RIGA TECHNICAL UNIVERSITY

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SUSTAINABILITY INDICATORS IN HEATING SYSTEMS TOWARDS CLIMATE NEUTRALITY

Summary of the Doctoral Thesis

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Toms Prodaņuks………………………(signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction; 3 Chapters; Conclusions; 29 figures; 15 tables; 1 appendix; the total number of pages is 154. Bibliography contains 88 titles.

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INTRODUCTION

The European Union has declared the goal of achieving climate neutrality by 2050, ensuring economy with zero net greenhouse gas (GHG) emissions. To achieve this goal, the EU has announced the European Green Deal which includes an action plan to accelerate efficient resource usage while moving towards circular economy as well as to restore biodiversity and reduce pollution. The transition to climate neutrality is urgent and offers an opportunity to build a better future. In order to achieve climate neutrality, society and all economic sectors must play their part [1].

The European Green Deal is the EU's growth strategy, which aims to achieve a just and prosperous society by improving its quality of life. The European Green Deal covers the establishment of modern, competitive, and resource-efficient economy. EU Strategic Agenda for 2019–2024 states as one of its priorities – "to create climate neutral, green, just and social Europe", which will require significant legislative changes and private and public investments [2], [3].

One of the tasks of the European Green Deal is to ensure clean, affordable, and secure energy. The development of the energy sector must be based on renewable energy sources in combination with phasing out coal usage and carrying out decarbonisation of gas. Furthermore, energy efficiency in the energy sector must be stated as a priority. The introduction of renewable resources, energy efficiency and other sustainable solutions in various sectors will help to achieve the decarbonisation goals at the lowest cost. Significant reductions in the cost of using renewable resources, together with various support mechanisms, have already helped to reduce GHG emissions. This confirms that the policies implemented have been successful, but further work is needed to achieve climate neutrality [4], [5].

New technologies, sustainable solutions and innovations are essential for achieving the goals of the European Green Deal. The EU must significantly increase the development and demonstration of new technologies in all sectors of the economy, creating new innovative chains of cooperation. The process of implementing the European Green Course also involves cooperation between universities, institutions, and companies [6].

The district heating sector, as part of the energy sector, has a major role to play in achieving the EU's climate neutrality goals. Energy efficiency measures are equally important for both energy consumers and producers. The EU has set the task to reduce energy consumption to end-users by significantly increasing the role of the district heating systems through the prism of renewable energy and energy efficiency. In Latvia, an important role is envisaged for the use of renewable energy resources in both district heating systems as well as local heating systems. It is planned to implement this by introducing new innovative technologies and methods of heat production. Achieving these goals would require the involvement of all stakeholders – the state, municipalities, companies, higher education institutions and the general public [7].

Research Topicality

Increasing the efficiency of heat production and reducing consumption is considered one of the key tools for achieving the EU's climate and energy goals by 2030, which envisage at least a 40 % reduction in GHG emissions, using 1990 as a baseline, at least a 32 % share of renewable energy and a 32.5 % increase in energy efficiency. In accordance with the EU climate and energy policy, the Latvia's National Energy and Climate Plan 2021–2030 has been developed, and it includes national objectives and main actions that are directly or indirectly related to the increase of the efficiency in heat energy production and the reduction of consumption focusing on renewable energy [7].

Latvia's progress towards climate neutrality by 2050 within the framework of the European Green Course envisages the implementation of the Low-Carbon Development Strategy, which includes the reduction of GHG emissions in all sectors of the economy and the increase of CO_2 capture. As the energy sector is the largest source of GHG emissions in Latvia, significant actions will be needed in the field of heat production and end-user consumption [8].

In order to achieve the EU and Latvia's national goals of reducing GHG emissions, increasing the share of renewable energy and increasing energy efficiency, a targeted analysis of the current situation should be carried out using various methodologies, and concrete proposals should be provided to heat producers, consumers and policy makers.

Research Scope

The overall aim of the present Doctoral Thesis is to evaluate heating systems in Latvia using sustainability indicators, including heat energy producers and end-users and to make proposals on potential methodologies to increase the efficiency of the heating system and to reduce GHG emissions, emphasizing the use of renewable energy sources.

To reach the aim of the Thesis, the following tasks have been set:

1) to analyse heat production efficiency calculations, studying three different calculation methods, which are based on flue gas condenser operation;
2) to carry out two and multifactor regression analysis for heat production equipment, evaluating its parameter's effect on system operation;
3) to create empirical model for optimization of flue gas condenser operation by determining statistically significant parameters;
4) to carry out an economical parameter assessment for local heat production systems, focusing on solar collectors;
5) to carry out multicriteria analysis for decision-making for district heating system using TOPSIS method;
6) to analyse CHP production system using emergy analysis and establishing emergy sustainability indicators;
7) to propose a methodology for development of municipal district heating development plan in the context of energy management.

Scientific Significance and Contribution

The Thesis is of high scientific significance for Latvia and in international context. An evaluation of various technologies and methods has been developed, which offers complex solutions for increasing the energy efficiency of heat energy producers. The research is based on the application of different methodologies to assess the eco-efficiency of heat production installations using different indicators. The Thesis is based on the use of the triple helix approach in the energy sector, including various indicators, methods, and levels.

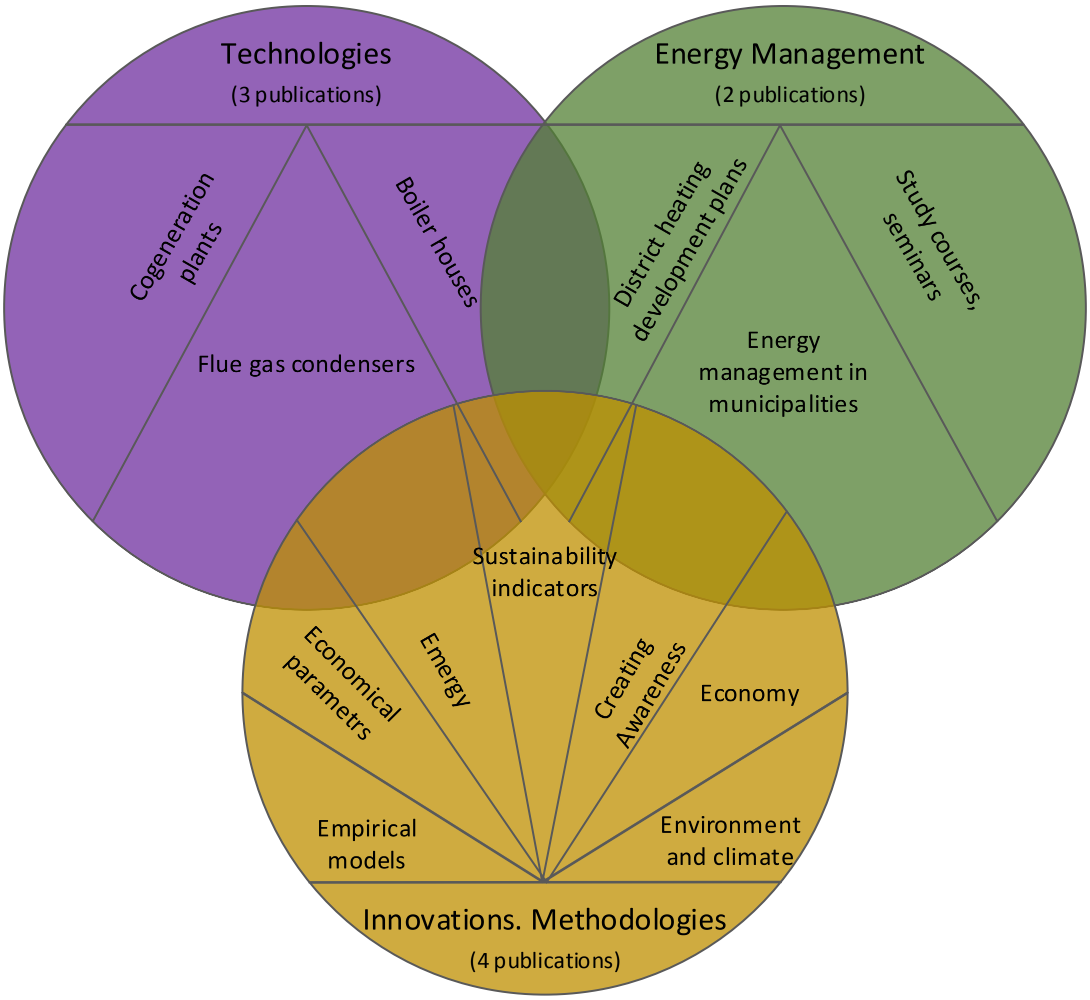

Fig. 1. Methodological approach of the Thesis.

Several methods (comparative analysis, statistical data processing and experimental data processing) have been used for heat production analysis and usage in different levels (technological processes, local and municipal energy supply, etc.). Various uses of analytical methods and indicators have also been demonstrated, based on the principle "from the simplest (collection and processing of statistical data) to the most complex (development of the methodology for determining the sustainability indicator)". A model of energy source emergy indicators has been developed, and approbated for the analysis of biomass cogeneration plant operation. Several sustainability indicators are considered in the context of cogeneration plants using energy and emergy analysis methods. The method of emergy analysis for cogeneration plant is used to analyse different proposed indicators for different operating modes. Empirical model for heat and mass transfer process for direct contact flue gas condenser has been established using experimental data. An algorithm for efficiency calculations in flue gas condenser is created by compering theoretical and practical energy efficiency values. Methodology for development of municipal district heating development plan is created including use of sustainability indicators.

Research Hypothesis

Latvia's progress towards climate neutrality by increasing the efficiency of heat production and end-users and the share of renewable energy resources within the framework of the European Green Deal can be assessed by heating system's sustainability indicators.

Practical Significance

The conclusions and findings obtained in the Thesis are useful in the process of increasing the energy efficiency for Latvia's heat producers and end-users, considering the set climate and energy goals and potential goals towards climate neutrality in 2050.

The indicators and methodologies discussed in the Thesis at the national level allow to determine the development status of the heat supply system towards climate neutrality. A methodology for the implementation of energy management in the heating sector has been developed for municipalities, providing a specific algorithm for cooperation with the district heating system operator. Heat producers, including district heating system operators, are provided with methodologies and indicators, which can help them to assess the suitability, efficiency, and economic performance of the technologies. At the level of heat energy users, local heat energy sources have been evaluated. The developed methodologies allow to assess the sustainability of the entire heating sector.

Research Framework

The Thesis is based on nine thematically related scientific publications, covering the heating sector from energy production to the end-user.

The Thesis consists of an analysis of the heating sector, including energy source and end-user. Using various methodologies (regression analysis, multi-criteria analysis and emergy model), individual components of the heating system were analysed: cogeneration plants, district heating energy producers, energy management and buildings. As a result of the performed analyses, sustainability indicators for heating have been obtained, which allows to evaluate the entire heat sector.

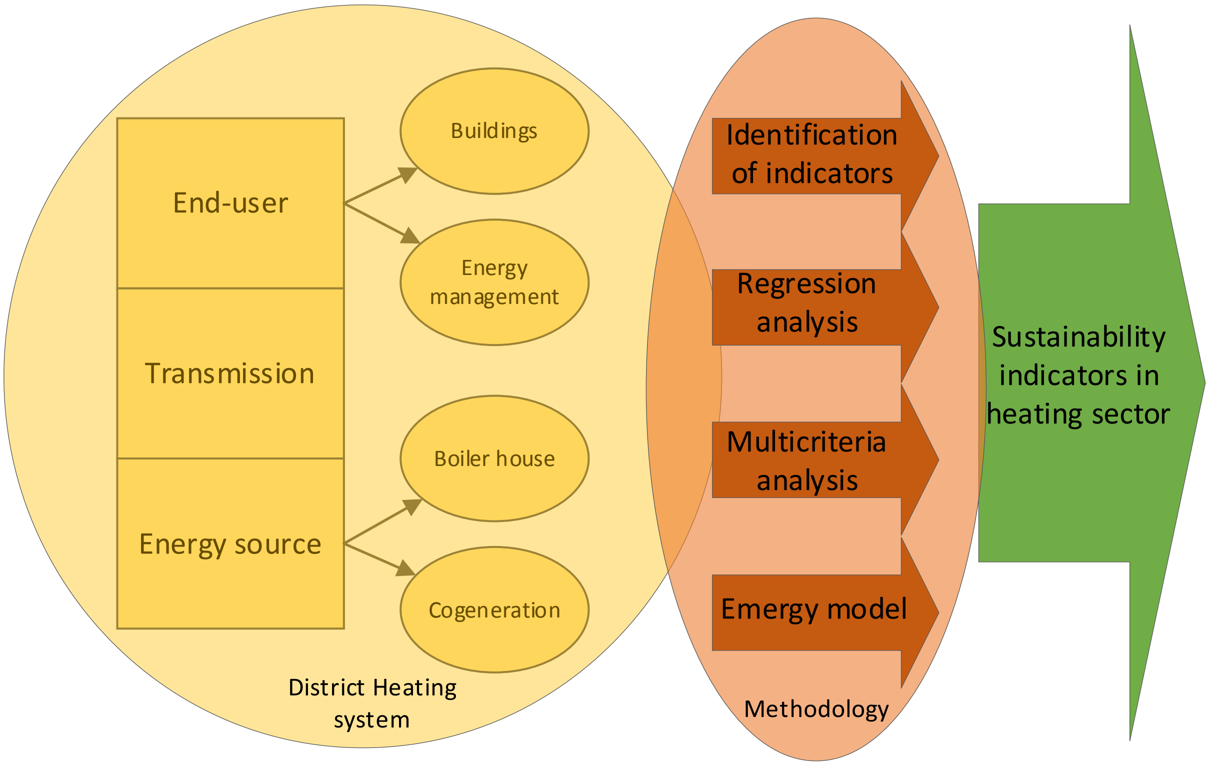

Fig. 2. Structure of The Thesis.

Approbation

Scientific publications included in the Thesis

1. Prodaņuks, T., Cimdiņa, G., Veidenbergs, I., Blumberga, D. Sustainable Development of Biomass CHP in Latvia. Energy Procedia, 2016, vol. 95, pp. 372–376. ISSN 1876-6102. Available: doi:10.1016/j.egypro.2016.09.026 (Indexed in SCOPUS and Web of Science).
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3. Cimdiņa, G., Prodaņuks, T., Veidenbergs, I., Blumberga, D. Review-Based Emergy Analysis of Energy Production. No: Environment. Technology. Resources: Proceedings of the 10th International Scientific and Practical Conference, Latvia, Rezekne, 18–20 June 2015. Rezekne: Rezekne Academy of Technologies, 2015, pp. 85–91. ISBN 978-9984-44-172-6. ISSN 1691-5402. e-ISSN 2256-070X. Available: doi:10.17770/etr2015vol2.629 (Indexed in SCOPUS).
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Participation in conferences

1. Prodaņuks, T., Cimdiņa, G., Veidenbergs, I., Blumberga, D. Sustainable Development of Biomass CHP in Latvia: International Scientific Conference "Environmental and Climate Technologies", CONECT 2015, October 14–16, 2015 Riga, Latvia.
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1. METHODOLOGY

1.1. Energy Efficiency Indicators and Analysis

The methodology for determining the efficiency of the equipment is based on calculations for flue gas condenser, which is approbated in several scientific publications. This chapter discusses different efficiency calculation methods, considering a flue gas condenser as a separate unit or a part in the energy production process. [9]

Condenser efficiency can be calculated in three ways:

1) as a ratio between the power of the condenser and the power of the boiler;
2) inspecting the condenser as a part of the boiler equipment;
3) inspecting the condenser as a separate equipment.

In many papers about different kinds of condensers the efficiency is estimated as a ratio between the power of the condenser and the power of the boiler in percentage:

$$\eta_{c1} = \frac{N_c}{N_{th}} \cdot 100, \tag{1.1}$$

where

η_{c1} – the efficiency of the condenser (type 1), %;
N_c – the power of the condenser, kW;
N_{th} – the power of the boiler, kW.

This type of efficiency shows the amount of boilers' power that can be recovered with flue gas condenser by utilizing the heat loss from flue gas. This indicator does not depict the complete amount of fuel consumption decrease, which would allow to determine the efficiency of the device.

To inspect the condenser as a part of the boiler equipment which, together with the boiler, provide heat demand, efficiency can be calculated as:

$$\eta_{b+c2} = \eta_b + \Delta\eta_{c2}, \tag{1.2}$$

where

η_{b+c2} – the total efficiency of both the boiler and the condenser;
$\Delta\eta_{c2}$ – the increase of boiler efficiency as a result of condenser usage.

The power of the condenser can be determined by calculating the difference of enthalpies in the condenser or by the change of water temperature in the condenser:

$$N_c = L_{wc} c_w (t_{wc2} - t_{wc1}), \tag{1.3}$$

where

L_{wc} – water mass flow in the boiler, kg/s;
c_w – the specific heat amount of water, kJ/kgK;
t_{wc2} – the outlet water temperature of the condenser, °C;
t_{wc1} – the inlet water temperature of the condenser, °C.

Efficiency of the condenser using the second method with lower calorific value is calculated as:

$$\Delta\eta_{c2} = \frac{N_c}{N_i}. \tag{1.4}$$

The flue gas condenser can be considered as a separate heat production equipment, where the inlet heat energy is the same as the heat loss from flue gas after the boiler. Its efficiency is determined by the ratio between the value of heated water and glue gas heat loss. To calculate the third type of efficiency, as it is in the second type of calculations, higher and lower calorific values can be used. The efficiency calculation using lower calorific value is shown in Equation (1.5).

$$\eta_{c3}^{L} = \frac{N_c}{N_2}, \tag{1.5}$$

where

η_{c3}^{L} – the efficiency of the condenser according to lower calorific value;

N_2 – the heat loss from flue gas, kW.

One of the most important parameters for energetic equipment is the consumption of fuel. Moreover, the decrease of fuel consumption as the energy efficiency is improved. To calculate fuel economy, the condenser must be considered as a part of the boiler's equipment. Fuel economy can be calculated as it is showed in Equation (1.6).

$$\Delta B = \frac{N_c}{Q_L^d \eta_{b+c2}^{L}} = \frac{N_c B}{N_b N_c}, \tag{1.6}$$

where

ΔB – fuel economy, kg/s.

Fuel economy can also be calculated using higher calorific value. This calculation is showed in Equation (1.7).

$$\Delta B = \frac{N_c}{Q_H^d \eta_{b+c2}^{H}} = \frac{N_c B}{N_b N_c}. \tag{1.7}$$

The third part of Equations (1.6) and (1.7) are the same This means that fuel economy is not influenced by the type of calorific value used in the efficiency calculations. To calculate the decrease in fuel consumption in comparison to other equipment, an equation for the fuel saving coefficient is introduced. The calculation is shown in Equation (1.8).

$$\delta B = \frac{\Delta B}{B}, \tag{1.8}$$

where

δB is fuel economy coefficient.

This coefficient can be used in condenser calculations and can be considered as the condenser efficiency according to decrease in fuel consumption.

1.2. Regression Analysis

Regression analysis determines the exact quantitative parameters of the random variation and expresses the significance of the stochastic link with functional relationships. The tasks of regression analysis are [10]:

- to determine the quantitative parameters of the statistical closeness of the independent and dependent random variables;
- to determine the coefficients of the regression equation (mathematical model).

Regression analysis consists of two parts: determination of regression equation with the least squares method or other method and statistical analysis of the obtained results. The variation of number of independent variables and different relations between independent and dependent variables allow to obtain different regression equations [11]:

- linear based on two factors;
- linear multifactor;
- linearized;
- non-linear.

In accordance to the type of regression equation, the determination of quantitative parameter's random variable estimation varies. Regression analysis begins with determining the distribution of dependent variables. It must comply with the rules of the normal distribution in order to be used in the subsequent distribution [10].

The correlation between independent and dependent random variables can be estimated using a correlation coefficient. The Pearson equation is used to estimate the two-factor mathematical model [12].

$$r = \frac{\sum_{i=1}^{m}(x_i - x)(y_i - y)}{S_x S_y (m-1)}, \tag{1.9}$$

where

x_i, y_i – independent variables and corresponding dependent variables;

x, y – the arithmetic means of the independent and dependent variables;

$S_x,\ S_y$ – the variables of the random variance.

In the case of multifactor correlation, the multifactor correlation coefficient R is used. This coefficient is not statistically interpretable, however, it is determined and used as an indirect indicator of the usefulness of the regression equation [13].

In the case of nonlinear regression, a correlation ratio is used instead of a correlation coefficient. The correlation ratio in nonlinear regression has the same application as the correlation coefficient in linear regression – it characterizes the grouping of results around the nonlinear regression line. The value of the correlation coefficient can vary from –1 to +1. If the correlation coefficient is equal to or close to 0, it indicates that there is no correlation between the variables. However, correlation coefficient values which are equal to or close to –1 or +1 indicate a functional relationship between independent and dependent variables. It should be noted that the square of the correlation coefficient is usually calculated for statistical data analysis. Correlation coefficient square R^2 indicates characteristics of the regression equation according to variance of dependent variables [14].

In Chapter 2.1 the results regression analysis between different flue gas condenser's parameters are shown as well as relationship between the produced energy with solar collectors and solar radiation.

Empirical analysis of flue gas condenser is carried out using *STATGRAPHICS Centurion XVI*. To carry out empirical analysis of flue gas condenser, multiple regression analysis was used [15].

Multiple regression analysis is carried out to obtain a mathematical model which describes dependent variable using two or more independent variables. In the next step, the coefficients of the linear regression equation must be determined by means of regression analysis, statistical analysis of the results, must be performed, and regression equation must be established.

$$y = b_0 + b_1x_1 + b_2x_2 + \ldots + b_nx_n, \tag{1.10}$$

where

y – dependent variable;

b_0 – intercept term;

$b_1, \ldots, b_n$ – regression coefficients;

$x_1, \ldots, x_n$ – independent variables.

To determine the statistical significance of regression coefficients $b_0 \ldots b_n$, T-test is used, which complies with Student distribution.

$$f = m - (n + 1). \tag{1.11}$$

Value m describes the amount of data subject to statistical analysis and n is the number of independent variables in the regression's equation. To carry out the analysis, each coefficient's, calculated by the program, t-value must be compared with t_{tab} which can be found in Student distribution tables according to the chosen significance level P-value and f-value. A significance level of $P = 0.05$ is often used in the processing of energy-related data which corresponds to a confidence probability of $1 - P = 0.95$. If the rule $|t| > t_{tab}$ applies to the evaluated coefficient, then it is significant and must be kept in the regression equation. Otherwise, this addition to the equation must be discarded and the analysis repeated until all omitted coefficients are statistically significant. The whole procedure is carried out with *STATGRAPHICS Centurion XVI.*

Estimation is performed by analysis of variance using F-ratio. These activities consider the ratio of the variance of the dependent variable to the variance of the residuals.

$$F(f_1, f_2) = \frac{S_y^2(f_1)}{S_{\mathrm{atl}}^2(f_2)}, \tag{1.12}$$

where

$S_y^2(f_1)$ – variance of dependent variable y;

$S_{\mathrm{atl}}^2(f_2)$ – variance of residual.

Residuals are determined as difference between the dependent variable and the amount of the result of regression analysis $y_i - y_i^{apr}$. The degrees of freedom f_1 and f_2 are calculated using equations:

$$f_1 = m - 1,$$
$$f_2 = m - 1. \tag{1.13}$$

If the value of *F*-ratio is bigger than critical *F*-ratio value, which is determined from *F*-ratio distribution tables using degrees of freedom f_1 and f_2 and significance level *P*, then the equation must be described using analysed data and can be used for further analysis [16].

1.3. Multicriteria Decision Making Analysis

Multicriteria decision analysis is being used to analyse economic, social, environmental, and institutional parameters of different system development scenarios. One of the methods used for multicriteria decision analysis is TOPSIS, which connects various factors and determines the best development scenario [17].

To carry out the TOPSIS analysis, an input data matrix must be compiled.

$$\begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccccc} b_1 & b_2 & \cdots & b_j & \cdots & b_n \end{array} \\ \begin{bmatrix} b_{11}^k & b_{12}^k & \cdots & b_{1j}^k & \cdots & b_{1n}^k \\ b_{21}^k & b_{22}^k & \cdots & b_{2j}^k & \cdots & b_{2n}^k \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ b_{i1}^k & b_{i2}^k & \cdots & b_{ij}^k & \cdots & b_{in}^k \\ \vdots & \vdots & \cdots & \cdots & \cdots & \vdots \\ b_{n1}^k & b_{n2}^k & \cdots & b_{nj}^k & \cdots & b_{nn}^k \end{bmatrix} \end{array}. \tag{1.14}$$

After compiling the matrix, the data are normalized using the following methodology:

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}. \tag{1.15}$$

The next step is to calculate the values of the weighted normalized matrix.

$$v_{ij} = w_j n_{ij}. \tag{1.16}$$

Then the separation measures from the positive ideal solution and the negative ideal solution are determined according to the calculations of relative positive ideal solution shown in Equation (2.17).

$$R_i = \frac{d_i^-}{d_i^- + d_i^+}. \tag{1.17}$$

The relatively positive ideal solution is calculated, and the rank of proposed solutions is determined. The results of the multicriteria decision analysis for the heat production development scenario are shown in Section 2.4.

1.4. The Model of Emergy Indicators

To carry out emergy analysis, deferent parameters and indicators are used. All the resources used to create a product or service are divided into four groups: renewable resources (R), non-renewable resources (N), goods (G), and services (S). In the calculations, materials and services are combined in one group representing imported energy (F). Renewable and non-renewable resources are taken from the environment and are not paid for directly, such as solar energy and wind. Materials and services are imported into the system from other systems [18].

Empower stands for the value of emergy's flow. Its unit of measurement is emjoules per year. Different types of flows can be compared, all expressed in terms of empower [18].

The ratio of the emergy of a product or service to its energy is defined as the transformity. The unit of transformity are solar emjoules per joule (seJ/J). The transformity is the emergy needed to generate one joule of energy needed to create a product or service. The more energy is required in conversion process in the production of a product, the higher the transformity value of that product. This is because each time energy is converted from one form to another, the available energy is used to create less of the other form of energy. Therefore, the emergy increases but the energy decreases, and the transformity value increases rapidly. The highest transformity value is for human services and information, because energy for information distribution is what provides the exchange of information, such as paper, hard disk, etc. For example, if 100 000 J of sunlight is needed to generate 100 J of energy from plants, then the conversion factor is 1000 seJ/J. The more energy is needed (transformity increases) to generate other types of energy form solar energy, the higher the quality of energy. [19]

To compare different systems, which are analysed with emergy methods, different emergy indicators are used [20]:

- emergy yield ratio (EYR);
- environmental load ratio (ELR);
- emergy sustainability index (ESI);
- empower density (ED);
- share of renewables (%R);
- emergy investment ratio (EIR).

EYR is an indicator that describes direct contribution of product or service to economy based in the product production and the provision of the service. This indicator is important for those systems that produce products that are important for the production of other products. EYR is calculated using Equation (1.18) [20].

$$EYR = \frac{Em}{Em_{\mathrm{F}}} = \frac{Em_{\mathrm{F}} + Em_{\mathrm{R}} + Em_{\mathrm{N}}}{Em_{\mathrm{F}}}, \tag{1.18}$$

where

Em – total emergy, seJ per year;

Em_{F} – total imported emergy, seJ per year;

Em_{R} – total renewable emergy, seJ per year;

Em_{N} – total non-renewable emergy, seJ per year.

EYR is the ratio between total emergy and imported emergy. The higher the value of EYR, the higher the consumption of renewable and non-renewable resources, which indicates the use of local resources [20].

ELR is the ratio between the sum of imported and non-renewable emergy and renewable emergy. ELR is calculated using Equation (1.19) [20].

$$ELR = \frac{Em_{\mathrm{F}} + Em_{\mathrm{N}}}{Em_{\mathrm{R}}}. \tag{1.19}$$

The higher the ELR value, the higher the load on the environment. A high environmental load is detected when the ELR value exceeds value ‘10’. The high load on the environment can be explained by high share of imported resources or large amount of non-renewable resources in the system [20].

Looking at the previous emergy indicators, it can be concluded that a high EYR and a low ELR are required for the system to be sustainable. This relationship is shown by the ESI, calculated using Equation (1.20) [20].

$$ESI = \frac{EYR}{ELR}. \tag{1.20}$$

If the ESI value is less than one, the production system has a high proportion of non-renewable resources, which indicates unsustainable production. The ESI value greater than one indicates that the system is sustainable. However, as the value of ESI grows, so does the share of renewables, but the number of services that affect the local economy, such as workers’ wages, decreases. [20]

Emergy calculations start with a diagram of the energy system. It helps to get an idea of the system, its components, processes, and problems. The energy system diagram shows the main parameters to be included in the emergy calculation table. Emergy and emergy per unit of currency are calculated for each incoming flow and product.

The uncertainty of the emergy analysis is significantly influenced by two factors. First of all, the insufficient and inaccurate data on the transformity values for input data should be noted. This is mainly the case for industrial products and transport systems. Another source of uncertainty comes from inaccurate process inventory and incomplete estimation of process inputs. For example, emissions from the production process create a load on the environment, and this load needs to be assessed. This requires information about the region’s ecosystem and requires a separate study and assessment.

When carrying out emergy calculations and using the transformity values for different input data, the origin of the data and the calculation chain must be carefully followed to avoid double accounting of input emergy.

2. RESULTS

2.1. Heat Production Efficiency

Efficiency calculations were carried out for flue gas condenser. As mentioned in the literature review and methodology, three types of efficiencies can be calculated for the flue gas condenser, and these efficiencies are:

1) power ratio between boiler and condenser;
2) efficiency of the condenser considered as a part of the boiler equipment;
3) efficiency of the condenser as an independent equipment.

All equations for the calculations of condenser efficiencies are shown in Section 1.1. Table 2.1 shows the results of calculated ratio between the boiler and condenser powers.

Table 2.1

Efficiency of Condenser (Type 1)

No.	Parameters	Unit	Value
1	Ratio to boiler capacity		0.302
1.1	Increase of efficiency using condenser $\Delta\eta_{c1}^{L}$		0.256
1.2	Increase of efficiency using condenser $\Delta\eta_{c1}^{H}$		0.2
1.3	Biomass economy ΔB	kg/s	0.19
1.4	Biomass economy δB		0.23

The first type of efficiency is often shown in manufacturer specifications; however, it is quite misleading for the heat plant operators. This type of efficiency helps to plan expected power and load, not the increase in total heat plant's efficiency.

The next type of efficiency calculated is the efficiency of a condenser that is considered as a part of boiler equipment. The results of calculations are shown in Table 2.2.

Table 2.2

Efficiency of Condenser (Type 2)

No.	Parameters	Unit	Value
2.1	Increase of efficiency using condenser $\Delta\eta_{c2}^{L}$		0.256
2.2	Increase of efficiency using condenser $\Delta\eta_{c1}^{H}$		0.2
2.3	Equipment (N_{th} + N_{c}) efficiency η_{b+c}^{L}	%	110
2.4	Equipment (N_{th} + N_{c}) efficiency η_{b+c}^{H}	%	86.23
2.5	Biomass economy ΔB	kg/s	0.19
2.6	Biomass economy δB		0.23

Using efficiency of the condenser, which is considered as a part of boiler equipment parameters 2.1, 2.2, 2.5, 2.6 are the same when Type 1 efficiency calculations are made. However, this efficiency shows the total efficiency of the heat plant. When lower calorific value is used, efficiency is 110 %, but when higher calorific value is used, efficiency of the heat plant is 86.23 %. The efficiency according to higher calorific value shows the real thermodynamic connection with fuel consumption.

The third type of energy efficiency of the condenser is calculated when the condenser is considered as a separate equipment. The results of these calculations are shown in Table 2.3.

Table 2.3

Efficiency of Condenser (Type 3)

No.	Parameters	Unit	Value
3.1	Efficiency of condenser η_{c3}^{L}	%	172.3
3.2	Efficiency of condenser η_{c3}^{H}	%	58

The results show that, when the condenser is used as a separate equipment, its efficiency should be calculated using only the higher calorific value. If a lower calorific value is used, then the water vapor in flue gas losses is not considered and calculations are against the laws of physics.

2.2. Regression Analysis

Two factor regression analysis

Two factor regression analysis was carried out for several systems to investigate its usefulness in the analysis of energy production systems. The first system which is analysed is biomass boiler with flue gas condenser.

In order to obtain the results, measurements of several parameters of the installed biomass boiler were carried out and the relationship between them was analysed. As mentioned in the methodology, Section 1.2, the parameters selected for regression analysis are based on literature analysis and parameter relationships.

At the beginning, the connection between the power of condenser and the return temperature from district heating system was analysed, and the results are shown in Fig. 2.1.

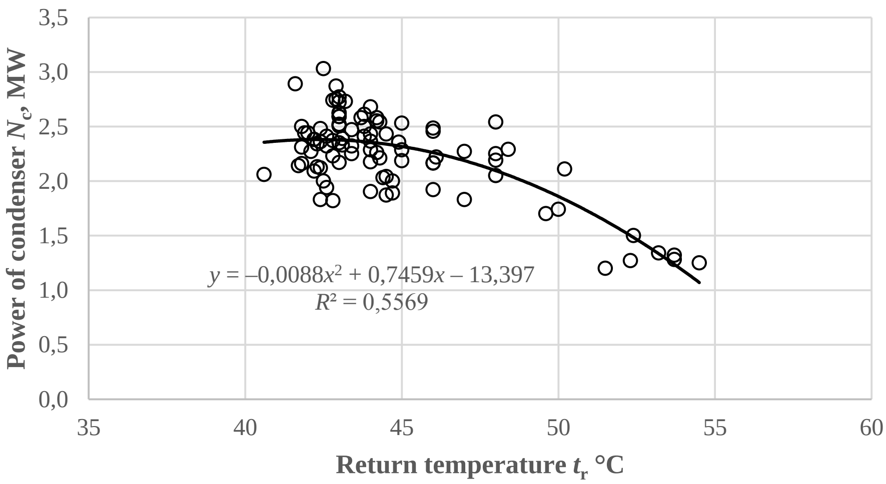

Fig. 2.1. Connection between condenser power and return temperature.

Figure 2.1 shows that the power of the condenser decreases when the return temperature is higher and increases when the return temperature is lower. The connection between them can be explained with the equation shown in Fig. 2.1. This observed connection agrees with the literature. When the return water is with higher temperature, it does not have a capacity to condense the entire vapor in flue gas, and that is why power of condenser is lower.

However, one of the main reasons why flue gas condensers are used is to increase efficiency of the heat plant. The increase of efficiency directly corresponds to the decrease of fuel consumption. That is why one of the parameters analysed in this work is the decrease of fuel consumption or, as it is called, the biomass economy (kg/s). To prove that the usage of condensers is useful, the connection between the biomass economy and the power on condenser is studied. This connection is shown in Fig. 2.2.

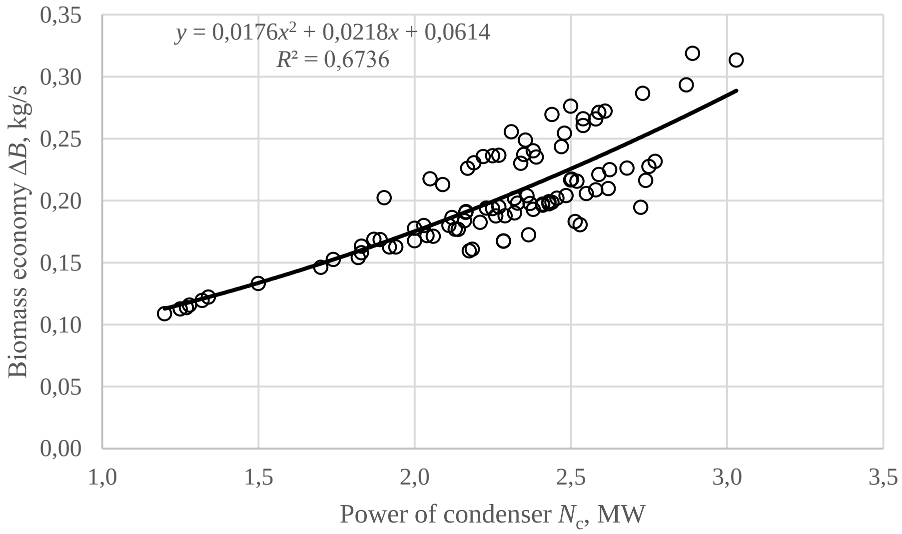

Fig. 2.2. Connection between biomass economy and power of condenser.

Figure 2.2 shows a very good connection between the two analysed parameters. This means that in order to increase efficiency of the power plant, the maximum power of the condenser must be used.

The second system analysed is solar collectors. The operation of solar collectors depends directly on the available solar energy. However, there are other factors in the solar collector system that can affect heat production. Figure 2.3 shows the relationship between the average monthly available solar radiation capacity and the monthly average heat production capacity.

The relationship between average monthly solar radiation and production capacity is shown in Fig. 2.3. In some cases, there are deviations from the average production curve, which indicates that other factors affect the operation of the collector system. This specific system is using 21 % of annual received solar energy.

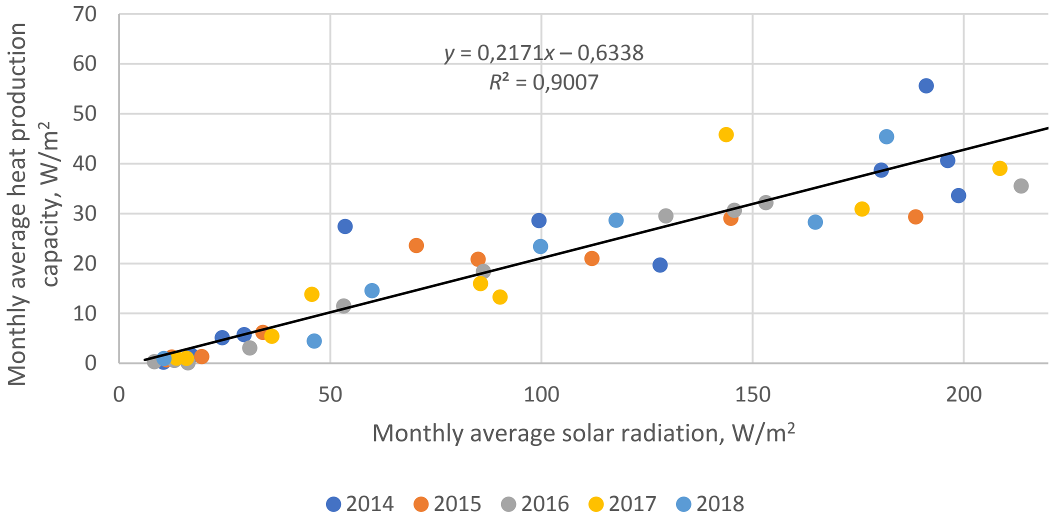

Fig. 2.3. Relationship between heat production capacity and solar radiation.

Multiple regression analysis

Multiple regression analysis is used to determine the effect of several factors (independent variables) on the dependent variable. Multiple regression analysis was approbated on a heat production system with a biomass boiler and a flue gas condenser. Since the two-factor regression analysis between the fuel savings and the condenser power showed a high correlation, the flue gas condenser power was chosen as the dependent variable for the multi-factor regression analysis to determine the optimal condenser operating conditions.

The aim of regression analysis is to gain multiple factor empirical equation, which describes the power of condenser quantitatively, which depends on different heat plants' parameters. This equation must consist of statistically significant variables and can be used for result projection and analysis of condenser.

Multiple regression is analysed by the following steps:

- the power of condenser as a dependent variable is tested for normal probability test;
- determined regression equation;
- statistical analysis of results.

Multiple regression analysis can be used if dependent variable, which in this case is the power of condenser, corresponds to the law of normal probability. This requirement does not correspond to independent variables. This test confirms that multiple regression analysis can be used if the result is positive. Table 2.4 shows the summary of statistics for normal distribution.

Table 2.4. shows summary statistics for the power of condenser. It includes variability measures, central tendency measures and shape measures. They are here for particular interest. It is used to detect if the sample has a normal distribution. Values outside the range of –2…+2 of standardized skewness and standardized kurtosis indicate departures from normality, which means that the used data is not describing. In this case the standardized skewness and standardized kurtosis values are in the expected range for data from normal distribution. This means that the data can be used for multiple regression analysis.

Table 2.4

Summary of Statistics for Normal Distribution of Condenser's Power

Count	94
Average	2.2499
Median	2.315
Standard deviation	0.377
Coeff. of variation	16.77 %
Minimum	1.2
Maximum	3.03
Range	1.83
Stnd. skewness	–1.99
Stnd. kurtosis	1.89

Multiple regression analysis started with a critical evolution of includable independent variables. It was decided that the independent variables for the analysis would be:

- the flow of flue gas in the condenser (G_k);
- the flow of spraying water (G_{sp});
- the power of the boiler (N_{kt});
- the amount of Oxygen in flue gas (O_2);
- the lower calorific value of fuel (Q_{zd});
- the temperature of return water (t_{k1});
- the air temperature (t_{ag});
- the temperature of flue gas before condenser (t_{g1});
- the temperature of flue gas after condenser (t_{g2});
- the temperature of sprayed water (t_{sp});
- the moisture content of the fuel (W_d).

The results of a multiple linear regression model, which is carried out as an output of program, describes the relationship between N_k and 11 independent variables. The results of multiple regression analysis are shown in Table 2.5.

Table 2.5

Results of Multiple Regression Analysis

Parameter	Estimate	Standard Error	*t*-Statistic	*P*-Value
Constant	–2.267 34	1.275 22	–1.778	0.0790
The flow of flue gas in condenser	0.005 339 73	0.001 369 33	3.899 52	0.0002
The flow of spraying water	0.380 81	0.074 631 5	5.102 54	0.0000
The power of the boiler	0.109 595	0.039 604 5	2.767 23	0.0069
The amount of Oxygen in flue gas	–0.069 192 5	0.029 251 4	–2.365 44	0.0203
The temperature of flue gas before condenser	0.011 138 8	0.004 565 9	2.439 57	0.0168
The temperature of return water	–0.037 789 4	0.008 455 31	–4.469 31	0.0000
The temperature of sprayed water	0.043 563 6	0.006 120 45	7.117 71	0.0000
The moisture content of the fuel	0.008 849 48	0.002 713 02	3.261 86	0.0016

As it is shown in Table 2.5, several chosen independent variables are removed from the equation. The equation of fitted model is

$$N_k = -2.267\,34 + 0.005\,339\,73 G_k + 0.380\,81 G_{sp} + 0.109\,595 N_{kt} - 0.069\,192\,5 O_2 + 0.011\,138\,8 t_{g1} - 0.037\,789\,4 t_{k1} + 0.043\,563\,6 t_{sp} + 0.008\,849\,48 W_d.$$

Since P-value in the ANOVA table is less than 0.05, there is a statistically significant relationship between the variables at the 95.0 % confidence level. The analysis of variance is shown in Table 2.6.

Table 2.6

Analysis of Variance

Source	Sum of Squares	*df*	Mean Square	*F*-Ratio	*P*-Value
Model	11.3595	8	1.419 93	63.91	0.0000
Residual	1.888 57	85	0.022 218 5		
Total (Corr.)	13.248	93			

The indication of R^2 value that the model explains 85.74 % of the variability in N_k. The adjusted R^2 statistic value is 84.40 %. It is more suitable for comparing models which have different numbers of independent variables. The standard error is calculated as 0.149. This value is used to construct reliable prediction limits.

With the developed model it is possible to determine the optimal parameters for the calculation of flue gas cogeneration capacity. Using this calculation model and analysing the values of the independent variables, it is possible to increase the capacity of the flue gas condenser, thus increasing the efficiency of the heat production system.

2.3. Economic Indicator Analysis for Local Heating Systems

The analysis is carried out on three different dwelling buildings where local heating systems are installed. The first building has a natural gas boiler, the second building has a combined system with a pellet boiler and a heat pump, and the third building has a combined system with a pellet boiler and a solar collector. The parameters characterizing the heating system are shown in Table 2.7.

Table 2.7

Characteristics of Heating Systems

	Natural gas boiler	Pellet boiler and water heat pump		Pellet boiler and solar collectors	
Installation year	2010	2018	2011	2011	2011
Heating system	*Buderus Logamax*	*NBE RTB*	*Stiebel Eltron WPF*	*GD-Turbo*	*TS300*
Capacity, kW	2 × 100	50	2 × 16.9	100	29
Maintenance costs, EUR per year	500	100	150	100	150
Efficiency, %	87.7	93.4	COP 3.1	82.9	–

After calculating the annual costs, the cost of energy production is determined for each heat production system. The costs of produced energy are shown in Fig. 2.4.

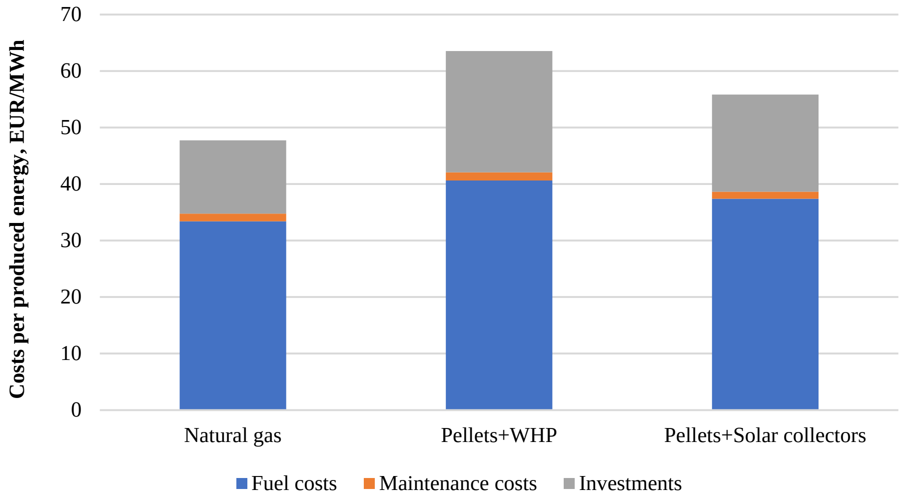

Fig. 2.4. Calculated costs per energy production.

The combined system of pellet boiler and solar collectors is discussed in depth further. Considering the amount of energy produced by solar collectors and investments, it was calculated that the annually averaged costs per produced energy were 234 EUR/MWh. To understand the scale of the required increase of solar collector system performance ratio and decrease of investments, Fig. 2.5 was created.

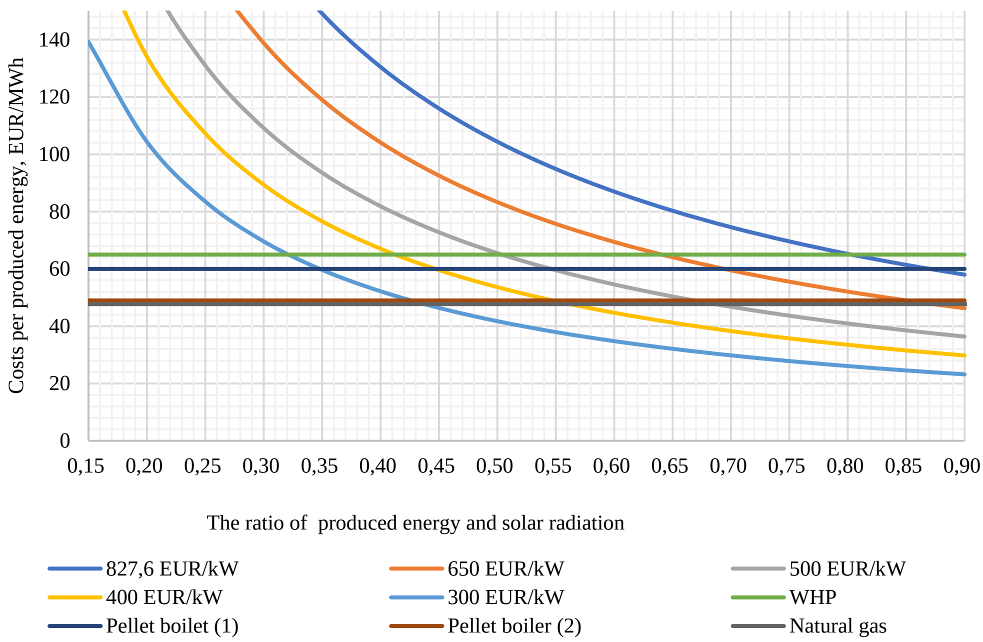

Fig. 2.5. Comparison of different heating systems and solar collector system.

Five different investment costs per kW were used from which 827.6 EUR/kW is the real situation to determine the point in which solar collector system performance ratio meets other heating systems. By analysing the established graph, it can be stated that the solar collector system performance ratio should reach 0.32 and the investments should decrease to 300 EUR/kW to meet the costs of other systems. The current situation in solar collector market shows that the quality of solar collectors is increasing, and different solar collectors reach efficiency up to 50 %, which allows to use solar energy more efficiently and produce much more energy per 1 m^2. At the same time, the cost of solar collectors has decreased significantly in the last ten years, which effects the investment costs and pay off time.

2.4. Multicriteria Decision Making Analysis

The created methodology has been approbated on one municipality's DH system in Latvia. DH system provides space heating and hot water for more than 100 buildings with end-use energy consumption of 25 000 MWh per year and DH distribution system length of 16 km.

Three midterm development scenarios were analysed using TOPSIS method for meeting the hot water demand in summer. Four indicators were chosen to analyse the proposed scenarios:

- investments, EUR/kW;
- fuel cost, EUR/MWh;
- emissions, t_{CO2}/MWh;
- Conformity to governmental and municipal planning documents.

A group of experts were asked to establish the weights on indicators and conformity to state and municipal planning documents, chosen indicators, development scenarios. The established indicators are shown in Table 2.8.

Table 2.8

Used parameters in Development Scenario Analysis

	Investments, EUR/kWh	Fuel costs, EUR/MWh	Emissions, t_{CO2}/MWh	Conformity to planning documents
Natural gas boiler	0	23.4	0.202	0
Wood chip boiler	250	18	0	1
Solar collectors with accumulation	650	0	0	1
Weights	0.3	0.2	0.35	0.15

The investment for a natural gas boiler is not considered 0, because currently the boiler house already has an existing natural gas boiler. The biggest investment is required to install a solar collector system with accumulation tank. Natural gas has the highest fuel costs and its use in the future does not comply with state and municipal planning documents.

According to TOPSIS methodology, which is described in Section 1.3, the obtained results are shown in Table 2.9.

Table 2.9

The Results of TOPSIS Calculations

	The positive ideal solution	The negative ideal solution	The relative positive ideal solution	Rank
Natural gas boiler	0.270	0.277	0.506	2
Wood chip boiler	0.208	0.248	0.544	1
Solar collectors with accumulation	0.292	0.216	0.425	3

The results show that the best choice would be the installation of wood chip boiler for supplying hot water in the analysed municipality.

2.5. The Model of Emergy Indicators

Emergy indicators for cogeneration plant in Latvia are calculated based on the provided methodology in Section 1.4. To carry out the calculations, a process scheme of cogeneration plant and system boundaries is established.

The results of emergy are as follows: emergy flow of renewable resources is $5.07 \cdot 10^{20}$ seJ per year, emergy flow of non-renewable resources is $4 \cdot 10^{18}$ seJ per year and emergy flow of imported services is $4.62 \cdot 10^{20}$ seJ per year.

By carrying out calculations for transformity value, the obtained results are as follows: weighted average transformity value is $4.18 \cdot 10^{5}$ seJ/J and combined transformity value is $4.1 \cdot 10^{5}$ seJ/J. As the weighted average transformity is higher than the combined transformity, resources are used efficiently.

The smallest part of inlet resources in the system is non-renewables, which are imported in the system directly. In order to provide services, non-renewable resources are also used indirectly, for example in transport, investments involving the construction of a facility, the electricity consumed, where part is produced from non-renewable resources, etc. Calculated emergy indicators are shown in Table 2.10.

Table 2.10

Emergy Analysis Indicators

Indicator	Symbol	Value
Emergy yield ratio	EYR	2.11
Environmental load ratio	ELR	0.92
Emergy sustainability index	ESI	2.29
Empower density	ED	$3.89 \cdot 10^{16}$
Share of renewables	%R	52.12
Emergy investment ratio	EIR	0.9

The calculated emergy yield ratio in analysed cogeneration plant is 2.11, which means that the system has a large amount of imported services. The environmental load ratio value is below 2, which means there is no large impact on environment by the cogeneration plant, because of the large amount of renewable resources. The emergy sustainability index value, which shows the ratio between emergy yield ratio and environmental load ratio, is higher than 1. This means that the produced energy in cogeneration plant is sustainable.

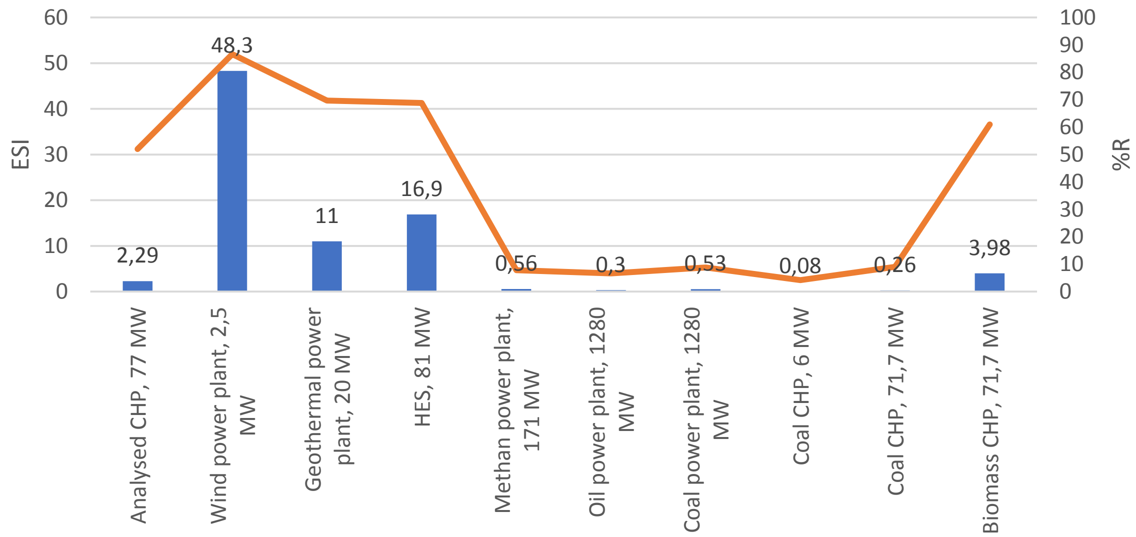

Fig. 2.6. Comparison of emergy indicators.

Comparing analysed cogeneration plant with other energy production systems, the results show that in energy systems where energy production is carried out without combustion process ESI value is significantly larger, despite the renewable share not being significantly different. However, in energy production systems where the share of non-renewables is large, ESI value is significantly lower.

2.6. Potential of Energy Management in Municipalities

Energy management in municipalities is critically necessary for the development of the energy sector in order to achieve the goals set by the state towards climate neutrality by reducing energy consumption, increasing efficiency and the share of renewable resources. As a significant part of final energy consumption in municipalities is heat energy, the development of a district heating development plan is important.

In order to prepare a successful district heating development plan, cooperation between the involved parties is very important, ensuring the effective exchange of the information as well as defining the responsibilities for involved parties. The actions of all parties involved must be defined in order to have an optimal assessment of the chosen development scenarios. In order to begin the development process, a decision by the municipality is necessary. In order to achieve an optimal result, the necessary tasks must be developed with the participation of all parties involved, including energy producer and/or district heating system operator (ES/OP) and energy consultant.

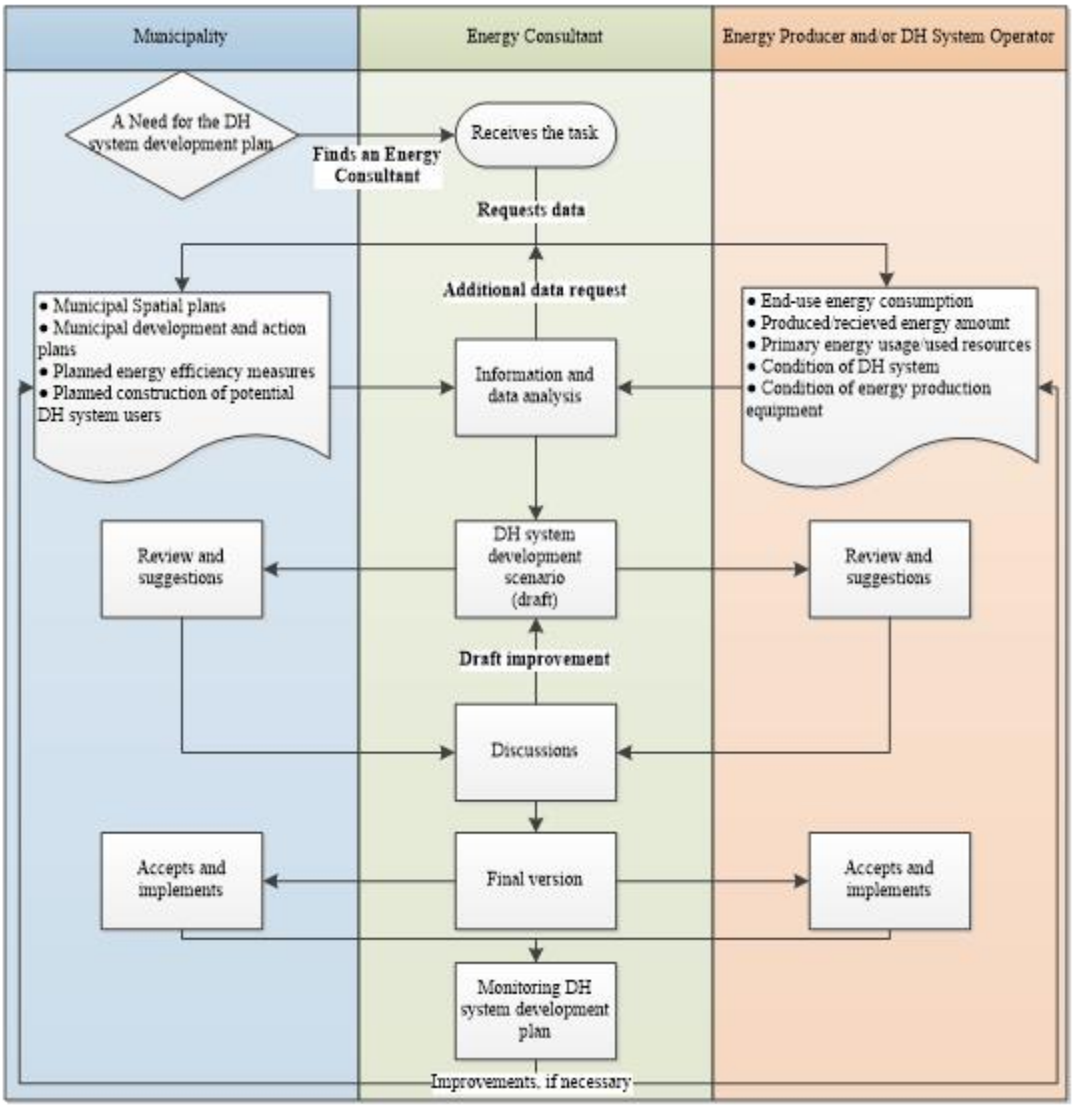

Fig. 2.7. An algorithm for implementation of DH system development plan.

After the tasks are defined, Energy Consultant develops a plan how to achieve the results and requests the necessary data from Municipality and EP/SO. Municipality must provide the information about the planned energy efficiency measures, potential increase of the district heating system users, give access to spatial, development and action plans that are related to the defined tasks. Municipality can request information for the involved parties, to ensure availability of requested information from Energy Consultant. EP/SO have to provide the technical information about the energy production, district heating system operation and end-use energy consumption.

Using the developed algorithm, it is possible to create a sustainable district heating development plan by incorporating sustainability indicators.

CONCLUSIONS

The evaluation of the sustainability indicators of the heating system has been performed using different methods, considering them in the context of the goal set by Latvia to achieve climate neutrality by 2050. Although various sustainability indicators for heating sector have already been proposed in literature, additional analysis of these indicators has been performed proposing new solutions and types of application, approbating them on existing heat supply systems in Latvia.

The Thesis discusses the calculations of heat production efficiency using flue gas condenser as an example. Three different types of efficiency calculations are considered indicating the advantages and disadvantages of their use. Flue gas condenser efficiency calculated as a power ratio between the condenser and the boiler can be used to plan the capacity to be installed, but it does not indicate an increase in the efficiency of the total heat production plant. In the case where the flue gas condenser is part of a heat production system, a more representative efficiency is done using the highest calorific value of the fuel, which allows to calculate the reduction in fuel consumption. The higher calorific value must also be used in the efficiency calculation if the flue gas condenser is considered as a separate heat production installation.

The Thesis consists of the regression analysis for two and more factors, for the analysis of flue gas condenser parameters, as well as the evaluation of solar collector efficiency. An empirical model for optimal flue gas condenser operation has been developed using a multi-factor regression analysis methodology. The developed model characterizes the variability of 84.4 % flue gas condenser power, determining statistically significant independent parameters. Using the developed model and analysing the values of independent variables, it is possible to increase the capacity of the flue gas condenser and thus increase the efficiency of the heat production system.

At the level of energy users, local heat production systems are analysed evaluating their economic parameters. The optimal investments required for the installation of solar collectors have been determined depending on the efficiency of the collectors in comparison with other local heat production systems. If the investment is 300 EUR/kW, the efficiency of solar collectors must be 35 % in order for it to be more profitable than the use of a heat pump and a pellet boiler. With an efficiency of 45 %, the annual use of solar collectors is more efficient than other analysed local heat sources.

The Thesis consists of multicriteria decision making analysis of the district heating system in Latvia, evaluating various development scenarios for energy installation. Including four different indicators, three types of energy source were analysed using the TOPSIS method. The results show that in the case of analysed district heating system the best solution is to install a new wood chip boiler.

By carrying out emergy calculations for cogeneration plant operating in Latvia, emergy flow for produced heat is $3.46 \cdot 10^5$ seJ/J and emergy flow for produced electricity is $5.59 \cdot 10^5$ seJ/J. In addition, emergy indicators have been calculated. Emergy sustainability index for the analysed cogeneration plant is 2.29 and the share of renewables is 52.1 %.

In the context of energy management, a methodology for a district heating system development plan has been created and approbated on a district heating system in Latvia. The responsibilities of the involved parties and the tasks to be performed for the development of a successful plan have also been determined.

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