ENERGY BALANCE OF SOLID BIOFUELS

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Introduction

In Polish agriculture straw is used for various purposes: as fodder, as lining for live stock, as organic fertiliser and as insulation material. Till half of 80's straw was mainly used in animal production. But at the beginning of 90's together with animal production decrease a straw surplus was about 8 mln of tons, what has caused the problem of straw utilisation for energy production to be noted. IBMER analysis has shown that it is technically and technologically feasible to obtain at least 131 PJ of energy from straw of cereals, oil and leguminous plants. Straw is more widely used for energy purposes. For energy sources produced in agriculture and forestry, such as solid biofuels made from straw or waste wood energy balances are particularly interesting. Due to the fact that the necessary basis for calculation of energy consumption significantly differ, the ATB has elaborated a database for about 6000 items concerning the production of machines, fertilizers, protective agents, etc. In the paper energy balances of 5 different solid biofuels produced with different technological processes are compared.

Description of the method

The following method applied to determine the energy input is based on the latest draft of the VDI guideline No. 4600 "Cumulative energy demand - terms, definitions, methods of calculation" [4]. According to this the expenditures are divided in each process stage into the material and energy input directly related to the process, and the indirect inputs, which can only be assigned by codes, for the provision of the implements, machinery and plant necessary for the process as well as for the conditioning of the surroundings.

This means that the cumulated energy input KEA indicates the entire energetic input which results in relation to the production H, the use N and the disposal as waste E of a supply item or a service:

\[ KEA = KEA_H + KEA_N + KEA_E \]  

As the relevant literature frequently differentiates between operation B (utilisation) and ongoing upkeep U (maintenance, repair, accommodation etc.) when discussing energy data for agriculture, it is advisable to use the following specification:

\[ KEA_N = KEA_U + KEA_B \]

During the "life cycle" of a supply item used in agricultural production, certain quantities of various final energy sources such as coal, fuel and electricity are used. Taking into account the relevant availability utilisation ratio, this is used to calculate the cumulative energy requirement (assessed in primary energy) of the supply item and from this the cumulative energy input for a process or a whole procedure, which may last for several years. Finally, to determine the input/output relation or the energy gain, the process-related cumulative energy input is compared with the energy output (See Figure 1).

Determination of specific cumulative energy input for agricultural and forestry supplies

In order to calculate the cumulative energy input of a particular supply item it is necessary to know its specific energy characteristics, often also called energy equivalents. The specialist literature contains numerous details of the energy expenditures for individual supply items or groups of supplies, e.g. the specific cumulative energy input for the manufacture of tractors, fertilisers and the like. A database called "Energy" was designed and set up in the ATB Potsdam-Bornim on the basis of the relational data base system MS Access in order to effectively collect and evaluate these data. So far it has been filled with approximately 6,000 record sets [5].
With the help of this database mean mass-related cumulative energy inputs $k_ea_H$ for production of agricultural machinery and implement groups are formed by calculating the mean value and/or a time-dependent regression function for each state (See Figure 2).

The specific energy input for the upkeep of technical tools $k_ea_U$ results essentially from the energy input for maintenance and repair as well as accommodation and/or storage. According to figures in literature maintenance and repair amount to between 15 and 145 % of the manufacturing energy input $k_ea_H$, depending on the machine group. As regards the accommodation of machines, standard values were ascertained, depending on the type of machine, the space it takes up and the useful service life, of 3 to 6 MJ/kg [5].

Energetic expenditures in the form of process energy and consumables e.g. electricity, heat, fuel, lubricants, twine are necessary for the operation of technical equipment. Since for the most part no concrete figures are available for this, and furthermore in the case under review comparable, generally valid energy expenditures for the operation of different machines are required, the specific energy input for the operation of agricultural machines and implements $k_ea_B$ is estimated in a close approximation with the help of the following parameters [5]:

- power requirement $P_N$ [kW],
  i.e. the necessary engine rating of the tractor or driving engine required to carry out the process under average conditions of use
- machine utilisation time $t_{MAS}$ [h/ha],
  i.e. the total working time of the machine/implement combination necessary with auxiliary process time but without stoppage times,
- nominal consumable consumption $a_{BN}$ [kg/h],
  i.e. the consumption of consumables under nominal conditions.

No special characteristic energy values are stated in the relevant literature for the waste disposal of agricultural machinery and implements. The energy input for this results essentially from the input for scrapping the metals and dumping of non-recyclable material parts. The energy expenditures determined so far for the waste disposal of machine tools, passenger cars and commercial vehicles amount to between 0.2 and 1.8 MJ/kg [5]. With the exception of trucks, whose value is very carefully determined, the waste disposal of agricultural machinery and implements is assumed to have a specific energy input of $k_ea_E = 0.5$ MJ/kg.

**Calculation program**

A special computer program "Energy balance" based on the above principles was developed by the ATB Potsdam-Bornim to calculate the cumulative energy input of agricultural and forestry plant production [5]. This program is built on the MS Access relational database system.

The database consists of the following five data tables:

- energy equivalents (specific cumulated energy inputs)
- machine data (power, capacity, weight, consumption, live etc.)
- material data (volume, form, density of transport and storage etc.)
- farm data (soil type, inclination, field area, transport distance etc.)
- process data (type and quantity of machines and materials, operational durations etc.)

Starting from the "process data" table, which is closely linked to the other four basic tables, a so-called table query of the process to be analysed is compiled. The data for processes, machines or materials which are not contained in the basic tables are determined and entered in the relevant tables. The basic data called up by the process query are linked with the mean specific cumulative energy expenditures from the "E-equivalents" table from the "Energy" database and in this way the energy input for the relevant working and expendable materials is calculated. Finally, the cumulative energy input for individual processes and for the entire process is determined by addition.
Agricultural process chains

The following energy balances relate to four agricultural and/or forest crops:

• winter rye
• Miscanthus sinensis
• poplar
• pine

Apart from whole plants, by-products are also included:

• winter rye straw
• pine harvest residual timber
• pine thinnings

This means that both conventional and unconventional but promising plants and plant residual substances are included which are suitable for burning or gasification. Various processes for the production and conditioning of each of the raw materials named are considered, with new processes currently under development also being included. As far as possible processes are assumed which correspond with general practice in agriculture and forestry. This requires that average conditions, machines and working times are assumed, which can be taken from the relevant tables. For new machines which are in some cases still under development it was necessary to rely on manufacturers’ statements. Process sequence, inputs and yields were coordinated with the FAL Braunschweig-Völkenrode, the Lehr- und Versuchsanstalt für Integrierten Pflanzenbau Güterfelde (Teaching and Test Institute for Integrated Plant Cultivation), the Institut für Schnellwachsende Baumarten Hann.-Münden (Institute for Fast-Growing Tree Types) and the Kuratorium für Waldarbeit und Forsttechnik Groß-Umstadt (Trusteeship for Forestry and Forest Technology) (See Figure 3).

Energy input

Generally energy sources are judged by the efficiency of their production and/or conversion, i.e. according to the input/output ratio (energy input/energy yield). Additionally for energy sources produced by agriculture and forestry the energy gain (energy yield - energy input) per unit of area is decisive. Due to the natural limits of the area available, energy crops or production processes should also be assessed according to the input/output ratio as well as the energy gain per hectare of land used.

Regarding the energy input there are significant differences between the energy raw materials of plant origin. Fuels from whole rye plants require the highest cumulative energy input at 19.5 to 22.2 GJ/(ha a) and pine chips at 0.1 to 1.0 GJ/(ha a) have the lowest cumulative energy input. The extremely low values for pine chips are attributable to the very long reference period of 140 years. And the high values for whole rye plants are a result of the relatively high energy expenditures for annual cultivation. Miscanthus sinensis, which requires the second-highest input at 12.4 to 15.2 GJ/(ha a), also requires a great deal of energy for its cultivation. This share results above all from energy-intensive mineral fertilisation. According to the Institute for Fast-Growing Tree Types, poplars do not require fertiliser, so here the total energy input is only 3.0 to 7.1 GJ/(ha a), although the inputs for harvesting and processing poplars are significantly higher than for the other fuels.

The process stages harvest + conditioning and storage + transport must be considered together. A higher energy input for e.g. compacting can be partly offset by lower expenditures for storage and transport processes. However, with the assumed transport distance of 5 km pelletising of the goods does not have a reducing effect on the total energy input. A similar situation applies to the compact roll method, where the energy input - at least for the current prototype press - is largely determined by the twine requirement. These two types of process only undercut the energy requirement for conventional round bale methods from transport distances of > 100 km (See Figure 4).
Energy gain and input/output ratio

The energy gain depends on the energy output (yield), and this one is directly proportional to the natural yield, the heating value and the water content of the material. Looking at the energy gain per unit of area and time, the highest values are achieved by poplars with 155 to 167 GJ/(ha a), Miscanthus with 154 to 158 GJ/(ha a) and rye with 137 to 140 GJ/(ha a). However, straw, either as a residual substance or a by-product, still achieves 90 GJ/(ha a). By far the lowest energy gain is achieved by pine because of the extensive cultivation of the land. Even for whole tree utilisation it amounts to only 24 to 27 GJ/(ha a). If the stocks are regularly thinned, about 50 GJ/(ha a) is generated.

The most favourable input/output ratio by far was achieved for pine production at approx. 1 : 50. Straw also achieved very good values of 1 : 25 to 1 : 40. And similarly favourable input/output ratios can be achieved in poplar production providing this can be sustained over a long period without the application of nitrogen. Miscanthus and rye still achieve input/output ratios of from 1 : 7 to 1 : 14 (See Figure 5).

Energy Structure

An analysis of the energy expenditures broken down by supplies and their individual "life phases" makes it clear that for rye and Miscanthus the greater part, namely 52 to 67 % is required for the production of consumable materials, especially for fertilisers. The other expenditures are caused by machines and other technical aids.

On average only 0.07 % of the total energy input of a supply item is required for the waste disposal of the item, for upkeep about 3 % is required and for production 10 to 40 %. By far the most energy is consumed during the operational phase, namely 60 to 90 %. This results mainly, but not exclusively, from the fuel consumption of the machines. Taking the example of the compact roll line we can see that other expendable supplies, such as the twine, can also make quite a difference.

Energetic efficiency of the use of nitrogen

The nitrogen fertiliser is the expendable material which requires the greatest energy input at about 55 %. This mineral fertiliser is extremely energy intensive to produce, requiring on average 59 MJ/kg . What is more, it is considered to be ecologically harmful, so its influence on the energy output will be briefly described here, taking whole rye plants as an example.

According to Kundler et al. the natural yield on sandy clay soil increases with a nitrogen application of 120 kg/ha by 75 % compared to zero fertilisation [6]. The energy yield also increases correspondingly. In contrast to this the input/output ratio remains almost constant. If all energetic expenditures are taken into account, it becomes clear that with high applications of nitrogen the input/output ratio even deteriorates slightly. Thus the energetic optimum is somewhere in the region of between 20 and 80 kg N/ha (See Figure 6).

Technologies used for straw combustion in Poland

Poland is starting a wider usage of biomass from forests and agricultural residues (straw) in district heating plants. First installations were based on Danish technical solutions. Actually biofuel-fired boiler plants of various capacities are operated to supply heat both to private farms and to public buildings. From the beginning of 90's in private farms have been installed about one hundred 25-55 kW straw-fired boilers. Hot water accumulation tank with large capacity is characteristic feature of those solutions. High investment costs are the main barrier in wider dissemination of this technology. On Polish market a few manufacturers of small straw-fired boilers (Elektromontaz, Gdansk, GRASO in Starogard, Boilers Plant in Pleszewo, ATEX in Zamosc) are operating.

As example of solutions introduced within district heating systems 1 MW straw-fired plant, owned and operated by Luban Energy Enterprise in Lower Silesia voivodship will be presented. In this region straw
overproduction has permanent character, what is connected mainly with technologies used in agricultural production and reduction of animal production. The above premises have decided that straw was included as one of basic energy carriers to the strategy of enterprise development. On basis of agreement with Danish company REKA A/S licence a production of basic equipment for 1 MW straw-fired, automatic boiler was started. First boiler was assembled in Luban and started to work on 15th of December 1998. Heat produced in new plant forms 4% of municipal heating system power. Straw is supplied on basis of long-term contracts signed with three farms. 1 MW straw-fired district heating plant is a first stage of implementation of biomass energy program in town. In preparation is 6MW straw-fired district heating plant.

Technology used in Luban heating system is based on equipment produced by Danish company REKA:
- boiler basement with grate, blowing and ashing system,
- section of feeding fuel on grate with fire protection.

and equipment produced by Polish companies:
- straw shredder
- transporter
- worm conveyer
- WCO - 80s boiler

Investment costs were covered by PEC Luban Sp. z o.o. own capital (242 151 PLN) and loan from Voivodship Fund for Environmental Protection and Water Management (400 000 PLN). As the result a significant reduction of pollutants emission was noted: CO$_2$ - 2000 tons per year and SO$_2$ - 6 tons per year as well as a reduction of fuel costs.

Summary
Solid fuels produced by agriculture and forestry are more and more important in energy planning. The reasons for this are the surplus of agricultural land, the favourable energetic efficiency and the inexpensive, long-term storability of these energy sources. Furthermore they could secure farmers and forest owners an additional, stable source of income.

The selective cultivation of conventional crops such as whole plant cereals can achieve energy yields of over 150 GJ per hectare and annum (1 GJ = 278 kWh = 23.5 kg oil equivalent). Even higher returns can be achieved with grass and fast-growing trees if these crops fulfil the expectations placed in them regarding yield stability and low nutrient requirements in practical conditions. The energy input for the production of these biofuels is comparatively low. Depending on the crop and the technology it is 3 to 22 GJ/(ha a). The greatest part of the input is required for cultivation. With the exception of the evidently undemanding poplar, nitrogen fertiliser alone accounts for about one third of the total energy input.

The energy yield for residual substances from agriculture and forestry such as cereal straw and timber thinnings is only about 50 to 90 GJ/(ha a), but at the same time these fuels have a very low energy input, if the expenditures for cultivation are allocated to the main product. This aspect, along with the relatively low availability costs and the ethical acceptance among the public - in contrast to e.g. whole plant cereals - is one of the reasons why these biofuels are most likely to be introduced on a wide scale.

One hectare of straw or specially cultivated energy-producing plants can satisfy the heating requirement of one or two single-family houses throughout the year. What is more, the energetic effectiveness of the production of these fuels is hardly any less favourable than that for coal briquettes. For each GJ of energy used, energy crops can provide 7 to 30 GJ and with by-products even up to 50 GJ of thermally utilisable energy, and this with hardly any additional CO$_2$ pollution.
Literature

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Rectangular bale line

Energy output / input

Energy yield in GJ/ha

Application rate in kg/ha

Natural yield by KUNDLER et al. for loamy sand