ENERGY AND CO_2 BALANCE OF BIO-ENERGY PLANTS AND OF VARIOUS FORMS OF BIO-ENERGY

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Abstract

Energy and CO2 balances are calculated for bio-fuels (bio-diesel and bio-ethanol), for the incineration of biomass and for the production of biogas. The complete life cycle of a bio-energy form is considered, taking into account the production of bio-energy crops on farmer's field as well as the conversion of the crop biomass into the respective bio-energy form (fuel, heat, electricity).

Crop production on farmer's field shows a positive energy and CO2 balance. The application of mineral N fertilizers further improve this balance. For instance, for wheat production in Western Europe it has been shown that the extra energy captured in the grain when using mineral N fertilizers at economic optimum rates is more than 6 times of the energy used to manufacture, transport and apply the fertilizer (Küsters, 1999). The CO2 balance of crop production is also positive, and the use of fertilizers helps to fix extra CO2 in the biomass. For winter wheat, an increasing yield obtained with N fertilizer resulted in an additional fixation of CO2 in the biomass. This CO2 fixation is substantially higher than the volume of CO2 and other greenhouse gases (N2O) emitted when producing, transporting and applying the fertilizer. The CO2 binding is not permanent, but short to medium term depending on the final use of the crop produced (food, feed, industry). The CO2 binding, however, helps to reduce fossil CO2 emissions if the biomass is used to substitute fossil fuels in heat and electricity generation or used in the transport sector as a bio-fuel.

Generally, the different bio-energy forms analyzed in this study have the potential to save fossil energy and to mitigate CO2 emissions. To what extent fossil energy is saved and CO2 is mitigated depends on the feedstock (kind of crop used) and the conversion technology that converts the feedstock into bio-energy. Bio-ethanol made from sugar cane and the production of heat and power from the incineration of biomass or biogas have the highest potential to save energy and to avoid CO2 emissions. However, land use changes for new plantations or the burning of the cane straw on the field can result in a significant deterioration of the energy and CO2 balance.

Introduction

Energy is the central issue of agriculture. Agriculture supplies energy by growing crops that convert solar energy into biomass, which in turn supplies energy to human beings and animals. The energy stored in the biomass (energy output) can be used for different purposes such as food, feed or bio-energy (bio-fuels, heat, electricity). On the other hand crop production requires relatively high amounts of fossil energy (energy input) for the production of farm inputs (especially mineral N fertilizer) and for the machinery use on farm. The calculation of energy balance sheets helps to determine the energy efficiency of crop production systems.

During growth crops bind CO2 from the air via the photosynthesis process, but crop production is also a source of climate gas emissions (CO2 and N2O). However, the CO2 binding by the crop is in most cases higher than the CO2 emissions. Hence, if the crops were used as a bio-energy source, they replace fossil energy carriers (oil, gas, coal) and can thereby contribute to a mitigation of fossil CO2 emissions.

In this paper the energy and CO2 efficiency of the production of bio-energy crops on field and the potential of different bio-energy forms to reduce CO2 emissions and to save fossil energy is investigated.

Materials and methods

The Life Cycle Assessment (LCA) methodology has been used to calculate the energy and CO2 balance of the crop production (Fig. 1). First step of a LCA is to define the system under investigation (e.g. wheat production) and to describe the system boundaries. In the following inventory the energy consumption and the CO2 emissions (CO2 and N2O calculated as CO2-

equivalents) associated with the system are compiled. Finally, energy consumption and CO2 emissions are balanced against the energy fixation and CO2 fixation in the harvested biomass.

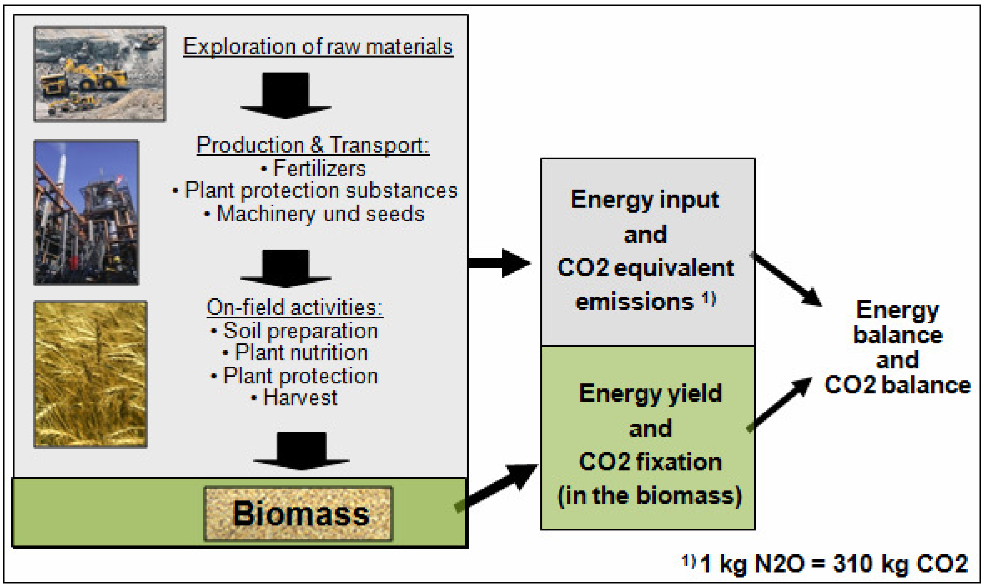

Figure 1: Energy- and CO2-balance in arable production following the LCA approach

Field trial data were the basis for the calculation of the energy and CO2 balance sheets for the crop production systems. The field trials were conducted on farmer's fields to calculate the economic optimum N application rate. Fig.2 shows the calculation for winter wheat as an example. A total of 139 field trials with increasing N rates have been analyzed. Without N fertilizer average yield has been 5.5 t grain/ha. With increasing N rates the grain yield increased to 9.3 t/ha at economic optimum N rate of 181 kg N/ha.

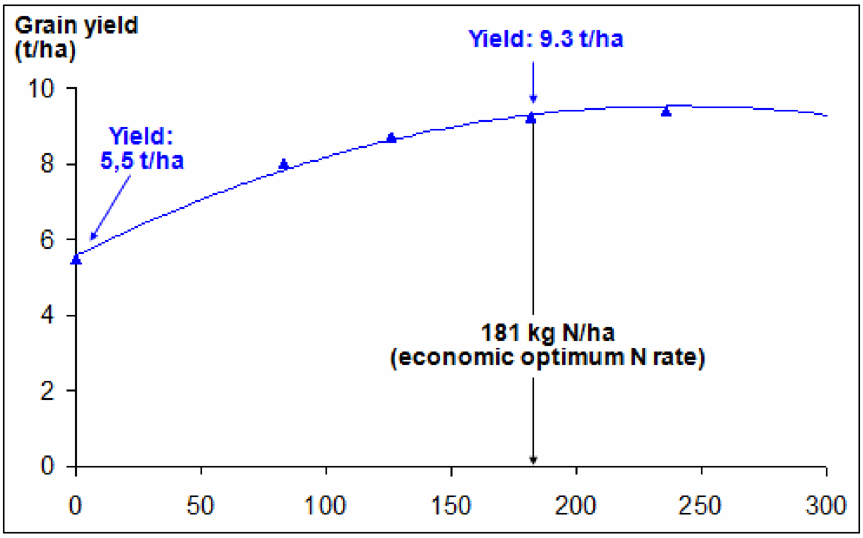

Figure 2: Calculation of the economic optimum N rate to winter wheat in 139 one-year field trials

Own data have been used for the energy consumption and CO2 emissions associated with the production of N fertilizers (Jenssen and Kongshaug, 2003). Data from literature (Jenssen and Kongshaug, 2003, KTBL, 2000, Küsters and Lammel, 1999) have been derived for the production, transport and application of other farm inputs such as P and K fertilizer, plant protection substances, seed and machinery. N2O emissions after application of N fertilizers on the field were estimated according to IPCC methodology (IPCC = Intergovernmental Panel of Climate Change) (Fig. 3). The IPCC (2006) considers direct and indirect N2O emissions at a rate of 1-2% N2O-N of the total N input (mineral and organic fertilizer).

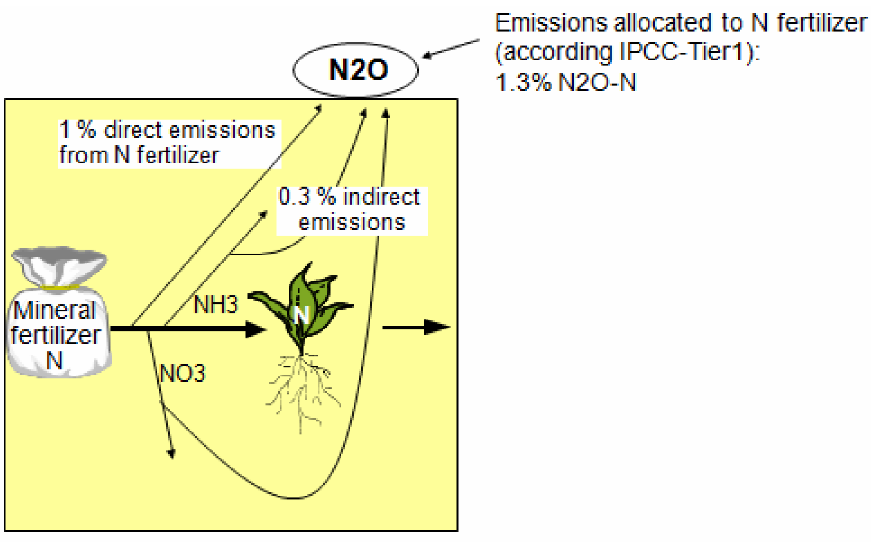

Figure 3: N2O emissions from N fertilizer use in arable production

Fig. 4 shows the energy balance of wheat production on field. When using N fertilizer at an economic optimum rate of 181 kg N/ha, wheat yields are 9.3 tons compared with 5.5 tons without N fertilizer. These 9.3 tons equate to 139 GJ* of solar energy captured in the form of biomass when nitrogen is applied, compared with only 82 GJ without N fertilizer. The extra 57 GJ captured when using N fertilizers are 7 times the 8 GJ used to produce, transport and spread the same fertilizers. The resulting net energy yield (energy output with harvested grain minus energy input) at economic optimum N rate is 123 GJ/ha.

When using solar energy to produce biomass, plants capture atmospheric CO2 as their main source of carbon. Taking the same example of wheat production as above, the higher grain yield obtained with N fertilizer means that more CO2 is fixed (Fig. 5): 13.3 tons compared with only 7.9 tons without N fertilizer. The extra 5.4 tons of CO2 captured are higher than the volume of CO2 and other greenhouse gases (N oxides) emitted when producing, transporting and applying the fertilizer. The resulting net fixation capacity (CO2 fixed in grain biomass minus CO2 emissions) is 10.5 t CO2/ha.

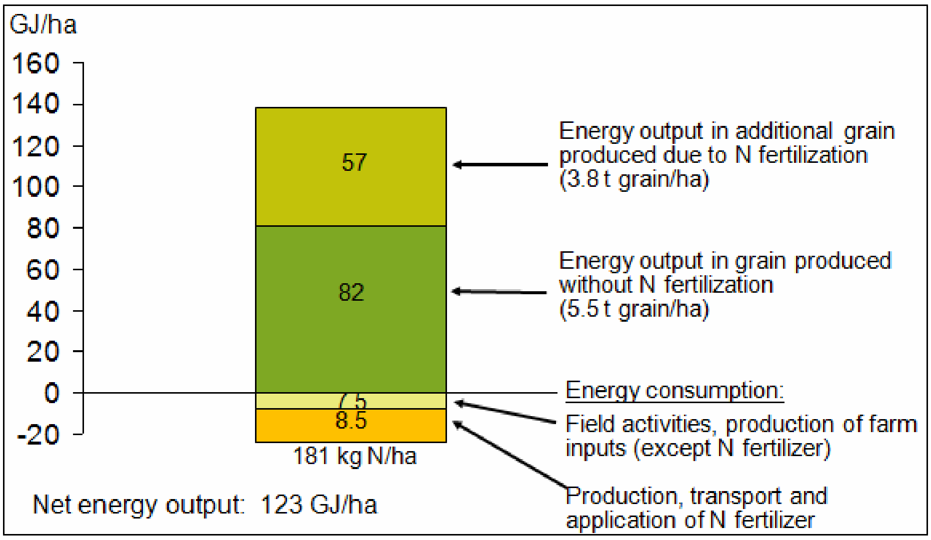

Figure 4: Energy balance of wheat production at economic optimum N rate

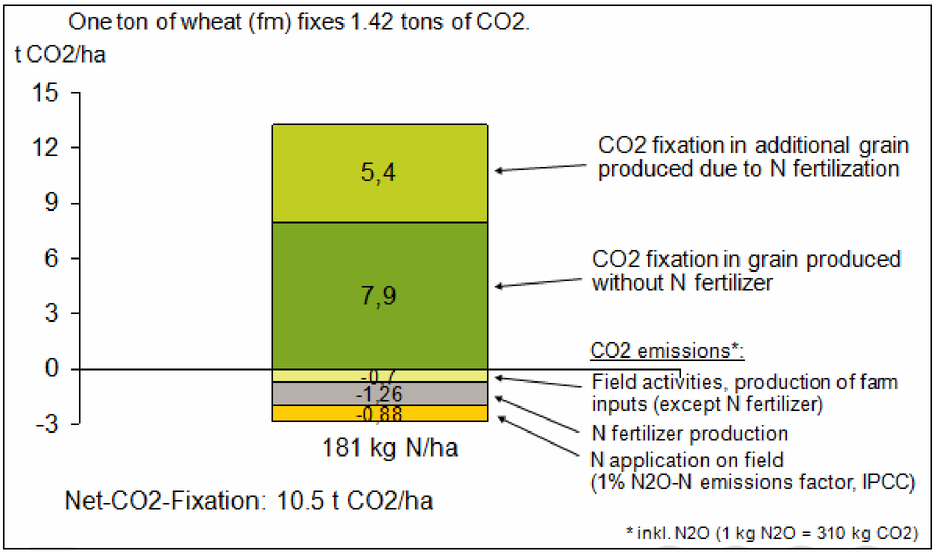

Figure 5: CO2 balance of wheat production at economic optimum N rate

Results and discussion

Energy and CO2 balance of arable crop production

The figures 6 and 7 show the energy and CO2 balance for different bio-energy crops grown at optimum production intensity (economic optimum N rate). For each crop the energy output and the CO2 fixation is much higher than the energy input and the CO2 emissions associated with the production of the crops. The balance for a crop, however, depends very much on the yield potential of the crop. Crops with a high biomass yield (e.g. sugar cane) show highest energy or CO2 balance sheets.

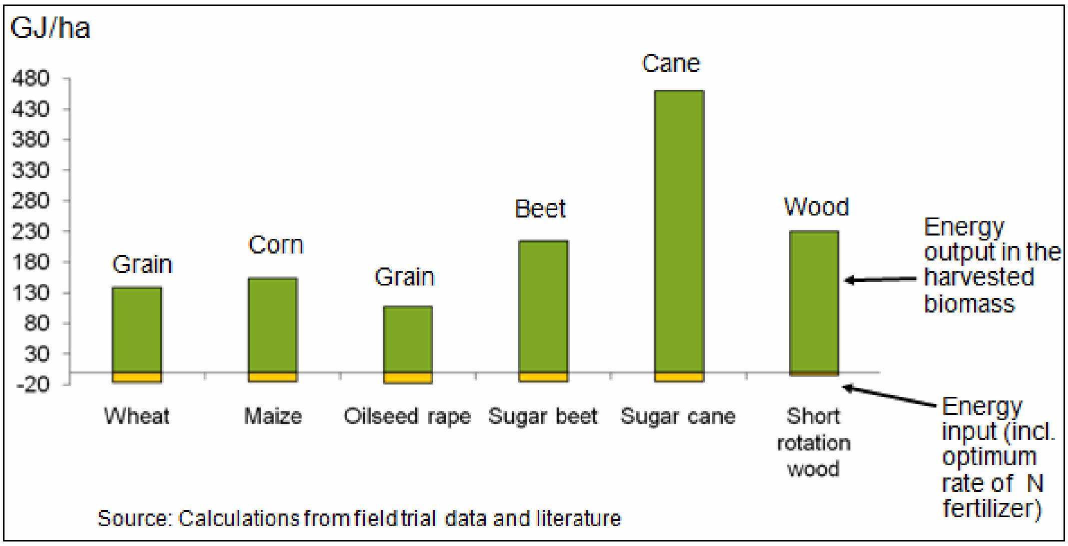

Figure 6: Comparison of the energy balance of the production of different crops

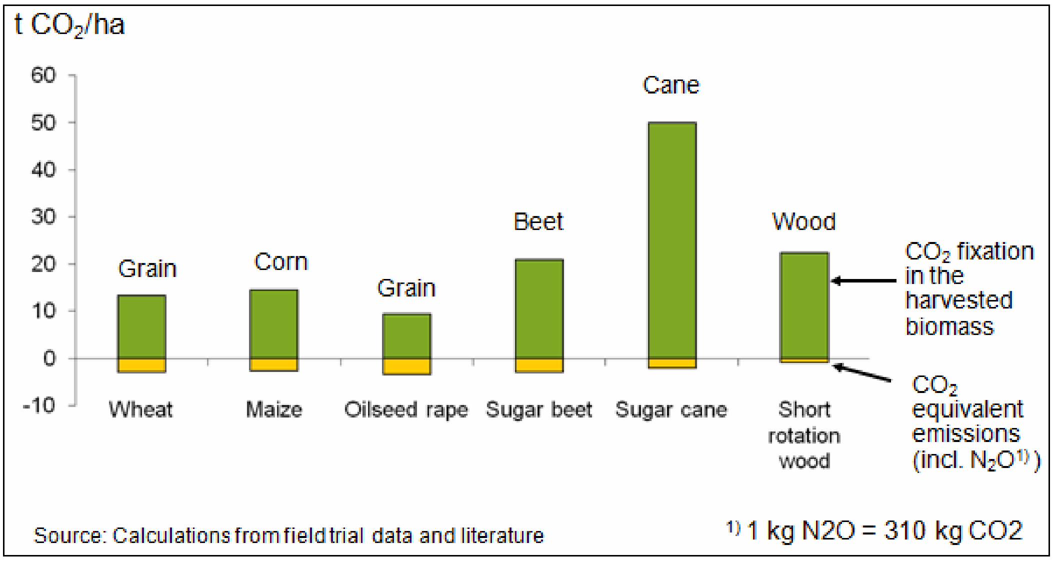

Figure 7: Comparison of the CO2 balance of the production of different crops (incl. N2O: 1 kg N2O = 310 kg CO2)*

Energy and CO2 balance of different bio-energy forms

The energy stored in the harvested biomass can be used to provide nutritional energy for humans or animals, or it can be used as a feedstock in the production of bio-energy (bio-fuels, electricity, heat). If used for bio-fuel production, it is possible to calculate the gross energy yield for each type of bio-fuel (Tab. 1). However, fossil energy inputs are required to produce the biomass on the field and to convert the biomass into the final bio-fuel (bio-diesel, bio-ethanol). Hence, this energy input needs to be substracted from the gross energy yield in the form of the harvested biomass. By doing so, the net energy gain can be calculated for each bio-fuel. Figure 8 shows a final net energy gain of 10-30% for bio-ethanol made from wheat. This means that 10 to 30 % of fossil energy inputs can be saved if gasoline is substituted by bio-ethanol.

Table 1: Gross bio-energy yield of different bio-fuels

	Biomass yield (t/ha)	Yield of fossil fuel equivalents (l/ha)
Bio-ethanol		
Cereals	6 – 10 t grain	1500 – 2500
Sugar beet	50 – 70 t beet	4000 – 6300
Sugar cane	70 – 110 t cane	4000 – 6300
Straw (Cellulose, 2nd gen.)	3 - 4 t straw	670 - 900
Bio-diesel		
Oil seed rape	3 – 5 t grain	1250 – 2100
Oil palm	26 – 25 t FFB [1)]	2500 - 4000
Wood [2)] (BTL-diesel, 2nd gen.)	10 – 15 t dry wood	2600 – 3900

1) FFB = Fresh fruit bunches
2) Short rotation wood

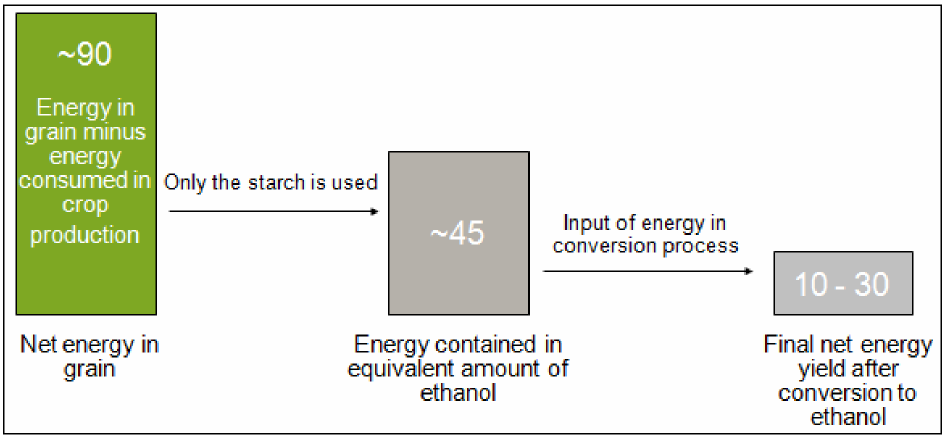

Figure 8: Energy balance of bio-ethanol production from wheat (relative, gross energy content of the grain = 100)

Table 2 shows the potential of different bio-energy forms to save energy and to mitigate CO2 emissions.
Each form of bio-energy has the potential to contribute to a saving of energy and to a mitigation of CO2 emissions. The type of crop and the conversion technology, however, influences the potential. Bio-ethanol from sugar cane and the production of heat and power from the incineration of biomass and biogas have the highest potential to save energy and to mitigate CO2 emissions. However, the potential could even be higher for all forms of bio-energy if the by-products were used (e.g. as animal feed). In this case energy and CO2 credits will be given which will further improve the potential savings. On the other hand, land use changes (e.g. cutting of rain forest for new plantations) or burning of the residues (e.g. cane straw) will deteriorate the CO2 balance.

Table 2: Energy saving and CO2 mitigation potential of different bio-energy forms

	Energy saving (in %, compared to fossil fuel)	**CO_2 emission savings (in %, compared to fossil fuel)**
Bio-ethanol		
- Cereals	10 – 35 %	max. ~ 30 % [1)]
- Sugar cane	70 – 85 %	70 – 80 %
Bio-diesel		
- Oil seed rape	40 - 60 %	30 – 50 %
- Oil palm	55 - 75 %	50 – 70 %
Incineration of biomass		
- heat or heat/electricity	70 – 85 %	70 – 80 %
Biogas (Silage maize, slurry) - heat/electricity or gas fed into public grid	70 – 80 %	~ 70 %

1) Liska et al. (2009): CO2 mitigation of 48 – 60% in case of using very modern technology and of using by-products as feed products (Maize, USA)

Summary

- The energy and CO_2 balance of arable crop production is generally positive, but depends on the crop.
- The application of mineral fertilizers at optimum rate improves the balance further.
- The energy and CO_2 balance of the bio-fuel production (conversion of crop into fuel) depends on the conversion technology.
- Bio-ethanol from sugar cane and the production of heat and power from the incineration of biomass and biogas have the highest potential to save energy and to mitigate CO_2 emissions.

- The use of by-products (e.g. as animal feed) will improve the energy balance and the CO_2 balance.
- Land use changes (e.g. cutting of rain forest for new plantations) or burning of the residues (e.g. cane straw) will deteriorate the CO_2 balance.

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