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Energy flows in food production systems – methods and examples for quantification and transformation between different forms of energy

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Abstract
Energy flow analysis contains basic information for LCA studies. It also provides information on energy efficiency. Dependent on goal and scope definition, extended process chains of food supply comprise different forms of energy. This contribution focuses on biomass energy flows along process chains of foods. The choice of the appropriate energy form, rules of accumulation and transformation between the different energy forms, and the selection of the functional units referred to have fundamental influence on the results. All this depends on the base question of the LCA, which itself may be different for different stakeholders.
A schematic system of a milk producing farm including alternative food and non-food applications is taken as an example for considerations on product, process, and farm level. Some specialities occurring are pointed out. The influence of changes in the subject under study is shown.

1. THE FOCUS

Studies on energy aspects in food production have to account for the underlying substance flows along the whole process chains involved. This occurs especially when biomass is not applied energetically within the system under study, like wood that is used for building construction. Furthermore, different forms of energy may appear on the input or output side within the same study:

- end energy use (e.g. process energy and/or energy incorporated in materials)
- primary energy use (i.e. end energy incl. energy loss before energy supply)
- lower (lhv) or higher (hhv) heating values, e.g. for supplies or biomass yield
- gross energy calculated by element composition
- gross energy of biomass products (calorific values)
- gross energy of nutrient fractions in biomass (e.g. crude protein)
- metabolisable energy of food products or animal feeds (ME, NEL)

The international LCA standards ISO 14040 to 14043 [1] provide general guidelines for system definition and data collection. In Germany, the VDI guideline 4600 on Cumulative Energy Demand [2] specifies some of those rules on energy. For biomass based systems like food production the provided rules are not sufficient for all possible applications. This ends in considerable differences in practical methodical approaches and in differing absolute energy figures describing a specific product or process (see [3], [4]). Decisions for calculations with one energy form or another finally depend on the goal definition and the scope of the study [5]. Apart from that, there can be several points in life cycle analysis of biomass products where the energy forms mentioned above are to be transformed from one into another to achieve a consistent documentation of energy flows. Table 1 shows some examples on how energy can be expressed for rape seed. The question which has to be answered is: which energy form fits for which application? Below, we will try to give an answer to this discussing some examples. Whole farm calculations pose once more different questions to be solved.

Table 1: Energetic characteristics of rape seed and its biomass products, expressed in terms of different energy forms (MJ/kg; several sources and own calculations)

	Rape seeds 85 % dry matter	Rape seed meal 85 % dry matter	Rape seed oil 99 %
Production of seeds (primary energy)	8.43	–*	–*
lhv			35.77
hhv			38.40
Gross energy (by nutrient fractions)	25.72	17.84	28.23
Metabolisable energy (ME, cattle)	15.98	10.91	29.88
Metabolisable energy (NEL, cattle)	9.78	6.65	19.23

* variies depending on allocation rules or substituting products

2. SOME PRINCIPLES OF ENERGY ACCOUNTING IN BIOMASS SYSTEMS

There are several types of energy analyses, which influence the way how biomass energy may be incorporated into the calculations:

1. The energy use is documented as a basic information on resource depletion and environmental impacts caused by the processes or products under study.
2. The energy demand is used as an information for calculating the overall energy efficiency or energy intensity of systems or products. In these cases the incorporated energy of biomass can be of high importance.

Of course also mixed types of energy investigations with special requirements on the rules of energy accounting may occur. Examples are discussed below. Concerning the input of energy two main groups may be distinguished: The application of non-renewable and renewable energetic resources: The first group includes direct finite energy sources as well as all indirect energy inputs e.g. by industrial processes. This group is not studied in detail in this contribution. The second group may be differentiated into two input forms:

- Direct bioenergy input: e.g. energetic use of biomass within the system under study
- Non-energetic biomass input: energy incorporated for example in seeds for arable production, purchase of animal feeds or animals, internal matter flows between vegetal and animal production

On the output side of the system sometimes a variety of products exists which may be included and energetically accounted for optionally, dependent on the subject under study. Figure 1 gives an example for a milk producing farming system:

- *milk, meat and calves* from animal production for sale
- *slurry* as a by-product or waste of animal production, usually an internal energy flow
- *energy from biogas*, gained from slurry and/or biomass of vegetal production and/or from food processing residues brought back to agriculture
- *yield* from vegetal production, as fodder or for sale
- *by-products* from vegetal production, e.g. straw or sugar beet leaves
- *residues* from vegetal production, e.g. roots and other parts left on the field

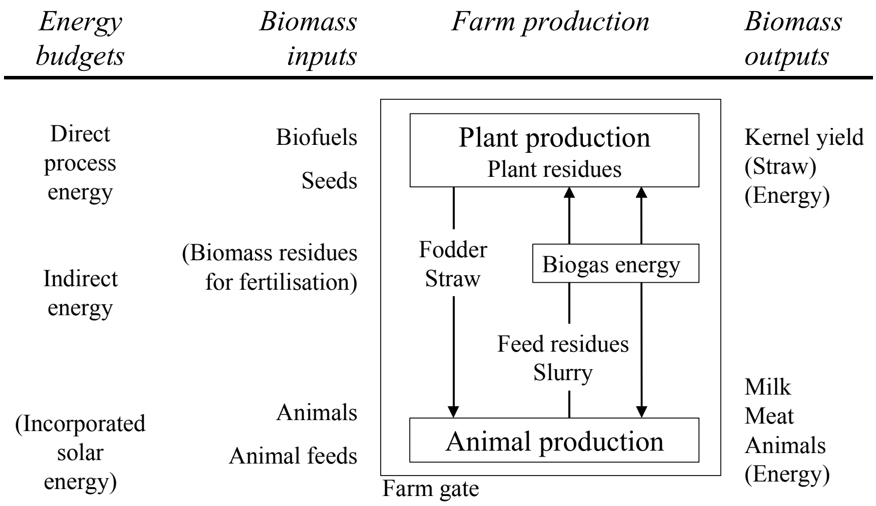

Figure 1: Schematic milk producing farming system and its biomass components

Different stakeholders will have different requirements of information: A food processing company will be interested in total energy requirements and additional environmental burdens of their biomass raw materials purchased. This can be expressed as fossil or as total primary energy demand per physical unit, optionally including non-energy inputs incorporated in biomass. From this, energy efficiency may be derived. A different way might be to provide the information as energy demand per unit of metabolisable energy in food produced. While this should be interesting rather for consumer decisions or for characterisation of consumer behaviour in nutrition, for the producing farmers information for system optimisation will have most relevance. They are interested in reducing the specific cost of production and energy. Finally, regional substance and energy flow studies are of increasing interest in order to give advice for political decisions.

3. THE MULTI-FUNCTIONAL SYSTEM OF MILK PRODUCTION AS AN EXAMPLE FOR DIFFERENT ENERGY TREATMENTS

The agricultural milk producing system shown in figure 1 focuses on biomass flows only. As biomass imports only the purchases of seeds, cattle, and animal feeds are assumed. The import of secondary raw materials like compost opens additional options of non-energetical biomass use at the farm. Arable products are produced for sale as well as animal feed for the cattle. From animal production milk, meat and calves are for sale. Feed residues and slurry are spread for fertilisation on arable land and pastures and optionally used before as (internal) energy source. This example gives us a first impression about the possible complexity of agricultural systems. It also makes clear, that different goal definitions may arise. With this, different subjects under study as well might derive including different treatments of biomass energy within the energy flow calculations. Some of these possibilities are discussed next, focussing farm level, process chain level as well as product level.

The farm level

At the farm gate, farm internal energy flows like slurry spread on the fields, straw used in the stable or animal feed produced for the cattle have little importance. The farm itself is regarded as a black box. In simplified calculations for net energy yield, the difference between input and output of solar energy incorporated in biomass can be determined by applying gross energy budgets at each side. But this can not be realised equally with the corresponding biomass substance flows. Furthermore, in reality at both sides considerable variation in gross energy budgets occurs, caused by variations in moisture content and in the share of nutrient fractions of the products.

When slurry is used for biogas production, the energy sold by the farmer can be considered as additional farm output and accounted for as heat and electricity with their heating values. Applied within the farm, biogas reduces the overall direct energy consumption of the farm.

When energy efficiency is under study, the accounting for incorporated energy of imported biomass like fodder or purchase of animals as gross energy is required. In animal production sometimes up to 80 % of total energy inputs (in production systems with very low intensity) are caused by animal feeds. Only a small part of them is due to process energy for feed production: primary energy requirements for the production of rape seed are 8.43 MJ/kg (see table 1), whereas the gross incorporated energy amounts to 25.72 MJ/kg. Dependent on the goal of the study, if the incorporated energy is included here, the calculated energy efficiency of the farm could be too optimistic. On the other hand the incorporated biomass energy has no direct impact on the environment.

The process chain level

For detailed energetic farm analyses, a separate calculation of energy performance in plant and milk production or even between different branches in plant production might be of interest. In this approach, energy equivalents for the various internal biomass energy flows between the subsystems are required. They can be added to the non-biomass energy inputs by using the gross incorporated energy as a reference. As functional units, a hectare of farmland or a production unit in the stable could be suitable, but also other units might be reasonable. The borders between the subsystems have to be clearly defined in order to specify well the energy amounts for e.g. slurry or biogas production.

The product level

When energy inputs are computed for a process chain like milk production, they have to be assigned to different outputs given by that process chain. In some applications the substitution in function of by-products can be used for their energetic valuation. For instance, slurry or fodder residues brought back to the field might be accounted for as a substitute for the chemical fertilisers providing the equivalent amount of plant nutrients – in milk production, this accounts as a credit.

In some cases, depending largely on the goal definition of the study, it might not be preferable (or not possible) to carry out the energetic analysis of the products by such a "credit system", e.g. when the milk production of figure 1 (producing also meat as a by-product) is compared to a combined milk and meat production. In that case, the distribution of energy amounts is to be made subject to allocation rules. Doing this, different allocation rules may be applied, economic ones, heating values or by mass relations are most common. Each way of allocation may lead to completely different results. Therefore different scenarios should be compared. See an example in table 2 comparing the different results for the production of corn starch and its by-products. Using heating values as another allocation rule, similar results are obtained as for allocation by quantity. Again, the appropriate way of defining the system boundaries (substitution and credits or allocation) once more must be included in the goal definition and depends on the goal of the study!

Table 2: Cumulated energy demand (CED) of exhaustible resources for corn starch (MJ/kg; several sources and own calculations)

	CED (by quantity) [MJ/kg]	CED (by value) [MJ/kg]	Quantity [kg/kg starch]	Value [DEM/kg starch]	Allocation keys by quantity	Allocation keys by value
Corn starch	18.14	22.45	1.000	0.800	0.658	0.814
Other corn constituents	9.43	5.13	0.519	0.182	0.342	0.186

Milk production at the farm can be considered as a part of a more extended process chain that includes all processes until use in households. To the customer the metabolisable energy of milk is provided as one attribute of food quality which is not equal for each type of milk. This is a percentage of the incorporated gross energy which amounts to about 3.5 MJ/kg milk. In contrast, milk has a negative lhv because of its high water content (86 %). Meat and animals for sale or their possible substitutes might be treated as credits at gross energy basis; this is valid also for biogas production. For this reason, biomass yield at farm should be expressed as gross energy first. Furthermore: In food processing different raw materials are mixed, boiled, or fried, which changes their nutritional characteristics and moisture content and makes allocation in end products difficult.

4. CONCLUSIONS

- Which form of energy is considered within a LCA and/or energetic analysis in agricultural systems depends on the goal of the study.
- For a useful discussion it is necessary to declare explicitly the energy form considered. Also, all energy sources – renewable and non-renewable – should be documented separately. Especially, the consideration of whether and how to incorporate biomass energy depends on the subject and the goal of the study.
- Also, the decision for product, process chain, or farm approach is subject to the questions to be answered.
- The possible variation of total energy input and its impact on energy intensity and energy efficiency should be illustrated by scenarios in compliance with the specific questions to be answered.
- Always, relevant assumptions and system boundaries have to be documented for interpretation of the results.

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