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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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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. 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 (see **table 1**)
- ***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; see **table 1**)

Decisions for calculations with one energy form or another finally depend on the goal definition and the scope of the study. 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.

2. A MILK PRODUCTION SYSTEM AS AN EXAMPLE

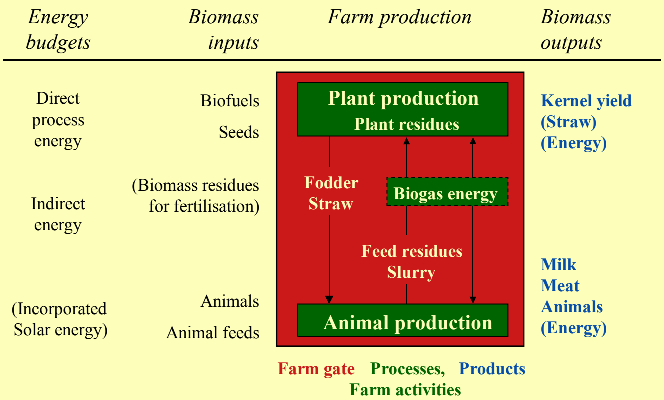

Figure 1: Schematic milk producing farming system and its biomass components

Selection of biomass energy flows (preferably outputs) visualised in **figure 1**:

- ***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 production***
- ***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

3. 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.
- Decision for product, process chain, or farm approach is subject to the questions to be answered.
- The impact of possible variations in total energy input 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.

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)

Energy characterisation	Rape seeds 91 % dry matter	Rape seed meal 85 % dry matter	Rape seed oil 99 % dry matter
Production of seeds (primary energy)	8.43	–*	–*
Lower heating values (lhv)	25.90**	17.80**	35.77
Higher heating values (hhv, no water)	27.80	18.10	38.40
Gross energy (by nutrient fractions)	25.72	17.84	28.23
Metabolisable energy (ME, cattle)	15.98	10.91	29.88
Net energy lactation (NEL, cattle)	9.78	6.65	19.23

* varies depending on allocation rules or substituting products
** water content: rape seeds 6-9 %; rape seed meal 11.1 %

This question has to be answered:
WHICH ENERGY FORM FITS BEST FOR WHICH APPLICATION?

Different subjects of study in energy analysis:

The farm level

The farm itself is regarded as a black box (**figure 1**).
The difference between input and output of solar energy incorporated in biomass can be determined by applying gross energy budgets at each side.
When slurry is used for biogas production, the energy sold by the farmer can be considered as an 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. Usually only a small part of biomass energy imports is due to process energy, as shown in **table 1** for rape seed.

The process chain level

For detailed energetic farm analyses, a separate calculation of energy performance in plant and milk production or between different branches in plant production might be of interest (**figure 1**).
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 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. See an example in **table 2** comparing the different results for the production of corn starch and its by-products.

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

	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