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A METHOD OF ESTIMATION OF THE CALORIC VALUE OF THE BIOMASS. PART I – BIOMASS ENERGY POTENTIAL

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Abstract: The caloric value of the crops is one of the fundamental parameters to be determined during the process of biomass production for the energy purposes. The variety of biomass and its reaction to the environmental and agrotechnical conditions forces the utilization of particularly accurate algorithms during the determination of the caloric value of the crops. While determining the caloric value of the directly combusted crops, the coefficients for the raw state caloric value should be used. Violation of this rule causes significant overestimation of the end-results. Using the biomass for the biogas production, the energy balance should take the methane into account. The literature data shows quite a big difference in gas production from various substrates (from 368 up 722 Ndm^3 per kg of dry mass) as well as a significant difference in the methane content (from 53 up to 76%). While planning the substrates selection for a biogas production plant, special attention should be put on proper estimation of the overmentioned coefficients.

Keywords: biomass, energy efficiency of biomass production

1. INTRODUCTION

The continuing energy crisis and growing environmental awareness tends the international community to pursue the renewable energy sources [1-4]. The biomass is a very promising energy source [5, 6]. In practice however, the principal part of the biomass used in the power sector should come from the energy crops [7, 8]. In order to provide the proper carbon balance of the soil, the by-products from agriculture like the straw should be used mainly for the livestock breeding or as a fertilizer [9].

All the plants useful in the power sector should be characterized by a high growth of the dry mass in the vegetation season, high caloric value, relatively high specific mass, low soil and climate requirements and high agrotechnical mechanization [9]. In practice, those conditions are fulfilled by the multiseason species [6, 10, 11]. The most commonly cultivated plants are the *Salix viminalis*, *Miscanthus* and *Malvales* [9, 12]. At the same time, the research on utilization of the other species like the *Panitum virgatum* [13], *Spartina pectinata*, *Phalaris arundinacea* and *Phragmites australis* [1], is being carried out. Every species of the energy plants may have a different production potential, soil requirements, water requirements, caloric value, vulnerability to pests and reaction to climate conditions. Those characteristics encourage to differentiate the selection of the biomass dedicated species and to avoid the large monocultures that are highly vulnerable to the pathogens [1].

The species dedicated to the energy sector produce a great amount of mass that implies a high demand on the nutrients that can be supplied in a form of the mineral or organic fertilizers of sewage sludge. The sewage sludge is especially useful for fertilizing the energy crops due to its high content of the nutrients [14, 15, 16], and the public disapproval to use the sewage sludge as a fertilizer in the agricultural sector. The best results for the *Miscanthus* were obtained with a sewage sludge fertilizer dose of 20 t per ha (dry mass) [17]. However, taking into account the difference between the content of nutrients in the sewage sludge and plants' demand for the nutrients, it is recommended to use them together with the supplementary dose of the mineral fertilizers [18].

While taking the decision about the cultivation of the energy crops, it is important to select the proper species and technology, taking into account the environmental conditions and other limitations [3, 19]. In practice, although the energy indicators are very important, the most important criteria are the economic issues. Expressing the costs and gains in terms of quantity of energy seems more fair, because of the constant change of prices of materials and services [19, 20]. Using the energy-intensity instead, enables to compare the different species of plants and technology of their production [21]. While evaluating the technology of production, it was discovered that energy used to grow the single-season willow equals 12.19 GJ per ha, and the three-season cycle 30.10 GJ per ha (for the whole cycle) [9]. Research of the other authors [22] however, prove that the energy demand required for growing the willow equals 15,63 GJ per ha. According to Kwaśniewski [23], this quantity, depending on the technology used, ranges from 345.2 up to 993.2 kWh per ha. Furthermore, harvesting and transporting the single-season crops account for additional 31.8 to 274.7 kWh per ha. While making the full analysis of the problem, apart from the energy input, the energy output should be taken into account. There are various methods for such estimations. In his research on alcohol production from the corn seeds, Shapouri [24] as the net energy uses the difference between the caloric value of the produced ethanol and the energy of the fossil fuels used during the process. The energy efficiency indicator, however, is used more often [9, 25, 26]. It represents the ratio of the caloric value of the crops and the required energy input [27]. This indicator usually refers to the unit of area (ha) or to the quantity of product (ex. tons of dry mass) [9]. Energy efficiency indicator in a range between 5 and 10 is considered as safe [30]. Values can also be expressed in ex. tons per ha of dry mass or GJ per ha. In this case, 8 to 12 tons per ha of dry mass or 180 to 190 GJ per ha [26] are considered safe. The range of the presented data, however, is quite large – from 54 up to 330 GJ per ha [28, 29].

The use of the energy efficiency indicator is common for the biomass production. However, the large range of the data presented [30] comes from the differences in the calculation methods and simplifications. A typical way to calculate the energy input is the cumulative energy-intensity method [31]. In practice, many modifications of this method are used. Starczewski [19] in his calculations of the energy input takes into account three streams – energy of the fuels, materials and human labour. It does not take into account the energy in a form of the aggregates used. Kamionka [22] estimates the energy input basing of four streams – materials, aggregates, fuels and human labour in man-hour. Węgrzyn and Zając [32] highlight that there is a big problem with estimation of the energy input in a form of the human labour. Every employee has different abilities and qualifications. Therefore, the energy input in a form of the human labour is often omitted. According to the authors, if the energy input in a form of the human labour is included in the research summary, it should be also expressed in man-hour.

Harvesting the biomass accounts for quite a big share of the energy input. According to Pasyniuk [33], the amount of energy required for this process is usually underestimated. The performance of the investigated *Salix viminalis* harvester, according to the standard, should exceed 2 ha per h. In reality however, this value equals 0.6 ha per h. The estimation of the total amount of the fuels used in the process is also an important issue in terms of calculation of the energy input. Klikocka [34] suggests calculating the amount of the fuel basing on the nominal power of the tractor (kW), duration time of the process (h) and the average fuel consumption coefficient (0.13 according to the author). Karwowski [35] presents another view, he claims that the calculations should take into account the nominal power of the tractor, unitary fuel consumption, time required for the process and the indicator of the load of the motor during the process.

2. A METHOD OF ESTIMATION OF THE ENERGY POTENTIAL OF THE BIOMASS

The potential of the biomass should be considered as an interdisciplinary issue. In most cases, there are the biological, technical, economic and available (utility) potentials. The biological potential, also known as the theoretical, covers all the biomass produced on a given area taking into account its caloric value. It does not take into account the limitations of the harvesting and utilization processes. The technical potential represents the biological potential reduced by the biomass used for the non-energy purposes. It takes into account the technological limitations and efficiency of the devices that process the biomass into the useful energy. The economic potential is strictly connected with the market. It represents the technically available biomass in terms of the economic feasibility of the project. The available potential represents the biomass energy stream that can be utilized for the energy purposes. A quantity of this stream in most cases is lower than the economic potential [36]. In practice, the threshold of the cost-effectiveness for the energy crops ranges between 8 and 12 ton of dry mass per ha [37].

While estimating the energy potential of the biomass, one should take into account the following parameters:

- origin of biomass (energy crops, by-product),
- type of biomass,
- amount of energy,

– energy conversion process,
– caloric value.

A group of plants dedicated to the energy purposes is quite numerous. The most important species are as follow: *Salix viminalis*, *Miscanthus* and *Malvales*, *Phalaris arundinacea*, *Helianthus tuberosus* or corn. The amount of crops and its humidity are the two factors deciding whether the plant is suitable for the energy purposes or not. During the preliminary assessment of productivity of the specific species conducted by Faber et al [38], it was clearly demonstrated that the amount of crops of the investigated plants depends on their species, genotype, environmental conditions (type of soil), planting arrangement, number of seasons and the harvesting date (Tab. 1).

The data presented in Tab. 1 were acquired in similar agrotechnical conditions, thus they reflect pretty well the change of the parameters of the energy dedicated species. At the same time, quite different data can be found in the literature. This phenomenon is especially important, because the amount of crops and its humidity are determining the amount of energy obtained from the biomass.

Another important parameter of the biomass is its caloric value. In practice, there are two parameters – lower caloric value and higher caloric value. The higher caloric value is the amount of thermal energy released during combustion of the dry biomass (dry mass). In reality, it is impossible to obtain this value. Thus, in most cases we deal with the lower caloric value of the biomass in the raw state. This parameter depends on type of the biomass, its higher caloric value and humidity of the sample.

On average, the lower caloric value of the solid fuels ranges between 6 and 8 MJ per kg (humidity 50 to 60 %), and between 15 and 17 MJ per kg (humidity 10 to 20 %) [39]. During the theoretical calculations, the lower caloric values are often overestimated, thus the overall results are overoptimistic. The biomass is not a pure material, so the caloric value may differ within the same type (Tab. 2).

A very popular way to convert the energy of the biomass is to pickle it and further to produce the biogas. In most cases the mixture of the silage or liquid manure is used [40]. While selecting the values of the biogas produced and methane content for the calculations, it should be taken into account that they vary depending on the species. Production of the biogas may vary from 368 (sorghum silage) up to 722 Ndm^3 per kg of dry mass (*Helianthus tuberosus* silage). In case of methane content, it may vary from 53 (*Phalaris* silage) up to 76% (*Helianthus tuberosus* silage) [41]. In such situation, for the methane content, it is recommended to use the data concerning the mass of dry silage or mass of dry organic silage (Tab. 3). While calculating the caloric value of the crops for the combustible plants, the following formula should be used:

$$Ep = Pb \cdot Wr \cdot 0.01 \cdot Wep \text{ [GJ per ha]}. \quad (1)$$

If we calculate the caloric value of the crops for the biogas purposes, the following formula should be used:

$$E_p = P_b \cdot W_{dk} \cdot Wk \cdot 0{,}01 \cdot P_m \cdot W_{met} \text{ [GJ} \cdot \text{ha}^{-1}\text{]}. \quad (2)$$

The scheme (Fig. 1) proposed by Piskier and Sekutowski [42] may serve as an example of such consideration of the amount of energy gained. While analysing the energy potential of the *Helianthus tuberosus*, use of both stems and tubers for the energy purposes was investigated. The energy was converted by the means of combustion of the stems, and the biogas production from the tubers. Combined utilization of stems and tubers for the energy purposes, ex. combustion of the stems and biogas/alcohol production from the tubers of the *Helianthus tuberosus*, is also possible.

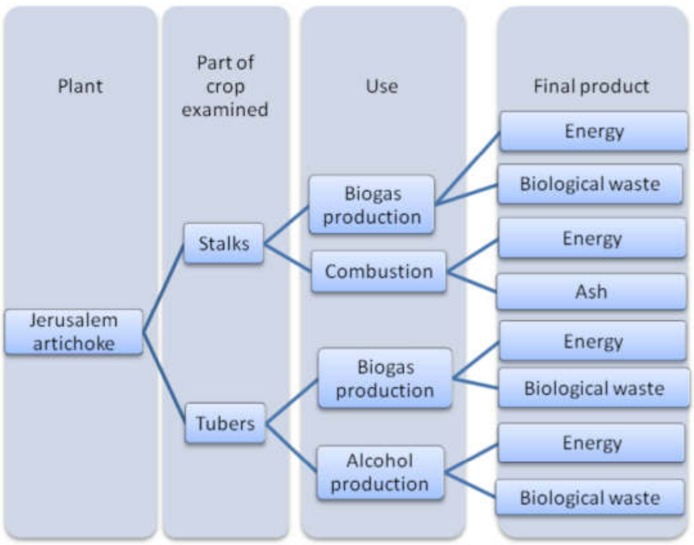

Fig. 1. Scheme for energy gain for *Helianthus tuberosus* [42]

Tab. 1. Dry mass crop yield and crop humidity of selected energy plants in the years 2004-2006 [38]

Species	Dry mass yield fluctuations, $t \cdot ha^{-1}$	Average dry mass yield, $t \cdot ha^{-1}$	Crop humidity, %
Common osier grown on heavy soil, harvested every year	10.1-16.6	12.9	52.0
Common osier grown on heavy soil, harvested every 3 years (average annual crop)	11.7-18.3	15.4	38.0
Common osier grown on medium soil, harvested every year	9.4-13.4	11.9	52.0
Common osier grown on medium soil, harvested every 3 years (average annual crop)	13.4-15.2	14.4	38.0
Miscanthus grown on heavy soil	8.4-21.7	15.0	45.5 (52.2-33.5)
Miscanthus grown on medium soil	10.4-26.8	17.1	42.8 (37.8-46.2)
Mallow grown on heavy soil, stock 10 thousand $pieces \cdot ha^{-1}$	7.4-10.3	9.2	25.3
Mallow grown on heavy soil, stock 20 thousand $pieces \cdot ha^{-1}$	14.8-20.8	18.7	25.3
Reed canary grass grown on heavy soil, crop from two swaths	16.3-19.8	18.1	I swath 58.0-71.4 II swath 45.4-62.1
Reed canary grass grown on heavy soil, crop from one swath	11.7-13.0	12.4	25.2-45.4
Jerusalem artichoke grown on light soil	7.8-13.2	9.7	no data available

Tab. 2. Calorific value of selected types of biomass depending on its humidity [39]

Type of biomass	Biomass humidity, %	Calorific value in working condition, $MJ \cdot kg^{-1}$	Combustion heat, $MJ \cdot kg^{-1}$
Wheat straw	15-20	12.9-14.1	17.3
Barley straw	15-22	12.0-13.9	16.1
Rape straw	30-40	10.3-12.5	15.0
Maize straw	45-60	5.3-8.2	16.8
Willow chips	40-55	8.7-11.6	16.5
Willow	49.3	8.8	19.7
Mallow	12.1	15.1	17.1

Tab. 3. Production capacity of biogas and methane from the silage of selected plants [41]

Plant species	Biogas production capacity		Methane production capacity		Methane content in biogas %
	$Ndm^3 \cdot kg^{-1}$ dry matter	$Ndm^3 \cdot kg^{-1}$ dry organic matter	$Ndm^3 \cdot kg^{-1}$ dry matter	$Ndm^3 \cdot kg^{-1}$ dry organic matter	
Phalaris	551	622	295	333	53
Rye	721	768	402	428	56
Jerusalem artichoke	722	812	551	619	76
Mallow	652	700	472	509	73
Triticale	406	435	266	285	66
Maize	427	445	280	292	65
Sorghum	368	394	268	286	73

Tab. 4. Jerusalem artichoke energy potential depending of energy acquisition method

Plant part examined	Yield, $t \cdot ha^{-1}$	Method to use yield	Production volume	Energy value of production, $GJ \cdot ha^{-1}$
Stalks	31-75 *	biogas production	3596-8700 m^3	109-262
	4-16 **	combustion	52-267 GJ	52-267
Bulbs	12-36*	biogas production	1392-4176 m^3	42-126
		alcohol production	Ca. 2610 dm^3	Ca. 70

* - yield expressed in fresh mass, ** - yield expressed in dry mass

Depending on the energy conversion method, *Helianthus tuberosus* can give from 52 up to 267 GJ per ha (direct combustion of, or biogas production from stems). Producing the biogas from tubers and combusting the stems however, can give up to 390 GJ per ha (Tab. 4).

The presented calculations consider only the energy plantations intended to full utilization for the energy purposes. While estimating the energy potential of a given area (farm, commune, region etc.), the by-products like straw, hay etc. should also be considered as the potential energy source. The excess of straw production can be calculated according to the following formula proposed by Kościuk [18]:

$$N = P - (Z_S + Z_p + Z_n) \text{ [t]}. \qquad (3)$$

While estimating the caloric value of the crops, the energy conversion method should also be taken into account. It requires another calculation methods and additional formulas.

3. CONCLUSIONS

1. Potential of the biomass for a given environment can be considered from different perspectives. There are the biological, technical economic and available potential. For the energy sector only the available (usable) potential matters.
2. Energy plantations are profitable in terms of energy gain only if the crops exceed 8-12 tons of dry mass per hectare.
3. Caloric value of the biomass crops is unstable and strongly depends on the species, humidity, production technology, soil and climate conditions.
4. On average, the caloric value of the biomass equals 15-17 MJ per kg (assuming 15% humidity).
5. Straw of the cereal crops is a potential source of the biomass, however, using it for the energy purposes a positive balance of the organic matter in the soil should be provided.
6. While selecting the plants for the biogas production, one should keep in mind that there is an evident correlation between the species and the biogas production and methane content. The highest methane content in the biogas can be obtained from Helianthus tuberosus and Malvales (74%). The efficiency of methane production from Helianthus tuberosus can reach up to 619 Ndm^3 per kg of dry organic mass.
7. Helianthus tuberosus seems to be a predestined species for the energy purposes. Its over-ground part can be utilized for direct combustion or biogas production, the under-ground part (tuber) can be utilized for biogas or alcohol production.
8. Energy potential of the Helianthus tuberosus, when the stems are directly combusted and the tubers utilized for the biogas production, can reach 390 GJ per kg.

Nomenclature

E_p – caloric value of crops, $GJ \cdot ha^{-1}$
N – excess of straw, t
P – production of straw, t
P_b – biomass crops, $t \cdot ha^{-1}$
P_m – methane produced from dry silage, $Ndm \cdot t^{-1}$ s.m.
W_{ep} – caloric value of crops in raw state, $GJ \cdot m^{-3}$
Wd_k – efficiency of biomass conversion into silage, %
W_k – humidity of silage, %
W_{met} – caloric value of methane content, 0.0397 $GJ \cdot m^{-3}$
W_r – humidity of crops in raw state, %
Z_n – demand of straw for plowing, t
Z_p – demand of straw for forage, t
Z_s – demand of straw for bedding, t

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