Chapter 9

Energy Chains Optimization for Selection of Sustainable Energy Supply

Srđan Vasković, Petar Gvero, Vlado Medaković and
Velid Halilović

Additional information is available at the end of the chapter

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Abstract

The notion of energy chain concept has been defined as the trajectory of energy transformations from the fuel source or energy sources to useful energy form to end users. Production of fuels, heat and electricity from different sources is defined by the appropriate energy supply chain. Every single energy supply chain can be uniquely defined by several sustainability criteria. These criteria are: total energy efficiency of production, total exergy efficiency of overall chain, the coefficient of exergy quality for different products at energy chains, economy of production, investment and environmental criteria. Optimal energy supply chain can be chosen by using multicriteria optimization which fulfils the above-mentioned sustainability criteria. This selected energy chain is close to ideal solution. The ideal energy supply chain is formed from the set of energy production ways which are defined from the perspective of sustainability criteria and which have connection with the current status of technologies, economic, environmental parameters, etc. The concept of optimization in practice is usually based on economics until recently, often neglecting all the other consequences of such a decision. Therefore, multicriteria decision making (MCDM) improves the opportunities in assessing the optimal variant of energy chain for defined ranking criteria. Before the optimization process, it is necessary to create a mathematical model for calculation of optimization criteria. Also, for each specific case of energy production, it is necessary to develop appropriate mathematical formulas to describe the energy chain. Numerical verification, all mathematical calculations and modelling have been applied and confirmed on wood biomass supply chain for energy production in this case. The reason for this is complexity of supply chains in the bioenergy and representation of renewable energy sources. For total ranking of energy chain for production of fuel or energy and selection of optimum variant, the multicriteria optimization and VIKOR method were applied. The significance of energy production from renewable energy sources is particularly expressed nowadays. Basically, the most significant part in the process of energy production from energy sources is the

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supply chain, final conversion of energy in useful form at the energy plant and the distribution process to end users. Due to the fact that there are various opportunities for the composition of energy chains of fuel supply and different ways of energy production, it is necessary to try to make a unique mathematical approach for this problem. With the proposed sustainability criteria and developed mathematical model, it is possible to unify the overall problem of energy supply chains' optimization. The proposed developed method can be used for the optimization of any kind of energy supply chains (electricity, heat, fuels or their mix). All of these are enabled by proper selection criteria for the description of overall energy transformations in energy chains and quality evaluation of the energy produced. The developed approach and mathematical model have a very practical application in the selection of optimal variant of energy production and of course in designing new energy chains.

Keywords: energy supply chains, optimization, exergy, mathematical modelling, optimization criteria, biomass, bioenergy, renewable energy

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1. Introduction

The process of energy and fuel production is closely related to sustainability. The use of fossil fuels causes harmful influences to the environment, while, on the other hand, the reserves of fossil fuels are limited. With the development of human civilizations, the needs for energy grow, which causes an accelerated consumption of fossil fuel reserves. The decrease of fossil fuel reserves and their harmful influences to the environment have forced the mankind to take the direction of the more intensive use of renewable energy sources as well. Observed from a thermodynamic aspect, for the analysis of an energy production process, it is necessary to evaluate the process both in terms of quantity and quality. For that reason, energy and exergy efficiencies of an energy production process were defined, and they have to be taken into account. The energy production chains can be defined in different ways, and in most cases the logistics of the fuel supply has a significant role. The selection of optimal variant of energy production presents a process that has to take into account a set of the most significant factors and criteria, which can be adequately used for the description of energy production chains. From the set of different energy production chains described by optimization criteria, it is possible to select the variant of energy production which is optimal for some particular case, based on the current state of development of energy production technology, economic and ecological parameters. The optimal variant of energy production selected in this way is not completely sustainable, but it presents a way and a path by which we get closer to a sustainable energy chain of energy production. It is obviously the best approach method for optimization of energy chains in the multicriteria decision making, which solves the selection problem of an optimal energy production. In this text, there is a description of multicriteria optimization application and the VIKOR method for the selection of optimal and sustainable energy supply process.

2. Concept of multicriteria decision making

Not long ago, the concept of optimization was based mostly on the economic criteria, while the other consequences of such a solution were often neglected.. It was thought that the increase in financial profit not only leads to the progress and general welfare of the society, but also to the satisfaction of all human needs. The accompanying effects of this concept, such as the deterioration of quality of water and air, and the pollution of environment in general, bad social influences, etc., undoubtedly indicate a wrong basis of such a model. Because of that, a new, still dominating, concept has been created, of the so-called sustainable development, that is, of such a development which is in harmony with the environment, corresponding to modern technical standards, economically and socially acceptable from the viewpoint of social disturbances that it may cause. So, such an approach enables the fulfilment of the present generation's needs, without disturbing the opportunity of other generations to meet their needs too. There is no unique and generally accepted definition of the notion of sustainable development. The most often stated definition of sustainable development is the one given by the United Nations World Commission on Environment and Development (the so-called Brundtland Commission) in its report with the title "Our Common Future". The definition is: "Sustainable development is the kind of development that meets the needs of the present without compromising the ability of future generations to meet their own needs too." For that reason, the need for searching an optimal solution in many criteria has been created, thus initiating the appearance of a new branch in the field of optimization, that is, of optimal decision making—multicriteria optimization—as a tool for assistance in the process of multicriteria decision making (MCDM). In the United States, multicriteria analysis is also often called MCDM, and in Europe, it is called multicriteria decision aid (MCDA) [1]. MCDM is a complex process of finding a solution, and it occurs at a few phases and a few levels of decision making. There are different methods of MCDM, and most of them belong to the category of discrete methods. In discrete methods, the problem of decision making is defined through finite number of options. In this paper, the MCDM methods are divided into [2]:

- Basic methods—The simplest forms of the MCDM method, and it is difficult to apply them in solving the optimization of energy chains due to the inadequacy of their simple preferential models.

- One-criterion approach—The methods where all the criteria are reduced to one criterion for comparison. The following methods belong to this group: MAUT, TOPSIS, SMART, AHP, etc. These methods belong to the American school of MCDM.

- Outranking methods—The methods where the alternatives are compared, and the preferences of one in relation to the other are identified. They include: NAIDE, ELECTRE, PROMETHEE, etc. These methods belong to the European school of MCDM.

- Target method, or the referent point method—This method identifies the options closest to the ideal one and the furthest from the anti-ideal point. These methods include the target and compromise programming, the VIKOR method.

- Fuzzy set theory—This uses the approach of imprecise and insecure information. It is used as a means which can be applied to any MCDM methodology, and not exclusively as a specific MCDM methodology.

The application of multicriteria optimization and decision making may have a significant role in the selection of technological, economical, more efficient and ecological criteria, and of many other criteria of acceptable solutions. This method also provides a good opportunity of application in the selection of optimal variants of energy production from biomass and the quality analysis of energy chains. Energy production from biomass is, by its nature, multidimensional and complex, with many available sources of biomass, technical possibilities and a diverse set of interested parties which have a multitude of opposed opinions. To develop and run a successful option of biomass utilization for energy purposes, there are many requirements which should be taken into account and met. Scott and associates have provided an overview of those academic papers which try to deal with the problems occurring within the bioenergy sector, by using the MCDM. These methods are especially appropriate for bioenergy production, if its multidimensional nature is taken into account as well, but they can also be equally relevant for other energy conversion technologies. The related articles which occur in international journals from 2000 to 2010 have been collected and analysed in such a way that the answers to the following two questions can be given: (1) which methods are the most popular ones? (2) what problems attract the highest attention? The overview discovers that the optimization methods are the most popular ones among the methods where the selection has been made within a small number of alternatives, and, as such, used in 44% of analysed papers, and among the methods where the selection has been made within many alternatives, they have been used in 28% of papers. The most popular application area of MCDM is in the selection of technologies, with 27% of analysed papers, while the application of MCDM to the decision-making policy participates with 18% [3].

3. Reasons for the application of multicriteria optimization in the selection of optimal energy supply chain

Generally, multicriteria optimization presents the finding of the variant (in our case, of an energy chain, a defined way of energy production), which will, in many ways, meet the required solution closest to the ideal one. The multicriteria optimization method occurred exactly from the striving towards a sustainable concept of the development of mankind. Because of that, the chosen methodology for the selection of optimal variant of energy production from biomass is good enough for the solving of this problem. The reason for that is more than simple. Biomass presents a renewable energy source and is an important part in the chain of sustainability. In the overviewed literature, a few papers have been found in which the VIKOR optimization method has been used. However, the real reason why this method is potentially good in solving the problem of selection of an optimal chain of the energy production from biomass is the possibility of different criterion weights definition and weights in decision-making strategies. Besides that, for all the obtained solutions, it is possible to check their stability mathematically as well, that is, whether they will be good enough if some parameters are given a greater importance in the optimization than others. Of course, the forming of the criterion matrix gives a systematic overview of all characteristics of the observed energy chains, among which the best option has been selected. In this way, the universal concept is formed, which can give many answers on the design, installation and exploitation of the systems for energy production from biomass in a much more comprehensive sense.

4. Definition criteria for evaluation of biomass supply chain and approach to the optimal variant of energy production

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 present a mathematical model for itself, as an elementary part of the energy chain. In literature, many studies have focused on techno-economic assessment to evaluate the economic feasibility of forest biomass utilization for the generation of heat [4], power [5], combined heat and power [6], and biofuel, heat and power [7]. The previous studies have compared alternative process technologies that use forest biomass to produce electricity [8] and alternative products that can be generated from a specific forest biomass base [9, 10]. Also, it is possible to minimize the cumulative fossil energy demand or the consumption of certain types of critical resources (e.g., labour, materials) associated with the unit of biofuel products, in order to achieve the maximum utilization of available resources [11]. For the most economic objectives, we often try to optimize the total quantity, that is, maximize total profit or minimize total cost. However, for environmental criteria, the “environmental impact per functional unit” is more critical [12]. This is because, for example, one may care more about the carbon footprint of producing one gallon of biomass-derived gasoline, rather than the annual total CO_2 emission of the entire biofuel supply chain. Therefore, the environmental impact evaluated based on functional unit is, in fact, the indicator of how “green” the supply chain is. All these studies did not find the optimal design of the forest biomass supply chain under analysis. Especially for conditions of optimization, this includes several different criteria such as technical, logistics, energetic, economic or environmental factors. This is a good direction for the development of the criteria for optimization of energy chains. The approach to the modelling of all 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 installed power of all energy consumers in the chain. Almost all the important elements of an energy chain for biofuel and energy production can be defined by the criteria $f_{1j}, f_{2j}, f_{3j}, f_{4j}, f_{5j}, f_{6j}$. The calculation of all the criteria functions is different for each of the chain variants (a_1, a_2, a_3 … a_n). But we have similar approach to the analysis of a single element of the chain. Well-defined criteria describe the overall energy chain based on biomass completely. For this reason, it is necessary to properly select the set of criteria which would have given a better assessment of the value chain of biomass energy. The following criteria must be defined:

- energy efficiency of observed chain; criteria function noted as f_{1j};
- exergy efficiency of chain; criteria function noted as f_{2j};
- the coefficient of exergy quality for different products at energy chains f_{3j};
- specific investment cost per total installed power of all machines and plants in the energy chain, €/kW; criteria function, f_{4j};
- production cost of energy chain per 1 kWh of the lower heating value of produced biofuels or energy, €/kWh; criteria function, f_{5j};
- CO_2 emission in the total chain due to the fossil fuels consumption for 1 kWh of the lower heating value of produced biofuel or energy, kg/kWh; criteria function, f_{6j}.

As we know, lower calorific value (or lower heating value, LHV) of a fuel portion is defined as the amount of heat evolved when a unit weight (or volume in the case of gaseous fuels) of the fuel is completely burnt and one part of that heat is used for water evaporation with the combustion products [13]. That is the main reason why we defined the previous criteria with lower heat value of fuels. It is the useful heat energy given in combustion process from chemical energy stored in all fuels and of course in biomass. The mentioned criteria are different for differently defined initial conditions of a problem. Solution to the problem of selecting the optimum variant of fuels and energy production consists of:

- Mathematical model for calculation of optimization criteria;
- Mathematical method for the selection of optimum variant of energy chain.

The significance of energy chains 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 [14]. To be able to evaluate the total energy consumption in an energy chain for fuel production at all, it is necessary to calculate all the consumed energies to the primary energy form. Primary energy is the content of energy in fuel related to lower heating value and weight of fuel. In that way, the total summation of all the consumed energy amounts in the energy chain of fuel/energy production is enabled. The principle of calculation of primary energy is defined by Equation 1 (see Figure 1):

$$\mathrm{LHV}_{\mathrm{fuel}} = \frac{\text{Output energy or work}}{\mu_1 \cdot \mu_2 \cdots \mu_n} \tag{1}$$

where $\mathrm{LHV}_{\mathrm{fuel}}$ (kWh) is the primary energy related to lower heating value of fuel, $\mu_{1} \ldots \mu_{n}$ are different coefficients of energy transformation. For example, overall energy efficiency for conventional power plants with pulverized coal firing has efficiencies as follows: 39–47%—steam turbine coal-fired power plant [15].

4.1. Function of energy efficiency for energy chain f_{1j}

Energy efficiency for the qth element of chain and jth energy chain of production is the ratio between the obtained energy and the energy consumed in the process of energy production in dimensionless unit, kWh/kWh. The value which is the ratio between the lower calorific value of the fuel consumption or any kind of energy (expressed in the form of primary energy, see Equation 1) and lower heating value of biomass processed in every single operation is important in the first part of the energy chain defined for biomass fuel production depending on the energy plant [16]. This approach to calculating efficiency involves the productivity of machines and equipment for processing of biomass, as well as defined energy and fuel consumption from certain processes (elements) in the energy supply chain [17]. All consumed energy is defined as primary energy in LHV fuel (see Figure 2).

Total energy efficiency factor of the energy chain including power plants, transmission losses in the network, as well as all levels of energy transformation is defined by

$$f_{1j} = \left(1 - \sum_{k=1}^{q} \frac{e_{ckj}}{e_{pkj}}\right) \cdot \mu_{bj} \cdot \mu_{ej} \cdot \mu_{tj} \cdot \mu_{gj} \cdot \mu_{dj} \cdots \mu_{end,usej}\,, \tag{2}$$

where e_{cqj} is the primary energy consumed in one element of the bioenergy chain, expressed in kWh; e_{pqj} is lower heating value of processed biomass in one element of the chain, expressed

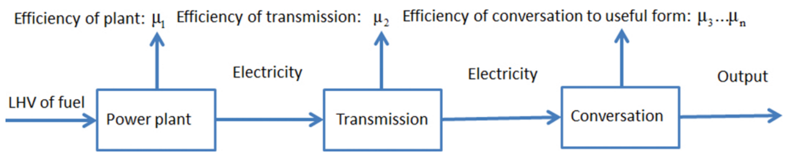

Figure 1. Principle of calculation of primary energy.

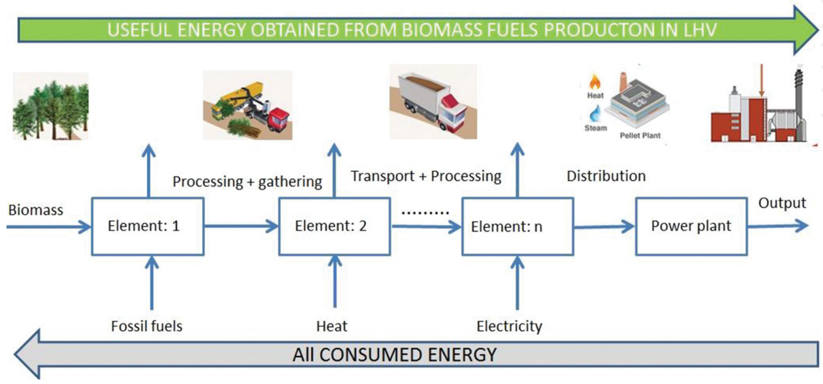

Figure 2. Part of supply chain for biofuels production up to power plant.

in kWh; *k* is the counter of elements in the energy chain; and *q* is the total number of elements in the energy chain; $\mu_{bj} \cdot \mu_{ej} \cdot \mu_{tj} \cdot \mu_{gj} \cdot \mu_{dj} \cdot \cdot \cdot \mu_{end,usej}$ are the factors of energy efficiencies for boilers, heat exchangers, turbines, generators, distribution, end users, etc. [15].

4.2. Function of exergy efficiency for overall energy chain f_{2j}

Different ways of formulating exergy efficiency (effectiveness, or rational efficiency) for various energy systems are given by Cornelissen [18]. The exergy performance of the system can be evaluated by means of the exergy efficiency. Two expressions of the exergy efficiency are often used in literature, the simple and the rational exergy efficiency [19, 20]. Their mathematical expressions are given in Equation 3.

$$\mu_{exsimple} = \frac{E_{xout}}{E_{xin}}, \mu_{exrat} = \frac{E_{xdes,out}}{E_{xin}}, E_{xin} = E_{xout} + I \tag{3}$$

where $\mu_{exsimple}$ is simple exergy efficiency, E_{xout} is total exergy output, E_{xin} is total exergy input, μ_{exrat} is rational exergy efficiency, $E_{xdes,out}$ is desired output exergy. The irreversibility of the process or exergy loss, *I*, is defined as the difference between desired exergy outputs E_{Xout} and the required exergy inputs E_{Xin} to it [20]. When we talk about the exergy efficiency of the entire bioenergy chain (from the source of biomass to the end user), then the individual exergy efficiency of single chain elements must be taken into account (see Figure 2). The total exergy efficiency of the energy chain is

$$f_{2j} = \left(1 - \sum_{k=1}^{q} \frac{e_{xckj}}{e_{xpkj}}\right) \cdot \mu_{exbj} \cdot \mu_{exej} \cdot \mu_{extj} \cdot \mu_{exgj} \cdot \mu_{exdj} \cdots \mu_{ex,end,usej}{}' \tag{4}$$

where e_{xckj} is exergy consumed in one element of chain, expressed in kWh; e_{xpkj} is exergy stored in the produced fuel, in kWh; *k* is the counter of elements in energy chain; *q* is the total number of elements in the energy chain; $\mu_{exbj} \cdot \mu_{exej} \cdot \mu_{extj} \cdot \mu_{exgj} \cdot \mu_{exdj} \cdot \cdot \cdot \mu_{ex,end,usej}$ are factors of exergy efficiencies for boilers, heat exchangers, turbines, generators, distribution, end users, etc. For more information about energy and exergy efficiencies of selected processes, see [21]. Energy and exergy analyses for three different cogeneration systems (steam cogeneration, gas-turbine cogeneration and diesel-engine cogeneration were performed by Kaushik [22]. It should be noted that the first part of the supply chain relates to the production of fuels from biomass; exergetic efficiency of this part of the chain is approximately equal to the energy efficiency. The main reason for this is a constant chemical exergy of biomass. There are cases when it comes to the occurrence of chemical exergy destruction, such as pyrolysis and gasification of biomass. Then it is needed to calculate the exergy efficiency of these processes.

4.3. The coefficient of exergy quality for different products at energy chains f_{3j}

Various forms of energy have different qualities. There are different basic energy forms: kinetic energy, potential energy, thermal energy, chemical energy, electrical energy, electromagnetic energy, sound energy and nuclear energy. It is said that energy can be "useful" if it can be entirely transformed by an ideal system (i.e., without losses) into any other type of energy. Useful energy, otherwise known as exergy, only represents a part of energy. Electrical and mechanical energies are "high quality" forms of energy; their exergy index is 100%, since exergy is equal to energy. Table 1 provides an overview of the coefficients of exergy quality for different energy forms:

Coefficients f_{3j}	Electricity	Fuel	Heat
	$E_j = 1$ kWh	$F_j = 1\text{kWh} \cdot \mu_{exp}$	$H_j = 1\ \text{kWh} \cdot \left(1 - \frac{T_0}{T}\right)$

Table 1. Coefficients of exergy quality.

where μ_{exp} is exergy efficiency for the production of electricity from different types of fuels from defined technology [21]; T_0 is environment temperature (K); T is temperature of heat reservoir (K); E_j, F_j and H_j are coefficients of exergy quality for electricity, fuel and heat, respectively. Also, we can define the combined coefficient of exergy quality as

$$f_{3j} = E_j \cdot e_j + F_j \cdot f_j + H_j \cdot h_j, \tag{5}$$

where $e_j + f_j + h_j = 1$, e_j, f_j, h_j are percentages of simultaneous production of electricity, fuel and heat at the energy chain.

The main difference between the quality factor of energy form (q) and coefficient of exergy quality (f_{3j}) is only that exergy quality factor takes into account the degree of conversion of chemical exergy into electricity. This factor provides a comparison of fuel and electricity.

4.4. Function of specific investment cost for energy chain f_{4j}

Engineers and investors typically interpreted and measured the performance of energy systems based on economic value such as investment and production costs. The most widely used economic performance metrics for comparing the economic value energy systems are net present value, total life cycle cost, rate of return, benefit–cost ratio and payback period. The economic principles and applications of these techniques are discussed in numerous standard engineering economics analyses and engineering economy texts [23, 24]. For energy chains, there are more elements included in their composition. Specific investment cost in the energy chain is the ratio between the total investment cost and the total installed power of all the elements in the chain:

$$f_{4j} = \frac{\sum_{k=1}^{q} I_{kj}}{\sum_{k=1}^{q} P_{kj}}, \tag{6}$$

where $\sum_{k=1}^{q} I_{kj}$ is the sum of all investment in the elements of energy chain [€]; $\sum_{k=1}^{q} P_{kj}$ is the sum of all installed power in the energy chain (kW, MW); q is the number of elements in the energy chain; k is the counter for the number of elements in the energy chain; j is the number of energy chains. If in the energy chain there are elements whose function cannot be expressed in units of €/ kW, it is necessary to bring these elements in similar correlations. For example, if the storage for biomass exists, then I_{kj} is certain value of investment in storage and P_{kj} (installed power) is equal to zero.

4.5. Function of specific production cost for energy chain f_{5j}

Investments are defined as the sum of all incurred expenses until plant operation reaches readiness, while operating costs occur during operation and depend on capacity utilization [25]. The production costs (operating and maintenance) were calculated by dividing the total annual costs as a fixed and variable, with the net generating capacity and net annual generation respectively, electricity and district heat or fuels. For electricity-generating technologies, including combined heat and power generation, the denominators are electric capacity and electricity generation. For heat-only technologies, the denominators are heat-generating capacity and heat generation. Often, the reference documents do not distinguish between fixed and variable production costs. Then the total production costs are expressed, typically in €/MWh or €/kWh. Function of total production costs f_{5j} for bioenergy plants is

$$f_{5j} = \frac{\left(\sum_{k=1}^{q}\left(\mathrm{Op}_{kj} + \mathrm{Mp}_{kj}\right) + \mathrm{Cr}_j\right)\cdot t}{\mathrm{Ep}\left(\mathrm{fuel/heat/electricity}\right)_j \cdot t}, \left[€/\mathrm{kWh}, €/\mathrm{MWh}\right], \tag{7}$$

where $(\mathrm{Op}_{kj} + \mathrm{Mp}_{kj})$ is the sum of all operating and maintenance costs in all elements of energy chain per year (€/h); Cr_j is the cost of biomass raw material (€/h); $\mathrm{Ep(fuel/heat/electricity)}_j$ is the productivity of different energy forms per chain (kWh/year, MWh/h). Operating and maintenance costs also include labour costs per kWh of energy produced.

4.6. Function of specific CO_2 emission for energy chain f_{6j}

A trend in GHG emissions from fossil fuel combustion illustrates the need for all countries to increase the use of more sustainable energy in future. The emission of GHG of particular species is often monitored because of the adverse environmental consequences that can cause photochemical smog, acid rain, global warming and ozone depletion. The details of, and standard methods used to measure, global warming potentials (GWPs) are defined by the IPCC [26]. For measurement of an energy system's environmental performance, the results are expressed through a mass of carbon dioxide equivalent emission per unit of desired output (e.g., kg-CO_2-eq./kWh elec.). The following equation can be used for the estimation of greenhouse gas emissions from the combustion of each type of fuel per energy chain [27]:

$$f_{6j} = \frac{\left(\sum_{k=1}^{q} \frac{m_{kj} \cdot ec_{kj} \cdot e_{fkj}}{3.6} \right) \cdot t}{Ep\left(\text{fuel / heat / electricity}\right)_j \cdot t}, \tag{8}$$

where m_{kj} is the quantity of fuel type consumption in one element of energy chain (kg/h); ec_{kj} is the energy content factor of the fuel according to each fuel (kWh/kg); e_{fkj} is the emission factor for each gas type (in our case CO_2) for different fuel types according to each fuel (kWh/kg) [28];Ep(fuel/heat/electricity)$_j$ is productivity of different energy forms for each chain per hour (kWh/h, MWh/h).

5. Mathematical model for the selection of optimum variant of energy chain for energy production from wood biomass

In this paper, for the actual problem of selection optimum variant of energy chain, VIKOR optimization method is applied as a proposal and as an adequate method for the solution of multicriteria optimization related to the selection of optimal energy chain of production. This method aims to collect all the most important factors which describe energy supply chains from biomass and make the selection of optimal supply chain. The VIKOR method (multicriteria compromise ranking) has been developed for the determination of a multicriteria optimal solution. The VIKOR method has been developed on such a methodological basis that a decision-maker is suggested as the alternative (or solution) to present a compromise between wishes and opportunities, the different interests of the decision-making participants. The VIKOR method has been developed for a multicriteria optimization of complex systems. It is focused on ranking and selection of the best solution from the given set of alternatives, with conflicting criteria [29]. 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, a general form of the problem has been set (evaluation matrix) for the specific case. The matrix of criterion functions for all variants of the production of fuels or energy from biomass is of $6 \times n$ dimensions (6 criteria and n alternatives of energy production from biomass), obtained from the calculation of different cases of energy chains' composition:

$$F = \begin{array}{c} \\ f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \end{array} \begin{array}{c} \begin{array}{ccccc} a_1 & a_2 & a_3 & \cdots & a_n \end{array} \\ \begin{bmatrix} f_{11} & f_{12} & f_{13} & \cdots & f_{1n} \\ f_{21} & f_{22} & f_{23} & \cdots & f_{2n} \\ f_{31} & f_{32} & f_{33} & \cdots & f_{3n} \\ f_{41} & f_{42} & f_{43} & \cdots & f_{4n} \\ f_{51} & f_{52} & f_{53} & \cdots & f_{5n} \\ f_{61} & f_{62} & f_{63} & & f_{6n} \end{bmatrix} \end{array} \tag{9}$$

where $\{a_1, a_2, a_3 \ldots a_n\}$, $j = n$ are a finite set of possible alternatives for the n energy chains of production; $\{f_1, f_2, f_3, f_4, f_5, f_6\}$, $i = 6$ are a finite set of criterion functions for five defined and adopted criteria on the basis of which the chains of energy production from biomass are analysed; $\{f_{11}, f_{12} \ldots f_{6n}\}$ are the set of all the criterion functions' values in matrix F. An ideal solution is determined on the basis of the criterion functions' values from the equation [29]:

$$f_i = \underset{j}{\mathrm{ext}}\, f_{ij}, \; i = 1, 2, \ldots, 6. \tag{10}$$

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 or other variables which are of interest to optimize (minimization or maximization criterion functions). This is the best way to define an ideal solution for energy production from different energy chains based on biomass. The criterion functions within the matrix F are commonly not expressed in the same measurement units (i.e., the belonging criterion space is heterogeneous). For that reason, in order to perform use of multicriteria optimization, it is necessary to convert all the criterion functions into dimensionless functions whose values will be in the interval [0, 1]. This process is called the normalization of dimensional units in the area of multicriteria mathematics. Firstly, the best values of criterion functions are determined. In our case, those are the maximum values of first three criterion functions (energy and exergy efficiency, the coefficient of exergy quality for different products at energy chains) and minimum values of the other three criterion functions (minimization of CO_2 emission per 1 kWh energy produced, production cost per 1 kWh energy produced and specific investment cost per kilowatt installed in the production chain). Then we have mathematically [29]

$$\begin{aligned} &\max f_1\left(f_{1j}\right) = f_1^*, \quad \max f_2\left(f_{2j}\right) = f_2^*, \quad \max f_3\left(f_{3j}\right) = f_3^*, \\ &\min f_4\left(f_{4j}\right) = f_4^*, \quad \min f_5\left(f_{5j}\right) = f_5^*, \quad \min f_6\left(f_{6j}\right) = f_6^*. \end{aligned} \tag{11}$$

In the same way, the worst values of the criterion functions can be determined, which are obtained by the same criterion functions [29]:

$$\begin{aligned} &\min f_1\left(f_{1j}\right) = f_1^-, \quad \min f_2\left(f_{2j}\right) = f_2^-, \quad \min f_3\left(f_{3j}\right) = f_3^- \\ &\max f_4\left(f_{4j}\right) = f_4^-, \quad \max f_5\left(f_{5j}\right) = f_5^-, \quad \max f_6\left(f_{6j}\right) = f_6^-. \end{aligned} \tag{12}$$

Then all the elements of the matrix *f* are converted in the value domain [0, 1]. This is achieved by the following formula [29]:

$$d_{ij} = \frac{f^* - f_{ij}}{f_i^* - f_i^-}, \text{and a matrix is formed, in the form } D = \left[d_{ij}\right], \text{ for } i = 1,\ldots 6 \text{ and } j = 1,\ldots n. \tag{13}$$

Considering the difference $f_i^* - f_i^-$ in the expression for d_{ij} it is necessary for all elements of the matrix *D* to be of the values in the interval (0, 1). The values of criterion functions are obtained by maximization or minimization of criterion functions. The criterion weights for the specific problem related to ranking variants of energy chains, for the six main criteria defined are mutually equal. The reason for this is very simple, because we strive for the minimal CO_2 emission quantities, production cost and specific investment cost per totally installed power in the energy chain. Also, at the same time, the aim is maximization of energy efficiency and exergy efficiency and quality of energy forms. All criteria functions have equal weight and importance. Due to that, it will be valid that the criterion weights are

$$w_1 = w_2 = w_3 = w_4 = w_5 = w_6 = w_j = \frac{1}{6}. \tag{14}$$

After that, the values of the elements of matrices S_j and R_j were calculated. Considering the equality of the criterion weights, they are obtained as [29]:

$$\begin{aligned} S_{j=1\ldots n} &= w_j \cdot \sum_{i=1}^{6} d_{ij} = \frac{1}{6} \cdot \sum_{i=1}^{6} d_{ij} = \left[\frac{1}{6} \cdot \sum_{i=1}^{6} d_{i1}, \frac{1}{6} \cdot \sum_{i=1}^{6} d_{i2}, \frac{1}{6} \cdot \sum_{i=1}^{6} d_{ij}, \ldots \frac{1}{6} \cdot \sum_{i=1}^{6} d_{in}\right], \\ R_{j=1\ldots n} &= w_j \times \max_i \left[d_{ij}\right] = \left[\frac{d_{i1}\max}{6}, \frac{d_{i2}\max}{6}, \frac{d_{ij}\max}{6}, \ldots \frac{d_{in}\max}{6}\right]. \end{aligned} \tag{15}$$

In this way, the problem is reduced from a multicriteria space to a two-criterion problem. The values of minimal and maximal elements are determined from the matrices S_j and R_j [29].

$$S^* = \min_j S_j, S^- = \max_j S_j, R^* = \min_j R_j, R^- = \max_j R_j. \tag{16}$$

The decision strategy weight will be taken as $\upsilon = 0, 6$. This is valid for the criterion number $m = 6$ [29]. For the other case and number criterion m [29], we have

$$\upsilon = \begin{cases} 0.5, & m \leq 4 \\ 0.6, & 5 \leq m \leq 10. \\ 0.7, & m \geq 10 \end{cases} \tag{17}$$

On the basis of that, it is possible to calculate the value of the matrix q_j pursuant to the equation [29]:

$$q_j = \upsilon \cdot \frac{\left(S_j - S^*\right)}{S^- - S^*} + \left(1 - \upsilon\right) \frac{R_j - R^*}{R^- - R^*}. \tag{18}$$

A certain value of q_j corresponds to every chain in the following matrix [29]:

$$\begin{array}{ccccc} & CH_1 & CH_2 & CH_j & CH_n \\ Q_j = \Big[& q_1; & q_2; & q_j; & q_n \Big] \end{array} Q^* = \min_j Q_j \tag{19}$$

The optimum variant of production is defined by the minimal value. The ranking of alternatives is formed from the lowest value of q_j to the highest value of q_j, which is from the best to the worst variant. In our case, the alternatives are the mentioned energy chains for fuels and energy production from biomass [29].

5.1. Acceptable advantage and stability of the selected variant of optimal energy chain on the basis of the VIKOR method

In the cases when values of criterion weights are different and some criteria are given a greater importance in relation to the others, the stability of the obtained optimal solution should be checked on the basis of the VIKOR method. The alternative (a') is suggested as a compromise solution, which is the highest ranked value on the Q measure (matrix). Then, two conditions have to be met:

(1) *Acceptable advantage*

$$Q\left(a''\right) - -Q\left(a'\right) \geq DQ \tag{20}$$

where a'' is the second-position alternative on the rank list (Q); $DQ = 1/(m - 1)$ advantage threshold, where m is the number of alternatives (energy chains).

(2) *Acceptable stability*

The alternative *a′* should also be ranked as the best in *S* and/or *R* rank (matrix). In that case, the solution has been selected correctly [29].

6. Enclosure of specific mathematical functions for elements in wood biomass supply chain

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 were analysed from the energy aspect in this paper, in the text that follows, mathematical descriptions will be given for the particular elements of an energy chain pursuant to the previously adopted concept for the calculation of functions for the elements in supply chain [16].

6.1. Biomass collection machines in a supply chain

Biomass collection machines are the first elements in a chain 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 were 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 volume unit per hour (m^3/h), the following relations were adopted to Equations 2–8 [16]:

$$f_{1j} = \frac{\sum_{q=1}^{n_1} \frac{\rho_{Fjq} \cdot Fc_{jq} \cdot t_{jq}}{1\ 000} \cdot Hv_{jq}}{\sum_{q=1}^{n_1} \frac{ehv_{0jq}(100 - w_{jq}) - (2.44 w_{jq})}{100} \cdot \rho_{0jq} \cdot \frac{10^4}{\left(100 - w_{jq}\right) \cdot \left(100 + \alpha_{vjq}\right)} \cdot Pr_{jq} \cdot t_{jq} \cdot \left(SVF\right)_{jq}} \tag{21}$$

$$f_{5j} = \frac{\sum_{q=1}^{n_1} Fc_{jq} \cdot t_{jq} \cdot c_{jq}}{\sum_{q=1}^{n_1} \frac{ehv_{0jq}(100 - w_{jq}) - (2.44 w_{jq})}{100} \cdot \rho_{0jq} \cdot \frac{10^4}{\left(100 - w_{jq}\right) \cdot \left(100 + \alpha_{vjq}\right)} \cdot Pr_{jq} \cdot t_{jq} \cdot \left(SVF\right)_{jq}} \tag{22}$$

$$f_{6j} = \frac{\left(\rho_{Fjq} \cdot Hv_{jq} \cdot \frac{e_{Fjq}}{10^6}\right) \cdot \sum_{q=1}^{n_1} Fc_{jq} \cdot t_{jq}}{\sum_{q=1}^{n_1} \frac{ehv_{0jq}(100 - w_{jq}) - (2.44 w_{jq})}{100} \cdot \rho_{0jq} \cdot \frac{10^4}{\left(100 - w_{jq}\right) \cdot \left(100 + \alpha_{vjq}\right)} \cdot Pr_{jq} \cdot t_{jq} \cdot \left(SVF\right)_{jq}} \tag{23}$$

$$f_{4j} = \frac{\sum_{q=1}^{n_1} I_{Mjq}}{\sum_{q=1}^{n_1} P_{Mjq}} \tag{24}$$

where $q = 1 \ldots n_1$ is the number of machines included in the work; Fc_{jq} is specific fuel consumption of the observed working machine, l/h; Pr_{jq} is productivity of the working machine, m^3/h; t_{jq} is working time of machine, h; Hv_{jq} is lower heating value of fuel (gasoline or oil, depending on the fuel type the machine uses), MJ/kg; $w_{jq} \geq 30\%$ wood moisture, %; $\rho 0_{jq}$ is wood density, kg/m^3; α_{vjq} is the percentage of wood swelling, %; $(SVF)_{jq}$ is fulfilment factor of volume $(0 \ldots 1)$; c_{jq} is the price of a litre of fuel (gasoline or oil); ρ_{Fjq} is the density of fuel at atmospheric conditions, kg/m^3; e_{Fjq} is coefficient of CO_2 emission for different fuels in kilograms of CO_2 per gigajoule of the fuel heating value, kg CO_2/GJ; I_{Mjq} is the cost price of a new working machine, €; P_{Mjq} is the maximal power of working machine in kilowatts, in which $j = 1, 2 \ldots n$.

It must be mentioned that the previously written equations are valid only for the working machines whose productivity is expressed in working hours [16]. Calculation defined criteria for trucks:

$$f_{1j} = \frac{\sum_{q=1}^{n_1} \frac{\rho_{Fjq} \cdot \mathrm{Ftc}_{jq} \cdot l_{jq}}{1\,000} \cdot \mathrm{Hv}_{jq}}{\sum_{q=1}^{n_1} \frac{\mathrm{ehv}_{0jq}\left(100 - w_{jq}\right) - \left(2.44 w_{jq}\right)}{100} \cdot M_{tjq} \cdot 1000} \tag{25}$$

$$f_{5j} = \frac{\sum_{q=1}^{n_1} \mathrm{Ftc}_{jq} \cdot l_{jq} \cdot c_{jq}}{\sum_{q=1}^{n_1} \frac{\mathrm{ehv}_{0jq}\left(100 - w_{jq}\right) - \left(2.44 w_{jq}\right)}{100} \cdot M_{tjq} \cdot 1000} \tag{26}$$

$$f_{6j} = \frac{\left(\rho_{Fjq} \cdot \mathrm{Hv}_{jq} \cdot \frac{e_{Fjq}}{10^6}\right) \cdot \sum_{q=1}^{n_1} \mathrm{Ftc}_{jq} \cdot l_{jq} \cdot c_{jq}}{\sum_{q=1}^{n_1} \frac{\mathrm{ehv}_{0jq}\left(100 - w_{jq}\right) - \left(2.44 w_{jq}\right)}{100} \cdot M_{tjq} \cdot 1000} \tag{27}$$

where Ftc_{jq} is specific fuel consumption in trucks, l/km; l_{jq} is transportation distance, km; M_{tjq} is maximal 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. The fuel consumption of machines which take part in the wood biomass supply chain is mostly expressed in litres per hour. Also, the working productivity of particular machines is given in the volume amount of biomass processed, attracted, collected or loaded by the machine in a time interval. In order 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 [17].

6.2. Biomass collection machines in a supply chain

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 which emanates in sawmills presents a significant amount of wood biomass for the production of solid biofuels. Besides the main products in sawmills, such as planks and lumbers, different forms of semi products, namely, the emanated wood residues, from processing are less important. The energy in primary wood processing is collectively consumed per volume unit of a final product. Thus, we have the following mathematical functions (f_{1j}, f_{5j}, f_{6j}, f_{4j}) for a sawmill [16]:

$$f_{1j} = r \cdot \frac{\dfrac{1}{\eta c_{el}} \cdot \left(\sum_{q=1}^{n_1} Fp_{jq} \cdot t_{jq} \cdot Ec_{jq} \right)}{\dfrac{1}{3.6} \cdot \left(\sum_{q=1}^{n_1} \dfrac{ehv_{0jq}(100 - w_{jq}) - (2.44\, w_{jq})}{100} \cdot \rho_{0jq} \cdot \dfrac{10^4}{(100 - w_{jq}) \cdot (100 + \alpha_{vjq})} \cdot Fp_{jq} \cdot t_{jq} \cdot (SVF)_{jq} \right)} \tag{28}$$

$$f_{5j} = r \cdot \frac{\dfrac{1}{\eta c_{el}} \cdot \left(\sum_{q=1}^{n_1} Fp_{jq} \cdot t_{jq} \cdot Ec_{jq} \cdot Ce_{jq} \right)}{\dfrac{1}{3.6} \cdot \left(\sum_{q=1}^{n_1} \dfrac{ehv_{0jq}(100 - w_{jq}) - (2.44\, w_{jq})}{100} \cdot \rho_{0jq} \cdot \dfrac{10^4}{(100 - w_{jq}) \cdot (100 + \alpha_{vjq})} \cdot Fp_{jq} \cdot t_{jq} \cdot (SVF)_{jq} \right)} \tag{29}$$

$$f_{6j} = r \cdot \frac{e_{Fj} \cdot \dfrac{\sum_{q=1}^{n_1} Fp_{jq} \cdot t_{jq} \cdot Ec_{jq}}{\eta c_{el}} \cdot \dfrac{3.6}{10^3}}{\dfrac{1}{3.6} \cdot \sum_{q=1}^{n_1} \left(\dfrac{ehv_{0jq}(100 - w_{jq}) - (2.44\, w_{jq})}{100} \cdot \rho_{0jq} \cdot \dfrac{10^4}{(100 - w_{jq}) \cdot (100 + \alpha_{vjq})} \cdot Fp_{jq} \cdot t_{jq} \cdot (SVF)_{jq} \right)} \tag{30}$$

where $q = 1 \ldots n_1$ is the number of sawmills; Fp_{jq} is productivity (sawmill capacity), m^3/h; Ec_{ijq} is specific consumption of electricity per cubic metre processed, kWh/m^3 (20–30 kWh/m^3 soft and hard wood) [30]; t_{ijq} is the working time of machine, h; ηc_{el} is the factor of efficiency of electricity production from a thermal power station (coal as a fuel, assumption); r is the factor of wood residue in primary processing, in the interval from 0.25 to 0.35 (soft and hard wood without bark) [30]; $w_{jq} \geq 30\%$ wood moisture, %; $\rho 0_{jq}$ is wood density, kg/m^3; α_{vjq} is percentage of wood swelling, %; $(SVF)_{jq} = 1$ is fulfilment factor of volume (timber); Ce_{jq} is the price of a kWh of electricity; e_{Fij} is coefficient of CO_2 emission for coal in kilograms of CO_2 per gigajoule of the fuel heating value, kg CO_2/GJ. It must be mentioned that it has been assumed that the sawmill consumes the electricity produced in a thermal power station. The factor ηc_{el}=0, 36 takes into account all the energy losses from the thermal power station to the motor which drives the system for woodcutting. The factor of loss includes the losses in boiler, turbine, generator and electric supply network [15]. It must be emphasized that all energy losses are reduced to the primary energy 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 thermal energy or electricity in question. Considering Equation 24, it has been previously defined. In this case, the power of motor P_{Mjq} 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_{Mjq}.

6.3. Plant for production of wood chips, drying, briquetting and pelleting

For the wood chips, briquettes or pellets production process, it is, as first, necessary to chop the initial wood residue to a certain granulation, and then dry it. If a wood chip is produced, then the production line ends with machines for rough chopping of wood to certain granulation. If we want to produce a wood briquette or pellet after rough chopping, the obtained wood chips are dried in rotary dryers, and then are additionally fine-chopped, to be briquetted or pelleted later. The mathematical functions ($f_{1j}, f_{5j}, f_{6j}, f_{4j}$) by which the production of wood chips, briquettes and pellets within a plant have been described are related to electricity consumption due to the mechanical work of chopping of wood residue. Thus, we have the following relations [16]:

$$f_{1j}=\frac{\dfrac{1}{\eta c_{el}}\left(\sum_{q=1}^{n_1}Pc_{jq}\cdot\eta_t\cdot t_{jq}\right)}{\dfrac{1}{3.6}\left(\sum_{q=1}^{n_1}\dfrac{ehv_{0jq}\left(100-w_{jq}\right)-\left(2.44w_{jq}\right)}{100}\cdot Fpc_{jq}\cdot t_{jq}\cdot 1\,000\right)} \tag{31}$$

$$f_{5j}=\frac{\sum_{q=1}^{n_1}Pc_{jq}\cdot\eta_t\cdot t_{jq}\cdot Ce_{jq}}{\dfrac{1}{3.6}\cdot\left(\sum_{q=1}^{n_1}\dfrac{ehv_{0jq}(100-w_{jq})-(2.44w_{jq})}{100}\cdot Fpc_{jq}\cdot t_{jq}\cdot 1\,000\right)} \tag{32}$$

$$f_{6j}=\frac{\dfrac{e_{Fjq}\cdot 3.6}{\eta c_{el}\cdot 10^3}\cdot\left(\sum_{q=1}^{n_1}Pc_{jq}\cdot\eta_t\cdot t_{jq}\right)}{\dfrac{1}{3.6}\cdot\sum_{q=1}^{n_1}\left(\dfrac{ehv_{0jq}(100-w_{jq})-(2.44w_{jq})}{100}\cdot Fpc_{jq}\cdot t_{jq}\cdot 1\,000\right)} \tag{33}$$

It will be emphasized again that the electricity for driving a plant has been produced from a thermal power station. Of course, that should not be a 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 Equations 31–33, we have the following values introduced: $q = 1 \ldots n_1$ is the number of plants; Pc_{jq} is the electrical power of the plant, kW; η_t is the 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_{jq} is the working time of machine in hours, h; Fpc_{jq} is the output productivity of the plant, t/h; Ce_{jq} is the price of 1 kWh of electricity; ηc_{el}=0, 36 takes into account all the energy losses from the thermal power station to the electricity user in a factory; e_{Fjq} is the coefficient of CO_2 emission for coal in kilograms of CO_2 per gigajoule of the fuel heating value, kg CO_2/GJ. In the case of wood chips production plants, pelleting and briquetting plants, the total installed electric power in the plant is taken as P_{Mjq}, while the price of the plant installation is taken as the cost price I_{Mjq}.

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%. In pellets and briquettes, there is a prescribed moisture value, between 9 and 12%. It can be concluded that the differences in wood chips, pellets and briquettes in production plants are seen only in the installed power of a plant, productivity, and in the electric power compensation factor.The mathematical functions (f_{1j}, f_{5j}, f_{6j}, f_{4j}) which describe the drying of chopped material before briquetting or pelleting process are the following ones [16]:

$$f_{1j}=\frac{\dfrac{1}{3.6\cdot\eta_b\cdot\eta_d}\left(\sum_{q=1}^{n_1}\left(\dfrac{w_{1jq}-w_{jq}}{100-w_{jq}}\right)\cdot M_{jq}\cdot t_{jq}\cdot L_e\right)}{\dfrac{1}{3.6}\left(\sum_{q=1}^{n_1}\dfrac{ehv_{0jq}(100-w_{jq})-(2.44w_{jq})}{100}\cdot M_{jq}\cdot t_{jq}\cdot\left(\dfrac{100-w_{1jq}}{100-w_{jq}}\right)\right)} \tag{34}$$

$$f_{5j}=\frac{\dfrac{1}{3.6\cdot\eta_d}\left(\sum_{q=1}^{n_1}\left(\dfrac{w_{1jq}-w_{jq}}{100-w_{jq}}\right)\cdot M_{jq}\cdot t_{jq}\cdot L_e\right)\cdot Ch_{jq}}{\dfrac{1}{3.6}\left(\sum_{q=1}^{n_1}\dfrac{ehv_{0jq}(100-w_{jq})-(2.44w_{jq})}{100}\cdot M_{jq}\cdot t_{jq}\cdot\left(\dfrac{100-w_{1jq}}{100-w_{jq}}\right)\right)} \tag{35}$$

$$f_{6j}=\frac{\dfrac{e_{Fjq}}{\eta_b\cdot\eta_d\cdot 10^3}\left(\sum_{q=1}^{n_1}\left(\dfrac{w_{1jq}-w_{jq}}{100-w_{jq}}\right)M_{jq}\cdot t_{jq}\cdot L_e\right)}{\dfrac{1}{3.6}\left(\sum_{q=1}^{n_1}\dfrac{ehv_{0jq}(100-w_{jq})-(2.44w_{jq})}{100}\cdot M_{jq}\cdot t_{jq}\cdot\left(\dfrac{100-w_{1jq}}{100-w_{jq}}\right)\right)} \tag{36}$$

In pelleting and briquetting plants, multipass 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 the thermal energy needed for drying chopped wood residue. 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 through the coefficients of losses in the boiler which supplies the dryer. We have the following parameters used in Equations 34–36: $q = 1 \ldots n_1$ is the number of dryers; M_{jq} is the input capacity of raw materials, m^3/h; t_{jq} is the dryer operation time, h; $w_{1\mathrm{jq}}$ is the moisture of the material at the entrance of the dryer (0 … 1); w_{jq} is the moisture of the material at the exit of the dryer (0 … 1); $L_{\mathrm{e}} = 2.44$ is the latent heat of evaporation for water [31], MJ/kg; $\eta_{\mathrm{b}} \approx 0.9$ is boiler efficiency [15]; η_{d} is rotary dryer efficiency, usually within the limits from 0.4 to 0.6 [32]; Ch_{jq} is the price of 1 kWh of thermal energy, €/kWh; e_{Fjq} is the coefficient of CO_2 emission for different fuels, in kilograms of CO_2 per gigajoule of the fuel heating value, kg CO_2/GJ. If wood biomass is used in the boiler for drying heat production, 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, Bosnia and Herzegovina" has been used for defining particular mathematical functions and logistic concept.

7. Model testing results in the case of the selection of optimal chain of energy and fuel supply from biomass

For the analysis and selection of an optimal chain of the production of electricity, fuel and thermal energy, three energy chains have been taken into account: CHP (combined heat and power) facility with the ORC process, pellet production and hot water boiler. All the facilities and processes are real, and the necessary data used for calculation are real and present the current state in the use of biomass for energy purposes in the Republic of Srpska and Bosnia and Herzegovina. As a fuel supply chain for the CHP facility with the ORC process and hot water boiler, the chain of wood chips obtained by means of a mobile chipper has been used. Table 1 presents the optimization criteria calculated with the help of a model made using MathCAD software for the analysed energy production chains. For the input of data which describe the real state of solid fuels production (wood chips and pellet), the data from sawmills and companies in Republic of Srpska/Bosnia & Herzegovina have been used. The companies are as follows: "Company for making of wood packaging and production of eco briquettes–pellets, EU PAL L.L.C. Pale", sawmill "GOD" L.L.C. Han Pijesak, sawmill "MTK OMORIKA" L.L.C. Han Pijesak, company for transportation of timbering and assortments "KINGDOM" L.L.C. Han Pijesak, City heating plant in Prijedor. For an average fuel consumption and the specification of wood mechanization included in the production of wood fuels, the results from study [17] have been used. The production of pellet is determined by a chain consisting of saw, tractor, lifter, truck, fork lift, dryer and facility for pelleting. In the pellet production chain, there are two transportations: the transportation of timbers (60 km) and the transportation of wood residue to the pellet facility (30 km). The total distance is 90 km of transportation to the final product. The production of wood chips by mobile wood chipper is determined by the chain which consists of saw, skidder, mobile chipper and truck for the transportation of wood chips. The work of skidder in the forest is predicted on a short distance of 1 km. The transportation of wood chips is performed with a truck with the total truck body volume of 60 m^3 at the distance of 90 km. Other data related to the biomass fuel supply chain are: the price of a litre of gas/oil of 1€, the price of wood residue from the sawmill—0.0563 €/kWh, drying of wood residue from 50 to 12% for pellet production, wage of 12–15 €/day for workers and wage of 25 €/day for a truck driver. For the calculation of parameters from f_{1j} to f_{6j} which are related to the production of pellet and wood chips by means of a mobile chipper, the formulae (1) and (21–36) have been used.

Energy chain: production of heat and electricity, production of pellets, heat generation			
Description of energy chains	CHP with ORC process	Process of production of wood pellets	Hot water boiler
Moisture content in wood fuel	50%	50%	50%
Solid wood fuels:	Wood chips from mobile chipper, fir	Sawmill wood residue, fir	Wood chips from mobile chipper, fir
Energy and exergy efficiency of wood chips produced by mobile chipper	$f_2 = f_1 = 0.97$		$f_2 = f_1 = 0.97$
Criteria for the selection of optimal energy chain obtained from the model developed in Mathcad software			
Overall energy efficiency of chain	0.743	0.684	0.807
Overall exergy efficiency of chain	0.223	0.684	0.155
Coefficient of exergy quality	0.385	0.122	0.287
Total specific investment cost per total installed power in the energy chain, EUR/kW	3.149×10^3	5.263×10^3	1.235×10^4
Total specific production cost, EUR/kWh	0.044	22.37×10^{-3}	0.054
Total specific emissions of CO_2, kg/kWh	0.015	51.695×10^{-3}	0.018

Table 2. Basic parameters and results of model testing at the selection of optimal variant of the energy chain.

The data on the analysed technologies for the ORC process and hot water boiler have been taken from the documentation for the installation of these systems in the City District Heating Plant from Prijedor (Bosnia and Herzegovina) [33].

General information about CHP plant with ORC process, option 1:

$P_n = 5140$ kW, nominal power of thermo-oil boiler

$P_e = 1000 - 50 = 950$ kW, installed electric power of plant reduced by own consumption

$P_t = 4095 - 400 = 3695$ kW, installed heat power of plant reduced by own consumption for drying fuel

$T = 353$ K, outlet temperature of water from CHP process to district heating grid

$T_0 = 273$ K, reference temperature of environment

$m_f = 2200$ kg/h, fuel consumption

$H_d = 9929$ kJ/kg, lower heating value of fuel for moisture content 43%

$I_M = 4083674.99$ €, total investment cost for plant

$P_M = 5095$ kW, total installed power of CHP plant

General information about wood pellet plant, option 2:

$\eta_{Cel} = 0.36$, the efficiency of electrical power generation from thermal power plants to the consumption

$F_{PC} = 2$ t/h, pellet plant productivity

$P_C = 500$ kW, total installed electrical power in pellet plant taken from real factory, EU Pale DOO

$eh_{V0} = 19.49$ MJ/kg, lower heating value of dry wood, fir

$w = 12\%$, moisture content

$\rho_0 = 450$ kg/m^3, density of dry wood, fir

$\alpha_v = 8\%$, the percentage of swelling for fir

$\eta_t = 0.8$, factor of simultaneity work of all electric drives in plant

$Ce = 0.09$ €/kWh, price of 1 kWh of industrial electrical energy

$e_f = 100$ kg CO$_2$/GJ, specific emission coefficient of CO$_2$ for stone coal

$I_M = 650{,}000$ €, total investment in pellet plant

$P_M = 1946$ kW, total installed power in pellet plant, heat + electrical power

General information about the hot water boiler, option 3:

$P_t = 10{,}000$ kW, output thermal power from heating plant

$T = 383$ K, outlet temperature of water from boiler

$T_0 = 273$ K, reference temperature of environment

$m_f = 5570$ kg/h, fuel consumption

$H_d = 7500$ kJ/kg, lower heating value of fuel for moisture content 50%

$I_M = 6{,}855{,}949$ €, total investment in boiler

$P_M = 10{,}000$ kW, thermal power of boiler

The calculation of criteria for the optimization of tested energy chains has been performed with the help of the formulae (2)–(6). For the selection of the optimal variant of energy chain, formulas (9)–(19) have been used. The check of stability and acceptability of the solution has been performed with the help of Equation 20.

Due to the optimization model at the comparison of incomplete energy chains and different qualities of energy production, the combined production of thermal energy and electricity in the facility with the ORC process has been obtained (the blue column in Table 2). This solution has both the necessary stability of the solution and the sufficient advantage in relation to the second-ranked variant. It is interesting to notice that pellet production is the second-ranked variant. It can be concluded from that that, under the conditions of testing with model, the advantage is given to pellet production in relation to heat production. However, for a complete valorization of the process, it is also necessary to take the process of pellet transportation into account. In that case, much clearer situation is obtained on this advantage of fuel production in relation to heat production. This case of model testing serves for the quality evaluation of different forms of energy (electricity, thermal energy and fuel). In that set, there are different and incomplete energy chains. Such analysis and optimization process are obtained by the factor of exergy quality (see Table 1 and Equation 5). Electricity has the highest factor of exergy quality, and it is equal to the number 1. All other values of this factor for heat and fuel are smaller than the number 1. In the analysed optimization process, at the selection of an optimal variant of energy chain, in the third case of the model testing, the factor of exergy quality for wood pellet fuel is equal to the exergy efficiency of electricity production in the ORC process, and is 0.122. Generally, if there had been several energy chains which produce electricity, either averaged values of this factor from several different technologies to be compared or the factor with the smallest value of transformation of fuel into electricity could be taken as a valid factor of exergy quality. The factor of exergy quality enables the reduction of energy production process per cumulative kilowatt hour of thermal energy and electricity. This effect has a large application in the evaluation of the production cost and specific emission of CO_2 reduced per cumulative kilowatt hour of thermal energy and electricity produced, 1 kWht+e. A conclusion can be made from this on the great significance of exergy-economic analysis of energy processes. All the data for the analysed technologies have been disclosed by the district heating plant in Prijedor.

8. Conclusions and discussion

Developed mathematical model described in this paper defines adequate universal criteria, which describe biomass energy chains and which are adapted to the process of multicriteria optimization. These criteria are related to total energy efficiency of a production chain, total exergy efficiency of a production chain, factor of exergy quality of different energy forms, total production cost per 1 kWh of energy produced, total investment cost per total installed power in an energy chain, total emission of fossil fuels consumed for the production of 1 kWh of fuel, heat or electricity. This approach combines the most significant specific criteria for the description of the entire chain of energy production and gives the possibility to compare the energy chains as well as selection of the optimal variant for the production of fuels and/or different forms of energy from biomass. The optimal variant is obtained on the basis of multicriteria optimization, by using the adapted VIKOR method. The verification of the developed mathematical method has been done on the application of energy and fuel supply from biomass. In the calculation part, three energy chains have been used for the verification of the concept, whose criteria for optimization are provided in Table l. These energy chains are the ORC process with combined production of thermal energy and electricity, the process of wood pellet production (solid fuel) and the process of thermal energy production by means of a hot water boiler, for district heating purposes. All three variants of energy chains produce different energy forms which have a different quality of output products. For that reason, such energy chains have been selected to demonstrate the universality of the model application to the analyses of other energy and fuel production processes as well. It should be noted that the exergy quality factor of produced energy allows comparison of different energy forms. The proposed criteria for optimization are closely related to technical–technological, thermodynamic, economic and ecological characteristics which describe energy chains. Of course, the physical basis of the proposed criteria for the optimization of energy chains is based on the concept of sustainability. Depending on the initial data on the basis of which the criteria for the optimization of energy chains are calculated, these criteria, at the same time, give the information on the current state of development at which the applied technologies and the ways of energy production are. From the set of different chains of energy production described with the suggested optimization criteria, it is possible to select the variant of energy production which is optimal. The selected optimal variant is, at the same time, the one closest to the sustainable way of production of energy and/or fuels in the observed set of defined energy chains. The developed mathematical model and the suggested concept have a large practical application in the selection of an optimal variant of production of biofuels and/or production of energy from biomass in defined real conditions. Besides that, the model can also be used in the process of designing and establishing of energy production chains, both from biomass and from some other sources. From the aspect of energy chains of energy production, the model is very universal and can be equally applied to any other energy supply chains.

Author details

Srđan Vasković[1*], Petar Gvero[2*], Vlado Medaković[1] and Velid Halilović[3]

*Address all correspondence to: srdjan_vaskovic@yahoo.com and gvero.petar@gmail.com

1 University of East Sarajevo, Faculty of Mechanical Engineering, East Sarajevo

2 University of Banja Luka, Faculty of Mechanical Engineering, Banja Luka

3 University of Sarajevo, Faculty of Forestry Engineering, Sarajevo, Bosnia and Herzegovina

References

[1] Vučijak B., 2007. Multicriteria optimization in space management, scientific contributions. Space, 33, 108–117.

[2] Mutikanga H.E., 2012. Water loss management: tools and methods for developing countries. Thesis, Delft University, Netherlands.

[3] Scott A., Ho W., Dey P.K., 2012. A review of multi-criteria decision-making methods for bioenergy systems. Energy, 42(1), 146–156.

[4] Chau J., Sowlati T., Sokhansanj S., Preto F., Melin S., Bi X., 2009. Techno-economic analysis of wood biomass boilers for the greenhouse. Applied Energy, 86(3), 365–371. doi: 10.1016/j.apenergy.2008.05.010.

[5] Kumar A., Flynn P., Sokhansanj S., 2008. Biopower generation from mountain pine infested wood in Canada: an economical opportunity for greenhouse gas mitigation. Renewable Energy, 33(6), 1354–1363. doi: 10.1016/j.renene.2007.07.008.

[6] Danon G., Furtula M., Mandić M., 2012. Possibilities of implementation of CHP (combined heat and power) in the wood industry in Serbia. Energy, 48(1), 169–176. doi: 10.1016/j.energy.2012.02.073.

[7] Ng K.S., Sadhukhan J., 2011. Techno-economic performance analysis of bio-oil based fischer-tropsch and CHP synthesis platform. Biomass and Bioenergy, 35(7), 3218–3234. doi: 10.1016/j.biombioe.2011.04.037.

[8] Bridgwater A.V., Toft A.J., Brammer J.G., 2002. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renewable and Sustainable Energy Reviews, 6(3), 181–246. doi: 10.1016/S1364-0321(01)00010-7.

[9] Kumar A., 2009. A conceptual comparison of bioenergy options for using mountain pine beetle infested wood in western Canada. Bioresource Technology, 100(1), 387–399. doi: 10.1016/j.biortech.2008.04.077.

[10] Sarkar S., Kumar A., Sultana A., 2011. Biofuels and biochemicals production from forest biomass in western Canada. Energy, 36(10), 6251–6262. doi: 10.1016/j.energy.2011.07.024.

[11] Althaus H.J., Bauer C., Doka G., Dones R., Frischknecht R., Hellweg S., Humbert S., Jungbluth N., Köllner T., Loerincik Y., Margni M., Nemecek T., 2010. Implementation of Life Cycle Impact Assessment Methods, St. Gallen, Swiss Centre for Life Cycle Inventories.

[12] Yue D., Kim M.A., You F., 2013. Design of sustainable product systems and supply chains with life cycle optimization based on functional unit: general modeling frame-

work, mixed-integer nonlinear programming algorithms and case study on hydrocarbon biofuels. ACS Sustainable Chemistry & Engineering, 1, 1003–1014.

[13] Librenti E., Ceotto E., Candello M., 2010. Biomass Characteristics and Energy Contents of Dedicated Lignocellulose Crops, Biomass and Waste 3, 7–8.

[14] Hall C., 2011. Introduction to special issue on new studies in EROI (Energy Return on Investment), Sustainability, 3(10), 1773–1777.

[15] Honorio L., Bartaire J., Bauerschmidt R., Ohman T., Tihany Z., Zeinhofer H., Scowcroft J., Vasco de Janerio K.H., Meier H., Offermann D., Lnagnickel U., 2003. Efficiency in electricity generation, Report drafted by Eurelectric "Preservation of resources", working groups "Upstream", Subgroup in collaboration with VGB.

[16] Vasković S., Halilović V., Gvero P., MedakovićV., MusićJ., 2015. Multi-criteria optimization concept for the selection of optimal solid fuels supply chain from wood biomass. Croatian Journal of Forest Engineering, 36(1), 123–129.

[17] Krajnc N., 2011. Wood Energy Technologies, Partnership Programmes—TCDC/TCC–TCP/YUG/3201 (D), Belgrade.

[18] Cornelissen R.L., 1997. Thermodynamics and sustainable development: the use of exergy analysis and the reduction of irreversibility. PhD thesis, University of Twente, The Netherlands.

[19] Torío H., Angelotti A., Schmidt D., 2009. Exergy analysis of renewable energy-based climatisation systems for buildings: a critical view. Energy and Buildings, 41, 248–271.

[20] Kotas T.J., 1985. The Exergy Method of Thermal Plant Analysis, Tiptree, Essex, Anchor Brendon Ltd.

[21] Acar B., 2008. An analysis on the utilization of energy and exergy in Turkey. Master thesis, Graduate School of Natural and Applied Sciences of Middle East Technical University.

[22] Kaushik S.C., Reddy V.S., Tyagi S.K., 2011. Energy and exergy analyses of thermal power plants: a review. Renewable and Sustainable Energy Reviews, 15, 1857–1872.

[23] Park C.S., Contemporary Engineering Economics, Fourth Edition, Prentice-Hall, 2007, New Jersey, USA, ISBN: 0131876287, 9780131876286.

[24] White J.A., Case K.E., Pratt D.B., 2009. Principles of Engineering Economic Analysis, Fourth Edition, John Wiley & Sons, Hoboken, New Jersey, USA.

[25] Geldermann J., Rentz O., 2004. The reference installation approach for the techno-economic assessment of emission abatement options and the determination of BAT according to IPPC-directive. Journal of Cleaner Production, 12, 389–402.

[26] IPCC Third Assessment Report: Climate Change, 2001. Technical report, Intergovernmental Panel on Climate Change, PUBLISHED BY THE PRESS SYNDICATE OF THE

UNIVERSITY OF CAMBRIDGE, The Pitt Building, Trumpington Street, Cambridge, United Kingdom, ISBN 0521 80767 0.

[27] NGA Factors, 2014. Australian National Greenhouse Accounts, Australian Government, Published by the Department of the Environment, Commonwealth of Australia, ISSN: 2202-333X.

[28] Herold A., 2003. Comparison of CO2 Emission Factors for Fuels Used in Greenhouse Gas Inventories and Consequences for Monitoring and Reporting under the EC Emissions Trading Scheme, ETC/ACC Technical Paper 2003/10, European Topic Centre on Air Pollution and Climate Change Mitigation, The Netherlands.

[29] Opricović S., 1998. Multicriteria Systems Optimization in Construction, Civil Engineering, University of Belgrade, Belgrade.

[30] Danon G., Bajić V., Isajev V., BajićS., Orešćanin S., Rončević S., 2003. Residues from wood biomass processing and possibilites for energy crops and forest, Chapter 2, in Energy Potential and Characteristics of Biomass Residues and Technologies for Application in Serbia, Belgrade, Faculty of Forestry, Public Company, Srbijašume, Institute for Poplars, pp. 25–26.

[31] Perrot P., 1998. A to Z of Thermodynamics, Published in the United States by Oxford University Press, Inc., New York, ISBN 0-19-856552-6.

[32] Devki Energy Consultancy Pvt. Ltd., 2006. Best Practice Manual “Drayers,”Indian Renewable Energy Development Agency, Vadodara, Ivory Terrace, New Delhi, India, 405 p.

[33] Grontmij A.B., 2014. Final Report: Heating Plant Prijedor–Feasibility Study, Contract Number EBDR C27868/SWME-2013-09-02, Financed by the Swedish Agency for International Development (Sida), Stockholm, Sweden., Enova Sarajevo d.o.o., Sarajevo.