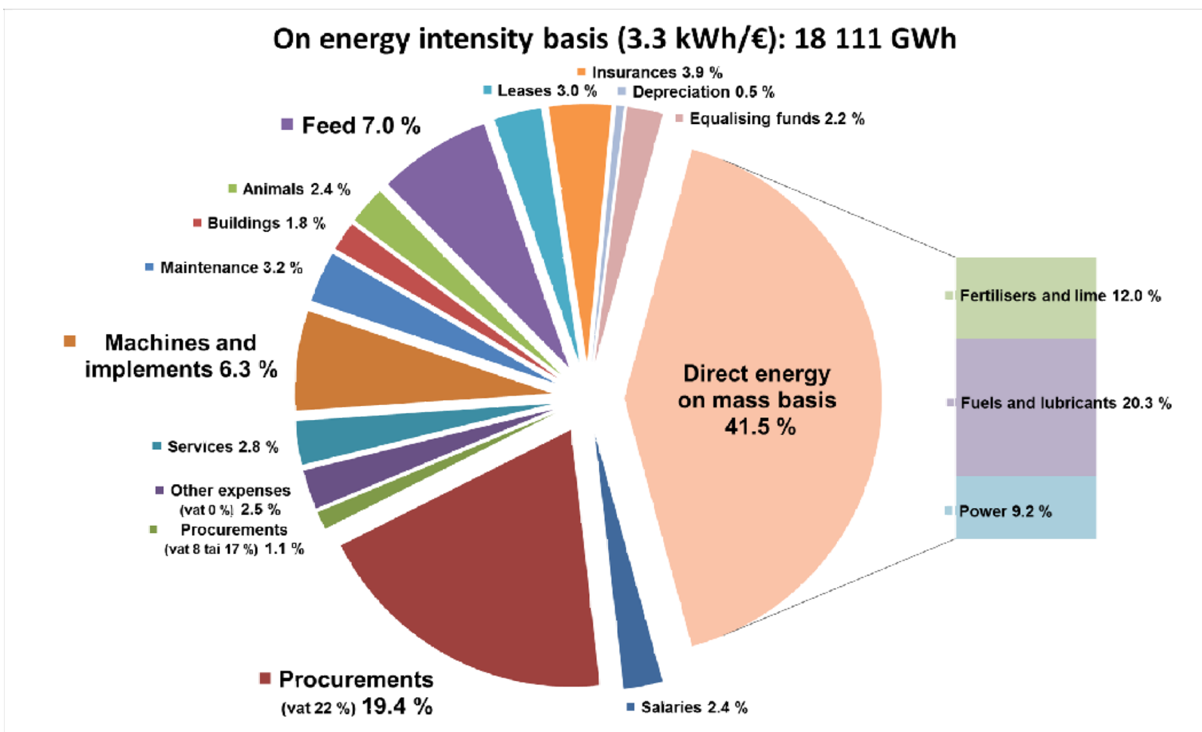

Figure 2: Energy input of Finnish agriculture in 2010 based on world primary energy intensity

put of agriculture is about 47% and exceeds the direct fossil energy input which amounts to about 23% of the total energy input. Most important indirect energy inputs are machinery, fertilisers, and feed. The right block of figure 1 show different types of renewable energy input which covers already now nearly a quarter of the total energy input. However, direct and embodied fossil energy sum up to about 15.2 TWh that is about 6573 kWh ha^{-1} corresponding 657 litres oil ha^{-1}.

The calculation on basis of energy intensity in figure 2 shows similar results as the calculation on mass basis in terms of overall energy input based on the expenditures of Finnish agriculture (Statistics Finland 2012b). However, the embodied energy of machinery is one magnitude greater than on mass basis. There may be two reasons: First, the machinery figures calculated on mass basis (Nyholm et al. 1005) are 10 years old and concern the manufacture of machinery in Finland not the machinery on farm. Second the mass to energy conversion factor is too high and the energy intensity for production of machinery is too low.

Direct energy input and fertiliser input were calculated on mass basis, because the energy intensity underestimates the heating value of fuels and the high fossil fuel input to produce fertilisers. Here, the direct energy input figure does not distinguish between renewable and fossil energy input. Yet the total direct energy input calculation of both methods shows similar results (23% fossil + 23% renewable = 45.7% in figure 1 and 41.5% in figure 2).

To replace fossil fuels the most competitive renewable fuels are those with the highest EROI. If the supply cost of a renewable fuel is known, the EROI can easily be calculated. As an example the biodiesel factory of UPM in Lappeenranta (UPM-Kymmene Oyj, 2012) illustrates the method.

Table 3: Estimated EROI of the UPM biodiesel without energy input and cost of black liquor

		Energy intensity	3.01	3.3	kWh/€
Assumptions		Cost	Energy		
Investment	150 000 000 €		451 500 000	495 000 000	kWh
Production	120 000 000	litre per year	1 200 000 000	1 200 000 000	kWh per year
Depreciation	20 years	0.06 € per litre	0.19	0.21	kWh per litre
Interest rate	20 %	0.25 € per litre	0.75	0.83	kWh per litre
Work force	200 man years				
Workers salary	50 000 € per year	0.08 € per litre	0,25	0.28	kWh per litre
Total		0.40 € per litre	1.19	1.31	kWh per litre
EROI			7.39	6.66	

In **table 4** some figures from literature are compiled.

Table 4: Estimated EROI of fossil fuels compared to renewable fuels (Farrell et al. 2006, Lötjönen et al. 2009, Pimentel 2008, Scholz et al. 1998). The EROI of fossil fuels was calculated from fuel price 2012 (www.boerse.de/rohstoffe) and EI.

Fuel	Heat	Power	Engine fuel
Diesel	6.3 to 7.1	2.5 to 3.3	6.3 to 7.1
Gasoline	n/a	n/a	3.8 to 4.3
Ethanol from sugar cane	0 to 0.2	n/a	0 to 0.2
Ethanol from waste	2.8	n/a	2.8
Wood gas	2.7 to 3.7	n/a	<2.7 to < to 3.7
Fire wood	21	8	n/a
Wood chips	21	8	n/a
Pellets	7.3	2	n/a
Solid bio fuels	12 to 50	n/a	n/a
Biogas from waste	0.7 to 2.3	0.3 to 0.9	0.6 to 1.8
Biogas from energy crops	0.6 to 2	0.2 to 0.8	0.5 to 1.6
RME	0.38 to 6	n/a	0.12 to 1.83

Even though energy from wood may have a high EROI, processing fuels from wood of low entropy makes no sense: Producing a table from a tree and burning the residues and the table at the end of its life-time renders the same energy gain as using the tree for firewood only. Consequently, the synthesis of carbon hydrates from CO_2 and water is the most promising path to replace fossil fuels by renewable ones. In the light of these techniques and their high efficiencies, energy crops for fuel technologies have no future.

Substitution of fossil fuels by renewable ones increases energy consumption and production cost. More important is the mitigation potential of embodied energy in goods and services. Organic crop production saves the embodied fossil energy of nitrogen fertilisers and the improved soil fertility may absorb up to 50 % of the CO_2 emissions of agriculture (FAO 2003, Mäder et al. 2002, Gattinger et al. 2012, Skinner et al. 2014.)

In agriculture the most efficient way to mitigate CO_2 emissions is to include the entropy of agricultural products in energy policy decision making. Thus, fossil energy outside the farm may be saved, e.g. fibre crops may replace raw material produced by fossil fuels, e.g. insulation material like pulp (Schäfer 2012).

Conclusions

The EROI of fossil fuels remains probably on high level during the next 50 to 100 years. Oil and gas will be replaced by coal as the increasing investment into coal power plants worldwide confirms (Davis & Socolow 2014), in Finland also by nuclear power, peat and wood.

Substitution of fossil fuels by renewable ones causes always additional costs, because all known techniques to provide renewable fuels from biomass need more energy than fossil fuel exploitation (Giampietro & Mayumi 2008). In other words: Polluting the environment is - for the time being – the most competitive alternative for Finnish farms.

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