TEKA. COMMISSION OF MOTORIZATION AND ENERGETICS IN AGRICULTURE – 2017, Vol. 17, No. 4, 55-60

Energy balance of wood biomass utilization. Part I – characteristics of the problem and research methodology

W. Kruszelnicka, P. Bałdowska-Witos, J. Flizikowski, A. Tomporowski, R.Kasner

Uniwersytet Technologiczno-Przyrodniczy im. J. i J. Śniadeckich w Bydgoszczy, 85-796, Polska, Bydgoszcz, Al. S. Kaliskiego 7;e-mail: weronika.kruszelnicka@gmail.com

Received Novemer 20.2017: accepted December 18.2017

Summary. The study deals with the problems connected with utilization and processing of wood biomass. This material has been used for energy production for a very long time. The goal of the study is to identify benefits and expenditures involved in the cycle of wood chips lifetime and to develop an original research methodology and biomass fuel assessment method. Methodology for assessment of wood biomass was developed on the basis of balancing benefits and costs involved in the material lifetime cycle. Energy efficiency indexes defining the relation of energy input to its acquisition and preparation as well as benefits from utilization of its combustion energy have been developed to assess the material usability.

Key words: biomass, wood chips, efficiency, fossil fuels, renewable energy sources.

INTRODUCTION

Biomass is one of the oldest energy providing materials used by humans. It has always been utilized to produce warmth for heating, preparing meals and lighting. The first energy source consciously used by people was biomass of animal and plant origin. [19].

The demand for energy has been increasing at an accelerating pace which, in the light natural resources depletion, leaves no choice but to search for new energy sources [12, 13].

Now one of the main energy sources is coal, oil and natural gas and also atomic energy. Due to exhaustibility of fossil fuels attention was focused again on energy sources available in the natural environment [11].

The goal of this work is to identify benefits and expenditures involved in the life cycle of wood chips and development of an original research methodology for assessment of energy. This goal can be reached through development and identification of mathematical models and assessment indexes integrating expenditures and benefits connected with biomass combustion for energy purposes, on the basis of collected literature data.

CURRENT STATE OF KNOWLEDGE AND BIOMASS PROCESSING TECHNOLOGY FOR ENERGY PRODUCTION

Biomass is one of the oldest energy sources used by people [14]. It consists of plant and organic materials. European jurisdiction extends the notion of biomass by defining it as: „Biomass – biodegradable parts of products waste or remnants of biological origin from agriculture (together with plant and organic substances), forestry and related industry sectors including fishery and aquaculture as well as biodegradable parts of industrial and municipal waste [23]". This definition covers many different types and kinds of biomaterials, both of plant and animal origin, as well as bio-waste. In this context biomass can be classified according to different criteria [25]:

- due to the physical state,
- due to the degree of processing.

The parameters of biomass with low content of moisture are similar to coal. Net calorific value of biomass ranges from 6-8 GJ/t for high moisture materials (moisture content 50-60%) to 19 GJ/t, for dry wood, which is lower as compared to coal; content of ash is several times lower than for coal (tab. 1.). Biomass burning is more environment friendly than burning other fuels [26]. To produce energy biomass can be subjected to many different processes. It can be used for production of both solid and gaseous fuels and by processing of energy material: thermal, mechanical and electrical energy is produced.

Table 1. Properties of biomass in comparison with coal [28]

Kind of fuel	Net calorific value [MJ/kg]	Ash content [% s.m.]
Coal	1.8-29.7	8.0-24.1
Chips	6-16	0.6-1.5
Yellow straw	14.3	4
Palettes	16.5-17.5	0.4-1
Piece wood	11-22	0.6-1.5
Bark	18.5-20	1-3

The methods for biomass processing are different, depending on the kind of biomass: e.g. oil plants are usually subjected to pressing for acquisition of oils (biodiesel), plant remnants and waste undergo anaerobic fermentation in order to obtain biogas, hard biomass (fibrous) is most commonly subjected to agglomeration procedures, whereas plant with high content of starch undergo fermentation processes. Figure 1 shows possibilities of biomaterial processing for energy production purposes [6, 16].

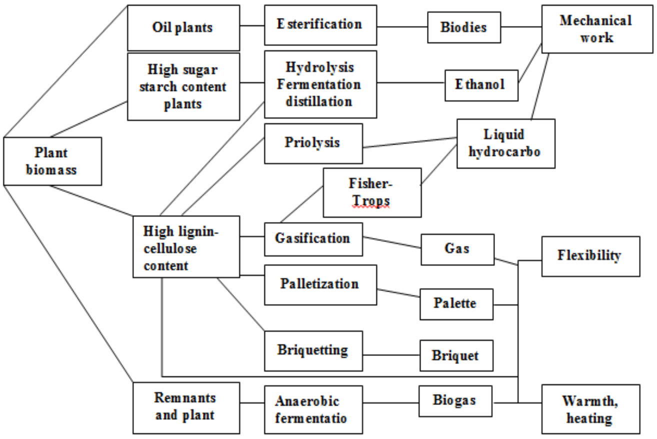

Fig. 1. Possibilities of utilization of biomaterials of plant origin for energy [16]

The most widespread methods of direct acquisition of energy from biomass are combustion, pyrolysis and gasification processes [10].

Combustion is the most common and the cheapest way to obtain energy from biomass. In this process, a chemical reaction takes place in the presence of oxygen. The energy of the chemical reaction is converted into heat energy. Efficiency of burning largely depends on the technology and efficiency of the combustion equipment. The amount of obtained heat is a measure of the process efficiency. Currently there are few systems to be used for combustion of biomass as the only input fuel. Systems of co-combustion of biomass with coal where addition of biomass accounts for 15-20%, are more popular [1, 10] These include:

- direct co-combustion,
- indirect co-combustion,
- parallel co-combustion.

Application of appropriate technology depends on the capacity of a system, properties of the combusted fuel and its form and size [6].

Pyrolysis is a method for biomass conversion into a fluid form in result of which biooils are generated. Pyrolysis occurs in temperature 450-550°C without oxidation factors, which causes pyrolytic disintegration of biomass. The prepared product has a significant amount of energy density and requires special transport and storage conditions [20].

The gasification process leads to formation of woody gas. Gasification process consists of the following stages [7]:

1. Drying (temp. ok. 150°C),
2. Separation of violatile parts from fuel (temp. 200-600°C),
3. Oxidation (temp. pow. 600°C),
4. Reduction of carbon dioxide and water vapor to carbon monoxide and hydrogen.

Biomass preparation processes

Biomass needs to undergo initial processing before being subjected to further treatment. Initial preparation can eliminate problems related to the process of burning and negative properties of biomass. The most frequently used procedures of initial treatment include [3, 7]:

- drying,
- grinding,
- chipping,
- palletization,
- baling,
- briquetting,
- torification,
- thermal treatment.

Drying involves removing moisture from biomass. It causes an increase in calorific value and improvement in storability. The smaller moisture content of biomass the smaller risk of mold and fungi occurrence. Drying is performed in special dry rooms or in fresh air. Drying in air depends on the weather conditions and is characterized by the process instability as the material dampness was possible, e.g. during precipitation [3, 7].

Biomaterials comminution is supposed to facilitate its transport and storage or preparation for further mechanical or chemical treatment through increasing bulk density of the material. Comminuted materials occupy less space making it possible possible to decrease costs incurred for transport and storage. High energy consumption of the comminution process and the possibility of comminuted biomass to self-ignite, due to increased activity of microorganisms, are disadvantages [3, 7].

Chipping involves cutting woody biomass to particles of size equal to a few mm. to several cm. In the process of chipping, chips are formed to provide an attractive fuel. Chips are recovered as waste of lumbermill production or energy plant cultivation e.g. willow. Wood choppers with drum, worm or disk tool system are most frequently used for chipping. Appropriate quality of chips, represented by their lengths, is a determiner to be used for assessment of the possibility of using them in advanced automated systems [4].

Palletization is a process of biomass preparation involving densification of the biomass (chips, sawdust, grain etc.), in result of which a homogenous product with energetic density increased as compared to loose biomass, high calorific value and low moisture, is obtained. The process of palletization enhances the biomass milling breakage susceptibility and facilitates its use in boilers and coal mills during co-combustion. Due to agglomeration of particles it is easier to transport them, though storage requires special conditions (low moisture) because of the pellet hygroscopy. The process of palletization consists of a few steps (Fig. 2.) [8].

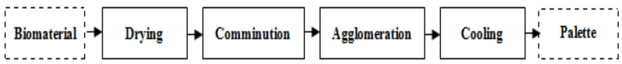

Fig. 2. Stages of the process of pellet formation. Own study on the basis of [8]

Baling, similarly to palletization, is supposed to increase the biomass energy density. Plant biomass of grass origin: mostly cereal straw and hay, undergoes baling. Baling facilitates storage and transport, however, using bales for energy purposes (combustion) requires comminution [3, 7, 15].

Briquetting is another form of agglomeration and biomaterial energy density increase. Baling, like palletization, facilitates storing and transport and causes reduction in necessary storage space necessary. Briquettes for energy purposes occur in the form of rolls and are created in presses in result of application of high pressure in briquetting machine and presses. Fuel with homogeneous properties is obtained in result of the briquetting process application. Briquettes to be used for energy production purposes occur in different dimensions, depending on the briquetting machine, in the form of cuboids and cylindrical pastilles. The process of briquetting, like palletization, consists of a few stages (Fig. 3.) [3, 7, 27].

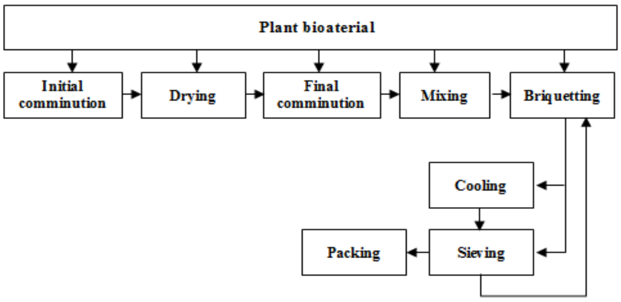

Fig. 3. Stages of briquette production from plant biomaterials. Own study on the basis of [27]

Torrefaction of biomaterials is a process which involves processing of biomaterials to achieve a solid product – biochar – under the influence of high temperatures 220-300°C without oxygen. Biochar exhibits better properties, similar to low calorific coal, than unprocessed biomass. Biomass biochar is characterized by higher energy density, better susceptibility to milling and higher tar content than raw biomass. These properties make biochar an attractive fuel for systems of direct co-combustion with coal mills and in the gasification processes as they do not cause the system pipe congestion. Despite many advantages of the torrefaction process it is not used very often due to high costs [21, 22].

Rinsing is supposed to remove alkaline compounds from biomaterials. Unfortunately, it involves a moisture increase and the necessity of drying [22].

MATERIALS AND METHODS

In the study, an energy balance for wood biomass processing for energy with the use of the developed index of energy efficiency is discussed. The biomass material accepted for analysis are wood chips. The chips parameters are presented in table 2.

The energy analysis included the following stages of the chips life cycle:

- the material manufacture process including planting a tree, its cutting and drying,
- the processes involved in transport to the place of processing,
- the process of chip comminution down to 3-4 mm size,
- the material use in a power plant,
- management of solid waste, including ash, on the landfill.

Table 2. Parameters of wood chips accepted for analysis [2]

PARAMETERS OF WOOD CHIPS	
Particle size [mm]	3-4
Ash content [% s.m.]	1.5
Moisture [%]	18
Combustion heat [kJ/kg]	17 300.0
Bulk density [kg/m^3]	400.0

Energy assessment model

Use of energy materials such as biomass in combustion and co-combustion processes is an environment friendly pro-ecological activity that takes advantage of integrated assessment indexes. They enable an extensive analysis of social, environmental and technical effects with the use of advanced research methodology, considering the analysis of minimal risk [17].

The economic factor is a subject of analysis in majority of projects. Economic factors determining an investment are the key element of the decision making process. However, this are the energy balance and the environmental factor that play a very important role in energy related investments [18].

The most frequently used assessment indexes include the economic, ecological and energy efficiency index. The figure presents the methodology for determination of efficiency on the basis of available aggregated technical data which allows to determine the values of indexes.

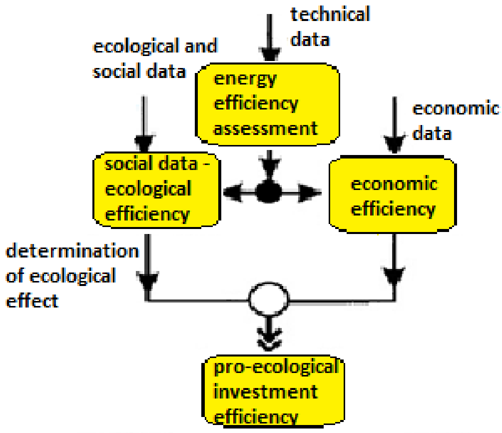

Fig. 4. Methodology of pro-ecological efficiency assessment [17]

Energy efficiency index can be used for evaluation of materials energy efficiency. Energy efficiency is understood as: „[...] a ratio of size of a given object usability effect, a technical device or a system, in typical service or conditions, to the amount of energy used by the object, technical device or a system or in result of service performed to obtain this effect" [24].

Efficiency is a notion used in many scientific disciplines and is defined as a measure of the effect (effectiveness, efficiency) of expenditures to gained profits which is described by index [9]:

$$E(t) = \frac{U(t)}{N(t)} \qquad (1)$$

where: *E(t)* – integrated efficiency index in *t* times of service in a lifetime cycle; *U(t)* – operation benefits, object utilization, technical system, resources during the operation time; *N(t)* – costs incurred to gain profits during the operation time; *t* – operation time.

It takes into consideration changes in phenomena and energy flow in time. It is not the most beneficial reference for the combusted materials due to constant variability of the combusted materials amount, whether in daily, monthly or yearly periods. It would be better to refer profits and expenditures to the combusted substance mass.

In order to make comparative assessment of energy materials an efficiency index was proposed. It allows to determine numerically a measure of utilization efficiency for a given material.
Hence:

$$E(m) = \frac{U(m)}{N(m)} \tag{2}$$

where: *E(m)* – material energy efficiency index; *U(m)* – benefit from energy material use; *N(m)* – expenditure involved in material manufacturing and preparing; *m* – unit mass of the combusted material.

Providing more detail, the index assumes the form:

$$E(m) = \frac{U(m)}{N(m)} = \frac{\sum_1^n U_j \cdot m}{\sum_1^n N_j \cdot m} \tag{3}$$

where: U_j – unit energy profits; N_j – unit energy expenditures for preparation of the considered process.

Since both expenditures and benefits depend on the mass of the prepared and combusted material it can be said that the index itself does not depend on the mass but on the type of material, its properties and the distinguished preparation processes. So defined index will be constant for a given material with specified properties and preparation processes.

The index has a form of a linear function *E(m) = a*, continuous, regardless of the material mass, which is depicted in figure 5. Effective use of energy materials occurs, when $E(m) > 1$, that is, benefits overweigh expenditures, whereas, when $0 < E(m) \leq 1$ use of materials is ineffective, expenditures overweigh benefits.

Benefits form use of energy materials is the energy obtained in the combustion process. The combustion heat that can be received from materials combustion is, in this case, a measure of benefits.

Heat of combustion defines how much heat can be obtained in the combustion process of materials taking into consideration heat from water steam condensation. Marking the heat of combustion is carried out in ideal conditions, with an assumption of total combustion of a material, that is reaching maximum value of energy during the process of combustion.

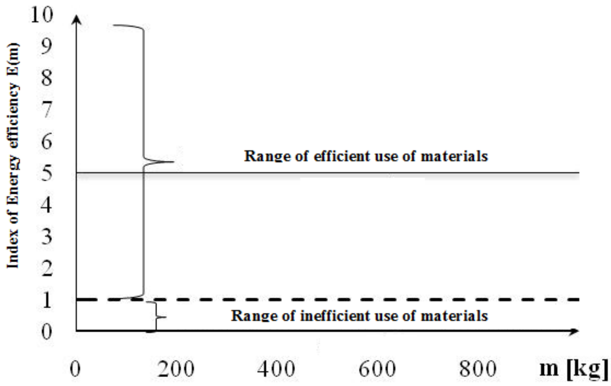

Fig. 5. Graphic interpretation of energy efficiency index [the authors' own study]

In this case, the combustion process requires constant volume of the mixture, compressed oxygen, combustion products have temperature 20°C, sulfur monoxides and carbon monoxides being combustion products, assume gaseous form, nitrogen does not oxidize and water is in a liquid state. Unit combustion heat is kJ/kg.

The amount of produced heat depends on the amount of the combusted material and its kind. Subsequently, benefits from combustion of materials for energy purposes are a function of the combusted materials mass.

$$U(m) = \sum_{i=1}^{n} U_{ji} \cdot m_i = Q_c \cdot m \tag{4}$$

With an assumption of constant value of combustion heat for a given material with constant parameters (i.e. moisture, ash content, chemical composition) the dependence of energy benefits can be graphically demonstrated in the form of a linear function $U(m) = Q_c \cdot m$. Graphic interpretation of this dependence is presented in figure 6.

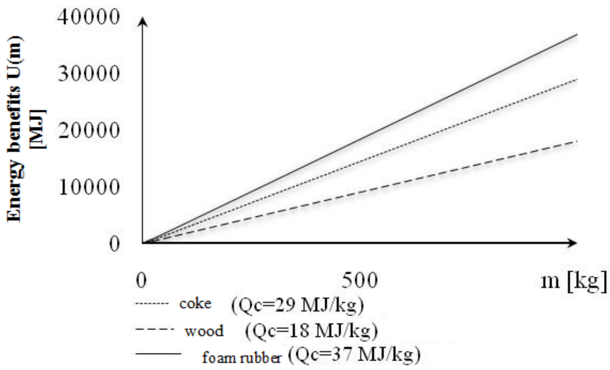

Fig. 6. Graphic interpretation of changes in energy benefits during materials combustion in dependence on the mass and kind of material [the authors' own research]

Energy benefits increase along with the combustion material mass growth. The type of material and its combustion heat has an influence on the amount of benefits.

Taking into account the whole life cycle of energy materials, these expenditures can be expressed as a sum of: expenditures involved in manufacturing of the energy material $N_w(m)$, expenditures involved in the process of the material preparation $N_p(m)$, those connected with the process of utilization $N_s(m)$, and expenditures for waste utilization $N_z(m)$:

$$N(m) = N_w(m) + N_p(m) + N_s(m) + N_z(m) \quad (5)$$

Generally, expenditures $N(m)$ will increase along with the media mass growth m. It is expressed by an equation:

$$N(m) = N_w(m) + N_p(m) + N_s(m) + N_z(m) = = \sum_{i=1}^{n} N_{wi} \cdot m_i + \sum_{i=1}^{n} N_{pi} \cdot m_i + \sum_{i=1}^{n} N_{si} \cdot m_i + \sum_{i=1}^{n} N_{zi} \cdot m_i = \sum_{j=1}^{k} N_j \cdot m_j \quad (6)$$

Expenditures for creation of an energy medium can include different processes depending on the energy medium. For biomass, these are cultivation and harvest processes.

Similarly, for energy expenditures needed to prepare an energy medium, these expenditures will differ depending on the considered medium.

Expenditures for utilization and management of waste will cover different processes depending on the medium utilization manner e.g.: combustion, gasification, pyrolysis, esterification, etc.

CONCLUSIONS

Current trends and actions to be taken in the direction of sustainable development focus primarily on energy efficiency.

Energy from energy materials (materials) can be received from processes of combustion, gasification, pyrolysis, esterification, fermentation or energy recycling. Energy can occur in different forms: thermal, electrical, fossil fuels. Index approach to assessment of materials enables actual representation of materials energy balance and determination of what kind of manufacturing and treatment processes are most energy consuming and how their modification can affect the value of the entire balance.

The proposed index of energy efficiency of materials use for energy production includes benefits and expenditures involved in use of a given material. This allows to identify relations between benefits and expenditures for a given material.

This index can be used for comparison of different types of materials. Its value is affected by the type of material which is characterized by given unit benefits of energy processes – combustion heat.

The value of efficiency index depends on energy expenditures, which are dependent on the applied technology of manufacturing, processing, utilization and waste management.

REFERENCES

1. **Al-Mansour F. and Zuwała J. 2010.** An evaluation of biomass co-firing in Europe. Biomass and Bioenergy, vol. 34, no 5., 620-629.
2. **Chen S. 2009.** Life Cycle Assesment of Wood Pellet. Master Thesis. Goteborg, Sweden: Chalmers University of Technology.
3. **Cocker-Maciejewska A. 2007.** Biomass pre-treatment for energy purposes. Environmental Protection and Natural Resources, no 30, 133-141 (in Polish).
4. **Frączek J. and Mudryk K. 2007.** The method of energy consumption measurement in the process of willow sprouts chipping. Agricultural Engineering, vol. 95., no 7., 47-53 (in Polish).
5. **Frączek J., Mudryk K. and Wróbel M. 2010.** Energy expenditures in the process of grinding of chips of the willow salix viminalis L. Agricultural Engineering, vol. 122., no 4., 43-49 (in Polish).
6. **Głodek E. 2010.** Combustion and co-combustion of biomass-guide. Opole: The Institute of Ceramics and Building Materials (in Polish).
7. **Głodek E. 2010.** Gasification of biomass. Guide. Opole: The Institute of Ceramics and Building Materials (in Polish).
8. **Jakubiak M. and Kordylewski W. 2010.** Biomass torrefaction. Burning Archive, vol. 10., no 1-2., 11-25
9. **Kasner R. 2016.** Assessment of benefits and investments for wind farm life cycle. Dissertation. Poznan: Poznan University of Technology (in Polish).
10. **Koppejan J. and van Loo S. 2008.** The Handbook of Biomass Combustion and Co-firing. London, Sterling VA: Earthscan.
11. **Kruszelnicka W., Cierlicki T., Madej O. and Mroziński A. 2017.** The study of the parameters of laboratory system of heat pump air-water monoblock type. Przegląd Mechaniczny, no. 1., 38-42 (in Polish).
12. **Kruszelnicka W., Kozłowska N. and Mroziński A. 2015.** Analysis of energy and economic efficiency of water heating system powered by photovoltaic module. Mechanik, no 10., 70-80 (in Polish).
13. **Kruszelnicka W., Tomporowski A., Madej O. and Kasner R. 2016.** The hybrid system photovoltaic – wind turbine, as a stable power supply. Ecology and Technology, nr 1., 46-50 (in Polish).
14. **Lewandowski W. M. 2010.** Pro-ecological renewable energy sources. Warsaw: WNT
15. **Livingston W. R. 2005.** A review of the recent experience in Britain with the co-firing of biomass with coal in large pulverised coal-fired boilers, Mitsui Babcock, Renfrew, Scotland, Proceedings of the IEA Exco Workshop on Biomass Co-firing, Copenhagen.
16. **Osiak J. and Dwórznik M. 2015.** Systems for storage, sale and distribution of biomass. Warsaw: Amicus Society (in Polish).
17. **Paska J., Sałek M. and Surma T. 2005.** Generating of electricity and heat in hybrid power systems. Wiadomości Elektrotechniczne. no 12., 3-13 (in Polish).
18. **Słomiński D and Reński A. 2005.** Development trends of small associated systems in Poland and in the world. Energy Market. no 5., 7-13 (in Polish).

19. **Soliński J. and Gawlik L. 2012.** Historical outline, development and the present condition of the world and Polish energy sector. Energetyka, no 3-4, 142-149 (in Polish).
20. **Wheelock T. D. and Markuszewski, R. 1984.** Coal preparation and cleaning. [in] B. R. Cooper, W. A. Ellingson, The Science and Technology of Coal and Coal Utilization. New York: Springer US, 47-123
21. **Zuwała J., Kopczyński M. and Robak J. 2014**. Coupled torrefaction-pelletization process for biomass co-firing, techno-economic issues. Energy Policy Journal, vol. 17., no 4., 147-158 (in Polish).
22. **Zyga, A. 2015.** Co-firing as a method of biomass conversion. [in] Modern Power Engineering of Central and Eastern Europe 2015. 1-28 (in Polish).
23. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC
24. Energy Efficiency Act of 20 May 2016. Dz. U. z 2016 r., poz. 831, Warsaw
25. http://portalrsi.it.kielce.pl/pl/top/rodla_biomasy_i_jej_rodzaje558?, entry: 2017.12.06
26. http://www.biomasa.org/index.php?d=artykul&kat=51&art=47, entry: 2017.12.06
27. paleko.com.pl/pliki/brykiet/4b.pdf, entry: 2017.12.06
28. http://paleko.com.pl/pliki/kotly/13k.pdf, entry: 2017.12.06

BILANS ENERGETYCZNY WYKORZYSTANIA BIOMASY DRZEWNEJ. CZĘŚĆ I – CHARAKTERYSTYKA PROBLEMU ORAZ METODYKA BADAŃ

W. Kruszelnicka, P. Bałdowska-Witos, J. Flizikowski, A. Tomporowski, R. Kasner

Streszczenie. Praca w całości poświęcona jest zagadnieniom wykorzystania i przetwarzania biomasy drzewnej. Materiał ten w celach energetycznych wykorzystuje się od bardzo dawna. Za cel pracy postawiono rozpoznanie korzyści i nakładów w cyklu istnienia zrębków drzewnych oraz opracowanie oryginalnej metodyki badań i oceny materiałów energetycznych. W pracy przedstawiono metodykę oceny energetycznej biomasy drzewnej w oparciu o bilans korzyści i nakładów w cyklu życia tego materiału. Na potrzeby oceny użyteczności materiału opracowano wskaźnik efektywności energetycznej określający relację nakładów energii na jego pozyskanie i przygotowanie oraz korzyści z energetycznego wykorzystania spalenia.

Słowa kluczowe: biomasa, zrębki drzewne, efektywność, paliwa stałe, odnawialne źródła energii.