Agronomy Research **12**(2), 455–468, 2014

Modelling of biomass cogeneration plant efficiency

G. Cimdina, I. Veidenbergs, A. Kamenders, J. Ziemele,
A. Blumberga and D. Blumberga*

[1]Institute of Energy Systems and Environment of the Riga Technical University, Kronvalda bulvaris 1, LV-1010, Riga, Latvia; e-mail: dagnija.blumberga@rtu.lv

Abstract. The paper presents the analysis of operation conditions of biomass cogeneration plant (CHP). The data set for analysis comprises the data measured on an hourly basis at the cogeneration plant in Jelgava. The volume of the data set is 467 modes. By means of statistical processing of the change in the plant's specific fuel consumption, by applying the methods of regression analysis, the most important factors describing the operation of the equipment or independent parameters were identified. The relationship between the change in the plant's specific fuel consumption and the parameters impacting it, is established by the regression equation obtained in data processing. According to the performed analysis: the change in the plant's specific fuel consumption is determined by the following four statistically important parameters: boiler efficiency; power generation efficiency; heat production efficiency indicators and outdoor temperature. The specific fuel consumption rate, calculated using regression equation, is compared to the specific fuel consumption rate observed in the CHP during operation. The assessment of the percentage difference shows that the specific fuel consumption rates calculated using the equation are useful in describing the plant data and can also be used to estimate future fuel consumption. It was observed that the rate difference is within the margins of 3.6 to 6.7 per cent.

Key words: specific wood chips consumption, cogeneration plant, power and heat generation efficiency indicators regression analysis.

INTRODUCTION

Reasons for analysis of operation mode of wood chips fueled combined heat and power generation plan (CHP) are different. For example, Pantaleo et al. (2014) presented the case study in order to evaluate the energy service companies (ESCO) approach for biomass heating. Sources of wood chips are several: produced from agricultural pruning residues, clean industrial and commercial wood waste, urban tree waste and forestry residues. There are legislative constraints on usage of biomass residues, environmental impact and potential impacts of poor fuel quality on equipment operation and control must be taken into consideration as well. It was found that the most influencing factors are the heat load rate, the investment cost, the baseline fossil fuel costs and baseline conversion efficiencies (that influence the thermal energy selling price under the selected 'shared savings' ESCO approach). The results of Pantaleo et al. (2014) showed that the use of biomass and wood chips in this particular case is highly profitable high heat load rates and high fossil fuel costs.

Wood chip fueled CHP is one of the most common biomass fired CHP technologies. James Keirstead et al. (2012) model of ‘eco town’ heating is based on State-Task Network (STN) and resource-technology network (RTN) approach. Two types of fuel were considered in modeling scenarios – forestry residues and wood chips from wood processing companies.

Analysis of operation mode is important in case of co-firing different fuels. A life cycle analysis for biomass co-firing with coal in CHP has been performed by Zuwała (2012). It was concluded that forest residues was better fuel for co-firing than willow wood chops in terms of life cycle GHG emissions.

Other analysis of operation of CHP: technical, economic and exergo – economic assessment of a combined heat and power (CHP) plant implementation in an animal feed industry with two possible fuels charcoal and wood chips the results are presented by Marcos Luiz de Macedo Rodrigues et al. (2013). They show that without selling electric power to the grid wood chips were economically non-feasible.

Transition from local, small scale community heating projects to city wide district heating based on cogeneration plant are analyzed by Karen N. Finney et al. (2013). Authors of that paper looked at two cities Barnsley and Sheffield each at different stage of networking, decentralization, city-wide energy deployment. It was found during the case studies that wood chip boiler had lover CO and NO emissions than coal and wood pellet boilers, the highest PM_{10} concentration O_2 percentage in similar operation mode. Karen N. Finney et al. (2013) wood chip boiler had lower effect to climate change than wood pellet boiler.

The literature review traces a wide range of issues related to the use of biomass, including: the uses of different sorts of biomass; economic and thermo-economic aspects of biomass usage; properties of co-burning; emission levels of gases and solid particles; as well as operational factors that influence consumption. The efficiency of cogeneration plants can be described by a specific fuel consumption rate, which is determined by relating the amount of fuel with the amount of generated energy. All the reviewed studies distinguish the dependency of the obtained data on a specific mode of operation. The article focuses on determining the essential factors of CHP operation, obtaining quantitative equations in order to determine woodchip consumption depending on operational factors.

METHODOLOGY FOR PROCESSING OF EMPIRIC DATA

Empirical data were processed by applying statistical methods for data processing: correlation and regression analysis. By means of correlation analysis, the mutual link and its strength between two variables is determined. Regression analysis is used to identify the statistical importance of the multi-factor regression model and its coefficients. The article evaluates the steps of implementing the correct regression analysis as described by Blasnik (1995).

The computer software STATGRAPHICS Plus was used for the statistical processing of data and development of the multi-factor empirical model.

Short description of the cogeneration plant and the data set for analysis

A simplified principal diagram of the Jeglava cogeneration plant is seen in Fig. 1.

The Jelgava cogeneration plant was commissioned in September 2013. Using woodchips as fuel (in the diagramme present as FUEL B), the plant produces electrical power by generator G of turbine, which is then fed into a network, and heat energy that is used for the heating supply of Jelgava. The chips are burnt in a fluid-bed boiler with a double air supply, generating overheated steam under the pressure of P_{1st} = 115 bars and temperature T_{1st} = 520°C. Chungen Yin et al. (2008) underline that fluidized bed boilers with two stage air supply is one of main competing technology in biomass combustion for combined heat and power production. The steam is used in a counter-pressure turbine. An important role is played by users of the heating system, who consume low-potential heat. The steam from the turbine and the low-pressure outlet is then used for preparing water for the two-step network in water heaters DH1 and DH_2. The network water with forward temperature T_1 is then fed into the heating system, where it is supplied to users, cooling the water in process to return temperature T_2. One of the essential energy parameters in the CHP is the correlation of two amounts of energy types. Usually, biomass plants generate 5 times less electrical power than heat. This is not the case at the Jelgava cogeneration plant. Thanks to high initial steam parameters as well as low-pressure steam use in covering the heat load, the plant has a high ratio of electricity against heat, $\alpha \approx 0.43$. The steam from turbine outlets is used for heating the boiler's water supply in low-pressure (LP) and high-pressure (HP) water supply heaters. Deaerator D plays role of degassing equipment and accumulation tank of boiler feed water. In order to ensure that the gas is rid of solid particles, the plant is equipped with an electric filter.

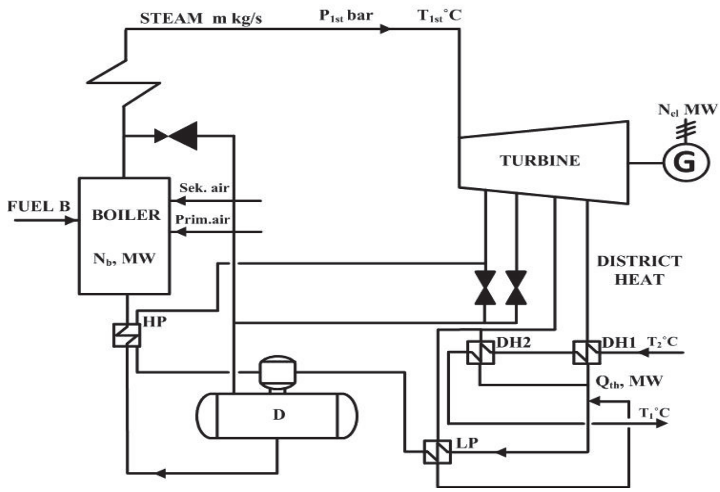

Figure 1. The principal technological diagram of the Jelgava cogeneration plant.

The data set for analysis comprises the data measured on an hourly basis at the cogeneration plant in Jelgava during the time period from 28 December 2013 to 23 January 2014. The volume of the data set is 467 modes, depending on the plant's heat and electric load.

The variables that were measured and used for analysis are as follows:

- Boiler capacity N_b, MW;
- Fuel consumption B, loose m^3 h^{-1};

- Heat load Q_{th}, MW;
- Flow of the network water G_{DH}, m^3 h^{-1};
- Forward temperature of the network water T_1, °C;
- Return temperature of the network water T_2, °C;
- Electrical capacity N_{el}, MW;
- Steam temperature at the inlet of the turbine T_{1st}, °C'
- Steam pressure before the turbine P_{1st}, bar;
- Steam flow in the turbine m_{st}, kg s^{-1};
- Outdoor temperature T_{out}, °C;

The relative variables describing the plant were identified on the basis of measured data:

- Specific fuel consumption of the plant - $b_{ch} = B/(Q_{th} + N_{el})$, loose m^3 MWh^{-1};
- Efficiency of heat production – Q_{th}/B, MWh/ loose m^3;
- Efficiency of power generation – N_{el}/B, MWh/ loose m^3;
- Efficiency of the boiler operation – N_b/B, MWh/ loose m^3;
- Ratio of the electrical and heat capacity of the plant $\alpha = N_{el}/Q_{th}$.

Correlation analysis of the data of the cogeneration plant

This chapter is aimed at establishing the linkage of parameters by means of performing the correlation analysis, in order to select the type of regression equation. In the article, the correlation analysis is considered to be a tool, which facilitates further regression analysis in order to render visible some useful connections between independent variables.

The strength of the mutual link of independent and dependent random variables (correlation) can be assessed by means of a correlation coefficient. In case of a single factor mathematic model, the Pearson's equation is used for its estimations:

$$r = \frac{\sum_{i=1}^{m}(x_i - x)(y_i - y)}{(m-1)S_x \cdot S_y}, \quad (1)$$

where: x_i, y_i – independent variables and pairs of corresponding dependent variables; x, y – mean arithmetic values of independent and dependent variables; S_x, S_y – selection dispersions of variables.

Correlation coefficients were used to evaluate the accuracy of mathematic models describing the strength of the correlation. It is assumed that a correlation is good if correlation coefficients equal 0.8; 0.9. It should be noted that in software for statistical data processing the squared correlation coefficient is usually calculated. When the value R^2 is multiplied by 100, the value (percentage) that characterises the changes of dependent variables described by the resulting empirical equation is obtained. For example, $R^2 = 0.9$ indicates that the relevant regression equation characterises 90% of the changes in dependent random variables.

In the present study, for the purpose of analysis of the operation of the plant, the correlation between the variable b_{ch} and independent variables is analysed.

The first correlation analysis is aimed at establishing whether there is a correlation between the dependent variable and the analysed independent variable describing the operation of the plant. The relationship between b_{ch} and the outdoor temperature T_{out} is presented as an example in Fig. 1.

However, the value of the correlation coefficient is low there is dispersion of data, leading to the conclusion that there is a considerable impact from other factors. The impact of other factors can be established by means of a multi-factor regression analysis.

Application of a multi-factor regression analysis is correct if there is no mutual correlation between independent variables. If there is such correlation the parameters will have to be excluded from the regression equation. The multi-factor regression analysis can be simplified by carrying out a single-factor correlation analysis of independent variables. Examples of this analysis are presented in Figs 2 and 3.

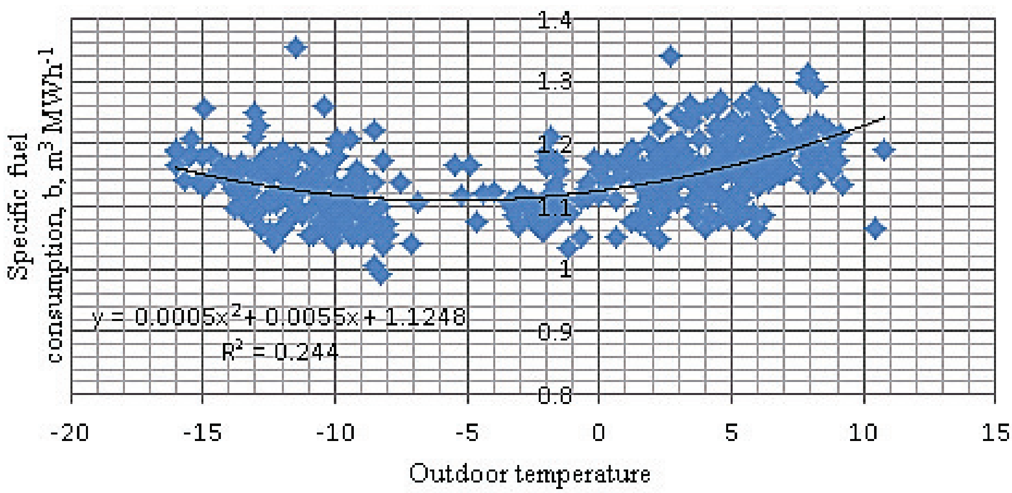

Figure 2. Change in specific fuel consumption depending on the outdoor temperature.

This figure shows a very good mutual correlation between both variables. The value of the squared correlation coefficient as determined by the analysis R^2 = 0.93. The relationship between the variables is non-linear and is defined by the following equation:

$$T_1 = 0.003 \cdot T_{out}^3 + 0.046 \cdot T_{out}^2 - 0.608 \cdot T_{out} + 48.87 \tag{2}$$

The equation (2) explains 94%of the analysed changes in the data and can be used for calculations. 6% of changes in the return temperature should be explained by the impact of other parameters. This means that the impact of other parameters is negligible. From the point of view of the regression analysis, returne water temperature cannot be included in the analysis.

The correlation analysis of the data demonstrates that there is a close correlation between power generation and heat production in cogeneration. The changes of values are presented in Fig. 3.

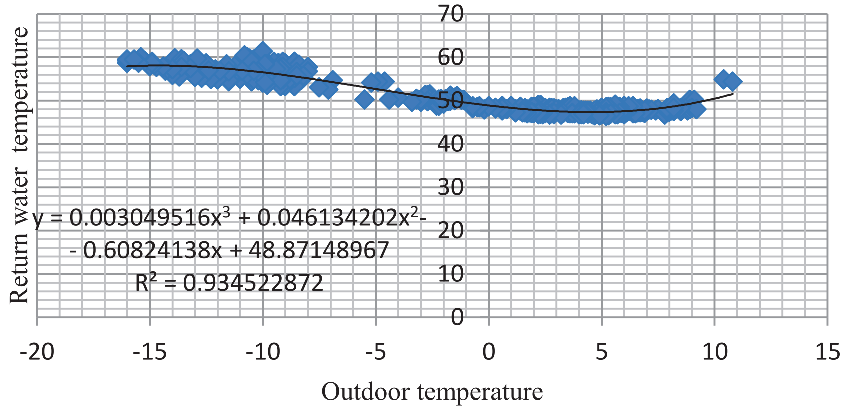

Figure 3. Change in return temperature of the heat network depending on the outdoor temperature.

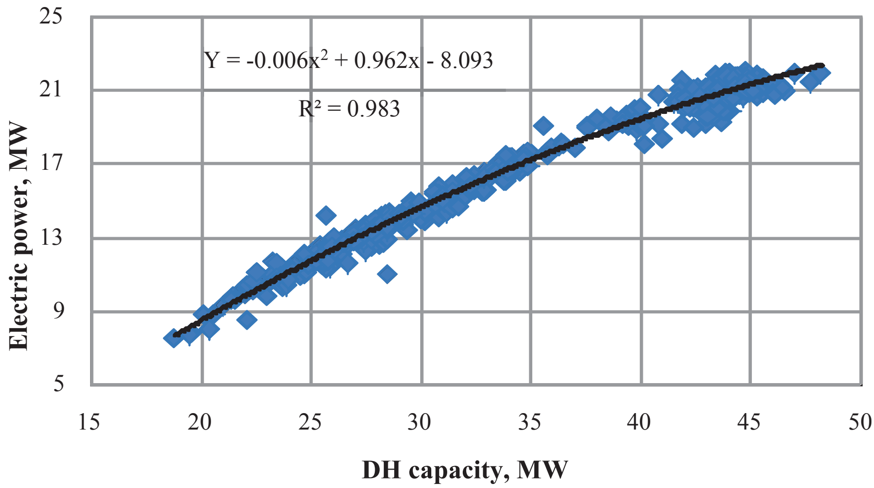

Figure 4. Change in the electrical capacity of the cogeneration plant depending on the heat load.

The mutual correlation of the analysed variables is described by the value of the squared correlation coefficient $R^2 = 0$. The relationship between the variables is non-linear and is defined by the following equation:

$$N_{el} = -0.006 \cdot Q_{th}^2 + 0.962 \cdot Q_{th} - 8.093 \qquad (3)$$

As the mutual correlation of the variables is very good, the equation (3) explains 98% of the changes in the studied data. The impact of other parameters is just 2% of the observed electrical capacity. The relationship between the electrical capacity vs the heat capacity is the relationship α describing the relevant technology. It means that two out of three variables – N_{el}, Q_{th} or α – can be used in the regression analysis. In the present study, new indices in the form of relationships between variables can be formed as Q_{th}/B, N_b/B or N_{el}/B.

In the result of the correlation analysis, it was concluded that within further multi-factor regression analysis the change of the dependent variable b_{ch} depending on the following four independent factors should be analysed – the boiler efficiency N_b/B, the power generation efficiency N_{el}/B, the heat production efficiency Q_{th}/B and the outdoor temperature

$$b_{ch} = f\left(\frac{N_b}{B};\frac{N_{el}}{B};\frac{Q_{th}}{B};T_{out}\right) \tag{4}$$

The data correlation analysis performed makes further regression analysis easier, as the set of factors that needs to be included in the multi-factor regression equation has been established.

Regression analysis of the data of the cogeneration plant

The regression analysis is aimed at obtaining an empirical equation that would provide a quantitative description of the change in the specific fuel consumption of the plant depending on statistically important operational indices of the plant and would serve as the basis for forecasting and evaluating the specific fuel consumption of the plant. Different use of regression model is discussed by Beloborodko et al. (2012). They developed empirical model for the evaluation of the quality for biomass pellets.

The regression analysis defines accurate quantitative parameters of the change in random variables, i.e. explains the importance of the stochastic link by functional relationships.

The sequence of the regression analysis was as follows:

- the law of the distribution of the dependent variable, i.e. the specific fuel consumption of the plant was verified;
- the regression equation was established by applying the smallest square method;
- the statistical analysis of the obtained results was performed.

According to Blasnik (1995), there are several main preconditions behind the application of the regression analysis. The use of the regression analysis of the data is correct if the normal distribution law is applicable to the dependent variable. This requirement is not applicable to independent variables. The above means that the analysis starts with the establishment of the distribution of dependent variables and the analysis may be continued if this distribution complies with the rule of the normal distribution.

The results of verification of the rule of distribution are presented in Fig. 4. The normal distribution within logarithmic coordinates is graphically presented with a line. As it can be seen in Fig. 4, the analysed data are placed close to the line in the graph. There are deviations at low and high values of the capacity. This means that the distribution is close to the rule of normal distribution and the application of the regression analysis is justified.

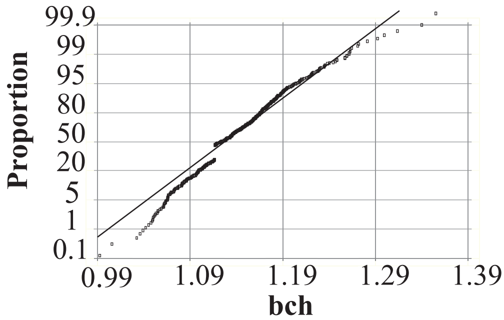

Figure 5. Distribution of the values of the specific fuel consumption of the plant.

When empirical models are developed in the form of the regression equation, several questions always need to be solved: whether the model comprises all the independent variables describing the analysed phenomenon and whether the model does not comprise unnecessary and non-essential variables, thus making the model too complicated. The answers to the above questions are provided by an evaluation of the statistical importance of the variables contained in the model and the dispersion analysis of the model.

The regression equation used by the authors does not contain the effects of the double and triple interaction of independent variables and it is as follows:

$$y = b_0 + b_1x_1 + b_2x_2 + \ldots + b_nx_n + \varepsilon = b_0 + \sum_{i=1}^{n} b_ix_i + \varepsilon, \tag{5}$$

where: y – a dependent variable; b_0 – a free member of regression; $b_1 \ldots b_n$ – regression coefficients; $x_1 \ldots x_n$ – independent variables; ε – residual error.

The regression equation that corresponds to the expression (4) and was obtained as a result of statistical data processing contains statistically important independent variables

$$f_{ch} = b_0 + b_1 \cdot \frac{N_b}{B} + b_2 \cdot \frac{N_{el}}{B} + b_3 \cdot \frac{Q_{th}}{B} + b_4 \cdot T_{out}, \tag{6}$$

where: Nb/B – the boiler efficiency; Nel/B – the power generation efficiency; Qth/B – the heat production efficiency; Tout – the outdoor temperature.

The values of the coefficients of the regression equation and their statistical evaluation, as obtained by the dispersion analysis, is presented in Table 1.

In the data processing the level of importance P = 0.1 has been selected and corresponds to the probability of credibility 0.90. Using an importance level of P = 0.05, an outdoor air temperature with the importance level P = 0.1 becomes inessential and can be discarded from the regression equation. Outdoor air temperature T_{out} is important in terms of physical processes taking place in the plant, and for it to be retained in the equation it was decided to use a lower credibility interval.

Table 1. Coefficients of the regression equation and their evaluation

Coefficients b_i	Values	t statistics	P value
Constant b_0	2.2903	530.37	0.0000
Coefficient b_1	-0.0225	-3.2590	0.0012
Coefficient b_2	-1.3964	-88.061	0.0000
Coefficient b_3	-1.3064	-128.491	0.0000
Coefficient b_4	-0.0000393	-1.6221	0.1004

For the purpose of evaluation of the statistical importance of coefficients b_0... b_n the t criterion with the Student's distribution with f freedom levels is applied.

$$f = m - (n + 1), \tag{7}$$

where: m – the volume of the data set subject to analysis; n – the number of independent variables in the regression equation.

The level of freedom is:

$$f = m - (n+1) = 4{,}673 - (4+1) = 462$$

The value of the t criterion corresponding to these variables as taken from the tables of the Student's distribution is t_{tab} = 1.6. As it can be seen from Table 1, in all the cases the relation I t I > t_{tab} is valid. This means that all the parameters are important and should be maintained in the equation.

The study has resulted in obtaining a regression equation that determines the change in the specific fuel consumption depending on the operational data of the cogeneration plant Jelgava

$$b_{ch} = 2.2903 - 0.0225 \cdot \frac{N_b}{B} - 1.3964 \cdot \frac{N_{el}}{B} - 1.3064 \cdot \frac{Q_{th}}{B} - 0.0000393 \cdot T_{out} \tag{8}$$

The value of R^2 as determined in the result of the statistical processing of the data of the established empirical model equals 0.99. It means that the established model (8) explains 99% of the change in the analysed data. The other 1% refers to the independent variables that have not been included in the equation or defined in the study or the effect of their mutual interaction.

Evaluation of the adequacy of the regression equation

The evaluation of the adequacy of the equation (8) is performed by means of the dispersion analysis by applying Fisher's criterion F.

For this purpose, the dispersion relationship of the dependent variable to the balance dispersion is analysed:

$$F(f_1, f_2) = \frac{S_y^2(f_1)}{S_{atl}^2(f_2)}, \tag{9}$$

where: S2y(f1) – dispersion of the dependent variable y; S2atl(f2) – dispersion of the balance.

The balance is defined as the difference between the dependent variable and the value calculated by means of the regression equation y_i - $y_i^{apr.}$

The value as determined by means of the dispersion analysis performed by the software is F=26,392

The obtained value is compared to the table value of the criterion determined by applying the values of the freedom levels:

$$f_1 = m - 1 = 467 - 1 = 466 \qquad \text{and} \qquad f_2 = m - n = 467 - 4 = 463$$

The table value of Fisher's criterion is F_{tab} = 1.19. As it can be seen, the relationship $F > F_{tab}$ is valid and it means that equation (8) is adequate and can be used for describing the analysed data within the framework of their change: Nb/B – the boiler efficiency from 0.89 to 1.15 MWh $(m^3)^{-1}$; Nel/B – the power generation efficiency from 0.21 to 0.32 MWh $(m^3)^{-1}$; Qth/B – the heat production efficiency from 0.51 to 0.69 MWh $(m^3)^{-1}$; Tout – the outdoor temperature from +9°C to -15.2°C.

Verification of the rules of correct application of the correlation analysis

Following the establishment of the regression equation, it is possible to perform the rules verification of the correct application of the regression analysis based upon a range of other indices. These are autocorrelation, multicolinearity and heteroscedasticity.

Verification of autocorrelation. By applying the Durbin-Watson's test, in the course of statistical treatment of the data and the data analysis, the DW criterion has been established. Its value equals 1.6 and exceeds the marginal value of 1.4. This means that there is no considerable autocorrelation of the balance and the assessments of values by means of the smallest squared values method in the course of the analysis are not deformed.

Verification of multicolinearity. The verification has been performed by analysing the correlation matrix of the coefficients calculated by means of the regression equation, presented in Table 2.

Table 2. Correlation matrix of the coefficients of the regression equation

Coefficient	Constant, t.	N_b/B	N_{el}/B	Q_{th}/B	T_{out}
Constant	1.0000	-0.4639	0.0763	-0.2188	-0.1871
N_b/B	-0.4639	1.0000	-0.4397	-0.5008	-0.2341
N_{el}/B	0.0763	-0.4397	1.0000	-0.2692	0.1854
Q_{th}/B	-0.2188	-0.5008	-0.2692	1.0000	0.2828
T_{out}	-0.1871	-0.2341	0.1854	0.2828	1.0000

The analysis of the correlation matrix of the coefficients of the regression equation demonstrates that there is no considerable correlation between the coefficients and independent variables. This is attested by the low values of the correlation coefficient in Table 2. The values presented in the Table are below 0.5 or close to this level, and this means that the evaluation of the coefficients of the regression equation is correct.

The verification of the heteroscedasticity has been performed by means of a graph analysis of the distribution of balances depending on the outdoor temperature. If the increase of variations can be seen in graphs (the points form a triangle or a wedge), it means that there is heteroscedasticity.

The distribution of balances is presented in Fig. 4.

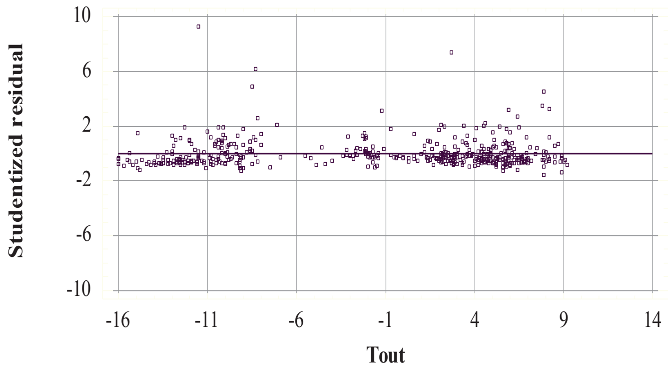

Figure 6. Distribution of balances depending on the outdoor temperature.

The figure shows that there are no considerable changes in the distribution of balances in the data set depending on the outdoor temperature. The balance values are similar along the whole range of changes in the outdoor temperature. The balance distribution has been analysed based upon other factors. In all cases, the conclusion is that there is no heteroscedasticity and the standard error has been identified correctly. The overall conclusion is that all terms of regression analysis have been correctly observed and the smallest square method values are undistorted; there are no observable errors in the evaluation of the regression equation coefficients – erroneous absolute values or incorrect marks; also, the standard error is observed correctly.

RESULTS AND DISCUSION

As a result of regression analysis, an empirical equation has been obtained, which can be used in determining the specific fuel consumption rate (b_{ch}) of woodchips for a unit of total generated heat and electrical power, m^3 MWh^{-1}. The equation includes such ratios:

- Boiler capacity against plant fuel consumption
- Plant electrical capacity against plant fuel consumption
- Plant thermal capacity against plant fuel consumption
- Outdoor temperature

The statistical relevance levels of all components are seen in Table 1. The ratios describe specific rates in relation to one cubic metre of fed fuel, and they correlate with the boiler's electrical and generated heat efficiency. The ratios would directly describe the efficiency coefficient if they were related to the energy from the fed fuel. In case of solid fuel, there are difficulties in determining the amount of fuel and burning heat, especially for timber whose burning heat rate is influenced by a number of factors, including moisture content, ash content, origin (forest woodchips, processing residues, or mix), etc. Therefore, the article offers an equation whose components are determined by measures of the amount of fuel. Outdoor air temperature T_{out} influence on the specific fuel consumption rate is not essential. However, it does affect the capacity of the process. Reduced outdoor temperature increases consumed heat capacity and the amount of cogenerated electrical power, which increases the capacity of the boiler. Outdoor temperature determines the capacity the plant operates in.

Using data from the CHP with the ratios of the specific regression equation (6), a calculation of specific fuel consumption was made, comparing the results with the consumption rate observed at the plant. Calculation results are presented in Table 3.

Table 3. Specific fuel consumption ratios

Nr	N_b/B MWh $(m^3)^{-1}$	N_{el}/B MWh $(m^3)^{-1}$	Q_{th}/B MWh $(m^3)^{-1}$	T_{out} °C	CHP b_{ch} m^3 MWh^{-1}	Estimated b_{ch} m^3 MWh^{-1}	Difference %
1	0.99	0.27	0.41	-3.9	1.47	1.36	7.5
2	1.0	0.25	0.65	4.4	1.11	1.07	3.6
3	0.99	0.2	0.5	10.3	1.43	1.335	6.6
4	0.96	0.26	0.44	-15.4	1.425	1.33	6.7

The difference between specific fuel consumption rates, the one during the plant's operation and the calculated one, is compared against the specific consumption rate observed at the plant. The assessment of the percentage difference shows that the specific fuel consumption rates calculated with the equation are useful in describing the data from the plant and can be also used for estimating future fuel consumption. It can be noted that in case of small rates of specific consumption the difference is smaller. When comparing a cogeneration plant's energy-generation processes, it can be observed that the boiler has the highest rate of efficiency, followed by the heat generation process for consumer needs, while the lowest is in the process of generating electrical power. This can be explained by losses in the energy generation network, which are higher in the case of power generating than in heat generating for consumer needs. The reduction of the specific fuel consumption rate is determined by possibilities of loss reduction within the plant's energy generating processes.

One of the ways to verify the regression equation is related to the verification of the signs of its constituents and whether the fact if there is a logical explanation behind the identified changes in the equation from the point of view of the physical nature of the described processes. In the regression equation (6) for determining the change in the specific fuel consumption the signs of all the parameters are negative and an increase in their value lowers the specific fuel consumption. The visible trends comply with the nature of the processes and there is a logical explanation behind them. It seems logical that when increasing the efficiency of energy generation processes the consumption rate for one unit of energy in the plant decreases.

The question of completeness of the correlation between the results calculated by means of the regression equation and the analysed data is among the basic questions regarding the use of empirical equations. Only with a satisfactory correlation can it be stated that the model adequately describes the situation in practice and its use for simulating the situation is correct. For the purpose of verifying the adequacy of the empirical equation, the empirical and calculated data have been compared. The graphic presentation of the data comparison is in Fig. 7.

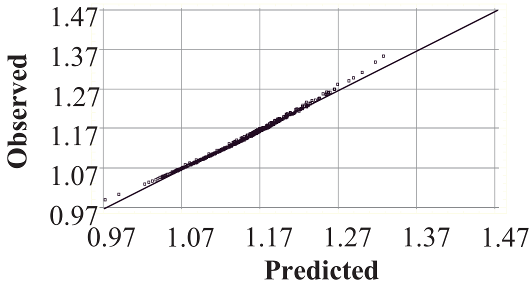

Figure 7. Comparison of analysed data on the change in the specific fuel consumption of the plant and the calculation data.

As seen from Fig. 5, there is a good correlation between both data sets. If the calculated value corresponded accurately to the surveyed data, the points would be located on the line in the figure. There is an increased dispersion of points at low and high values of the specific fuel consumption of the plant. This fact complies with the conclusion made apparent by the comparison of specific fuel consumption rates in Table 3.

CONCLUSIONS

1. By means of statistical processing of the change in the plant's specific fuel consumption, by applying the methods of regression analysis, the most important factors describing the operation of the equipment or independent parameters were identified. The relationship between the change in the plant's specific fuel consumption and the parameters impacting it, is established by the regression equation obtained in data processing:

$$b_{ch} = 2.2903 - 0.0225 \cdot \frac{N_b}{B} - 1.3964 \cdot \frac{N_{el}}{B} - 1.3064 \cdot \frac{Q_{th}}{B} - 0.0000393 \cdot T_{out} \quad (10)$$

2. According to the performed analysis the change in the plant's specific fuel consumption is determined by the following four statistically important parameters:

- Boiler capacity against plant fuel consumption
- Plant electrical capacity against plant fuel consumption
- Plant thermal capacity against plant fuel consumption
- Outdoor temperature.

3. Evaluation of the adequacy of the regression equation show that it is adequate and can be used for describing the analysed data within the framework of their change: Nb/B – the boiler efficiency from 0.89 to 1.15 MWh $(m^3)^{-1}$; Nel/B – the power generation efficiency from 0.21 to 0.32 MWh $(m^3)^{-1}$; Qth/B – the heat production efficiency from 0.51 to 0.69 MWh $(m^3)^{-1}$; Tout – the outdoor temperature from +9°C to -15.2°C.

4. Using the data from the CHP with the ratios of the specific regression equation, the calculation of specific fuel consumption was made, comparing the results with the consumption rate observed at the plant. The assessment of the percentage difference shows that the specific fuel consumption rates calculated with the equation are useful in describing the plant data and can also be used for estimating future fuel consumption. It can be seen that in the case of small rates of fuel consumption, the difference is 3.6 per cent, and it is smaller than with bigger consumption rates, where the difference is 6.7 per cent.

5. When comparing cogeneration plant's energy-generation processes, it can be observed that the highest rate of efficiency is in the boiler, followed by heat generation for consumer needs, while the lowest is in generating electrical power. It can be explained by losses in the energy generation network, which are higher in the case of power generating than in heat generating for consumer needs. The reduction of the specific fuel consumption rate is determined by possibilities of loss reduction within plant's energy generating processes.

6. Further research is associated with an in-depth study of energy-generation processes in the plant, including spring and summer modes of operation in order to improve the obtained empirical model.

REFERENCES

Beloborodko, A., Timma, L., Žandeckis, A. & Romagnoli, F. 2012. The regression model for the evaluation of the quality parameters for pellets. *Agronomy Research* **1**, Special Issue, 17–24.

Blasnik, M. 1995. *The need for statistical analysis and reporting requirements: some suggestions for regression models. Energy Program Evaluation Conference,* Chicago, 15–17 October, 1995, pp. 14.

Chungen Yin., Lasse A. Rosendahl, Soren & Kar, K. 2008. Grate – firing biomass for heat and power production. *Progress in Energy and combustion Science* **34**, 725–754.

James Keirstead, Nouri Samsatli, A. Marco Pantaleo &, Nilay Shah. 2012. Evaluating biomass energy strategies for a UK eco-town with an MILP optimization model// *Biomass and Bioenergy*, **39**(April), 306–316.

Karen, N. Finney, Jue Zhou, Qun Chen, Xiaohui Zhang, Chian Chan, Vida N. Sharifi, Jim Swithenbank, Andy Nolan, Simon White, Simon Ogden & Richard Bradford. 2013. Modelling and mapping sustainable heating for cities. *Applied Thermal Engineering* **53**(2), May 2013, 246–255.

Marcos Luiz de Macedo Rodrigue, Felipe Raúl Ponce Arrieta & José Ricardo Sodré. 2013. Small scale biomass CHP plant: An assessment for an animal feed industry. *Applied Thermal Engineering* **59**(1–2), 25 September 2013, 174–181.

Pantaleo, A., Chiara Candelise, Ausilio Bauen & Nilay Shah. 2014. ESCO business models for biomass heating and CHP: Profitability of ESCO operations in Italy and key factors assessment. *Renewable and Sustainable Energy Reviews* **30**(February), 237–253.

Zuwała, J. 2012. Life cycle approach for energy and environmental analysis of biomass and coal co-firing in CHP plant with backpressure turbine. *Journal of Cleaner Production* **35**(November), 164–175.