Multi-Criteria Optimization Concept for the Selection of Optimal Solid Fuels Supply Chain from Wooden Biomass

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Abstract

Production of solid fuels from wooden biomass is defined with appropriate energy chain of supply. Production procedure of solid fuels from wooden biomass, starting with technology for gathering wood residues and residues from logging up by the system of fuel production (system for milling, crushing, chopping, drying and pressing of wood residues), represents the energy chain of supply of solid fuel from biomass. Every single energy chain of supply and production of certain form of solid fuel from wooden biomass can be uniquely defined with three general criteria. These criteria are: energy efficiency of production, economy of production and environmental criteria. Efficiency of production is the relation of overall energy consumption per 1 kWh of heating value of produced fuel. When we talk about the economical aspect of production of solid fuels we take into account all production costs per 1 kWh of heating value of biofuel produced. Forest biomass is scattered and the need for its collection and transport require certain consumption of fossil fuel. Consumption of fossil fuel is needed to run mechanization to collect, transport and prepare biomass. Consumption of fossil fuels causes the emission of GHG. Ecological criteria for the estimation of production process of bio energy can be defined as emission of GHG per 1 kWh of heating value of produced fuel. Besides general criteria to estimate the quality of production of energy from biomass, there are specific criteria. Specific criteria regarding several characteristics are tightly related to applied technologies, potentials and barriers during the use of biomass. This paper analyzes only specific investment in selected chain of energy supply. The paper mathematically describes four characteristic cases of solid biofuel production from wooden biomass. These cases are: production of wooden chips from forest biomass with mobile chipper, production of wooden chips from wooden residues transported from sawmill to processing terminal, production of wooden briquette from mill residues transported into briquette factory, production of wooden pellet from mill residues transported into pellet factory. For overall ranking of energy chain of wooden biomass supply and selection of optimum variant, multi-criteria optimization and VIKOR method is used.

Keywords: forest biomass, chips, briquette, pellet, energy chain, multi-criteria optimization, VIKOR method

1. Introduction

Biomass represents a solar energy stored in the photosynthesis process in the form of chemical compounds that form the structure of plants. During the time of biomass combustion, the oxygen from the atmosphere joins with the carbon in the biomass, and CO_2 and water are obtained again as the combustion products. This is the main reason why the energy obtained in this way is considered as CO_2 neutral. The use of biomass as a fuel provides significant opportunities for the decrease of harmful influences of GHG to the environment (WEA 2004, Karp and Shield 2008, Demirbas 2009). With the increase of crude oil price, various countries and institutions do the research trying to find the best ways of energy production from renewable sources (Inyang 2005). However, certain amounts of CO_2 emissions occur directly from fossil fuels used at cutting, collecting, processing and transportation of biomass. The energy production from biomass has been defined by adequate energy chain. The notion of energy chain is little known in the available literature. However, the notion of supply chain has been more defined in some other research areas, which are not of technical nature. Nowadays, in the scientific and professional literature of numerous papers, mixed opinions can be found on defining, management, basic elements, coverage and characteristics of a supply chain (Cooper et al. 1997).

The energy chain concept has been defined as the trajectory of energy transformations from the fuel source to the end users (Hamamatsu et al. 2004). An energy chain is the way in which the energy is used from an adequate fuel, starting from the fuel collection technology to the system for energy or fuel production (systems for transformation of energy from one form to the other). The production of solid fuels from wood biomass is defined for sure with an adequate energy chain. In different conditions in which the fuels are produced from wood biomass, different production costs of these fuels also occur. However, it is not enough to talk only about the production cost of particular fuels from wood biomass. It is also necessary to perceive some other aspects of fuel production process such as: energy efficiency of the process, consumption of fossil fuels, CO_2 emission and investment cost in energy chain.

The research in the field of the structures of energy chains for production of fuels and energy from biomass is of a relatively recent date. Generally, the increased interest for such a research has occurred with global problems such as: global warming process, increase of fuel prices due to the decrease in reserves of fossil fuels, tendency to decrease the dependence on fossil fuels supply with the use of local biomass resources, environmental pollution, etc.

2. Overview of research of supply chains based on biomass

In the developing countries, about 22% of the used energy is obtained from biomass, however that is a traditional way of use with a very low energy efficiency and increased emission of pollutants. Many scenarios predict a significant increase of share of the energy from biomass in the future (IEA 2010). For that reason, it is necessary to work constantly on the process of introducing the new technologies for energy production from biomass with an improved energy efficiency.

The research dealing with the composition of energy chains of supply and general use of biomass as a fuel is relatively new. The optimization of supply chains by biomass is mostly performed in accordance with the transportation distances and moisture of the biomass to be transported. The description of modelling a regional supply structure of wood biomass as a fuel, depending on the transportation costs, was given by Gronalt and Rauch (2007).

The model of linear biomass supply chain, which includes the transportation, storage and preparation of biomass, was discussed in Silke Van Dyken et al. (2009). The main focus of the paper is finding the linear dependence between the moisture content in biomass and energy content of biomass and economic indicators. The case of passive drying of biomass in the storage process was specifically discussed.

The planning and logistics in the use of wood biomass for energy production were discussed by Frombo et al. (2009). The decision making variables in this approach are the plant capacity and collected biomass from the adequate area, while the target function is minimization of total costs in the process of wood biomass utilization.

The productivity and cost of mechanized cutting and collecting of wood for energy purposes were discussed by Roser et al. (2011). The paper presents an analysis and overview of costs that occur at different production combinations of wood chips production (in plants, near the road, at the terminal), according to transportation distance.

In the analysis of transportation costs of energy wood supply chains at greater distances in Finland, the ways of transportation by means of trucks for wood chips, transportation of baled cutting residues by means of a truck or train, transportation of scattered residues, etc. were analysed (Tahvanainen and Anttila 2011).

Also, there are several studies about wooden residues as follow: Feasibility study for commercial use of wood residues in central Bosnia as a project for regional economic development 2006, Wood Energy Technologies, Partnership Programmes – TCDC/TCC –TCP/YUG/3201 (D), Belgrade, March 2011, etc.

3. Problem definition and approach to solution

Utilization of wood biomass for the production of fuels depends on many factors. Primarily, biomass is scattered and must be collected and processed to become a fuel. For cutting, collecting and transportation of biomass to the processing plant, it is necessary to engage the following mechanization: chainsaws, tractors, forwarders, trucks, technology for milling and crushing, draying, densification, etc. It, logically, results in corresponding energy consumption. Each operation of collecting, processing and transportation of biomass requires some energy consumption at related costs. The consumed fuel in the biomass supply process is usually of fossil origin. That consequently carries the harmful CO_2 emissions, which occur in collecting and processing of biomass. Every machine for cutting, chopping and transportation requires certain investment costs, as well as a biofuel production plant. For that reason, to be able to select an optimum variant of a fuel production energy chain, it is necessary to apply a multi-criteria optimization method. In this paper, VIKOR optimization method is applied. Before selecting the optimum variant of fuel production from wood biomass, it is necessary to define the optimization criteria. The following criteria have been defined:

⇒ consumed energy per 1 kWh of the lower heating value of produced biofuel, kWh/kWh (K_1);

⇒ energy chain production cost per 1 kWh of the lower heating value of produced biofuel, EUR/kWh (K_2);

⇒ CO_2 emission in the total chain due to the fossil fuels consumption for 1 kWh of the lower heating value of produced biofuel, kg/kWh (K_3);

⇒ specific investment cost per totally installed power of all machines and plants in the energy chain, EUR/kW (K_4).

As we know, lower calorific value of a fuel portion is defined as the amount of heat evolved when a unit of weight (or volume in the case of gaseous fuels) of the fuel is completely burnt and water vapor leaves with the combustion products without being condensed. This is the main reason why the above three criteria were defined with lower heat value of biofuels. It is the useful heat energy obtained by combustion from chemical energy stored in biomass.

We can say that the first three criteria are of general character, while the fourth criterion is specific, and they are all together used to evaluate the acceptability of biomass based energy supply chains. The above mentioned criteria are different for differently defined initial conditions of a problem. The solution of the problem of selecting the optimum variant of fuel production from wood biomass comes down to the development of:

⇒ a mathematical model for the calculation of optimization criteria;

⇒ a mathematical method for the selection of optimum variant of fuel production from wood biomass with the application of VIKOR method.

The significance of energy chain analysis from the aspect of invested energy is very important. In the literature, we can find the so-called EROEI factor (Energy Returned on Energy Invested), which presents the quotient of utilizable energy from a certain fuel (or from a way of energy production) and the energy consumed to convert the fuel or energy to a useful form (Hall 2011). The diagram (Fig. 1) shows that among the discussed fuels and ways of energy production, there is no biomass. The answer to the question why the EROEI factor for biomass is not defined in the diagram is very simple. The energy production from biomass depends on many variable parameters and that is why a clear value of this parameter cannot be defined. However, EROEI factor interval related to the production of fuels and energy from biomass can be obtained by mathematical modelling of biomass supply chains and numerical calculations for different initial conditions. Such an approach to the analysis of energy production from biomass has not been sufficiently researched and requires further research.

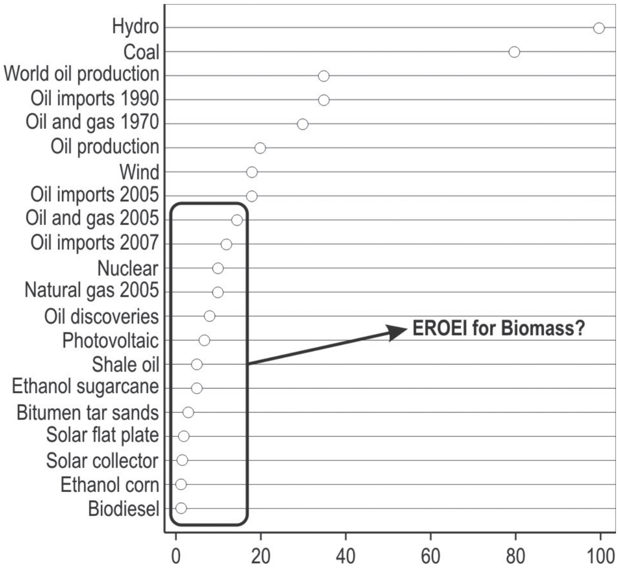

Fig. 1 EROEI – USA, Ratio of Energy Returned on Energy Invested for different kinds of renewable energy (Murphy and Hall 2010)

To be able to evaluate the total energy consumption in an energy chain of fuel production at all, it is necessary to convert all consumed energies into the primary energy form (heating value). In this way, all the consumed energy in the energy chain of fuel production from biomass can be summed. It practically means that all the energy conversions that occur in machines and plants in an energy chain are defined by corresponding efficiency factors. One of the main indicators of energy contents within a biomass fuel is the heating value. The heating value of biomass depends on its chemical composition, as well as on the moisture content.

4. Specific characteristics of wood biomass as a fuel

The most important characteristic of biomass related to combustion and its other thermochemical processes is the moisture content, with the increase of which the heating value of biomass decreases. The value of the lower heating value of wet wood can be calculated by the following equation (Hartmann et al. 2000):

$$ehv_{\mathrm{w}} = \frac{ehv_0 \times (100 - w) - (2.44 \times w)}{100} \tag{1}$$

Where:

ehv_{w} lower heating value of wood in relation to moisture content, MJ/kg;

ehv_0 heating value of dry wood, MJ/kg;

2.44 energy needed for water evaporation at 25°C, MJ/kg;

w moisture content in total mass expressed in percentage.

The volumetric mass or density of wood ρ_0 is defined as the relation between the dry mass of wood (kg) and the volume it occupies. The value varies widely, depending on the type of wood but is mostly in the range between 320 and 720 kg/m^3. The heating value per a volume unit can be calculated by taking into account the lower heating value ehv_{w} and density of wood:

$$ehvv_{\mathrm{w}} = ehv_{\mathrm{w}} \times \rho_{\mathrm{w}} \tag{2}$$

For the moisture content per dry wood basis higher than 30%, the density of wet wood is:

$$\rho_{\mathrm{w}} = \rho_0 \times \frac{\left(1 + \frac{u}{100}\right)}{\left(1 + \frac{\alpha_{\mathrm{v}}}{100}\right)} = \rho_0 \times \frac{10^4}{(100 - w) \times (100 + \alpha_{\mathrm{v}})} \tag{3}$$

For the moisture content per dry wood basis lower than 30%, the density of wet wood is:

$$\rho_{\mathrm{w}} = \rho_0 \times \frac{\left(1 + \frac{u}{100}\right)}{\left(1 + \left(\frac{\alpha_{\mathrm{v}}}{100} \times \frac{u}{100}\right)\right)} = \rho_0 \times \frac{3000}{3000 - 30w + \alpha_{\mathrm{v}} \times w} \tag{4}$$

Where:

$ehvv_{\mathrm{w}}$ heating value per volume unit, MJ/m^3;

u moisture content per dry basis $u = \frac{100 \times w}{100 - w}$, %; (5)

ρ_0 density of dry wood, kg/m^3;

ρ_{w} density of wood with moisture content, kg/m^3;

α_{v} percentage of swelling, % (Hellrigl 2006).

The volume occupied by wood fuels depends on the shape, size and organization of particular pieces of wood. Fulfilment factor of the volume also depends on that. It should be mentioned that a significant factor in biofuel supply and at the selection of their transportation is the shape in which biofuels are transported. For that reason, the SVF

Table 1 Criteria K_1, K_2, $K_{3,}$ K_4 for all four variants of fuel production from wood biomass

OPTIMIZATION CRITERIA: K_1, K_2, K_3, K_4 (kWh/kWh, EUR/kWh, kg/kWh, EUR/KW)				
	$j = 1$	$j = 2$	$j = 3$	$j = 4$
	CHAIN CH_1 mobile chipper	CHAIN CH_2 plant for production of wood chips	CHAIN CH_3 plant for briquetting	CHAIN CH_4 plant for pelleting
$i = 1$	E_{11}, C_{11}, G_{11}, P_{11} chainsaw	E_{12}, C_{12}, G_{12}, P_{12} chainsaw	E_{13}, C_{13}, G_{13}, P_{13} chainsaw	E_{14}, C_{14}, G_{14}, P_{14} chainsaw
$i = 2$	E_{21}, C_{21}, G_{21}, P_{21} tractor provided with winch for forest operations	E_{22}, C_{22}, G_{22}, P_{22} tractor provided with winch for forest operations	E_{23}, C_{23}, G_{23}, P_{23} tractor provided with winch for forest operations	E_{24}, C_{24}, G_{24}, P_{24} tractor provided with winch for forest operations
$i = 3$	E_{31}, C_{31}, G_{31}, P_{31} forwarder	E_{32}, C_{32}, G_{32}, P_{32} lifter for loading of timber	E_{33}, C_{33}, G_{33}, P_{33} lifter for loading of timber	E_{34}, C_{34}, G_{34}, P_{34} lifter for loading of timber
$i = 4$	E_{41}, C_{41}, G_{41}, P_{41} medium power chipper	E_{42}, C_{42}, G_{42}, P_{42} truck for transportation of timber	E_{43}, C_{43}, G_{43}, P_{43} truck for transportation of timber	E_{44}, C_{44}, G_{44}, P_{44} truck for transportation of timber
$i = 5$	E_{51}, C_{51}, G_{51}, P_{51} truck for transportation of wood chips to the end user	E_{52}, C_{52}, G_{52}, P_{52} crane for unloading of timber	E_{53}, C_{53}, G_{53}, P_{53} crane for unloading of timber	E_{54}, C_{54}, G_{54}, P_{54} crane for unloading of timber
$i = 6$	0	E_{62}, C_{62}, G_{62}, P_{62} sawmill	E_{63}, C_{63}, G_{63}, P_{63} sawmill	E_{64}, C_{64}, G_{64}, P_{64} sawmill
$i = 7$	0	E_{72}, C_{72}, G_{72}, P_{72} crane for loading of wood residues on truck	E_{73}, C_{73}, G_{73}, P_{73} crane for loading of wood residues on truck	E_{74}, C_{74}, G_{74}, P_{74} crane for loading of wood residues on truck
$i = 8$	0	E_{82}, C_{82}, G_{82}, P_{82} truck for transportation of wood residues to the chips production plant	E_{83}, C_{83}, G_{83}, P_{83} truck for transportation of wood residues to the briquettes production plant	E_{84}, C_{84}, G_{84}, P_{84} truck for transportation of wood residues to the pellets production plant
$i = 9$	0	E_{92}, C_{92}, G_{92}, P_{92} crane for unloading of wood residues	E_{93}, C_{93}, G_{93}, P_{93} crane for unloading of wood residues	E_{94}, C_{94}, G_{94}, P_{94} crane for unloading of wood residues
$i = 10$	0	E_{102}, C_{102}, G_{102}, P_{102} chips production plant	E_{103}, C_{103}, G_{103}, P_{103} plant for rough and fine chipping	E_{104}, C_{104}, G_{104}, P_{104} plant for rough and fine chipping
$i = 11$	0	E_{112}, C_{112}, G_{112}, P_{112} loading of wood chips	E_{113}, C_{113}, G_{113}, P_{113} drying plant	E_{114}, C_{114}, G_{114}, P_{114} drying plant
$i = 12$	0	E_{122}, C_{122}, G_{122}, P_{122} truck for transportation of wood chips to the end user	E_{123}, C_{123}, G_{123}, P_{123} plant for briquetting	E_{124}, C_{124}, G_{124}, P_{124} plant for pelleting
$i = 13$	0	0	E_{133}, C_{133}, G_{133}, P_{133} loading of briquettes on trucks	E_{134}, C_{134}, G_{134}, P_{134} loading of pellet on trucks
$i = 14$	0	0	E_{143}, C_{143}, G_{143}, P_{143} truck for transportation of briquettes to the end user	E_{144}, C_{144}, G_{144}, P_{144} truck for transportation of pellet to the end user
F	$f_{11} = \sum_{i=1}^{n} E_{i1}$ $f_{21} = \sum_{i=1}^{n} C_{i1}$ $f_{31} = \sum_{i=1}^{n} G_{i1}$ $f_{41} = \sum_{i=1}^{n} P_{i1}$ $n=14$	$f_{12} = \sum_{i=1}^{n} E_{i2}$ $f_{22} = \sum_{i=1}^{n} C_{i2}$ $f_{32} = \sum_{i=1}^{n} G_{i2}$ $f_{42} = \sum_{i=1}^{n} P_{i2}$ $n=14$	$f_{13} = \sum_{i=1}^{n} E_{i3}$ $f_{23} = \sum_{i=1}^{n} C_{i3}$ $f_{33} = \sum_{i=1}^{n} G_{i3}$ $f_{43} = \sum_{i=1}^{n} P_{i3}$ $n=14$	$f_{14} = \sum_{i=1}^{n} E_{i4}$ $f_{24} = \sum_{i=1}^{n} C_{i4}$ $f_{34} = \sum_{i=1}^{n} G_{i4}$ $f_{44} = \sum_{i=1}^{n} P_{i4}$ $n=14$

– solid volume content has been defined. The SVF represents the relation between the solid volume the wood would occupy without air holes at its current density and the total volume which it occupies in the form of various types of complex wood assortments and fuels. The factor is lower than one (Pottie M.A. and Guimier D.Y., 1986).

In order to calculate the amount of energy (heating value) of wood fuel in a volume in which it is, for example, transported, we will use the previously mentioned equations (1, 2, 3, 4, 5), but also the values of density ρ_0 and the SVF, so as to get the following relations for the moisture content higher than 30% and lower than 30%;

$$H_{\mathrm{w}\geq 30}=\frac{\dfrac{ehv_0(100-w)-(2.44w)}{100}\times\rho_0\times\dfrac{10^4}{(100-w)\times(100+\alpha_{\mathrm{v}})}\times V\times SVF}{3.6} \tag{6}$$

$$H_{\mathrm{w}<30}=\frac{\dfrac{ehv_0(100-w)-(2.44w)}{100}\times\rho_0\times\dfrac{10^4}{(100-w)\times(100+\alpha_{\mathrm{v}})}\times V\times SVF}{3.6} \tag{7}$$

Where:

V volume occupied by a material, for example the volume of a truck during transportation;

$H_{\mathrm{w}\geq 30}, H_{\mathrm{w}<30}$, $[kWh]$ total energy value of a fuel in a given shape and the volume it occupies as a function of moisture percentage w for the moisture content higher or lower than 30%.

5. Mathematical model for the calculation of criteria for energy chains optimization

The energy chains modelling should be based on modularity. It practically means that it is necessary to do a mathematical modelling of every energy chain element as an independent entity, which will for itself present a mathematical model as an elementary part of the energy chain. In this paper, the mathematical modelling is performed for: machines for cutting and collecting of biomass, means of transportation, plants for chopping and preparation of biomass, plants for drying, plants for pressing and pelleting of biomass. The approach to the modelling of all the elements is based on the analysis from the aspect of consumed energy in every element of the chain. The calculation of other criteria comes down to the calculation of production costs, CO_2 emission and investment cost per the installed power of all energy consumers in the chain. Table 1 gives an overview of all the elements of an energy chain for biofuel production defined by the criteria (K_1, K_2, K_3, K_4). The calculation of all the criteria functions of the matrix F is obtained by summation of all the elements in a table column for each of the chain variants (CH_1, CH_2, CH_3, CH_4).

Where:

E_{ij} ratio of invested energy per an obtained kWh of heating value of the processed wood for the i^{th} element of chain and j^{th} energy chain of production, kWh/kWh;

C_{ij} production cost for obtaining a kWh of heating value of processed wood for the i^{th} element of chain and j^{th} energy chain of production, kWh/kWh, EUR/kWh;

G_{ij} CO_2 emission per a produced kWh of heating value of processed wood for the i^{th} element of chain and j^{th} energy chain of production, kg/kWh;

P_{ij} investment cost per installed power for the i^{th} element of chain and j^{th} energy chain of production, EUR/KW.

Mathematical formulations of the functions E_{ij}, C_{ij}, G_{ij}, P_{ij} are given in the Enclosure 7.

6. Mathematical model for the selection of optimum variant of energy chain for the production of solid fuels from wood biomass

The VIKOR method (Multi-criteria compromise ranking) has been developed for the determination of a multi-criteria optimal solution. The VIKOR method has been developed on such a methodological basis that a decision maker is suggested the alternative (or solution), which (Opricović 1998) presents a compromise between:

⇒ wishes and opportunities;

⇒ different interests of the decision-making participants.

The VIKOR method has been developed for a multi-criteria optimization of complex systems. It is focused on ranking and selection of the best solution from the given set of alternatives, with conflicting criteria. The VIKOR method requires the values of all the criteria functions for all the alternatives in the form of a matrix to be familiar. Because of that, at the beginning of the optimization process, we set a general form of the problem (evaluation matrix) for our case. The matrix of criterion functions for all four variants of the production of solid fuels from wood biomass is of 4 x 4 dimensions, (4 alternatives of biofuel production from wood biomass and 4 criteria), obtained from Table 1.

$$F = \begin{array}{c|cccc|} & a_1 & a_2 & a_3 & a_4 \\ f_1 & f_{11} & f_{12} & f_{13} & f_{14} \\ f_2 & f_{21} & f_{22} & f_{23} & f_{24} \\ f_3 & f_{31} & f_{32} & f_{33} & f_{34} \\ f_4 & f_{41} & f_{42} & f_{43} & f_{44} \end{array} \quad (8)$$

Where:

$\{a_1, a_2, a_3, a_4\}$ is a finite set of possible alternatives to which the four energy chains of production correspond (CH_1, CH_2, CH_3, CH_4), $m = 4$;

$\{f_1, f_2, f_3, f_4\}$ is a finite set of criterion functions for four adopted criteria on the basis of which the chains of fuel production from wood biomass are analysed (K_1, K_2, K_3, K_4), $n = 4$;

$\{f_{11}(\cdot), f_{12}(\cdot), \ldots, f_{ij}(\cdot), \ldots, f_{44}\}$ is the set of all the criterion functions values.

An ideal solution is determined on the basis of the criterion function values from the equation:

$$f_{\mathrm{i}} = \underset{\mathrm{j}}{ext}\, f_{\mathrm{ij}},\ \mathrm{i} = 1, 2, \ldots, n. \quad (9)$$

The operator ext denotes a maximum if the function f_{i} describes a benefit or profit, and a minimum if f_{i} describes damages or costs. This is the best way to define an ideal solution. The criterion functions within the matrix F are commonly not expressed in the same units of measurement (i.e. the belonging criterion space is heterogeneous). For that reason, in order to perform the multi-criteria optimization, it is necessary to convert all the criterion functions to dimensionless functions whose values will be in the interval [0, 1]. Firstly, the best values of criterion functions are determined. In our case, these are the minimum values of all the criterion functions (minimization of: invested energy per the obtained one, production cost, CO_2 emission and investment cost per an installed kilowatt in the production chain):

$$\min f_1(\mathrm{f}_{1\mathrm{j}}) = f_1^*,\ \min f_2(\mathrm{f}_{2\mathrm{j}}) = f_2^*,\ \min f_3(\mathrm{f}_{3\mathrm{j}}) = f_3^*,\ \min f_4(\mathrm{f}_{4\mathrm{j}}) = f_4^* \quad (10)$$

In the same way, the worst values of the criterion functions can be determined, which are obtained by maximization of the criterion functions, i.e.

$$\max f_1(\mathrm{f}_{1\mathrm{j}}) = f_1^-,\ \max f_2(\mathrm{f}_{2\mathrm{j}}) = f_2^-,\ \max f_3(\mathrm{f}_{3\mathrm{j}}) = f_3^-,\ \max f_4(\mathrm{f}_{4\mathrm{j}}) = f_4^- \quad (11)$$

Then all the elements of the matrix f are converted in the value domain [0, 1]. Thit is achieved by the following equation:

$$n_{\mathrm{ij}} = \frac{f^* - f_{\mathrm{ij}}}{f_{\mathrm{i}}^* - f_{\mathrm{i}}^-}, \text{ and a matrix is formed, in the form } D = (-1) \cdot \left[n_{\mathrm{ij}} \right] = \left[d_{\mathrm{ij}} \right], \text{ for } i = 1, \ldots n \text{ and } j = 1, \ldots \mathrm{m} \quad (12)$$

Considering that there is a negative difference $f_{\mathrm{i}}^* - f_{\mathrm{i}}^-$ in the expression for n_{ij} it is necessary to multiply all the elements of n_{ij} with – 1 to satisfy the condition that the values of elements of the matrix D are in the interval [0, 1]. The negative difference occurs due to the nature of the problem in which a lower value of criterion functions is obtained by maximization, while a higher value is obtained by minimization.

The criterion weights for our problem, for the named four criteria are mutually equal. The reason for that is very simple, because we strive for the minimal: energy consumption, production cost, CO_2 emissions and investment cost per totally installed power in the energy chain. Consequently, the criterion weights are:

$$w_1 = w_2 = w_3 = w_4 = w_j = \frac{1}{4} \tag{13}$$

After that, the values of the elements of matrices S_j i R_j are calculated. Considering the equality of the criterion weights, they are obtained as:

$$\begin{aligned} S_{j=1\ldots4} &= w_j \times \sum_{i=1}^{4} d_{ij} = \frac{1}{4} \times \sum_{i=1}^{4} d_{ij} = \left[\frac{1}{4} \times \sum_{i=1}^{4} d_{i1} \;\; \frac{1}{4} \times \sum_{i=1}^{4} d_{i2} \;\; \frac{1}{4} \times \sum_{i=1}^{4} d_{i3} \;\; \frac{1}{4} \times \sum_{i=1}^{4} d_{i4} \right], \\ \mathrm{R}_{j=1\ldots4} &= w_j \times \max_i \left[d_{ij} \right] = \left[\frac{d_{i1} \max}{4} \;\; \frac{d_{i2} \max}{4} \;\; \frac{d_{i3} \max}{4} \;\; \frac{d_{i4} \max}{4} \right] \end{aligned} \tag{14}$$

In this way, the problem is reduced from a multi-criteria space to a two-criterion problem. The values of minimal and maximal element are determined from the matrices S_j and R_j.

$$S^* = \min_j S_j,\; S^- = \max_j S_j,\; R^* = \min_j R_j,\; \mathrm{R}^- = \max_j R_j \tag{15}$$

The decision strategy weight will be taken as $\upsilon = 0,5$. This is valid for the criterion number $m \leq 4$ (Opricović 1998). On the basis of that, it is possible to calculate the value of the matrix Q_j pursuant to the equation:

$$Q_j = \upsilon \cdot \frac{\left(S_j - S^*\right)}{S^- - S^*} + \left(1 - \upsilon\right) \frac{R_j - R^*}{R^- - R^*} \tag{16}$$

A certain value of Q_j corresponds to every chain, as shown in the following matrix:

$$\begin{array}{cccccc} & & CH_1 & CH_2 & CH_3 & CH_4 \\ Q_j = & [& Q_1 & Q_2 & Q_3 & Q_4 \;] \end{array} \tag{17}$$

The optimum variant of production is defined by the minimal value $Q^* = \min_j Q_j$. The ranking of alternatives is formed from the lowest value of Q_j to the highest value of Q_j, that is from the best to the worst variant. In our case, the alternatives are the mentioned chains of solid fuel production from wood biomass.

7. Enclosure of mathematical functions E_{ij}, C_{ij}, G_{ij}, P_{ij} from the energy chain elements

For the production of biofuel from wood biomass, it is necessary to engage: different types of mechanization, plants for converting biomass to useful fuel, human and other resources. Due to the fact that the energy chains for biofuel production are analysed from the energy aspect in this paper, in the text that follows mathematical descriptions will be given for particular elements of an energy chain pursuant to the previously adopted concept for the calculation of functions (E_{ij}, C_{ij}, G_{ij}, P_{ij}).

7.1 Biomass collection machines in a supply chain

Biomass collection machines are the first element in a chin from which the entire biomass supply process starts. Different operations in wood biomass collection require different machines, whose selection for use practically depends on the application conditions. In the structure of the analysed energy chains discussed in this paper, the following machines are used: chainsaw, tractor, truck, hydraulic crane, mobile chipper and forwarder. For all the production machines whose fuel consumption is expressed in litres per hour (l/h), and the labour productivity in the volume unit per hour (m^3/h), the following relations apply:

$$E_{\mathrm{ij}}=\frac{\displaystyle\sum_{\mathrm{q=1}}^{\mathrm{n_1}}\frac{\rho_{\mathrm{Fij}}\times Fc_{\mathrm{ijq}}\times \mathrm{t}_{\mathrm{ijq}}}{1000}\times Hv_{\mathrm{ijq}}}{\displaystyle\sum_{\mathrm{q=1}}^{\mathrm{n_1}}\frac{ehv_{\mathrm{0ijq}}(100-w_{\mathrm{ijq}})-(2.44w_{\mathrm{ijq}})}{100}\times\rho_{\mathrm{0ijq}}\times\frac{10^4}{\left(100-w_{\mathrm{ijq}}\right)\times\left(100+\alpha_{\mathrm{vijq}}\right)}\times\mathrm{Pr}_{\mathrm{ijq}}\times t_{\mathrm{ijq}}\times\left(SVF\right)_{\mathrm{ijq}}}\tag{18}$$

$$C_{\mathrm{ij}}=\frac{\displaystyle\sum_{\mathrm{q=1}}^{\mathrm{n_1}}Fc_{\mathrm{ijq}}\times \mathrm{t}_{\mathrm{ijq}}\times \mathrm{c}_{\mathrm{ijq}}}{\displaystyle\sum_{\mathrm{q=1}}^{\mathrm{n_1}}\frac{ehv_{\mathrm{0ijq}}(100-w_{\mathrm{ijq}})-(2.44w_{\mathrm{ijq}})}{100}\times\rho_{\mathrm{0ijq}}\times\frac{10^4}{\left(100-w_{\mathrm{ijq}}\right)\times\left(100+\alpha_{\mathrm{vijq}}\right)}\times\mathrm{Pr}_{\mathrm{ijq}}\times t_{\mathrm{ijq}}\times\left(SVF\right)_{\mathrm{ijq}}}\tag{19}$$

$$G_{\mathrm{ij}}=\frac{\left(\rho_{\mathrm{Fij}}\times Hv_{\mathrm{ijq}}\times\dfrac{e_{\mathrm{Fij}}}{10^6}\right)\times\displaystyle\sum_{\mathrm{q=1}}^{\mathrm{n_1}}\mathrm{Fc}_{\mathrm{ijq}}\times \mathrm{t}_{\mathrm{ijq}}}{\displaystyle\sum_{\mathrm{q=1}}^{\mathrm{n_1}}\frac{ehv_{\mathrm{0ijq}}(100-w_{\mathrm{ijq}})-(2.44w_{\mathrm{ijq}})}{100}\times\rho_{\mathrm{0ijq}}\times\frac{10^4}{\left(100-w_{\mathrm{ijq}}\right)\times\left(100+\alpha_{\mathrm{vijq}}\right)}\times\mathrm{Pr}_{\mathrm{ijq}}\times t_{\mathrm{ijq}}\times\left(SVF\right)_{\mathrm{ijq}}}\tag{20}$$

$$P_{\mathrm{ij}}=\frac{\displaystyle\sum_{\mathrm{q=1}}^{\mathrm{n_1}}I_{\mathrm{Mijq}}}{\displaystyle\sum_{\mathrm{q=1}}^{\mathrm{n_1}}P_{\mathrm{Mijq}}}\tag{21}$$

Where:

$q = 1...n_1$	the number of machines included in the work;
Fc_{ijq}	specific fuel consumption of the observed working machine, l/h;
$\mathrm{Pr}_{\mathrm{ijq}}$	productivity of the working machine, m^3/h;
t_{ijq}	working time of machine, h;
Hv_{ijq}	lower heating value of fuel (gasoline or oil, depending on the fuel type the machine uses), MJ/kg;
$w_{\mathrm{ijq}} \geq 30\%$	wood moisture, %;
ρ_{0ijq}	wood density, kg/m^3;
α_{vijq}	percentage of wood swelling, %;
$\left(SVF\right)_{\mathrm{ijq}}$	fulfilment factor of volume (0,...1);
$\mathrm{c}_{\mathrm{ijq}}$	price of a litre of fuel (gasoline or oil);
ρ_{Fij}	density of fuel at atmospheric conditions, kg/m^3;
e_{Fij}	coefficient of CO_2 emission for different fuels in a kilogram of CO_2 per a gigajoule of the fuel heating value, kg CO_2/GJ;
I_{Mijq}	cost price of a new working machine, €;
P_{Mijq}	maximum power of working machine in kilowatts, at which $j = 1, 2...4$.

It must be mentioned that the above equations are valid only for the working machines whose productivity is expressed in working hours.

Table 1 is related to the table elements which are in the cells marked with grey colour. Thit is, for the first energy chain: E_{ij}, C_{ij}, G_{ij}, P_{ij} ($i = 1...4$, $j = 1$). The second energy chain is defined with E_{ij}, C_{ij}, G_{ij}, P_{ij} ($i = 1...3, 5, 7, 9, 11$, $j = 2$). The third energy chain is the one with: E_{ij}, C_{ij}, G_{ij}, P_{ij} ($i = 1...3, 5, 7, 9, 13$, $j = 3$). The fourth energy chain: E_{ij}, C_{ij}, G_{ij}, P_{ij} ($i = 1...3, 5, 7, 9, 13$, $j = 4$). Also, for the operation of a hydraulic crane for loading into trucks, a minimal average fuel consumption of a truck will be used (work in idle state). A truck, as an element of biomass supply chain used for transportation of either wood chips or timber, will differ slightly in terms of calculating the values E_{ij}, C_{ij}, G_{ij}, while for the calculation of P_{ij} value a previously defined equation will be used completely. The reason for that lies in the calculation of the truck fuel consumption per passed kilometres for an average defined load.

$$E_{ij}=\frac{\sum_{q=1}^{n_1}\frac{\rho_{Fij}\times Ftc_{ijq}\times l_{ij}}{1000}\times Hv_{ijq}}{\sum_{q=1}^{n_1}\frac{ehv_{0ijq}(100-w_{ijq})-(2.44w_{ijq})}{100}\times M_{tijq}\times 1\ 000} \tag{22}$$

$$C_{ij}=\frac{\sum_{q=1}^{n_1}Ftc_{ijq}\times l_{ij}\times \mathrm{c}_{ijq}}{\sum_{q=1}^{n_1}\frac{ehv_{0ijq}(100-w_{ijq})-(2.44w_{ijq})}{100}\times M_{tijq}\times 1\ 000} \tag{23}$$

$$G_{ij}=\frac{\left(\rho_{Fij}\times Hv_{ijq}\times\frac{e_{Fij}}{10^6}\right)\times\sum_{q=1}^{n_1}Ftc_{ijq}\times l_{ij}\times \mathrm{c}_{ijq}}{\sum_{q=1}^{n_1}\frac{ehv_{0ijq}(100-w_{ijq})-(2.44w_{ijq})}{100}\times M_{tijq}\times 1\ 000} \tag{24}$$

Where:

$\mathrm{F}tc_{ijq}$ specific fuel consumption of trucks, l/km;
l_{ij} transportation distance, km;
M_{tijq} maximum truck load, t.

It must be emphasized that the load of a truck for wood chips is different from the load of a truck for timber transportation. If the analysis of a truck, as an element for biomass transportation in an energy chain, is observed through the maximum volume it can transport, then the equations for the calculation of the heating value which they transport are given in the expressions (6, 7).

The fuel consumption of machines, which take part in the wood biomass supply chain, is mostly expressed in litres per hour. Also, the productivity of work of particular machines is given in the volume of biomass processed, attracted, collected or loaded by the machine in a time interval. To obtain some proper units of fuel consumption and productivity of different machines for wood biomass collecting, it is necessary to perform different measurements and explorations in the exploitation conditions (Krajnc 2011).

7.2 Primary mechanical wood processing

Mechanical wood processing implies the type of processing at which, in the first place, the shape and dimensions of wood are changed by using mechanical means (saws, knives, etc.). The residues generated in sawmills present a significant amount of wood biomass for the production of solid biofuels. Besides the main product at sawmills such as planks, lumber, different forms of semi products, wood residues generated from processing is less important. The energy in primary wood processing is collectively consumed per the volume unit of a final product. Thus, the mathematical functions (E_{ij}, C_{ij}, G_{ij}, P_{ij}) for a sawmill are as follows:

$$E_{ij}=r\times\frac{\frac{1}{\eta c_{el}}\times\left(\sum_{q=1}^{n_1}Fp_{ijq}\times t_{ijq}\times Ec_{ijq}\right)}{\frac{1}{3.6}\times\left(\sum_{q=1}^{n_1}\frac{ehv_{0ijq}(100-w_{ijq})-(2.44w_{ijq})}{100}\times\rho_{0ijq}\times\frac{10^4}{\left(100-w_{ijq}\right)\times\left(100+\alpha_{vijq}\right)}\times Fp_{ijq}\times t_{ijq}\times\left(SVF\right)_{ijq}\right)} \tag{25}$$

$$C_{\mathrm{ij}} = r \times \frac{\sum_{\mathrm{q=1}}^{\mathrm{n_1}} Fp_{\mathrm{ijq}} \times t_{\mathrm{ijq}} \times Ec_{\mathrm{ijq}} \times Ce_{\mathrm{ijq}}}{\frac{1}{3.6} \times \left(\sum_{\mathrm{q=1}}^{\mathrm{n_1}} \frac{ehv_{\mathrm{0ijq}}(100 - w_{\mathrm{ijq}}) - (2.44 w_{\mathrm{ijq}})}{100} \times \rho_{\mathrm{0ijq}} \times \frac{10^4}{\left(100 - w_{\mathrm{ijq}}\right) \times \left(100 + \alpha_{\mathrm{vijq}}\right)} \times Fp_{\mathrm{ijq}} \times t_{\mathrm{ijq}} \times \left(SVF\right)_{\mathrm{ijq}} \right)} \tag{26}$$

$$G_{\mathrm{ij}} = r \times \frac{e_{\mathrm{Fij}} \times \frac{\sum_{\mathrm{q=1}}^{\mathrm{n_1}} Fp_{\mathrm{ijq}} \times t_{\mathrm{ijq}} \times Ec_{\mathrm{ijq}}}{\eta c_{el}} \times \frac{3.6}{10^3}}{\frac{1}{3.6} \times \sum_{\mathrm{q=1}}^{\mathrm{n_1}} \left(\frac{ehv_{\mathrm{0ijq}}(100 - w_{\mathrm{ijq}}) - (2.44 w_{\mathrm{ijq}})}{100} \times \rho_{\mathrm{0ijq}} \times \frac{10^4}{\left(100 - w_{\mathrm{ijq}}\right) \times \left(100 + \alpha_{\mathrm{vijq}}\right)} \times Fp_{\mathrm{ijq}} \times t_{\mathrm{ijq}} \times \left(SVF\right)_{\mathrm{ijq}} \right)} \tag{27}$$

$$P_{\mathrm{ij}} = \frac{\sum_{\mathrm{q=1}}^{\mathrm{n_1}} I_{\mathrm{Mijq}}}{\sum_{\mathrm{q=1}}^{\mathrm{n_1}} P_{\mathrm{Mijq}}} \tag{28}$$

If we look at Table 1, the above defined functions correspond to the table elements marked with E_{ij}, C_{ij}, G_{ij}, P_{ij} ($i = 6$, $j = 2, 3, 4$) in the cells.

Where:

$Q = 1 \ldots n_1$	number of sawmills;
Fp_{ijq}	productivity (sawmill capacity), m^3/h;
Ec_{ijq}	specific consumption of electricity per a processed cubic metre kWh/m3 (20–30 kWh/m^3 soft and hard wood) (Danon et al. 2003);
t_{ijq}	working time of machine, h;
ηc_{el}	factor of efficiency of electricity production from a thermal power station (coal as a fuel, assumption);
R	factor of wood residues in primary processing, in the interval from 0.25 to 0.35 (soft and hard wood without bark) (Danon et al. 2003);
$w_{\mathrm{ijq}} \geq 30\%$	wood moisture, %;
ρ_{0ijq}	wood density, kg/m^3;
α_{vijq}	percentage of wood swelling, %;
$\left(SVF\right)_{\mathrm{ijq}} = 1$	fulfilment factor of volume (timber);
Ce_{ijq}	price of a kWh of electricity;
e_{Fij}	coefficient of CO_2 emission for coal in kilograms of CO_2 per a gigajoule of the fuel heating value, kg CO_2/GJ;
I_{Mijq}	cost price of a machine for wood cutting and primary processing, €;
P_{Mijq}	maximum power of cutting machine in kilowatts kW.

It must be emphasized that it has been assumed that the sawmill consumes the electricity produced in a thermal power station. The factor $\eta c_{\mathrm{el}} = 0,36$ takes into account all the energy losses from the thermal power station to the motor, which drives the system for wood cutting. The factor of loss includes the losses in boiler, turbine, generator and electric supply network (Honorio et al. 2003). It must be emphasized that all energy losses are reduced to the primary form (heating value). In such a way, the opportunity of a simple summation of heating values equivalent to certain forms of energy consumption is obtained, regardless of whether thermal energy or electricity is in question. The equation 28 has been previously defined. In this case, the power of motor P_{Mijq} which drives the cutting system is taken for the sawmill, while the price of a plant for primary processing is taken as the cost price I_{Mijq}.

7.3 Plant for production of wood chips, drying, briquetting and pelleting

For the wood chips, briquettes or pellets production process, it is first necessary to chop the initial wood residues to a certain granulation, and then to dry them. If wood chips are produced, then the production line ends at machines for rough chopping of wood to certain granulation. When producing wood briquettes or pellets, after the rough chopping, the obtained wood chips are dried in rotary dryers, and then additionally fine-chopped, to be briquetted or pelleted later.

The mathematical functions (E_{ij}, C_{ij}, G_{ij}, P_{ij}) by which the production of wood chips, briquettes an pellets within a plant have been described, are related to electricity consumption due to the mechanical work of wood residue chopping. In this case, the following relations apply:

$$E_{ij}=\frac{\dfrac{1}{\eta c_{el}}\left(\sum\limits_{q=1}^{n_1}Pc_{ijq}\times\eta_t\times t_{ijq}\right)}{\dfrac{1}{3.6}\left(\sum\limits_{q=1}^{n_1}\dfrac{ehv_{0ijq}(100-w_{ijq})-(2.44w_{ijq})}{100}\times Fpc_{ijq}\times t_{ijq}\times 1000\right)} \tag{29}$$

$$C_{ij}=\frac{\sum\limits_{q=1}^{n_1}Pc_{ijq}\times\eta_t\times t_{ijq}\times Ce_{ijq}}{\dfrac{1}{3.6}\times\left(\sum\limits_{q=1}^{n_1}\dfrac{ehv_{0ijq}(100-w_{ijq})-(2.44w_{ijq})}{100}\times Fpc_{ijq}\times t_{ijq}\times 1000\right)} \tag{30}$$

$$G_{ij}=\frac{\dfrac{e_{Fij}\times 3.6}{\eta c_{el}\times 10^3}\times\left(\sum\limits_{q=1}^{n_1}Pc_{ijq}\times\eta_t\times t_{ijq}\right)}{\dfrac{1}{3.6}\times\sum\limits_{q=1}^{n_1}\left(\dfrac{ehv_{0ijq}(100-w_{ijq})-(2.44w_{ijq})}{100}\times Fpc_{ijq}\times t_{ijq}\times 1000\right)} \tag{31}$$

$$P_{ij}=\frac{\sum\limits_{q=1}^{n_1}I_{Mijq}}{\sum\limits_{q=1}^{n_1}P_{Mijq}} \tag{32}$$

For the elements of Table 1, which are in the cells denoted with E_{ij}, C_{ij}, G_{ij}, P_{ij} to which an ordered set of counters corresponds ($i=10$, $j=2, 3, 4$), ($i=12$, $j=3, 4$), the above mathematical formulations apply. It should be emphasized again that the electricity for driving a plant has been produced from a thermal power station. Of course, this does not have to be the case. If, it is assumed, for example, that the drive of a plant has used the electricity obtained from a hydroelectric power station, then the CO_2 emission factor is equal to zero for the plant.

In the equations (29, 30, 31, 32), the following values are introduced:

$q=1...n_1$ number of sawmills;

Pc_{ijq} electrical power of the plant, kW;

η_t simultaneity factor of the operation of all electric motors in the plant (0.7–0.95), which depends on whether the plant has an installed electric power compensation system or not;

t_{ijq} working time of machine in hours, h;

Fpc_{ijq} output productivity of the plant, t/h;

Ce_{ijq} price of 1 kWh of electricity;

$\eta c_{el}=0{,}36$ takes into account all the energy losses from the thermal power station to the electricity user in a factory;

e_{Fij} coefficient of CO_2 emission for coal in kilograms of CO_2 per a gigajoule of the fuel heating value, kg CO_2/GJ.

In the case of wood chip production plants, and pelleting and briquetting plants, the total installed electric power P_{Mijq} in the plant is taken into account, while the price of the plant installation is taken as the cost price I_{Mijq}.

The output moisture value of wet wood chips can vary significantly depending on the input moisture of wood to be chopped, and is usually in the interval from 30 to 50%. Pellets and briquettes have a prescribed moisture value, between 9 and 12%. It can be concluded that the difference in production plants of wood chips, pellets ad briquettes is seen only in the installed power of a plant, productivity, and in the electric power compensation factor.

The mathematical functions (E_{ij}, C_{ij}, G_{ij}, P_{ij}), which describe the drying of chopped material before briquetting or pelleting, are as follows:

$$E_{ij}=\frac{\dfrac{1}{3.6\times\eta_b\times\eta_d}\left(\sum_{q=1}^{n_1}\left(\dfrac{w_{1ijq}-w_{ijq}}{100-w_{ijq}}\right)\times M_{ijq}\times t_{ijq}\times L_e\right)}{\dfrac{1}{3.6}\left(\sum_{q=1}^{n_1}\dfrac{ehv_{0ijq}(100-w_{ijq})-(2.44w_{ijq})}{100}\times M_{ijq}\times t_{ijq}\times\left(\dfrac{100-w_{1ijq}}{100-w_{ijq}}\right)\right)} \tag{33}$$

$$C_{ij}=\frac{\dfrac{1}{3.6\times\eta_d}\left(\sum_{q=1}^{n_1}\left(\dfrac{w_{1ijq}-w_{ijq}}{100-w_{ijq}}\right)\times M_{ijq}\times t_{ijq}\times L_e\right)\times Ch_{ijq}}{\dfrac{1}{3.6}\left(\sum_{q=1}^{n_1}\dfrac{ehv_{0ijq}(100-w_{ijq})-(2.44w_{ijq})}{100}\times M_{ijq}\times t_{ijq}\times\left(\dfrac{100-w_{1ijq}}{100-w_{ijq}}\right)\right)} \tag{34}$$

$$G_{ij}=\frac{\dfrac{e_{Fij}}{\eta_b\times\eta_d\times10^3}\left(\sum_{q=1}^{n_1}\left(\dfrac{w_{1ijq}-w_{ijq}}{100-w_{ijq}}\right)M_{ijq}\times t_{ijq}\times L_e\right)}{\dfrac{1}{3.6}\left(\sum_{q=1}^{n_1}\dfrac{ehv_{0ijq}(100-w_{ijq})-(2.44w_{ijq})}{100}\times M_{ijq}\times t_{ijq}\times\left(\dfrac{100-w_{1ijq}}{100-w_{ijq}}\right)\right)} \tag{35}$$

$$P_{ij}=\frac{\sum_{q=1}^{n_1}I_{Mijq}}{\sum_{q=1}^{n_1}P_{Mijq}} \tag{36}$$

For the elements in Table 1, which are in the cells denoted with E_{ij}, C_{ij}, G_{ij}, P_{ij} to which an ordered set of counters corresponds ($i = 11$, $j = 3, 4$), ($i = 12$, $j = 3, 4$), the above mathematical formulations for the dryer apply. In pelleting and briquetting plants, multi pass rotary dryers are used. Due to the complexity of the mathematical model of the rotary dryer for sawdust drying, this paper presents a simplified approach to the calculation of needed thermal energy for chopped wood residue drying. It is assumed that for the evaporation of every kilogram of water from a wet material, it is necessary to invest the amount of heat equal to the latent heat of evaporation increased by the coefficient of losses in the dryer. Also, the reduction of heat energy consumed for drying to primary energy has been done via the coefficients of losses in the boiler which supplies the dryer. The following parameters are used in the equations (33, 34, 35, 36):

$Q = 1...n_1$ is the number of dryers;
M_{ijq} input capacity of raw material, m^3/h;
t_{ijq} dryer operation time, h;
w_{1ijq} moisture of material at the entrance of the dryer (0…1);
w_{1ijq} moisture of material at the exit of the dryer (0…1);
$L_e = 2.27$ latent heat of evaporation for water (Perrot, 1998), MJ/kg;
$\eta_b \approx 0.9$ boiler efficiency (Honorio et al. 2003);
η_d rotary dryer efficiency, usually within the limits from 0.4 to 0.6 (Devki Energy Consultancy, 2006);
Ch_{ijq} price of 1 kWh of thermal energy, €/kWh;
e_{Fij} coefficient of CO_2 emission for different fuels in kilograms of CO_2 per a gigajoule of the fuel heating value, kg CO_2/GJ.

If wood biomass is used in the boiler for producing drying heat, then the CO_2 emission is equal to zero. In this paper, the data from a real pellet production plant »Enterprise for making of wood packaging and production of eco-briquettes – pellets EU PAL factory Pale« has been used for defining particular mathematical functions and logistic concept.

8. Conclusion and further research directions

The significance of energy production from biomass has been increasingly expressed in recent times. Basically, the most significant part in the process of energy production from biomass is the supply chain. If we succeed in performing the minimization of production costs, significant savings occur, especially in terms of energy. Due to the fact that there are various opportunities for the composition of energy chains of supply with wood biomass solid fuels, it is necessary to try to make a unique mathematical approach to this problem. With the mathematical model, it is possible to unify different types and a great number of parameters. This is exactly the main issue when dealing with wood biomass supply chain. This paper contains a synthesis of a few approaches to solving the problem of wood biomass solid fuels supply, such as:

⇒ approach to logical composition of energy chains based on wood biomass,
⇒ approach of multi-criteria optimization for the selection of optimum variant of an energy chain,
⇒ approach of mathematical modelling of energy chain elements based on wood biomass,
⇒ approach of reduction of all the types of consumed energies to the primary value of energy (heating value).

The above mentioned approaches 2 and 4 are especially important. For the selection of the optimum variant of an energy chain of supply, VIKOR method has been selected, as it was completely adjusted to the given problem. For the adopted criteria (K_1, K_2, K_3, K_4), an equal degree of importance has been taken at the selection of the optimum variant of an energy chain for biomass fuel supply. The approach of reduction to primary energy form has enabled a mathematical estimation of the total energy consumed for the production of particular types of wood fuels. With this approach, the consumed thermal energy and electricity could be summed. For model testing and specific numerical calculations for the selection of the optimum variant of an energy chain of supply, it is necessary to provide good input data, and based on them to verify the model and check its practical applicability. At the same time, it presents a new research direction. Also, efforts will be made to develop a significantly greater number of mathematical functions of energy chain elements, which have not been described in this paper. The developed mathematical apparatus and model have a very practical application in the selection of the optimal variant of solid biofuels production from wood biomass for the defined conditions. As this paper contains many equations and mathematical descriptions, we did not show the numerical calculation and verification model. However, the next paper in this journal will present all results and discussion with more interesting conclusions.

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Received: June 12, 2014
Accepted: August 20, 2014