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Energy balance for wood biomass utilization. Part II – tests results

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Summary. World energy consumption is constantly growing. In the light of fossil fuels exhaustion, alternative energy sources such as biomass are becoming very important energy materials. The aim of this work is to analyze and assess the possibilities of using wood chips for energy purposes on the basis of a universal index and energy balance. Wood chips have been analyzed. Expenditures and energy benefits have been identified and values of the developed energy efficiency index have been determined. The impact of energy expenditures on the index value have been analyzed as well as the applied technology and technical conditions. It was found that the use of wood chips energy benefits overweigh the costs involved in their obtainment. This proves high energy efficiency of this material combustion process.

Key words: biomass, wood chips, energy efficiency index, energy balance, renewable energy sources

INTRODUCTION

The need to use different forms of energy goes back to prehistoric times. Energy is one of the essential needs of humans and the ability to use it reflects the civilization development as without access to energy people would be totally dependent on the environment. The first step in energy production development was using fire to generate warmth. The first energy source and energy material was biomass of plant and animal origin [6].

Now, a significant growth in energy demand is being reported. In view of the prospect of exhaustion of conventional energy resources such as: coal, oil, natural gas, this is even a more alarming issue. Such a situation involves a need to search for new materials to be used for energy purposes, e.g. in the process of combustion [4, 5].

One of the main energy sources, whether heat or electricity, is coal. Oil, natural gas and nuclear energy are still major energy sources. Due to exhaustibility of fossil fuels people have turned to natural energy sources – wind, sun, geothermal energy [3].

Biomass with low moisture content has parameters similar to coal. Calorific value of the biomass ranges from 6 to 8 GJ/t for high moisture materials (moisture content 50-60%) to 19 GJ/t for dry which is a value lower as compared to coal, ash content is several times lower than for coal [8].

The aim of this study is to analyze and evaluate the possibilities of using wood biomass for energy purposes (combustion), on the basis of universal indexes and energy balance. This aim will be achieved by analyses of energy expenditures and benefits on the basis of literature data and analytical-research procedures and determination of the Energy efficiency index value.

The research problem was formulated in the form of a question: what is the impact of technical conditions (applied technology, energy consumption, type of material), preparation of energy medium to reach the desired states, that is, highest possible energy efficiency of the combustion process, on the final assessment of a material functional quality and possibilities of its being used for energy purposes?

RESULTS AND ANALYSIS

Determination of a biomass utilization energy efficiency is possible by identification of benefits and costs incurred for utilization of this material. Wood chips have been accepted for analysis. The index of biomass (wood chips) utilization for energy purposes assumes the following form:

$$E_B(m)\frac{U_B(m)}{N_B(m)} = \frac{\sum_1^n U_{Bj}\cdot m}{\sum_1^n N_{Bj}\cdot m} = \\ = \frac{Q_{cB}\cdot m}{N_{Bwj}\cdot m + N_{Btj}\cdot m + N_{Brj}\cdot m + N_{Bsj}\cdot m + N_{Bzj}\cdot m} = \\ = \frac{Q_{cB}}{N_{Bwj} + N_{Btj} + N_{Brj} + N_{Bsj} + N_{Bzj}} \quad (1)$$

where:
Q_{cB} – chip combustion heat [MJ/kg];
m – chip mass [kg];
N_{Bwj} – unit energy input for generation of [MJ/kg];
N_{Btj} – Unit energy input for transport [MJ/kg];
N_{Brj} –Unit energy input for grinding [MJ/kg];
N_{Bsj} – Unit energy input for energy medium combustion [MJ/kg];
N_{Bzj} – Unit energy input for waste management [MJ/kg].

Energy benefits

Energy benefits are defined to be the amount of energy received from a substance combustion. In table 1 there are unit benefits Q_{cB} (combustion heat) and total benefits $U_B(m)$ for chips.

Table 1. Energy benefits from wood chips [own research]

ENERGY BENEFITS FROM WOOD CHIPS	
$U_B(m)$ [MJ]	Q_{cB} [MJ/kg]
66989025.4	17.3

Energy inputs

Energy inputs have been identified and described on the basis of LCA analysis of wood chips acquisition on the example of Swedish experiments presented in work [1].

Energy inputs for acquisition of wood to produce chips are a sum of energy consumed during 8 stages of tree cultivation. Energy inputs are as follows [1]:

- stage I – preparation of seedlings
  - operation of machine with power of 6 kW for peat application and sowing
  - use of tractors with power of 60 kW for transport of seedlings to a greenhouse,
  - use of diesel oil to heat the greenhouse.
- stage II – preparation of soil
  - use of fuel to prepare soil is which gives 45 l/ha, 1602 MJ/ha.
- stage III – sowing
  - use of fuel by trucks for transport of 40000 seedlings,
  - use of fuel by tractors with power of 30 kW.
- stage IV – cleaning of the plantation
  - use of fuel by saws for tree felling and trimming.
- stage V – thinning
- stage VI – fertilization
  - use of fuel by helicopters and tractors for fertilization
- stage VII – wood cutting
  - use of fuel by wood cutting equipment.
- stage VIII – loading
  - use of fuel for wood loading and wood transport.

The process of wood acquisition uses the following energy media: electrical energy, diesel oil, petrol and kerosene.

In order to identify respective unit inputs the following converter has been accepted:

- **acquisition of 1000 MJ energy requires combustion of 57.8 kg chips, I_m = 0.0578 kg/MJ.**

By referring the converter to LCA analysis whose results are given in MJ/MJ of produced energy, unit energy inputs per 1 kg of material were provided according to formula :

$$N_{iJ} = \frac{I_E}{I_m} \tag{2}$$

where:

N_{iJ} – unit Energy input [MJ/kg];

I_E – index of energy inputs for generation of 1 MJ energy [MJ/MJ];

I_m – index of mass of the medium used for generation of 1 MJ of energy [kg/MJ].

In table there are components of energy inputs for acquisition of wood for production of chips.

Table 2. Components of energy inputs for acquisition wood for chips. Own research on the basis of [3]

Medium	Index of inputs I_E	Index of mass I_m	Unit input N_{Bwj}
Electrical energy	0.00036	0.0578	0.006
Diesel oil	0.1300	0.0578	2.249
Petrol	0.0008	0.0578	0.014
Paraffin oil	0.0009	0.0578	0.016
Total			**2.285**

Analogically, energy inputs for transport of the material to the power plant was calculated assuming I_E = 99.7 MJ/m^3 and I_m = 400 kg/m^3:

$$N_{Btj} = \frac{I_E}{I_m} = \frac{99.7}{400} = 0.24925 \tag{3}$$

The process of wood grinding for chips is divided into two sub processes: cutting bale into pieces and the process of specific grinding. In table 3, there are quantitative energy inputs for cutting wood bales. Index of inputs I_E was taken from work [1]. Unit inputs were determined according to formula (3).

Table 3. Energy demand for wood bales cutting. Own research on the basis of [1]

Medium	Input index I_E	Index of mass I_m	Unit input N_{Brj}
Electrical energy	0.0033	0.0578	0.057
Heat energy	0.0820	0.0578	1.419
Fuels	0.0390	0.0578	0.675
Constant energy	0.0027	0.0578	0.047
Total			**2.197**

Specific grinding down to particle size 4 mm was analyzed for a beater mill of POR ECOMEC model C120. Also unit energy inputs for larger chip sizes,10 mm i 15 mm and after multiple grinding, were analyzed:

- down to 10 mm for coarse grinding to 15 mm (15 and 10),
- down to 4 mm for coarse grinding to 10 mm (10 and 4),
- down to 4 mm for coarse grinding to 15 mm (15 and 4),
- down to 4 mm for coarse grinding to 15 mm and 10 mm (15-10-4).

Table 4 shows unit inputs for specific grinding in dependence on the chip size and the number of grinding cycles in the mill.

After combustion of chips, ash is left which needs to be utilized. For the analyzed case the amount of ash is:

- 0.031 kg of ash/1 kg of chips.

Energy used for utilization of wood chip combustion waste involves its transport to the storage area, with assumption of diesel consumption at the level of 0.0012 per 1 kg of waste. Energy value of diesel fuel was assumed to be 36 MJ/l [7]. After calculation of fuel consumption this yields 0.0432 MJ/kg of waste.

Table 4. Unit inputs for specific grinding in dependence on the chip size and the number of grinding cycles in the

beater mill [2]

Size of chip [mm]	Unit input for specific grinding [MJ/kg]
15	0.051516
10	0.127656
10 (15 and 10)	0.139428
4	0.235332
4 (10 and 4)	0.215244
4 (15 and 4)	0.225180
4 (15-10-4)	0.236844

Unit energy inputs for wood waste combustion are equal to:

$$N_{Bzj} = 0{,}031 \cdot 0{,}0432 = 0{,}0013392[\mathrm{MJ} \cdot \mathrm{kg}^{-1}] \quad (4)$$

Unit energy inputs for wood chips were determined on the basis of analysis of energy expenditures, necessary to establish the values of wood chips energy efficiency index. Table 5 shows the values of unit inputs considering grinding which consists of two processes: cutting and specific grinding to reach 4 mm size chips.

Table 5. Unit energy inputs for chips [own research]

UNIT ENERGY INPUTS [MJ/KG]					
Acquisition		Preparation		Combustion	Waste management
Cultivation N_{wj}	Transport N_{tj}	Grinding N_{rj}		Combustion N_{sj}	Storage N_{zj}
		Cutting:	2.197		
2.285	0.249	Specific grinding (4 mm):	0.235	5.211	0.001
		Total:	2.433		

Energy inputs for specific grinding depend on the targeted size of the comminuted chips and multiplicity of grinding cycles. The smaller chips the higher energy expenditures for grinding. A multiple grinding also involves an increase in energy inputs (Fig. 1., Tab. 6.). The smallest energy unit inputs for specific grinding was reported for 15 mm chips (0.051516 MJ/kg), the highest (0.236844 MJ/kg) for 4 mm chips for three step grinding (15-10-4).

Table 6. Results of analysis of unit energy input for grinding for total inputs [own research]

Particle size [mm]	Unit input for specific grinding [MJ/kg]	Unit input for grinding [MJ/kg]	Unit inputs [MJ/kg]	Inputs for specific grinding for total unit inputs
15	0.052	2.249	9.995	0.005
10	0.128	2.325	10.071	0.013
10 (15 and 10)	0.139	2.337	10.083	0.014
4	0.235	2.433	10.179	0.023
4 (10 and 4)	0.215	2.412	10.159	0.0211
4 (15 and 4)	0.225	2.422	10.169	0.022
4 (15-10-4)	0.237	2.434	10.180	0.023

Analyzing the share of unit energy inputs for specific grinding in total unit energy inputs it is noticeable that they do not make a significant share in the inputs - maximally 2.33% (chips 4 mm (15-10-4)), minimally 0.52% (chips 15 mm), however they do not affect their value. Figure 1 shows a percentage share of unit inputs for grinding in unit total inputs for chips depending on their target size.

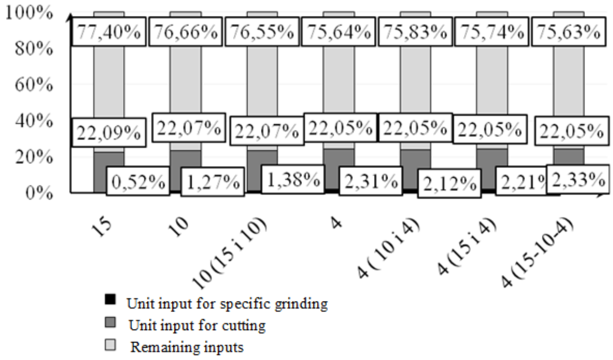

Fig. 1. Total unit energy inputs foe chips depending on the chip target size [own research]

Energy balance

Index of energy efficiency for chips was determined on the basis of data from tables 1 and 5 by substituting appropriate values to formula (1) it is received (Tab. 7.):

– Considering grinding down to fraction 4 mm.

$$E_B = \frac{Q_{cB}}{N_{Bwj} + N_{Btj} + N_{Brj} + N_{Bsj} + N_{Bzj}} = \quad (5)$$
$$= \frac{17{,}3}{2.2848 + 0.2493 + 2.4326 + 5.2109 + 0.0013} = 1.700$$

The value index is higher than 1 which means effective utilization of wood chips. (Fig. 2.). Energy inputs for acquisition, transport, utilization and management of waste are smaller than energy benefits from wood chips combustion. It is possible to produce almost two times more energy from wood chips than the amount of energy used for their acquisition and combustion.

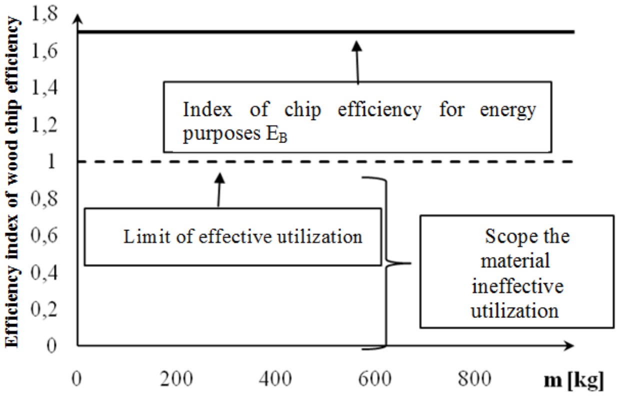

Fig. 2. Graphic interpretation of wood chip energy efficiency [own research]

As mentioned before, energy inputs change according to the size of chips (disintegration degree). Therefore, it was investigated how a change in unit energy inputs for specific grinding will affect the wood chip energy efficiency index.

Table 7 shows the energy efficiency index values with energy unit inputs for specific grinding depending on the targeted size of chips.

Table 7. The index of wood chip energy efficiency depending on the targeted size of chips [own research]

WOOD CHIPS ENERGY EFFICIENCY INDEX		
Particle size [mm]	Unit Energy input for specific grinding [MJ/kg]	Efficiency index
15	0.051516	**1.731**
10	0.127656	**1.718**
10 (15 i 10)	0.139428	**1.716**
4	0.235332	**1.700**
4 (10 i 4)	0.215244	**1.703**
4 (15 i 4)	0.225180	**1.701**
4 (15-10-4)	0.236844	**1.699**

An analysis of data shows that like in the case of unit energy inputs for specific grinding, the value of chip wood energy efficiency is affected by the chip size (Fig. 3). The highest value (1.731) of energy efficiency was found for 15 mm. chip size, the lowest (1.699) for 4 mm ship size for three-cycle grinding (15-10-4). It was found that along with a decrease in the chip size the energy efficiency index decreases.

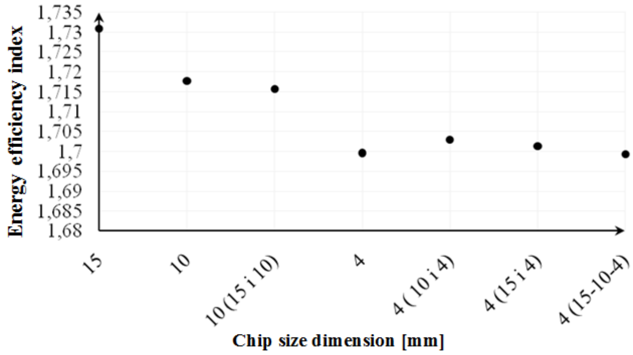

Fig. 3. Dependence of the wood chip energy efficiency index on the targeted chip size [own research]

Unit energy inputs for specific grinding make up one of the components of total unit energy inputs, hence their changes will cause changes in the efficiency index of wood chips which is shown in figure 4.

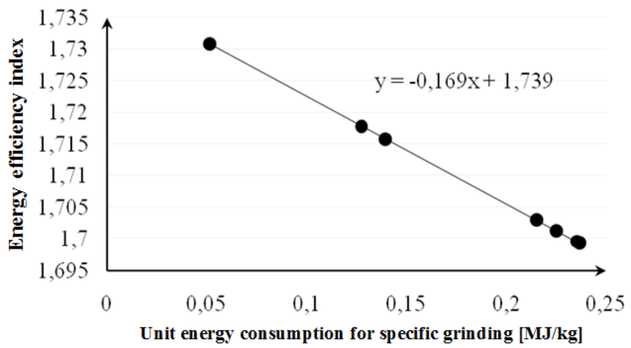

Fig. 4. Dependence of wood chip energy efficiency index on unit energy consumption of specific grinding [own research]

The analysis shows that the energy efficiency index for wood chips depends linearly on unit energy inputs for specific grinding.

$$E_B(N_{Brjw}) = -0.1698 \cdot N_{Brjw} - 1.7395 \quad (6)$$

The higher the inputs the lower the value of wood chip energy efficiency index (Fig. 4).

Unit energy inputs for specific grinding are related to the size of chips obtained from grinding (Tab.6). The degree of fineness is a function of the chip size. The higher degree of fineness the higher unit energy inputs for specific grinding. Since the degree of fineness is one of the grinding process parameters allowing to define its quality. It was checked how the degree of fineness affects the value of wood chip energy efficiency index.

The analysis shows that wood chip energy efficiency index depends proportionally on the material degree of fineness. For the analyzed case this dependence has form:

$$E_B(i) = 1.736 \cdot i^{-0,013} \quad (7)$$

The higher values of the degree of fineness is received during chip grinding the lower the values of wood chip energy efficiency index (Fig. 5).

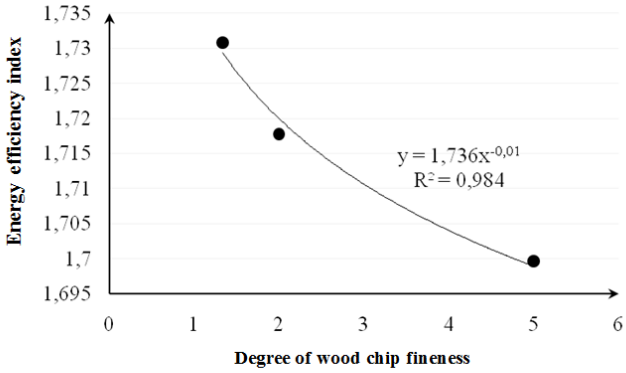

Fig. 5. Dependence of efficiency index on the degree of material fineness [own research]

SUMMARY AND CONCLUSIONS

The value of the energy efficiency index for wood chips ranges from 1.699 to 1.731 depending on the chip size (Tab. 7.). An analysis of the energy efficiency index shows that the most effective method is to use large size chips in combustion processes - then the energy expenditure for grinding is the lowest and the value of energy index is the highest.

On the basis of materials assessment for energy production it was found that:

1. The value of energy efficiency will rise along with an increase in energy benefits
2. A decrease in energy inputs will cause an increase in the energy efficiency index.
3. Unit energy inputs for grinding account for insignificant share in energy expenditures and they cause small changes in the energy efficiency index according to the dependence that the higher energy inputs for grinding the lower values of the material energy efficiency index (Tab. 7.).
4. The energy efficiency index for the analyzed energy media does not depend on the mass and assumes a constant value for established parameters.

In order to determine the energy efficiency index is necessary to identify energy benefits and inputs. Analysis LC (Life Cycle Assessment) can be used for this purpose.

The analysis carried out in this study, especially the one concerning energy input, required application of simplifications, due to complexity of the process of wood chips acquisition, preparation and combustion.

The next research step to be taken should be ecological and economic evaluation of a given material to provide full assessment of wood chip biomass at three levels: environmental impact, energy efficiency and economic profitability.

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BILANS ENERGETYCZNY WYKORZYSTANIA BIOMASY DRZEWNEJ. CZĘŚĆ II – WYNIKI BADAŃ

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Streszczenie. Światowe zużycie energii nieustannie rośnie. W obliczu przewidywań o kończących się zasobach paliw kopalnych, alternatywne źródła energii takie jak biomasa stają się ważnymi surowcami energetycznymi. Celem pracy jest analiza i ocena możliwości wykorzystania zrębków drzewnych na cele energetyczne w oparciu o uniwersalny wskaźnik oceny i bilans energetyczny. Analizie poddano zrębki drzewne. Rozpoznano dla nich nakłady i korzyści energetyczne oraz wyznaczono wartość opracowanego wskaźnika efektywności energetycznej wykorzystania materiałów na cele energetyczne. Przeanalizowano jaki wpływ na wartość wskaźnika mają nakłady energetyczne oraz zastosowana technologia i warunki techniczne. Stwierdzono, że w przypadku zrębków drzewnych korzyści energetyczne przewyższają nakłady na ich uzyskanie, co świadczy o energetycznej efektywności spalania tego materiału.

Słowa kluczowe: biomasa, zrębki drzewne, wskaźnik efektywności energetycznej, bilans energetyczny, odnawialne źródła energii.