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Section: Energy for Buildings

Sustainable Development of Renewable Energy resources. Biomass Cogeneration Plant

Ginta Cimdina, Dzintra Slisane, Jelena Ziemele, Valdis Vitolins, Girts Vigants, Dagnija Blumberga

Riga Technical University, Kalku 1, Riga, Latvia

Abstract

Biomass cogeneration plants differ in terms of installed capacities, technological solutions, operational efficiency and other essential aspects. The use of wood-chips at cogeneration (CHP) plants brings up a range of issues that have to be solved simultaneously, not only when owners select the installed electrical and heat capacity, but also during plant operation, in order to secure maximum energy efficiency and loading.

Two radically contradictory solutions are possible when choosing the installed capacity of CHP plants: compliance with the base load of the heating system, ensuring operation of the CHP plant for 4000 – 8000 hours/ year and compliance with the optimum heat load of the heating system during the whole year, providing heat to consumers until the moment when heat consumption starts decreasing.

A methodology has been developed to enable a comparison of various alternative solutions for the purpose of analysing the efficiency of the use of primary energy resources. The multi-criteria based analysis methodology has been used to implement rating of alternative technological solutions of biomass CHP plants.

The methodology was verified to analyse the development options for district heating system of the Jelgava city heat supply system. A comparison of three alternative solutions was performed. Results show that the highest rating is for large CHP operation in partly condensing regime than small scale cogeneration only for hot water supply load.

Keywords: cogeneration; biomass; multicriteria analysis.

Nomenclature

A_i	Alternative
A^+	Positive Ideal Solution
A^-	Negative Ideal solution
b_{ij}	coefficient
c^*	TOPSIS rating (Relative Closeness to the Ideal Solution)
S^+	Separation from Positive Ideal solution
S^-	Separation from Negative Ideal solution
v_{ij}	values before normalisation
w	moisture content
w_j	criterion weight

1. Introduction

The European Union (EU) Directive for renewable energy sources points to the necessity of increasing the share of renewable energy resources in Member States. Increasing the use of biomass plays an important role in the Baltic countries. Therefore, it is important to analyze the potential of these energy resources and technologies. The article focuses on the analysis of innovative solutions and possibilities of using wood-chips.

Energy efficient society and CO_2 emission reduction are two of the main goals of "Energy 2020". Problem of correct sizing and capacity of cogeneration (CHP) has been discussed in several studies. Studies by Paweł Gładysz and Andrzej Ziębik [1–2] describe the influence of the share of hot tap water and the biomass co-firing on the optimal value of the share

Corresponding author: Dagnija Blumberga. E-mail address: dagnija.blumberga@rtu.lv

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of cogeneration in district heating systems with a CHP unit (with and without thermal storage). In cogeneration units cooperating with district heating systems, turbines power rating should not cover maximum demand of heat, because then it would operate for a long time uneconomically. Power rating of the turbine should be chosen taking into account the ratio of the maximum heat flux from the heating steam turbine to the maximum demand for heat (coefficient of the share of cogeneration).

A study in Croatia evidences that biomass CHP plants in district heating (DH) give larger primary energy savings than small scale CHP for individual heating and gas-fired CHP for DH [3].

Sizing algorithm for a biomass-fired Organic Rankine Cycle (ORC) CHP System with heat storage has been developed by Gregor Taljan *et al.* [4]. It has been piloted on an existing DH system in Australia. Proposed CHP model with heat storage was proven to be economically non-viable, enchanted flexibility given by heat storage gives larger number of full load operating hours, but the profit does not cover investments. However, ORC without heat storage is economically profitable if the annual heat demand is higher than 5 GWh and biomass price lower than 17 EUR/MWh.

Biomass CHP can be assessed using various indicators such as efficiency [5], primary energy savings [6], emergy efficiency [7], internal rate of return (IRR), net present value (NPV) and costs of heat and power production [8], [4].

A simulation model representing CHP operation within Direct heating system (DHS) has been developed by Alessandro Pini Prato *et al.* [5]. Two simulation software Matlab/Simulink ambient AEDO and economic-energetic optimizer based on the interaction between a MILP Linear Programmer and a "supervisor" written in high level language (Fortran), called DIOGENE, was combined to develop dynamic CHP/DHS model. One of the main CHP feasibility indicators is efficiency (heat vs. work ratio). Dynamic parameters characterizing the distribution system (piping and heat carrier fluid) are time delays, control logic and heat storage capacity, energy delivery efficiency, heat losses. Heat demand is variable throughout the year, simulation tool generates approximated load curve. At last, physical and thermo-dynamical dynamics are integrated into the model together with the dynamics of financial data. Developed methodology has been applied to assess the economic and energy sustainability of a biomass and natural gas fired CHP/district heating network (DHN) project in Northern Italy. An idea of heat distribution networks capacity to be used as dynamic heat storage was tested and recognized as feasible.

Techno–economical evaluation of electricity production with various small scale biomass CHP technologies in Norwegian market conditions was carried out by Rajesh S. Kempegowda [8]. Indicators used in this study are IRR, NPV and cost of power generation. Realistic Norwegian biomass for bio energy potential is about 33 TWh/year (wood biomass, agricultural residues, biogas and biomass originating waste). It was concluded that in near future the most promising small scale CHP biomass based technologies are steam turbine based CHP. In medium term future gasification, gas engine or boiler + steam turbines may be profitable. The lowest costs of power generation can be achieved using biogas engine, industrial backpressure turbine and municipal solid waste backpressure turbine.. These three technologies are also the only ones that have positive NPV without any additional support (other technologies proved to be profitable with the support of green certificates, grid fee reduction or investment support).

An analysis of biomass-fired ORC unit coupled to a heat storage system (HSS) in an existing DH system was performed by Michel Noussan et.al. [6]. Study aims to analyze the economical, energy and environmental aspects of proposed system with multi-criteria approach. Overall CHP system efficiency and primary energy savings were selected as the main CHP performance indicators. Analysis was carried out changing CHP nominal power (400 kWe to 1.2 MWe) and the HSS size (up to 250 m3). Overall CHP systems efficiency decreases with increasing CHP size, this effect is learned a little with the installation of HSS. In case study (Italia), the highest efficiencies are reached for a HSS size of 150 m^3/MW.

CHP plants and biofuel production require the same feedstock. Sylvain Leduca *et al.* [9] investigate which should be supported in EU. A mathematical model with the aim to minimize the cost of biomass supply chain (harvest, transportation, conversion, transportation of product) was developed and used for the comparison. Cost for emitting CO_2 is included in the model. The model chooses the least expensive pathways between the supply chain elements. The results showed that CHP plants are preferred over biofuel production plants for carbon cost over 50 EUR/tCO_2 and biofuel support below 10 EUR/GJ. More biofuel plants would be set up if biofuel support exceeded 15 EUR/GJ irrespective of the carbon cost. The highest potential for both biofuel and CHP is in the countries around Baltic Sea, Austria, Czech Republic, Hungary and Poland. The highest CO_2 emission substitution can be achieved with increased carbon cost and low biofuel support, that is, using majority of biomass for CHP.

Biomass CHP plants differ in terms of installed capacities, technological solutions, operational efficiency and other essential aspects. The use of wood-chips at CHP plants brings up a range of issues that have to be solved simultaneously, not only when owners select the installed electrical and heat capacity, but also during plant operation, in order to secure maximum energy efficiency and loading.

Two radically contradictory solutions are possible when choosing the installed capacity of CHP plants: compliance with the base load of the heating system, ensuring operation of the CHP plant for 4000 – 8000 hours/ year and compliance with the optimum heat load of the heating system during the whole year, providing heat to consumers until the moment when heat consumption starts decreasing.

2. Methodology

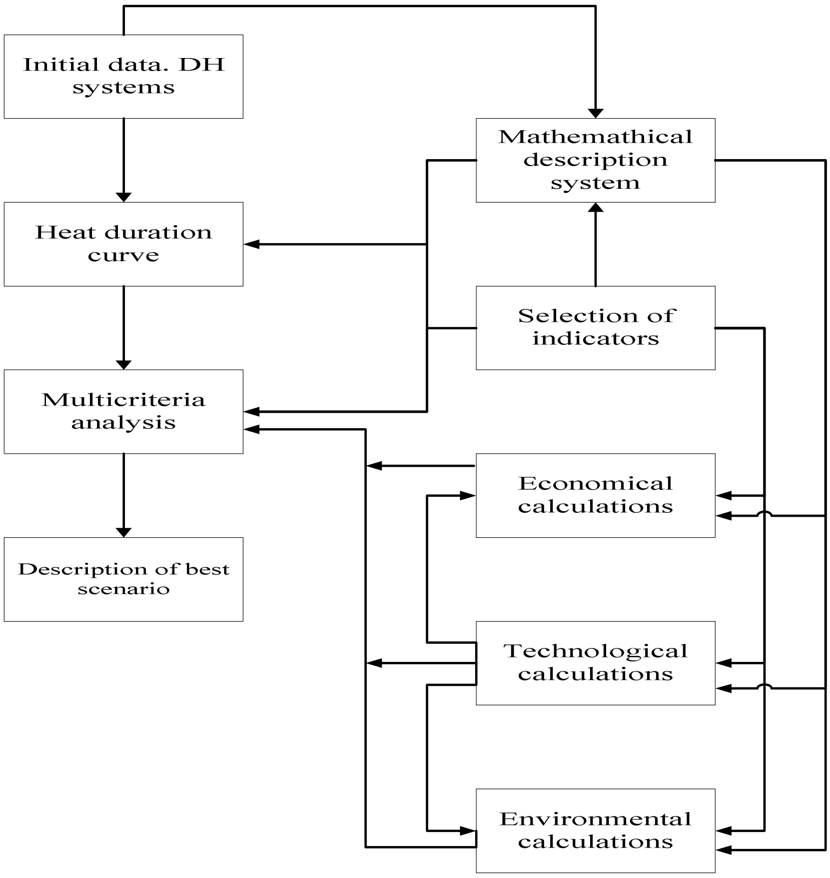

Fig.1. Algorithm of the multi-criteria analysis methodology

A methodology has been developed to enable a comparison of various alternative solutions for the purpose of analyzing the efficiency of the use of primary energy resources.

2.1. Algorithm of Methodology

In order to evaluate the installed capacity of a biomass-fired CHP unit, a methodology was developed and its algorithm is presented in Figure 1.

The multi-criteria analysis module is the main module included in the methodology. The other eight modules are additional modules by means of which data for the multi-criteria analysis module are provided. The module of the input data of the DH system, as well as the schedule of the heat load length and calculation modules are equally important. However, special focus has been placed on the selection of criteria. The criteria that are used for the multi-criteria analysis are summarized in Table 1. Each criterion has specific weight, respective criterion weight determines how influential this criterion is for the decision makers.

Table 1. Criterions and criterion weights

	Criterion	Weight
1	Energy efficiency	0.39
2	Operational costs, Euro/MWh	0.22
3	Investment costs, Euro/MW	0.22
4	Load coefficient, MWh/MWh	0.17

Three different wood chip steam cycle CHP alternatives are proposed:

- small scale CHP;
- large scale CHP1 in condensing regime;
- large scale CHP 2 in cogeneration regime.

In order to decide on the best selection from three proposed alternatives several Multi-criteria Decision Making Methods (MCDM) can be used. A classical and widely used method The Technique of Order Preference by Similarity (TOPSIS) was selected for this study. Criterion weights were determined by specialists (see Table 1). For TOPSIS analysis total sum of criterion weights must be equal to 1.

To start TOPSIS analysis, data must be arranged in form of decision making matrix, with n evaluation criterions (x_j) and m alternatives (A_i). Normalized data are also arranged in a matrix and then weighted multiplying them with criterion weights (w_j) (1)[17]

$$\begin{array}{c|cccccc|} & w_1b_1 & w_2b_2 & \cdots & w_jb_j & \cdots & w_nb_n \\ \hline A_1 & w_1b_{11}^k & w_2b_{12}^k & \cdots & w_jb_{1j}^k & \cdots & w_nb_{1n}^k \\ A_2 & w_1b_{21}^k & w_2b_{22}^k & \cdots & w_jb_{2j}^k & \cdots & w_nb_{2n}^k \\ \vdots & \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ A_i & w_1b_{i1}^k & w_2b_{i2}^k & \cdots & w_jb_{ij}^k & \cdots & w_nb_{im}^k \\ \vdots & \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ A_n & w_1b_{n1}^k & w_2b_{n2}^k & \cdots & w_jb_{nj}^k & \cdots & w_nb_{nm}^k \end{array} \quad (1)$$

2.2. Analysis of Criterion

The equations of the trend of capital investment of steam cycle biomass-fired power plants were developed based on research [10–11]. It can be seen from data presented in Figure 2 that a specific capital investment is lower at higher capacity levels.

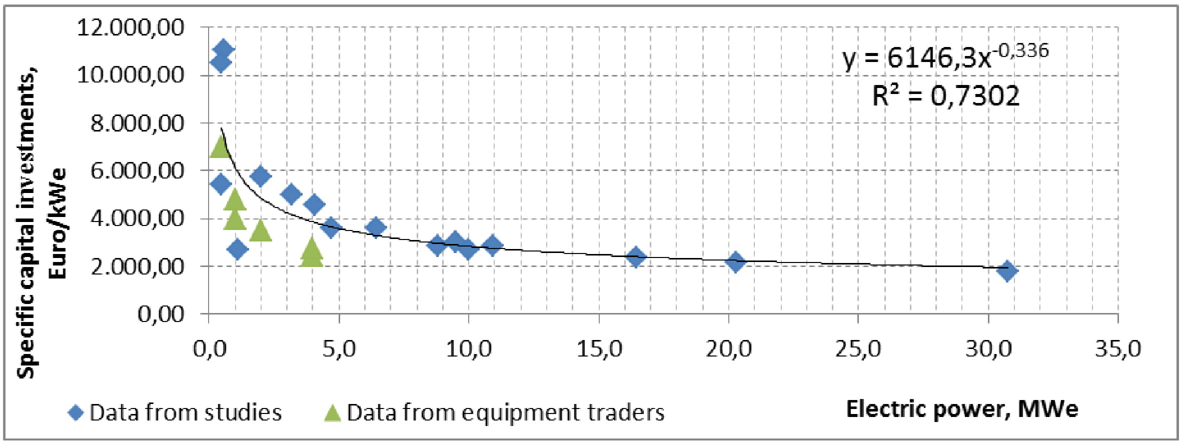

Fig. 2. Specific capital investment of steam cycle power plants

Based upon the evaluation of data from various studies, in order to establish the operational costs of biomass-fired power plants, the following distribution of costs is considered [10–13]:

- labor costs – depend on the number of personnel and wages, Euro/ year;
- service and repair costs – 3% (CHP and wood gasification) and 5% (ORC) of capital investment, Euro/ year;
- insurance and other costs – 1.5% of capital investment, Euro/ year;
- electricity for self-consumption – depends on the purchase price of electricity and power consumption, 3% (CHP and wood gasification) and 5% (ORC) of gross power generation, Euro/ year;
- fuel costs – depend on power generation (efficiency ratios of the plant) and the type of fuel (calorific value) and its price, Euro/ year.

Fuel costs represent a major item within operational costs, and in further calculations the following assumptions are applied:

- the number of operational hours 5500 h/ year –in 2012 biomass-fired cogeneration power plants (plants that only operate during the heating season are excluded) have been in operation for 6500 h/ year on average. Taking into account the plants that have also been in operation during the heating season, this index is 4400 h/ year on average. Therefore, 5500 hours or approximately 7 months of operation may be considered an optimum number of operating hours;
- power generation efficiency [10–11]; 0.12 – 0.23 CHP; 0.14 – 0.2 ORC; 0.32 – 0.35 wood gasification;
- power/ heat ratio of the power plant (alfa) [10, 14]; 0.23 (ORC), 0.7 (wood gasification), 0.17 (CHP);
- net calorific value of the fuel (calorific value) – 2.5 MWh/t (w = 45%) [16];
- the price of fuel (wood chips) – 10.67 Euro/loose m^3 (wood density – 0.3 t/ loose m^3) [10, 14–15].

Taking into account the above split of operating costs, Figure 3 presents the change in specific operating costs depending on installed electrical capacity, the technological solution, the number of operating hours per year and regulatory requirements of the Latvian legislation [17].

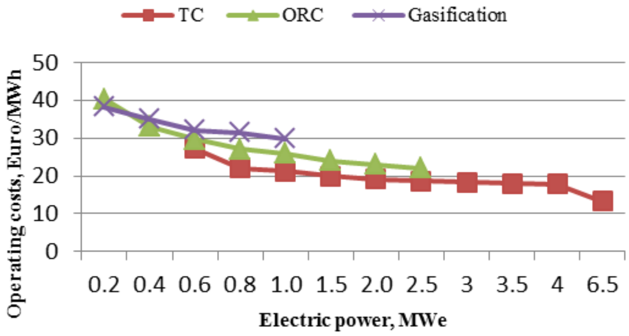

Fig. 3. Specific operational costs

In this figure it can be seen that specific operational costs are lower for higher capacity power plants. It is also visible that steam cycle CHP plants have the lowest specific operational costs, because in comparison to wood gasification and the ORC solution, operational costs are lower and the total efficiency of the plant is higher.

The efficiency of energy sources depends on technological parameters and load utilization. The load ratio demonstrates load of the cogeneration plant during a year. It explains load utilization of the cogeneration plant. The example of changes in the load coefficient depending on the outdoor temperature at the Jelgava city CHP plant is presented in Figure 5.

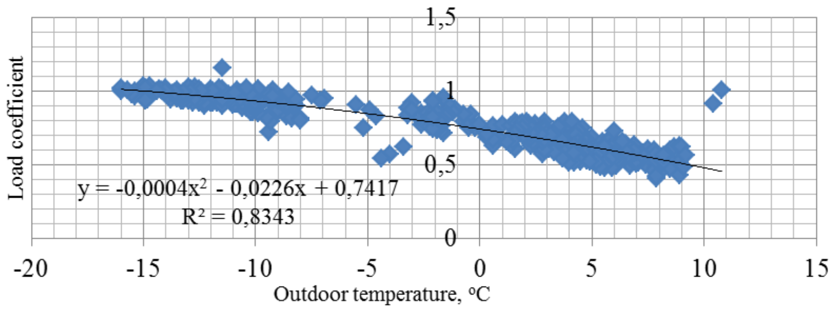

Fig. 4. Changes in the load coefficient in dependence from outdoor temperature

3. Testing of Methodology. Results and Discussion

The methodology was verified to analyze the development options for energy sources for the Jelgava city heat supply system. Data describing the CHP plant of Jelgava city

- Input power 76 MW
- Electrical capacity 23 MW_e
- Heat capacity 45 MW_{th}
- Minimum load 35%
- Superheated steam temperature 527 °C
- Steam pressure 119 bar

Multi-criteria analysis of above mentioned three alternative solutions was performed (see Table 2).

Table 2.Matrix for multi-criteria analysis

	Alternative	Energy efficiency	Operational costs, Euro/MWh	Investment costs, Euro/MW	Load coefiient. MWh/MWh
1	Small scale CHP	0.87	20	3800	0.2
2	Large scale CHP 1	0.6	13	2100	0.39
3	Large scale CHP 2	0.9	13	2100	0.25
	Weight	0.35	0.2	0.2	0.15

The data are normalized according to the matrix (1) and the obtained results are summarized in Table 3. Positive and negative ideal solutions and distribution can be found using equations 2, 3, 4, 5, 6, 7.

Positive Ideal solution:

$$A^{+} = \mathrm{Max}_{\mathrm{i}} w_j b_{ij}\text{ , if max value is preferable for the criterion} \tag{2}$$

$$A^{+} = \mathrm{min}_{\mathrm{i}}\ w_j b_{ij}\text{ , if min value is preferable.} \tag{3}$$

Negative Ideal solution:

$$A^{-} = \mathrm{min}_{\mathrm{i}}\ w_j b_{ij}\text{ , if max value is preferable} \tag{4}$$

$$A^{-} = \mathrm{Max}_{\mathrm{i}} w_j b_{ij}\text{ , if min value is preferable.} \tag{5}$$

When positive Ideal solution and negative Ideal solution for each criterion has been determined, the separation measure of each alternative from overall Positive Ideal and Negative Ideal solution is calculated.

Separation from Positive Ideal solution (S^{+}) is calculated by following formula:

$$S^{+} = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^{+}\right)^2}\ , \quad i = 1, 2, ..., m \tag{6}$$

Separation from Negative Ideal solution:

$$S^{-} = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^{-}\right)^2}\ , \quad i = 1, 2, ..., m. \tag{7}$$

The results of perfect positive and negative alternatives are summarized in Table 3.

Table 3. Summary of the results

	Alternative	Energy efficiency	Operational costs, Euro/MWh	Investment costs, Euro/MW	Load coefficient, MWh/MWh	S+	S-
2	Small scale CHP	0.206	0.154	0.168	0.049	0.145	0.064
3	Large scale CHP 1	0.142	0.100	0.093	0.096	0.082	0.104
4	Large scale CHP 2	0.213	0.100	0.093	0.062	0.063	0.117
A+		0.213	0.077	0.062	0.111	0.000	0.161
A-		0.142	0.154	0.168	0.049	0.161	0.000

The last step is calculation of alternatives rating

$$\boldsymbol{C_i^{*}} = \frac{\boldsymbol{S_i^{-}}}{\left(\boldsymbol{S_i^{+}} - \boldsymbol{S_i^{-}}\right)}, \quad i = 1, 2, 3\ [18][19] \tag{8}$$

TOPSIS analysis results are shown in Figure 5. The alternative with the highest rating should be selected. High capacity CHP plants operating in the CHP mode represent the best scenario with the highest rating. According to the analysis of the Jelgava city heat supply system, the operation of the CHP plant in the CHP mode is also better compared to the alternative of installing a small scale CHP plant.

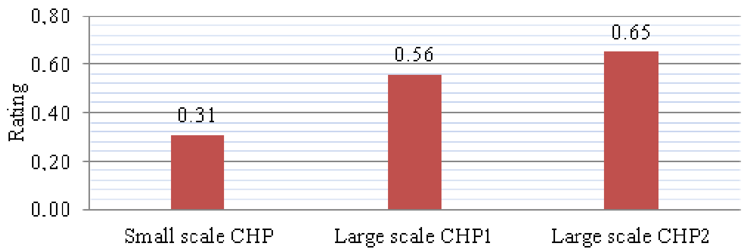

Fig. 5. Rating of selected alternatives

4. Conclusions

- The multi-criteria analysis allows prioritization of alternative technological solutions by selecting technological and economic criteria. In order to avoid the impact of political decisions upon the operational indices of the CHP plant, the state aid mechanisms for CHP plants were not selected among the criteria.
- According to the multi-criteria analysis, it is important to build large-scale plants that cover sufficient heat supply load by operating as CHP plants and even partially in condensing mode. Building small-scale CHP plants only to cover the hot water supply load is not justified from either an economic or technological point of view.
- As additional heat loads are required to increase the cogeneration mode, it is important to build sufficiently large cogeneration plants and to look for solutions for increasing heat consumption.

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