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ENERGY AND EXERGY INDICATORS FOR INCREASING ENERGY SYSTEM EFFICIENCY

Summary of the Doctoral Thesis

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To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on ______________________________, 2019 at the Faculty of Power and Electrical Engineering of Riga Technical University, 12/1 Azenes Street, Room 115.

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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 Engineering Sciences is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Edvīns Terehovičs ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of Introduction; 3 chapters; Conclusions; 68 figures; 8 tables; the total number of pages is 128. The Bibliography contains 127 titles.

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NOMENCLATURE

A

a – smoked sprats (Baltic sprat and herring) in oil, MWh/month

B

b – roasted sprats (Baltic sprat and herring) in oil or in tomato sauce, MWh per month

C

COP – coefficient of performance (heat pumps, refrigeration / cooling systems)
c – fish balls, MWh per month

D

d_{ziv} – fish pate, MWh per month

E

EE – energy efficiency
E_k – energy released from the system as a product, kJ
E_{el} – specific electricity consumption, MWh_{el}/t
E_n – energy fed into the system with raw material, kJ
E_p – physical or chemical transformation of the raw material, kJ
E_{saule} – electricity from the solar energy, MWh
E_{zud} – energy loss, kJ
Ex_n – exergy fed into the system with raw material, kJ
$E_{no\ tīkla}$ – electricity from the grid, MWh
Ex/E; Ex/Q – Exergy factor
Ex_k – exergy released from the system as a product, kJ
Ex_{zud} – exergy losses in the environment, kJ
$Ex_{noārd}$ – exergy destruction in the power system, kJ
$E_{x,c}$ – heat carrier exergy in the heat supplied to the consumer, MWh
$E_{x,i}$ – heat carrier exergy after boiler house, MWh
$E_{x,lossA}$ – loss of exergy due to heat loss, MWh
$E_{x,lossB}$ – loss of exergy during transportation of the heat carrier, MWh
$E_{x,lossC}$ – loss of exergy caused in the heat exchanger, MWh
$E_{x,w}$ – exergy of electricity for circulation pump, MWh
e – Atlantic Ocean fish in oil or in tomato sauce, MWh per month
e_1 – exergy of air before dryer, kJ/s
e_{p2} – wet product exergy before dryer, kJ/s
e_{p4} – wet product exergy after dryer, kJ/s
e_{w2} – exergy of water in the product before dryer, kJ/s
η – energy efficiency
η_{ex} – exergy efficiency

G

GDP – gross domestic product

H

$h_{1\ NH3}$ – enthalpy of ammonia vapor before compressor, kJ/kg
$h_{1ž}$ – specific enthalpy of air before dryer, kJ/kg
$h`_{1NH3}$ – enthalpy of ammonia vapor before first stage compressor, kJ/kg
$h_{2\ NH3}$ – enthalpy of ammonia vapor after compressor, kJ/kg
$h`_{2\ NH3}$ – enthalpy of ammonia vapor after first stage compressor, kJ/kg
$h_{3ž}$ – specific enthalpy of air after dryer, kJ/kg
$h`_{3\ NH3}$ – enthalpy of ammonia vapor before second stage compressor, kJ/kg
$h_{5\ NH3}$ – enthalpy of ammonia before evaporator, kJ/kg
$h`_{5\ NH3}$ – enthalpy of ammonia vapor after second stage compressor, kJ/kg
$h`_{8\ NH3}$ – enthalpy of ammonia vapor after condenser before inlet in flash chamber, kJ/kg
$h`_{9\ NH3}$ – enthalpy of ammonia liquid in flash chamber, kJ/kg
$h`_{10\ NH3}$ – enthalpy of ammonia liquid before evaporator, kJ/kg
h_{p_2} – specific enthalpy of product before dryer, kJ/kg
h_{p_4} – specific enthalpy of product after dryer, kJ/kg
h_{w_2} – specific enthalpy of water in the product before dryer, kJ/kg
h_{w_4} – specific enthalpy of water in the product after dryer, kJ/kg

M

M_A, M_B – mass components of the substance introduced into the system, kg
M_C – mass of the final product substance, kg
M_{zud} – losses that occur during the process of evaporating part of the mass while remaining in the system, kg
m_a – air mass flow rate, kg/s
m_p – product mass flow rate, kg/s
m_{w_2} – mass flow rate of water in the product before dryer, kg/s
m_{w_4} – mass flow rate of water in the product after dryer, kg/s

Q

$\dot{Q}_{zud}$ – heat loss from dryer surface, W

R

RES – renewable energy resources
ΔR_{CO2} – emission factor for CO_2 emission reduction, t_{CO2}/MWh
R^{el}_{CO2} – emission factor for electricity from the grid, t_{CO2}/MWh
R^{saule}_{CO2} – emission factor for electricity from the solar energy, t_{CO2}/MWh

INTRODUCTION

Topicality of the Doctoral Thesis

The reality of the Latvian economy is that Latvia is located in a climatic zone where the consumption of energy resources for heat generation needs to be increased for almost six months a year. Most of the heat comes from fossil fuels, mainly based on gas, oil and coal. In the territory of Latvia, the abovementioned minerals are not available in the required amount. Therefore, it is important to use energy efficient technologies for successful development of the Latvian economy. This means that a thorough analysis of the power system, energy and exergy is required before any technological project is implemented. This analysis is based on the finding that the energy efficiency and energy system efficiency indicators are closely related to the power system indicators – system efficiency factor and energy and exergy losses.

The basic elements of any power system are the energy producer (converter), transmission and energy consumer. The national economy functions through technological processes and equipment of production and processing. The improvement of technological processes and their equipment, determination and research of optimal constructions and regimes is based on physical and mathematical modeling. In order to develop the mathematical models of the process and its equipment, one has to understand the processes and the mechanism of operation of the equipment and be able to express it mathematically. Analyzing the process, an analogy between these processes can be found, i.e., they are described by similar formulas.

Technological processes are the processing of raw materials and semi-finished products in industry. The technological process involves the mass of materials and aims to change the properties of these materials in the specified direction. The change in material properties is achieved by implementing energy and mass transfer between individual parts of the technological system. The technological process can be properly organized and monitored if its mass and energy balance is known.

Any technological process involves the consumption of certain substances and energy as well as the specific equipment that maintains the required operating mode (temperature, pressure, concentration, etc.) during the process. Generally, technological processes are classified according to the basic laws to which they are subject. Hydromechanical technological processes are subject to the basic laws of hydrodynamics. These processes include, for example, fluid transfer, settling, filtering, etc. Hydromenal technological processes are driven by pressure differential, centrifugal force. The technological processes of heat are related to the change of temperature in the participating environments. Such processes include heating, cooling, evaporation, etc. The thermal process is driven by the temperature difference. Mass-exchange (diffusion) technological processes involve the exchange of masses between phases. These processes include sorption (absorption, adsorption), extraction, drying, distillation, etc. These processes are driven by the concentration difference in separate phases. The mechanical technological processes are based on the fact that the material to be processed is subjected to mechanical forces, i.e., shredding, sieving, transportation of solids, pressing, etc. These processes are driven by mechanical pressure and centrifugal force. Chemical technological processes are associated with changes in the chemical structure of the material to be treated, i.e., chlorination, nitration, neutralization, etc. Chemical technological processes are driven by chemical propensity (direction), temperature, pressure, concentration.

Depending on the length of the technological processes, all processes can be divided into periodic and continuous processes. In a periodic technological process, its separate stages take place in the same plant at different times. In a continuous technological process, its separate stages are realized simultaneously in different equipment. Continuous technological processes compared to periodic processes have the following advantages: improved quality of products, simpler devices, more comfortable working conditions, processes easier to be automated.

The technological process can be properly organized and monitored if its mass and energy balance is known. The mass balance is based on the law of mass loss and the mass balance of real processes is described in equation

$$M_{\mathrm{A}} + M_{\mathrm{B}} = M_{\mathrm{C}} + M_{\mathrm{zud}}. \quad (1)$$

where M_{A}, M_{B} is substance weight components introduced into the system as a raw material, M_{C} is mass of the final product substance, and M_{zud} is losses occurring during the process, part of the evaporation of the mass remaining on the walls of the apparatus and pipes leaking through leaking places and so on.

Mass balance data are used for equipment calculations and their selection, energy balance compilation and other technological and economic calculations, as well as for a proper organization of the technological process. The energy balance shows how the energy required for a technological process breaks down in the process.

Using analogy with the mass balance, the energy balance can be expressed in general terms as follows:

$$E_{\mathrm{n}} + E_{\mathrm{p}} = E_{\mathrm{k}} + E_{\mathrm{zud}}. \quad (2)$$

Using analogy with the energy balance, the exergy balance can be expressed in general terms as follows:

$$Ex_{\mathrm{n}} = Ex_{\mathrm{k}} + Ex_{\mathrm{zud}} + Ex_{\mathrm{no\bar{a}rd}}. \quad (3)$$

Energy and exergy balance have similar mathematical description, but the difference is that the exergy balance takes into account not only the losses that occur in the environment, but also the losses that occur in the system itself.

After the restoration of Latvia's independence, various studies have been intensively conducted in the scientific environment on the issues of energy efficiency. The developed Doctoral Thesis or is related to solving specific problems, namely, the creation of an exergy balance model of power systems and its approbation using a specific practical problem example.

Aim and Tasks of the Doctoral Thesis

The aim of the Doctoral Thesis is to analyze energy efficiency in different energy supply objects using both energy and exergy balance and to find their use ranges and interactions.

The tasks of the Doctoral Thesis are two-dimensional, one dimension being the scope of the energy supply companies:

1) heat supply company;
2) fish processing company;
3) pellet production company;
4) solar power plant.

This scope makes it possible to capture the diversity of power systems to analyze energy efficiency.

The second dimension is the scope of the analysis of these companies:

1) energy analysis using energy balance method;
2) exergetic analysis with the use of exergy balance;
3) comparison of the results of energy and exergy analysis and finding out the interaction.

This scope provides an opportunity to develop a universal approach to energy and exergy balance of the abovementioned companies and to formulate their use ranges and interactions.

The work consists of three chapters. In the first chapter, using different sources of literature, an understanding of exergy, the theoretical foundations of mathematical calculation of exergy and an overview of the peculiarities of exergy analysis of district heating systems in different European countries are formulated. Nowadays, the scientific perception of energy is that it is the sum of exergy and energy, and exergy is the part of energy that characterizes the useful work of the thermodynamic system. Efficient management of energy saving is directed specifically at reducing anergy growth and increasing exergy.

In the Chapter 1 of the Thesis, using the special and scientific literature, the basics of calculating the exergy calculations of the thermodynamic system were formulated, as well as the creation of the exergy balance of the thermodynamic system was studied. The following system thermodynamic parameters are used in the closed system for the exergy calculation of the substance: internal energy, entropy, temperature, pressure and volume. Calculation of heat flow exergy is related to the fact that the functioning of the technological system is conditioned by the energy exchange with the environment. By transferring from one body to another body and the environment energy in the form of heat flow (heat exchange), a certain amount of exergy moves along with the flow. The exergy balance is formed on the basis of an efficient operation of the thermodynamic system in determining exergy parameters. For any real system, such balance is the integration of all exergy flows at the entrance and exit from it taking into account the loss of exergy consumption. Chapter 1 also examines the exergy analysis of district heating systems in Denmark, Sweden, Turkey and Slovenia and the experience of using them in these countries. For example, the use of exergy analysis could determine the quality of the energy supplied, thus determining which fuel to use to reduce the loss of exergy. For exergy analysis it is useful to use several model calculation scenarios. Exergy of heat energy should be taken into account when determining the heat price.

In Chapter 2 of the Thesis, a model of calculation of exergy balance of a district heating system was created and certain exergy losses in each element of the heating system, i.e., a specific research methodology for the task solution is offered. Technical data of operation of a heat production plant has been taken as output data. The output data block includes data on the capacity of a boiler house, the heat produced, heat losses of the district heating network, the flow and return temperatures, electricity consumed by the circulation pump, the heat supplied to the consumer and other data. The model of exergy balance of the district heating system is based on the second law of thermodynamics, which states that wherever and whatever changes in the material systems occur, they are always accompanied by energy conservation and entropy changes in isolated systems and by energy changes and entropy changes in open systems. The mathematical calculations of exergy changes in the district heating system are based on the exergy balance. The exergy balance determines how the exergy of heat energy changes from the district heating system to the consumer, which allows us to estimate the stage at which the greatest losses occur.

Chapter 3 of the Thesis is a practical approbation of the exergy balance model on different power systems. The approbation of the exergy calculation model was carried out within the framework of the implementation of various scientifically practical research projects. The following data are taken as output data: amount of heat produced, heat carrier flow and return temperature, ambient (outdoor) temperature, boiler house capacity, heat losses, electricity consumed by the circulation pump, amount of heat supplied to the consumer and other process parameters of the process. The approbation data of exergy balance model are summarized in tables and graphs and compared with European countries' experience.

Hypothesis of the Doctoral Thesis

The hypothesis of the Doctoral Thesis – the use of energy and exergy balances will create an opportunity to improve understanding of the causes of energy system losses and possibilities of their reduction, which, in turn, will create theoretical foundations for elimination of errors and shortcomings in practice.

Examining the correctness of the hypothesis put forward, a study was carried out on the possibilities of assessing energy efficiency of a power system by reducing unnecessary energy consumption. In order to carry out the research it was necessary to find out:

- internal structure and characteristics of energy;
- the amount of exergy in the power system using the theoretical foundations of exergy calculations;
- energy and exergy changes in the power system.

Methodology of Reasearch

During testing of the proposed hypothesis, various research methods were used that would make it possible to clearly identify energy efficiency and energy and exergy indicators. The interaction of these indicators is illustrated in Fig. 1.1.

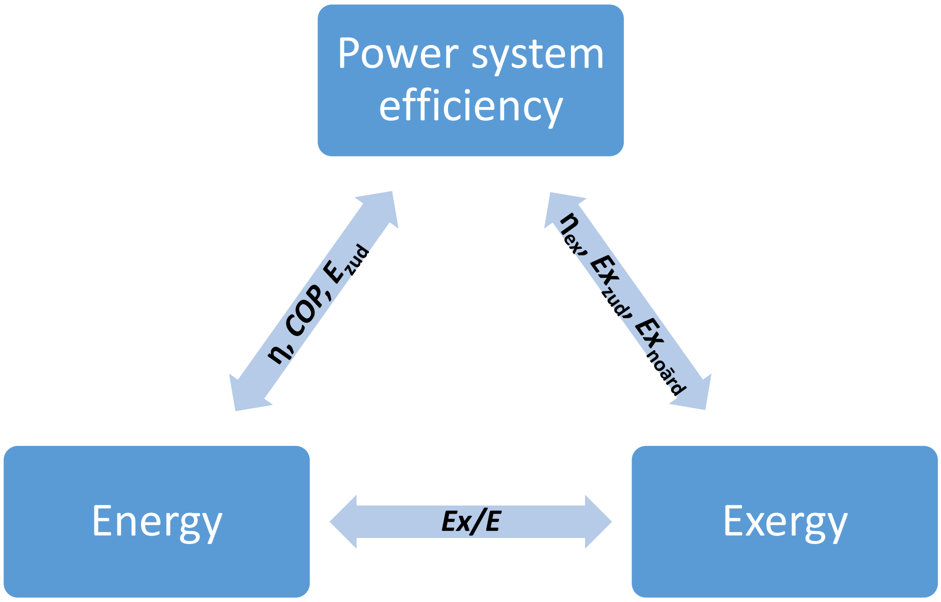

Fig. 1.1. Interaction between power system efficiency and its indicators "energy" and "exergy".

For illustration of research results, the following was taken into account:

1. Use of energy balance to link energy and power systems using the following indicators: η – energy efficiency; *COP* – coefficient of performance (heat pumps, refrigeration / cooling systems); E_{zud} – energy loss.
2. Use of exergy balance to link exergy and power system using the following indicators: η_{ex} – exergy efficiency; Ex_{zud} – loss of exergy, depending on the amount of energy loss; $Ex_{noārd}$ – exergy destruction in the power system.
3. Use of exergy factor to link energy and exergy using the following indicator: *Ex*/*E* – Exergy factor.

The choice of each appropriate method was dependent on the complexity of the specific task, the available data, and the boundaries of the research, as well as on the constraints that were conditional in the particular situation at each stage of the study.

Scientific Significance of the Doctoral Thesis

During the process of the research, a complex study was made on the possibilities of using energy and exergy balance, thus improving the understanding of the causes of energy system losses and possibilities of their prevention. In this way, a study was carried out on the development of models for calculating the energy and exergy balance of different energy systems.

This study is based on theoretical approaches to energy and exergy and mathematical basics of calculations. An empirical test of interaction between energy efficiency indicators has been performed. This type of approach and mathematical basics of calculation have been used to define three different directions of the research: 1) use of energy balance in energy system assessment by identifying essential indicators that can be used to study energy efficiency of a power system; 2) use of exergy balance in evaluation of a power system by identifying the most important indicators that can be used to study energy efficiency of a power system; 3) use of exergy factor to link energy and exergy to the energy system energy efficiency assessment.

Practical Significance of the Doctoral Thesis

The results of the Doctoral Thesis can be used to improve understanding of interaction of efficiency, energy and exergy of energy systems.

Based on this perception, there is an objective opportunity to develop specific practical recommendations for certain energy-intensive sectors of the economy, such as district heating system, large-scale production processes in companies, etc.

During the process of the research the author of the Doctoral Thesis was able to demonstrate the correctness of the chosen research methodology in calculating energy and exergy balance in district heating system, food production using solar energy, wood pellet production and fish processing.

In this way, the results of the promotion work can be used by:

1) ministries and agencies in drafting legislative documents;
2) energy-intensive industry professionals, such as specialists of heat supply and of large-scale production processes in energy-efficient companies;
3) as a training tool for educating energy specialists, especially in areas related to monitoring energy efficiency of power systems.

Approbation of Research Results

The research results have been approbated in 4 international scientific conferences and published in 7 full length articles in international scientific journals and conference proceedings.

Conferences

1. Terehovics E., Veidenbergs I., Blumberga D. Exergy analysis for district heating network. International Scientific Conference “Environmental and Climate Technologies”, CONECT 2016, 12–14 October 2016, Riga, Latvia, 2017, pp. 189–193.
2. Terehovics E., Khabdullin A., et. al. Why solar electricity has high potential for Kazahstan industries. International Scientific Conference “Environmental and Climate Technologies”, CONECT 2016, 12–14 October 2016, Riga, Latvia, 2017, pp. 417–422.
3. Terehovics E., Veidenbergs I., Blumberga D. Energy and exergy balance methodology. Wood chip dryer. International Scientific Conference “Environmental and Climate Technologies”, CONECT 2017, 10–12 May 2017, Riga, Latvia, 2017, pp. 551–557.
4. Terehovics E., Soloha R., Veidenbergs I., Blumberga D. Analysis of fish refrigeration electricity consumption. International Scientific Conference “Environmental and Climate Technologies”, CONECT 2018, 16–18 May 2018, Riga, Latvia, 2018, pp. 649–653.

5. Terehovics E., Soloha R., Veidenbergs I., Blumberga D. Cleaner production nodes in fish processing. Case study in Latvia. 10th International Conference on Applied Energy (ICAE2018), 22–25 August 2018, Hong Kong, China, 2018, pp. 3951–3956.
6. Terehovics E., Veidenbergs I., Blumberga D. Parameters that affect electricity consumption in fish freezing. Case study. Environmental and Climate Technologies. Special Issue. 2019. 12 p. (In press). Scopus and Web of Science Data base.
7. Terehovics E., Veidenbergs I., Blumberga D. Analysis of operation parameters of fish refrigeration by exergy analysis. Case study. Environmental and Climate Technologies. Special Issue. 2019. 12 p. (In press). Scopus and Web of Science Data base.

Scientific papers

1. Terehovics E., Veidenbergs I., Blumberga D. Exergy analysis for district heating network. Energy Procedia 113 2017, pp. 189–193.
2. Terehovics E., Khabdullin A., et. al. Why solar electricity has high potential for Kazahstan industries. Energy Procedia Volume 113, May 2017, pp. 417–422.
3. Terehovics E., Veidenbergs I., Blumberga D. Energy and exergy balance methodology. Wood chip dryer. Energy Procedia 128 2017 pp. 551–557.
4. Terehovics E., Soloha R., Veidenbergs I., Blumberga D. Analysis of fish refrigeration electricity consumption Energy Procedia Volume 147, August 2018, pp. 649–653.
5. Terehovics E., Soloha R., Veidenbergs I., Blumberga D. Cleaner production nodes in fish processing. Case study in Latvia. Energy Procedia Volume 158, February 2019, pp. 3951–3958.
6. Terehovics E., Veidenbergs I., Blumberga D. Parameters that affect electricity consumption in fish freezing. Case study. Journal of Environmental and Climate Technologies. Special Issue. 2019. 12 p. (In press). (Scopus and Web of Science Data base).
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1. RESEARCH METHODOLOGY

1.1. Determination of Exergy Balance of Heat Supply System

The possible use of any technological process involves a thorough analysis of its necessity, the selection of possible technological processes and the analysis of basic parameters of each selected process, the choice of the optimal process and the development of its model. In technological processes, the main purpose of which is heat supply, which is closely related to the efficient use of energy resources, it is important to create the exergy balance model of the heating system and to have its practical approbation. The exergy balance model of the heat supply system is based on a thorough algorithm of mathematical calculation of heat and mass exchange processes, which includes determination of the required information blocks and their impact on the final results.

Each element of the heating system can be viewed as an independent thermodynamic system. Efficiency of the element work can be evaluated by comparing the working capacity of the body at the entrance to this element and the size of the loss of capacity (as a result of irreversible processes in the system elements). The advantage of the exergy method lies in the fact that it allows to analyze the thermodynamic processes of a heating system element without the need to evaluate the useful work of the whole heat supply system and its losses in all its elements; this somewhat facilitates the calculation process. Due to the fact that in most cases the operation of heat supply equipment is related to the continuous flow of the working substance (heat carrier), it would be necessary to use the concept of system capacity in case the processes in this system flow in order to facilitate the analysis of the operation of these equipment [1].

1.2. Aspects of Model of Calculation of Exergy Balance of Heat Supply System

The model of exergy balance of a heat supply system consists of a sequence of the following activities: compilation of the exergy balance, obtaining the necessary output data, making assumptions about unknown values followed by the calculation itself, analysis of results, and graphical representation of the final results. The model of exergy balance of the heat supply system is shown in Fig. 1.1.

The output data block contains data on the technical data of operation of the heat production plant. For any calculation method the choice of output data is important. Output data in this model is the second most important component of formulas. The choice of data depends mainly on the chosen formulas. The output data block includes data on boiler house capacity, heat output, heat losses of heating networks, flow and return temperatures, electricity consumed by the circulation pump, heat supplied to the consumer, and other data.

The assumption data block firstly depends on the actual temperature data. For example, the room comfort temperature depends on the traditional way of life and the custom of dress. In different countries it is as follows: 18–20 °C in Switzerland, 18–20 °C in Germany, 19.6–21.8 °C in USA, and 15.5–20 °C in England. The release of body heat into the environment is possible through four channels: conduction, convection, evaporation, and radiation. Conducting is associated with heat transfer in direct contact with environmental surfaces. Convection provides heat through contact with ambient air. The energy consumption of the warm water supply of modern apartments is 30 % of the total heat consumption. Therefore, this process can generate a lot of energy savings. This is achieved by adjusting the water temperature to a constant low level; in most cases 55 °C is a completely sufficient temperature, as it reduces the scale deposits and has no danger of scalding [2]. Secondly, the assumption data block depends on the fact that the heat supply can take place in different heating systems, such as furnace heating, centralized water heating, centralized heating or radiation (drying) [3].

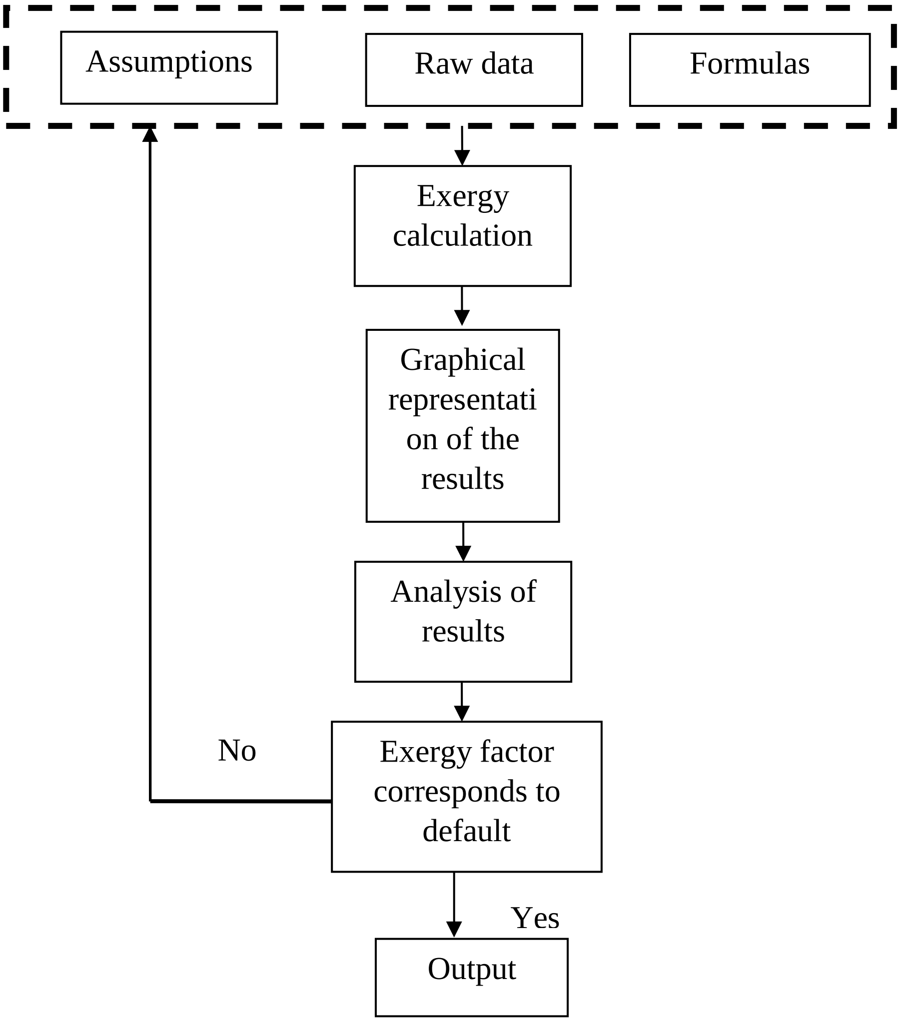

Fig. 1.1. Algorithm of exergy balance model of heat supply system.

Thirdly, the data block of assumptions includes theoretical knowledge that is relevant to contemporary science. The idea of a heat supply system is based on the Carno cycle. The operation of heat supply system is based on the possibilities of exergy of the heating system, which are based on the following opinions [4]:

1. Entropy is a measure of loss of system performance due to irreversible processes. The loss of work from irreversible processes is directly proportional to the increase in entropy. The impact of irreversibility on job loss can be quantified. The maximum share of heat, which is transferred from one system to the other, can be modified into the system's work, which is defined by the Carnot coefficient of useful work.
2. Entropy is a measure of system performance, technological efficiency (value) of heat. Increasing the entropy of an isolated system is associated with a fall in the energy value, i.e., a decrease in its exergy potential.
3. Entropy is a measure of system disorder, degradation and disorganization. If heat is removed from the system, its entropy is reduced. Thus, the order of the system increases, as the chaos of molecular and atomic heat transfer decreases. As a result of all possible irreversible measurements, the system regenerates, degrades and moves to the next state:
   - all system bodies reach the same temperature;
   - all the useful amount of work is converted into heat;
   - substance concentration and pressure equalize;
   - substance in the system has undergone extreme shattering and uniform mixing.

The thermodynamic method is based on the fact that, wherever and without any changes in the material systems, in isolated systems they are always accompanied by energy conservation and entropy changes, but in open systems – by energy changes and entropy changes [4].

Currently, two approaches to research on exergy in technical systems are used in thermodynamics. The first approach is based on Carnow's direct and reverse cycle analysis methods. A typical example is the creation of an absolute temperature scale, where several sequentially linked Carno cycles are artificially entered. These methods, based on the first and second laws of thermodynamics, make it possible to find a link between the amount of heat and work and the parameters of the system. When compiling the exergy balance of the system, it is possible to find the coefficients that characterize the study cycle and compare them with the coefficients of the corresponding ideal cycle. In this case, it is possible to determine the total loss of work due to irreversibility of the processes in the given system. These losses could be divided into two parts. The first part, which is related to the cycle process imperfection, refers to internal losses. The second part of the loss is related to the interaction between the system and external energy sources and recipients and refers to external losses [4].

The second approach is based on the application of thermodynamic potential to analyze the transformation of energy into different systems. The cycle method requires purely artificial shapes / constructions and roundabouts to solve specific tasks. With the development of thermodynamics, this method has given its place to the second approach based on the creation of thermodynamic functions. The number of thermodynamic functions, which are large enough, is highlighted in the middle of so-called characteristic functions, which have the characteristic that the individual characteristics of the characteristic function according to the parameters are the same for one or another system parameter. Because of this, such derivatives obtain the simplest expression and clear physical meaning. The functions characterizing the condition are called functions by which all the thermodynamic properties, including state equations, can be clearly expressed through the various layers of derivatives. Characteristic functions that completely define all the thermodynamic properties in the system are also called thermodynamic potential [4].

Potentially, thermodynamics allow to directly find the size of any type of job in those or other conditions. They can be used to evaluate the energy flow and the working capacity of a substance at any point of the system under consideration, regardless of its structure and complexity [4].

Exergy, unlike the energy associated with the fundamental qualities of matter, is a separate concept that characterizes the validity of energy in given environmental conditions. An exemplary method is called a research method based on the analysis of loss of capacity for thermodynamic processes. Exergy indicators are directly related to the technical characteristics of the equipment; it allows to find the most favorable parameters and sizes of the planned thermal power plant [4].

Exergy depends on the energy and ambient temperatures. The less reversible the process and the more work is done, the more exergy there will be. All this allows us to introduce the concept of exergy efficiency of the so-called process, or the exergy efficiency coefficient. This is determined by the relationship between exergy used and exergy delivered. In heat exchangers, this will be the ratio of exothermic output of the heat carrier to its exertion at the entrance. Exergy efficiency coefficient allows to take losses into account only due to irreversible processes, because only irreversible processes are lost in exergy. Therefore, it is not applicable to all feedback cycles, i.e., in all cases $\eta_e = 1$ [4].

Exergy calculation combines output data, assumptions and formulas. Calculations should be made over several months to get an idea of the efficiency of the heat supply system at different loads. It is better to make such large calculations in MS Office Excel for quick and accurate results. In the event of an error in the output data or formula, it can be corrected quickly.

The mathematical calculations of exergy changes in the heat supply system are based on the exergy balance. The exergy balance allows us to describe and clarify how the exergy of heat energy changes from the heat center to the consumer, which allows to assess at which stage the greatest losses occur. Exergy balance is determined according to Equation (2.1) [5]:

$$E_{\mathrm{x,i}} + E_{\mathrm{x,w}} = E_{\mathrm{x,lossA}} + E_{\mathrm{x,lossB}} + E_{\mathrm{x,lossC}} + E_{\mathrm{x,c}}. \tag{2.1}$$

On the left side of the balance, $E_{\mathrm{x,i}}$ is exergy of the heat transfer fluid after boiler house and $E_{\mathrm{x,w}}$ is electric power exergy of the circulation pump. On the right side of balace, $\dot{E}_{\mathrm{x,lossA}}$ shows exergy losses resulting from the losses of heat, $E_{\mathrm{x,lossB}}$ is exergy losses during the time of transporting the heat transfer fluid, $E_{\mathrm{x,lossC}}$ is exergy losses arising at the heat exchanger, and $E_{\mathrm{x,c}}$ is is the exergy provided for consumer. The left side of the exergy balance shows how much exergy has been fed into the heat supply system, but on the right side – how the total exergy breaks down by the specific losses.

2. RESULTS AND DISCUSSION

2.1. Exergy Analysis of District Heating Network

The approbation of exergy analysis of district heating system was performed on the example of the Ludza heat supply system. The Ludza heating system, which is managed by "Ludzas Bio-enerģija" Ltd, consists of branched pipelines that deliver heat from the boiler house to the consumer. The pipeline system is divided into 25 main sections. The main elements of such a system are the boiler house and the pipelines. The heat produced in the boiler house is transferred from a higher to a lower temperature environment, which results in a reduction in the quality of heat. The pipelines are used to transport the heat produced to the consumer and are one of the main sources of heat loss. In the system under review, heat losses were accounted for 8.54 % of the heat produced on average. The pipeline system was renovated 13 years ago, replacing the Soviet-era pipes with modernly insulated pipes that meet modern requirements. The internal diameter of these pipelines is between 37 mm and 263 mm.

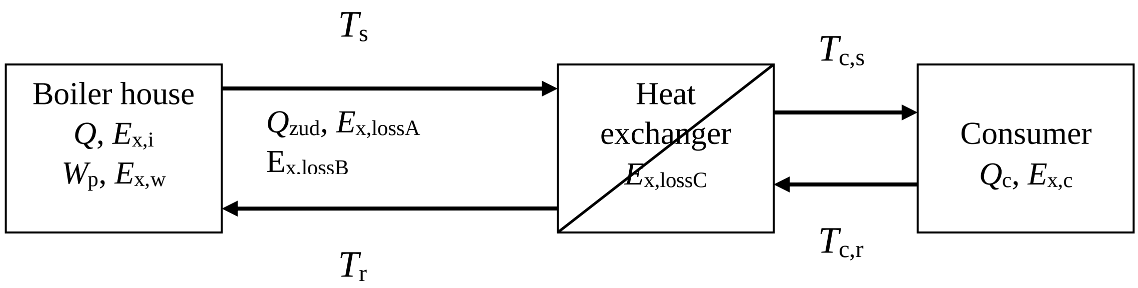

Fig. 2.1. Principal scheme of district heating system.

The total length of the pipelines is 9770 m. The average flow and return temperature in the heating circuit is 71.31 °C and 47.13 °C, while the average pressure is 8 bar. On the consumer side, the average flow and return temperature was 63.32 °C and 39.15 °C, respectively, but the pressure depends on the atmospheric pressure. Thermal energy is transferred from the heating pipeline to the consumer's heating network using a plate heat exchanger.

The approbation of the model is based on the heat supply data of "Ludzas Bio-enerģija" Ltd. Exit data were collected for 2008/2009. The annual heating season lasted from October to April inclusive, totaling 214 days. Information for the whole year was not available because the recording of heat consumption during the summer months was not regularly documented in the accounting journal. The following daily average data were taken from the heat supply system logbook:

- amount of heat produced;
- heat carrier supply and return temperature;
- ambient (outdoor) temperature;
- boiler house output;
- heat loss;

- electricity consumed by circulating pump;
- the amount of heat supplied to the consumer.

In the process of calculations, it was assumed that the average temperature drop in the heat exchanger between the heat carrier of the heating line and the heat carrier of the consumer circuit is 5 °C. The heat carrier temperature drop from the boiler house to the last consumer is 3 °C. As no holiday data was available, it was assumed that the weekly holiday data is the arithmetic mean between the day before the holiday and the day after the holiday.

Exergy calculation combines output data, assumptions and formulas to perform exergy analysis of a heating system. Thus, calculations have to be done over several months to get an idea of the efficiency of the heat supply system at different loads. It is better to make such large calculations in MS Office Excel for quick and accurate results. In case of an error in the output data or formula, it can be corrected quickly.

Graphically rendered results are easier to analyze because it is possible to detect possible errors in the calculation, which results in loss of results from the overall result dynamics. The main cause of these errors is an incorrectly entered formula in calculation model or output data.

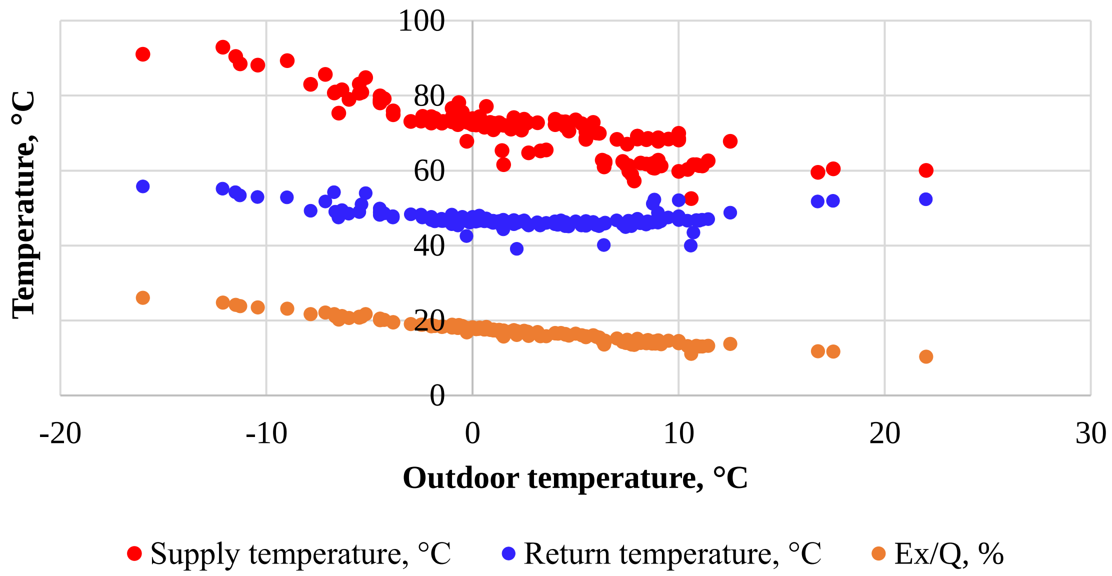

Fig. 2.2. Changes in temperature and exergy factors depending on outdoor temperature.

Comparison of changes in the temperature and exergy factor of the district heating system depending on outdoor temperature is shown in Fig. 2.2. From Fig. 2.2, it can be concluded that as the temperature of the environment decreases the supply temperature increases, as a result of which the exergy factor increases. The return temperature depends mainly on the needs of consumer. As can be seen in the figure, the difference between flow and return temperatures increases as the outdoor temperature decreases, but decreases as the outdoor temperature increases. This can be explained by the fact that, when the weather gets cooler, the heat output from the radiators increases, reducing the heat carrier temperature. But as the weather gets warmer, the heat output decreases, so the temperature drop in the heat carrier is lower.

When comparing the obtained exergy factors with the standard values of exergy factors found in the literature for district heating systems, it is possible to find out whether the calculations made are correct. The obtained results on the Ludza district heating system compared with the annual average values of the district heating system of other countries (see Fig. 2.3). In this case, the comparison is made with the Swedish and Danish district heating systems.

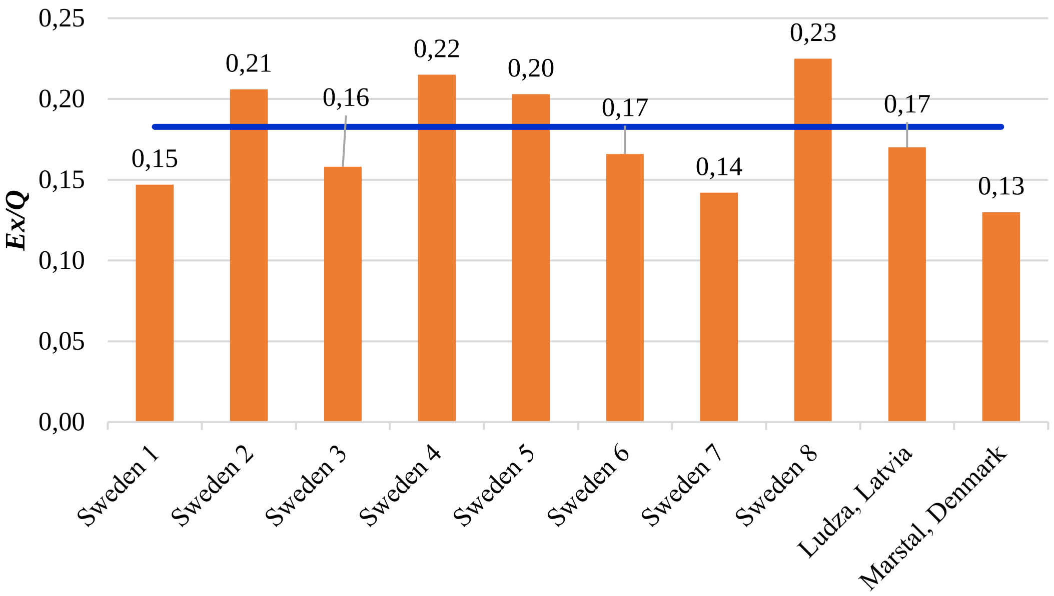

Fig. 2.3. Comparison of exergy factors [6].

Compared to the district heating systems of other countries (see Fig. 2.3), it can be concluded that the factor of exergy of the Ludza district heating system is closer to the Swedish heat supply exergy factor than the Danish. Changes in exergy factor are related to outdoor, flow and return temperatures. As the flow and return temperatures increase, while the outdoor temperature decreases, the exergy factor increases and vice versa. From the point of view of the district heating system, the exergy factor should be as low as possible, thus reducing the total loss of exergy.

Exergy losses due to heat loss, during heat transport, in the heat exchanger are reflected in Fig. 2.4. Largest exergy losses occur in the heat exchanger and during heat transportation. The slightest loss of exergy results from heat loss. In order to reduce the exergy losses in the exchanger, the technical condition of the heat exchanger should first be assessed. For older heat exchangers, heat exchange surfaces overlap with sediment, resulting in reduced efficiency and increased loss of exergy. Technical condition of heat exchangers should therefore be monitored regularly.

Exergy loss during transportation of the heat carrier depends on the temperature of the heat carrier – the higher the temperature, the less is the loss of exergy. But on the other hand, higher heat carrier temperatures mean more heat loss.

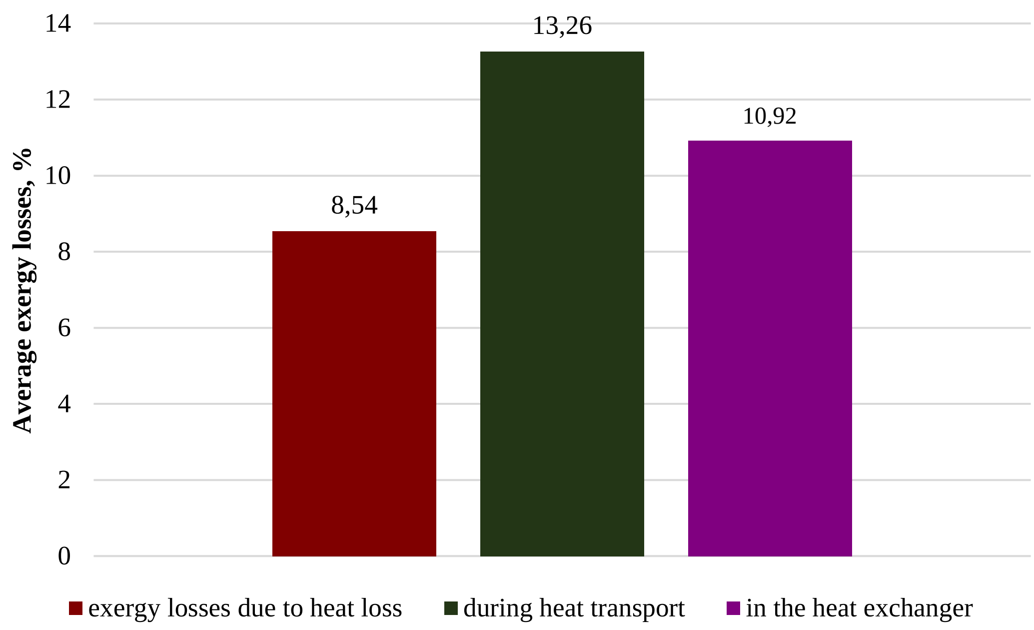

Fig. 2.4. Exergy losses of district heating system.

Losses generated during the transport of the heat carrier can be reduced by selecting energy efficient circulating pumps with the required capacity capable of delivering the required pressure in the heating circuit. Another way to reduce power consumption is by installing frequency converters for pumps. Thus, it is possible to change the pump speed without reducing the efficiency. Frequency converter reduces power consumption by 30 %.

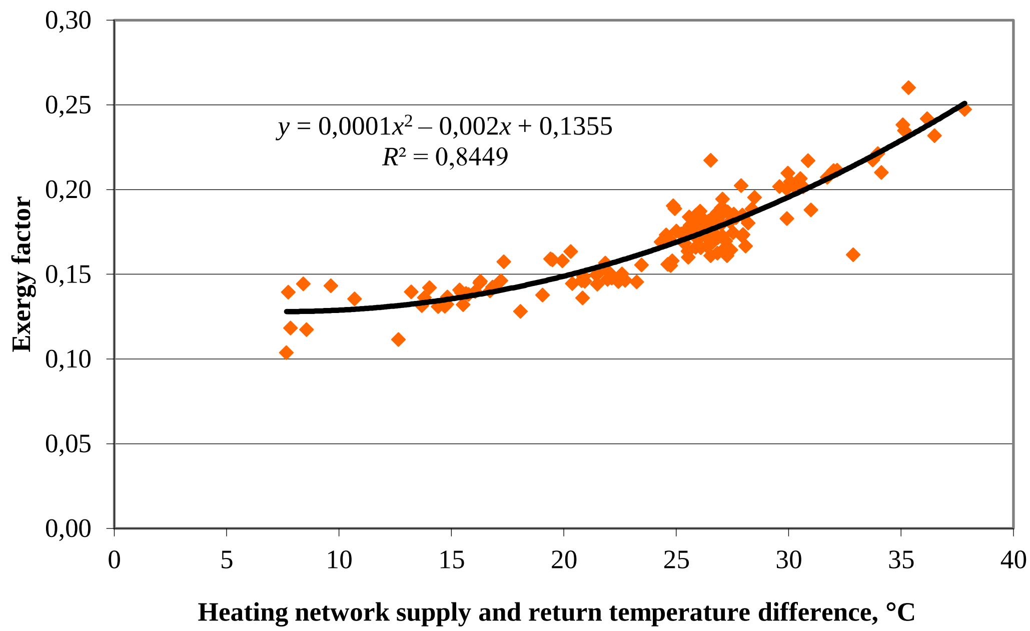

Fig. 2.5. Changes in exergy factor depending on the ratio of the supply and return temperature of the district heating system.

With the difference between the supply and return temperatures of the heat supply network (see Fig. 2.5), the exergy factor increases nonlinearly. In the case of small temperature differences, the exergy factor increases minimally, but the temperature difference increases faster. From the correlation coefficient it can be concluded that the temperature difference between the network flow and return temperatures correlates very well with the exergy factor.

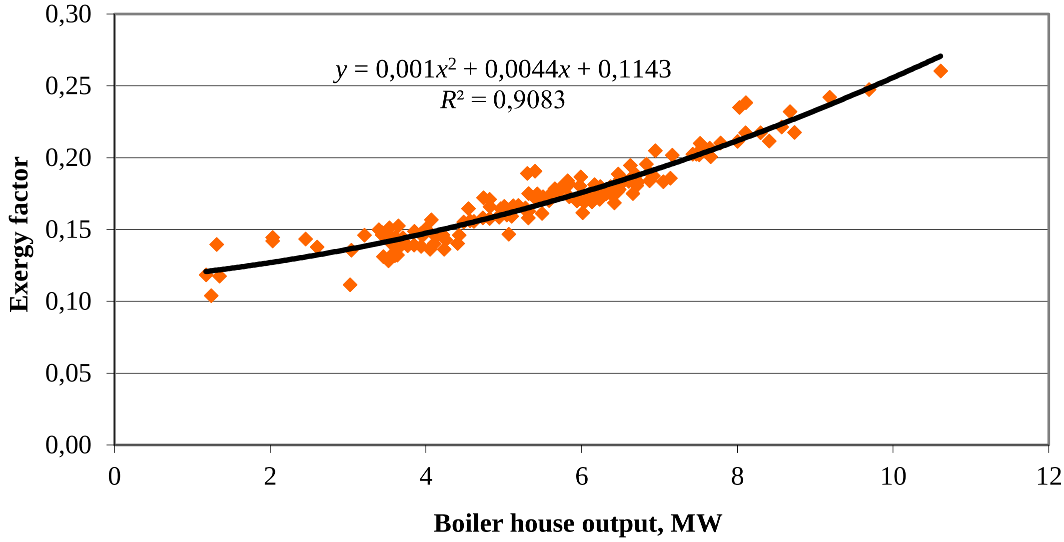

Fig. 2.6. Changes in exergy factor depending on boiler house output.

Figure 2.6. shows the effect of boiler power on the exergy factor of the district heating system. As can be seen from the graph, the exergy factor increases with increasing boiler capacity. Boiler capacity depends on the temperature the heat carrier has to reach – the higher the heat carrier temperature, the more boiler house output is needed. From this it can be concluded that the higher heat carrier temperature has a higher exergy factor. This correlation is very well reflected in correlation coefficient R^2.

2.2. Determining the Energy Efficiency of Solar Energy in the Food Industry

The research emphasis is on electricity produced by the solar energy and energy efficiency improvement potential by reducing the amount of CO_2 emissions in Kazakhstan food industry and the economy as a whole.

In order to find the CO_2 emission reduction options, the research deals with one economic sector – food industry data analysis, based on the comparison method of specific indicators. Possibilities of food industry are studied for two reasons. Firstly, this type of industry is developed in each country and therefore equal comparison is possible. Secondly, the food industry has a wide range of electricity consumption at a time.

Methodology includes comparison of two types of indicators.

1. The source of energy – determination of the potential of using renewable electrical energy.
2. The energy user – electrical energy consumption in food industry.

Using these two types of indicators, it is possible to evaluate the potential for reducing GHG emissions and thus to find an explanation, how to take steps to mitigate the effects of climate change and allow Kazakhstan to meet climate targets.

Low level of energy efficiency creates risks both for energy security and sustainable development as well as competitiveness, but the increase of this level is the fastest and most cost effective way to reduce risks, while creating additional working places and promoting economic growth. Therefore, it is important to identify each country's renewable energy potential and energy efficiency improvement opportunities. In order to solve this problem it is necessary to analyze current trends in the use of renewable energy in electricity generation and their impact on the amount of CO_2 emissions. In order to objectively appraise, renewable energy potential parameters need to be compared with the analogous indicators in other countries. In the frame of the study, the Kazakh renewable energy trends are compared with the analogous indicators in Latvia, specific indicators of the European Union are taken as the assessment criteria.

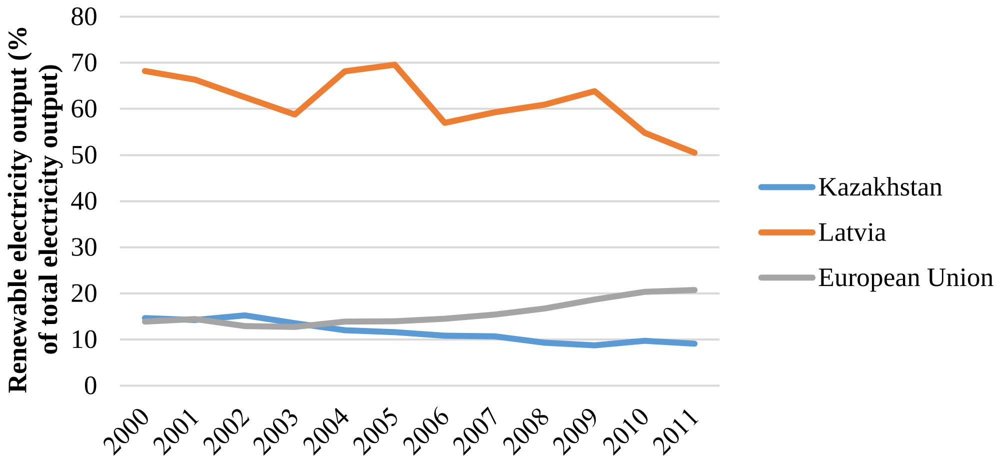

Fig. 2.7. Renewable electricity output (% of total electricity output) [7].

Figure 2.7 reflects information on the percentage of electricity derived from renewable sources in the total electricity volume. In Latvia, electricity produced from renewable energy sources in the period from 2000 to 2011, is more than 60 % of the total amount of electricity generated. In Kazakhstan, during the period under review, the share of electricity produced from renewable energy sources in average fell from 15 % to 10 %. In the European Union during the same period the share of electricity from renewable sources increased from 15 % to 20 %.

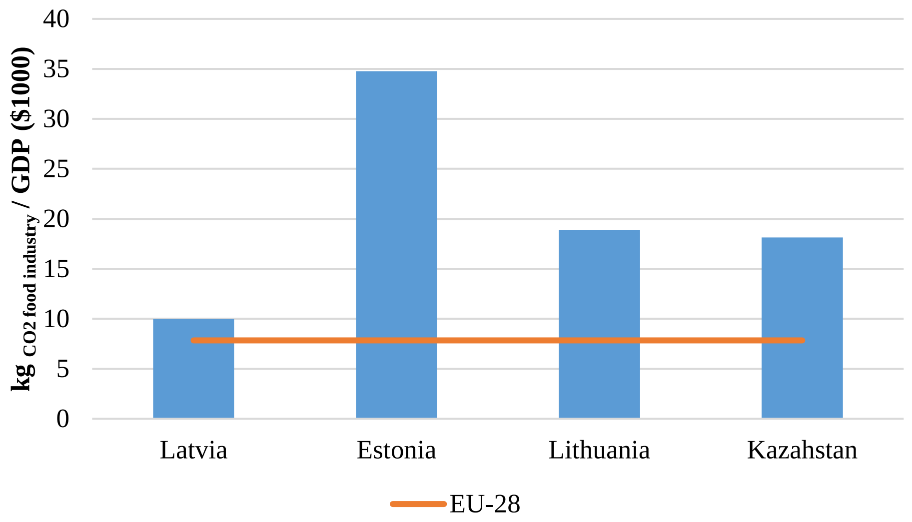

Fig. 2.8. CO_2 emissions in the food industry per GDP [9]–[12].

Figure 2.8 reflects information on the amount of CO_2 emissions from the electricity produced by the food industry per GDP. Analysing the figures, it could be concluded that Kazakhstan's CO_2 emissions per GDP in the food industry is about 2.3 times higher than in the European Union, but in comparison with Latvia's indicators it is 1.8 times higher. Of the Baltic states Estonia has the highest CO_2 emissions, but Latvia – the lowest per GDP in the food industry.

Reduction of CO_2 emissions from the use of produced solar electricity is calculated using the Formula (2.2):

$$\Delta R_{\mathrm{CO2}} = \frac{R^{\mathrm{el}}_{\mathrm{CO2}} E_{\mathrm{no\ tīkla}} - R^{\mathrm{saule}}_{\mathrm{CO2}} E_{\mathrm{saule}}}{E_{\mathrm{no\ tīkla}} - E_{\mathrm{saule}}}. \quad (2.2)$$

$R^{el}_{CO_2}$ in Latvia is 0.109 t_{CO2}/MWh[13], but in Kazakhstan – 0.485 t_{CO2}/MWh [14].

From the assessment of Kazakhstan's and Latvian's potential of electricity produced by solar energy and energy efficiency it was assumed that 10 % will be covered by solar energy, and with the help of energy efficiency measures the electricity consumption in the food industry will be reduced by 10 % starting from 2012.

Based on Formula (2.2) and assumptions mentioned in Chapter 2, Latvia's and Kazakhstan's reduction in CO_2 emissions per each kWh of electricity consumed in the food industry and per GDP is compared. The calculation results are summarized in Table 2.1.

Table 2.1

Reduction of CO_2 Emissions in the Food Industry of Latvia and Kazakhstan [9]–[12]

	Latvia			**Kazakhstan**		
	$kg_{CO_2\ food\ industry}$/GDP	$kg_{CO_2}/kWh_{food\ industry}$	$CO_{2\ food\ industry}$, kt	$kg_{CO_2\ food\ industry}$/GDP	$kg_{CO_2}/kWh_{food\ industry}$	$CO_{2\ food\ industry}$, kt
Before the implementation of RES and EE	9.98	1.02	261.82	18.14	3.43	3031.88
After the implementation of RES and EE	9.78	1.00	256.51	17.64	3,.33	2947.98
Reduction gain	**2.03 %**	**2.03 %**	**5.31**	**2.77 %**	**2.77 %**	**83.90**

Table 2.1 reflects information on solar power and energy efficiency measures and the impact on the Latvian and Kazakh food industry economic indicators. As the basis the available data of 2012 are taken. In carrying out the comparative analysis of the data, it can be concluded that replacing 10 % of fossil energy electricity produced by solar PV generated electricity and increasing energy efficiency by 10 % in the food industry, it is possible to reduce CO_2 emissions in the food industry and in the economy as a whole.

2.3. Determination of Energy and Exergy Efficiency of Wood Chip Drying Process

In the study, wood chip drying process was investigated with a perspective of energy and exergy analyses. Energy and exergy analyses are conducted on drying process in order to improve the operating conditions and system efficiency.

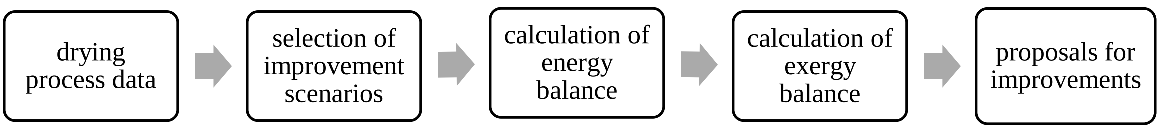

Fig. 2.9. Algorithm of methodology.

In the first element of algorithm (see Fig. 2.9) the drying process data are identified, and with the help of energy and exergy balance also analysed. In the next block, improvement scenarios are analysed using energy and exergy balance, for example, the outside air temperature impact on drying efficiency. Further energy and exergy balance calculations were made by using data from previous blocks. After calculation the results were analysed and presented visually. Conclusions of results were written during the last block.

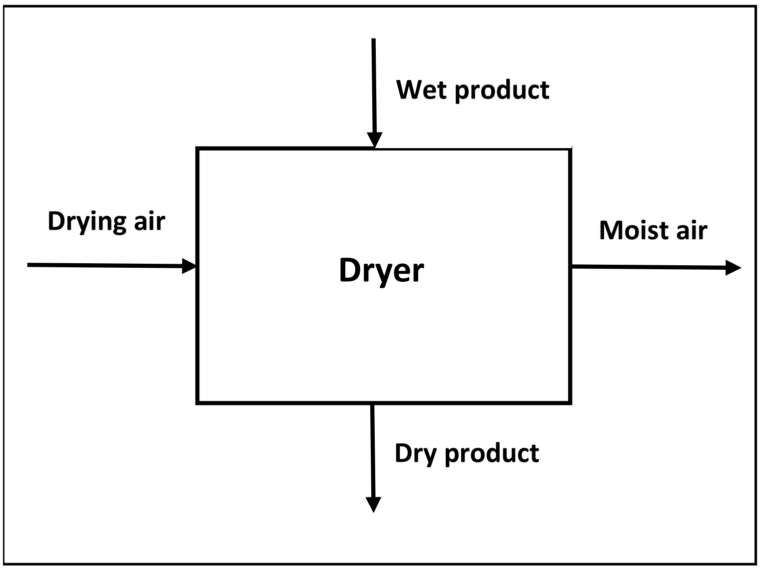

Fig. 2.10. Drying process with input and output terms.

Energy balance includes input and output heat as well as heat losses in drying process. Input heat includes three components of exergy and mass flow: drying air, product, water in product, which depends on moisture in the material and product. Output heat consists of four elements: air with high moisture, which depends on vapour content in air, water in product, which depends on moisture of material, product and heat losses from the surface of dryer [15], [16]:

$$m_{\mathrm{a}}h_1 + m_{\mathrm{p}}h_{\mathrm{p_2}} + m_{\mathrm{w_2}}h_{\mathrm{w_2}} = m_{\mathrm{a}}h_3 + m_{\mathrm{p}}h_{\mathrm{p_4}} + m_{\mathrm{w_4}}h_{\mathrm{w_4}} + Q_1. \quad (2.3)$$

Exergy balance includes input and output exergy as well as exergy losses and destruction in drying process. Input exergy includes three components of enthalpy and mass flow: drying air, product, and water in product, which depends on moisture in material and product. Output exergy consists of five elements: air with high moisture, which depends on vapour content (air humidity) in air; water in product, which depends on moisture of material; product; exergy losses from dryer; and exergy destruction [15], [16]:

$$m_{\mathrm{a}}e_1 + m_{\mathrm{p}}e_{\mathrm{p_2}} + m_{\mathrm{w_2}}e_{\mathrm{w_2}} = m_{\mathrm{a}}e_3 + m_{\mathrm{p}}e_{\mathrm{p_4}} + m_{\mathrm{w_4}} + E_{\mathrm{q}} + E_{\mathrm{d}}. \quad (2.4)$$

Methodology was tested for wood chip dryer in pellet production to perform the analysis of dependence of drying process efficiency from operation data: outdoor air temperature, humidity of air, and air mass flow. Calculation methodology includes some assumptions:

1) drying air temperature is constant, 80 $^{\circ}$C;
2) moisture of wet product is constant, 55 %;
3) drying material flow rate does not exceed 1 t/h;
4) heat exchanger for drying air does not exceed 480 kW.

The energy and exergy efficiency of wood chip dryer is calculated based on the energy and exergy balance equations and assumptions presented in the methodology chapter. The calculation results are showed in the Figs. 2.11 and 2.12.

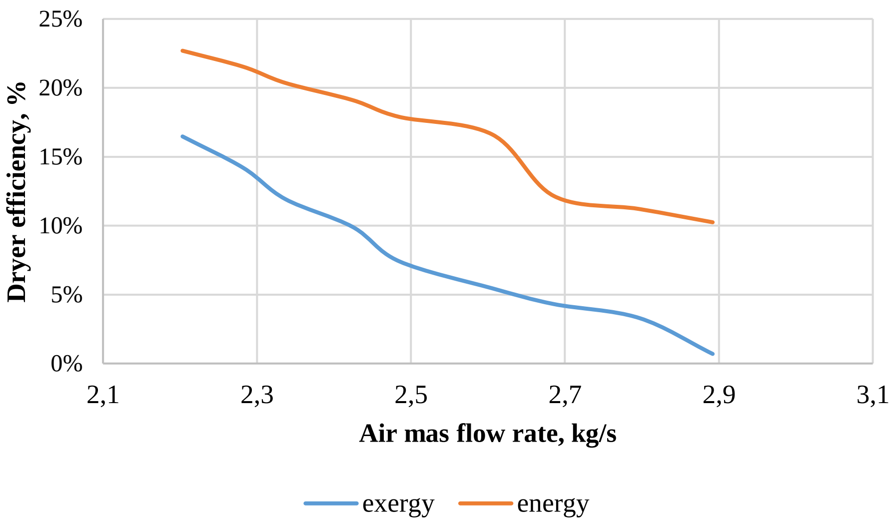

Fig. 2.11. Dryer efficiency versus the flow rate of drying air mass.

Figure 2.11 reflects the energy and exergy efficiency changes depending on the drying air flow. With the increase of drying air mass flow, energy and exergy efficiency decreases. This is because less heat is required to heat smaller drying air mass flow.

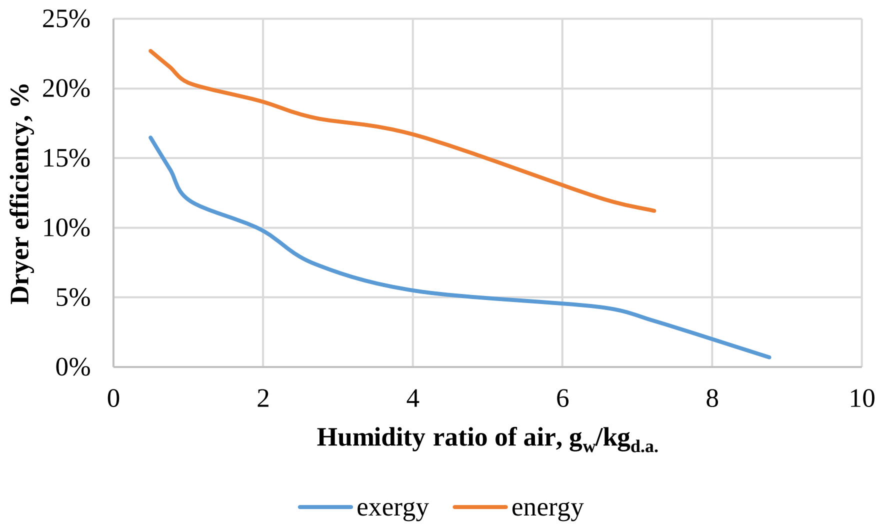

Fig. 2.12. Dryer efficiency versus humidity ratio of drying air.

Figure 2.12 reflects the energy and exergy efficiency changes depending on the humidity ratio of drying air. The decreasing drying air humidity ratio before dryer increases energy and exergy efficiency. This is because the drying air with smaller humidity ratio content is able to attract more moisture from the drying product.

2.4. Determining Energy Efficiency in Fish Refrigeration Processes

A specific company was selected in Latvia, which produces canned fish. The company's basic production scheme is shown in Fig. 2.13.

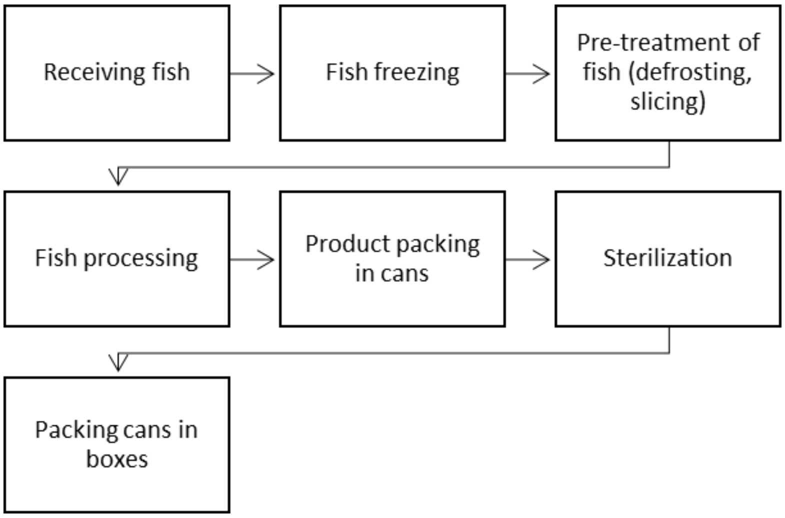

Fig. 2.13. Basic production scheme of canned fish.

Fish processing in the company is organized in 7 stages. During the first stage, fish are purchased from fishermen or other providers. During the second stage, the delivered fish are frozen or stored in a freezer until the beginning of treatment. During the third stage, fish are defrosted and cut to be heat-treated at a later stage. During the fourth stage, fish are fried or smoked. During the fifth stage, the fried or smoked fish are canned, with the addition of sauce or oil. During the sixth stage, the cans are heat-treated with steam and then cooled down. During the seventh stage, cans are packed in boxes and then sent to traders.

Fig. 2.14. Algorithm of analysis of electricity consumption of fish refrigeration.

The algorithm (see Fig. 2.14) consists of 4 blocks. In the first block, data of the technical and operational parameters of the refrigeration unit are collected. In the second block, based on the previously collected data, calculations of the specific electricity consumption for the fish refrigeration unit are made. In the third block, data analysis and comparison with other fish processing companies is performed. The last block offers proposals for reducing electricity consumption of fish refrigeration.

Figure 2.15 shows data of electricity consumption in the Latvian fish processing company in 2017. The largest electricity consumption is from February to May and from August to December. From the data presented in the graph, it can be concluded that electricity from freezers forms a significant part of total electricity consumption.

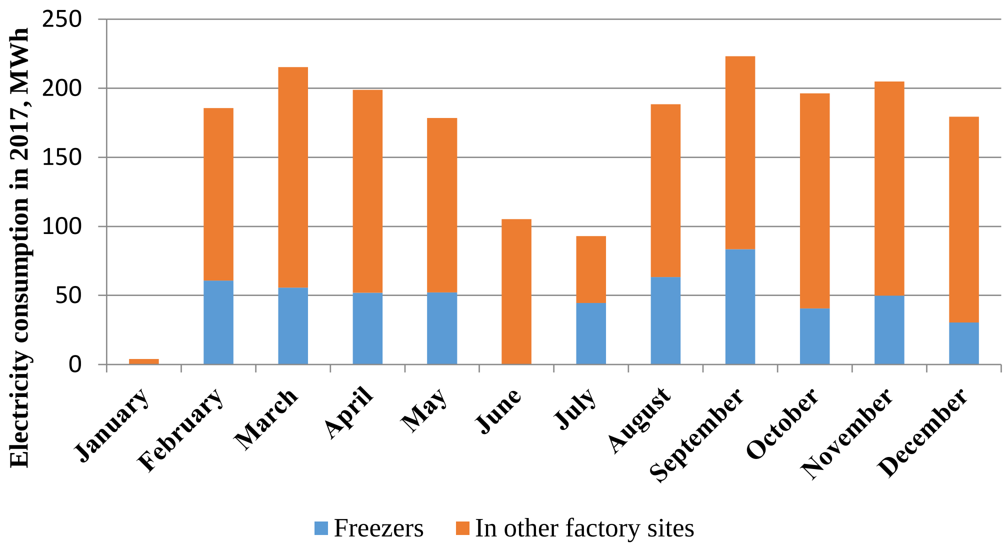

Fig. 2.15. Electricity consumption in fish canning factory.

Energy consumption for fish processing depends on installation, equipment and process. The process of heating uses approximately 29 % of the total energy in the canning sector, and the process of cooling and refrigeration builds up about 16 % [17]. In our case, refrigeration builds up about 24 % in average.

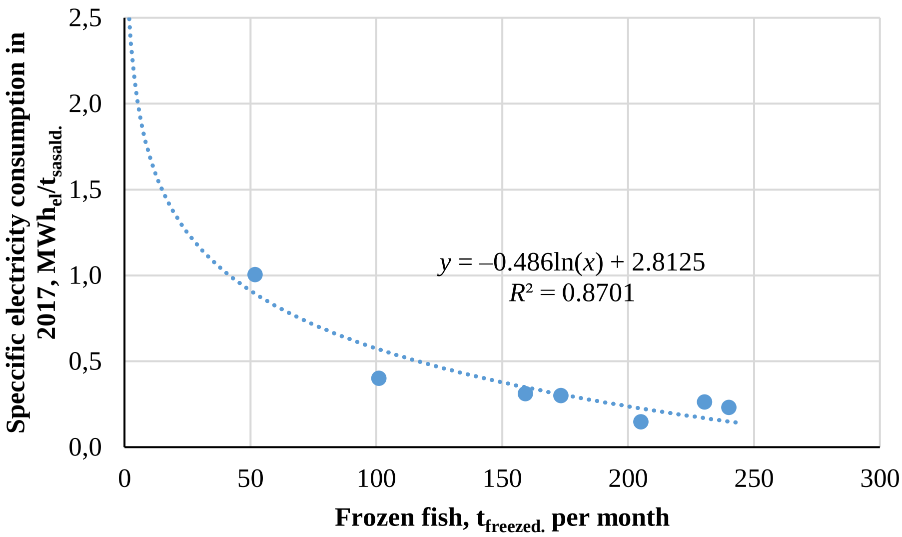

Fig. 2.16. Specific electricity consumption for fish refrigeration.

Figure 2.16 shows data on the specific energy consumption per ton of frozen fish per month. From the data, it can be concluded that the specific electricity consumption decreases with the increase in the amount of frozen fish. This correlation is also confirmed by the regression analysis coefficient R^2, the value of which is 0.87. The average electricity consumption for fish refrigeration at the factory is 380 kWh per ton of product. In literature sources it can be found that electricity consumption for industrial freezers is 70–130 kWh per ton of product [18], [19].

There are several measures that can be implemented to reduce fish refrigeration energy consumption.

1. Reducing of the condensation temperature can increase COP and reduce power consumption. This can be achieved by installing an appropriate heat exchanger in order to achieve a sufficiently low condensation temperature also during summer months. Low condensation temperatures can also be ensured if the heat exchanger in the condenser is kept clean and old exchangers are replaced by new ones [17].
2. In case of increasing the refrigerant evaporation temperature in the evaporator by 1 °C, the COP increases by 4 %, but the refrigeration capacity increases by 6 % [17];
3. The food industry often encounters the fact that the freezer isare occasionally not used due to the lack of products to be frozen. During these periods of inactivity, it is necessary to maintain sufficiently low temperatures so that, in the event of supply, the products can be quickly frozen. This can be done by running the evaporator fan at low speed using frequency converters. Frequency converters make it possible to reduce the fan power without reducing their efficiency [17].

2.5. Energy Analysis of Cleaner Production Measures in Fish Processing

The aim of the current research was to evaluate the current state of the company, which can be used as a baseline scenario for further optimization. The data acquired from the company are monthly data in years 2016 and 2017.

The aim of data analysis was to conduct material and energy flow analysis and find out what are the links between raw materials, energy (heat and electricity), water and the production. This has been done by calculating specific performance indicators:

1) specific electricity consumption (MWh_{el}/t of net production);
2) specific water consumption (m^3/t of net production);
3) specific heat consumption (MWh_{th}/t of net production).

In order to evaluate the calculated indicators, whenever possible, indicators were compared to the values available in BAT documents, e.g. one of the documents that was used as a reference was *BAT in fish processing industry: A Nordic perspective* [20].

The analyzed fish processing company has been established in 1949 and is located in the Northern part of Latvia along the Gulf of Riga. The main scope of production of the company is canned fish products: smoked fish and roasted fish. Other products that are produced are fish balls and fish pate. Main fish species that are used in the production of canned products are Baltic sprat and herring. Figure 2.17 shows some of the fish processing processes in the analyzed company.

Baltic sprat constitutes approximately 64 % of the total fish consumption in 2017, Baltic herring – 17 %, but fish of the Atlantic Ocean – 19 %. Consumption of raw fish in 2017 equals to 2856 t per year. The total production in 2017 is 12 342 t per year (including packaging), from this amount the net weight of the fish in the final product equals 2593 t per year.

Figure 2.18 shows a simplified scheme of the analyzed fish processing company. Within the company there are 3 main utilities: production facility, boiler house, and wastewater treatment.

Fig. 2.17. The analyzed fish processing company: fish grading (on the left), fish roasting (on the right).

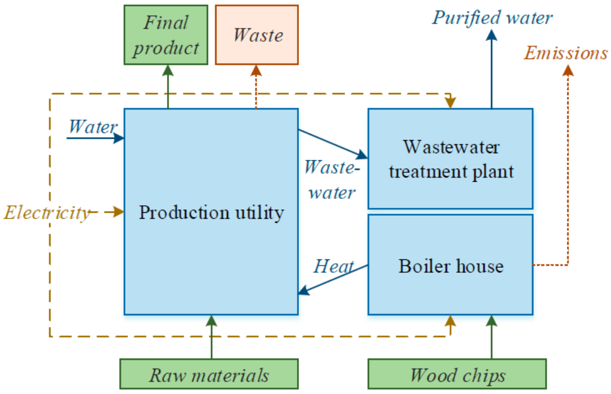

Fig. 2.18. Simplified scheme of the analyzed fish processing company.

The main flows among the facilities (Fig. 2.18) are resources, materials, energy (heat and electricity), and water. The processes that take place in the production facility are cleaning, refrigeration, thawing, grading, smoking and roasting, packaging in cans, sealing, washing, sterilization of cans, addition of labels, packaging in boxes.

Figure 2.19 shows part of the conducted research. Methodology starts with the data acquisition and mathematical data processing to arrange the data that has been received from the company. Then the procedure continues with data analysis in which data that is not suitable for the analysis, has been excluded. For example, data can be eliminated from the analysis if it does not correspond to the production. After that specific performance indicators can be calculated by linking specific and corresponding variables together. Then, whenever possible, the calculated indicators have been compared with BAT values on fish processing.

The obtained data was screened to understand whether there are some unsuitable data (not related to production) that should not be included in the analysis. Statistical analysis includes calculation of specific indicators, as well as correlation and regression analysis among various parameters. Results of regression analysis is closely linked to data quality. In this work multiple regression analysis has been performed using data analysis tool *STATGRAPHICS Plus*.

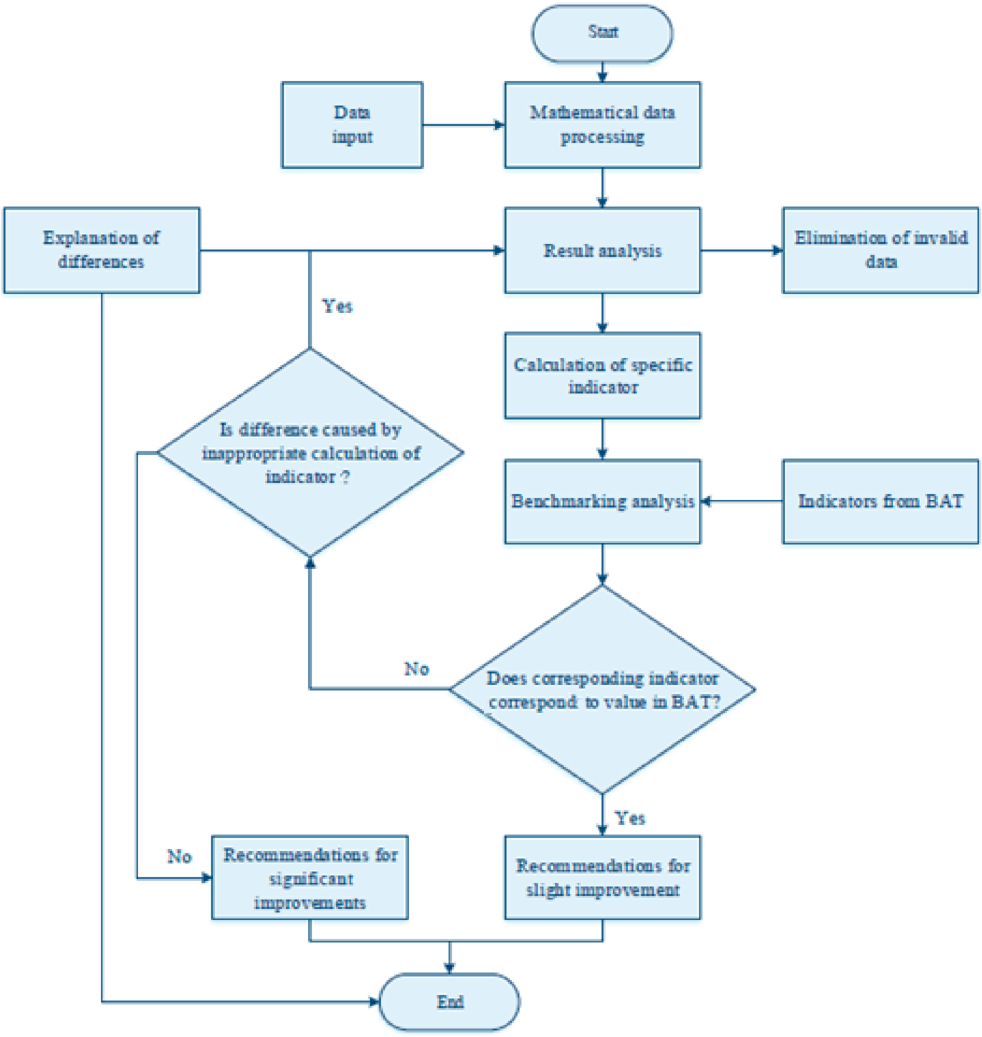

Fig. 2.19. Flow chart of data analysis methodology.

Multiple regression analysis has been performed to evaluate how varying fish production influences specific electricity consumption. In total 18 data points from different months are used in multiple regression analysis. Some months have been excluded from the analysis due to no production during those months. In regression analysis there is 1 dependent variable and 5 independent variables (different products). The company produces around 190 different products (mainly different packaging or spices added). In order to conduct a statistical analysis the amount of products has been scaled down to only 5. Grouping has been done on the basis of the used fish processing technique.

Multiple regression Equation (2.5) of the fitted model is as follows:

$$E_{el} = 0{,}855 - 0{,}000916a - 0{,}00171b - 0{,}00239c - 0{,}00587d_{ziv} - 0{,}0022e. \qquad (2.5)$$

According to the analysis of variance, there is a statistically significant relationship between variables at the 99 % confidence level. Fitted R^2 equals to 75.4 %, but adjusted R^2, which is more suitable at comparing various models, is equal to 65,1 %.

p values for coefficient *a* and coefficient *b* are >0.05, which means that these values do not correspond to 95 % confidence interval. The highest *p* value is for coefficient a and it corresponds to 74 % confidence level. According to the model it has been suggested to remove this independent variable from the analysis, but as it is smoked fish, which corresponds to the majority of production, it was decided to leave this variable in the model. However, the reason which could explain why smoked fish is not significant is that heat consumption plays more important role in its production (heat and smoke). However, as there was not enough heat consumption data, it was not possible to perform multiple regression analysis on this.

Table 2.2

Correlation Matrix for Coefficient Estimates

Koef.	Constant	*a*	*b*	*c*	*d*	*e*
Constant	1.0000	–0.7549	–0.1047	–0.4313	0.0509	–0.1331
a	–0.7549	1.0000	–0.1509	0.0581	–0.4264	–0.2498
b	–0.1047	–0.1509	1.0000	–0.1132	0.0193	–0.2155
c	–0.4313	0.0581	–0.1132	1.000	0.2911	0.1286
d	0.0509	–0.4264	0.0193	0.2911	1.0000	0.0162
e	–0.1331	–0.2498	–0.2155	0.1286	0.0162	1.0000

As can be seen in the correlation matrix (Table 2.2), all absolute values of correlation are not bigger than 0.5, therefore there is no serious multicollinearity. The relation between the observed and predicted values (calculated by equation) can be seen in Fig. 2.26.

As can be seen in Fig. 2.20, the equation describes the observed and predicted (calculated by regression equation) data. The acquired equation can be used to forecast electricity consumption in varying production processes.

Multiple regression analysis has been performed to evaluate how well different products (independent variables) influence electricity consumption (dependent variable) in the production process. The acquired multiple regression equation predicts specific electricity consumption in different production conditions. The obtained equation describes 75 % of the analyzed data (R^2 = 0.754) and can be used as a baseline scenario for further analysis.

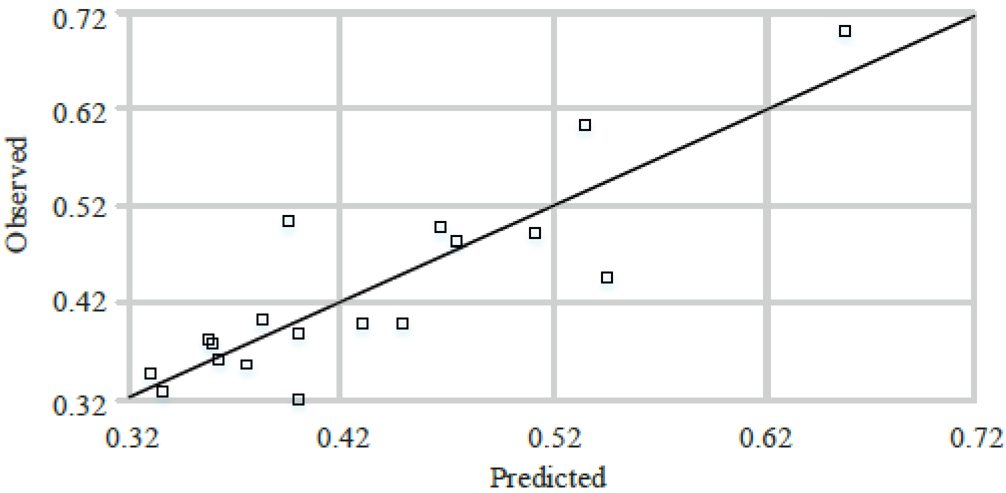

Fig. 2.20. Plot of specific electricity consumption (MWh_{el}/t of net production) – predicted versus observed values.

2.6. Analysis of Parameters That Influence Electricity Consumption in Fish Refrigeration

Within the framework of this study, the operation of freezers in the Latvian fish processing company is discussed. The company owns six freezers. Two freezers are used for freezing fish, but four for storing frozen fish and finished products. All freezers are operated by 5 two-stage compressors and 3 single-stage compressors. Usually one two-stage or/and one single-stage compressor works. Single-stage compressors are used to provide the required temperatures in freezers where frozen fish and finished products are stored. Two-stage compressors, however, are used to maintain the freezer temperatures in which fresh fish are frozen. Ammonia is used as a refrigerant in compressors, but local river water is used for cooling condensers and compressors.

Within the framework of this study, electricity consumption for freezing fish and storing frozen products and street products, as well as coefficient of performance or *COP* of compressors and parameters affecting *COP* were analyzed.

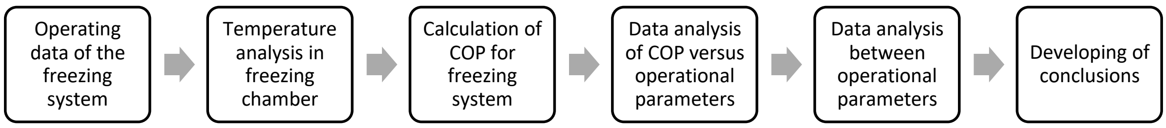

Fig. 2.21. Algorithm of the analysis of electricity consumption of freezer.

The algorithm consists of 6 blocks (see Fig. 2.21). In the first block, data of the technical and operational parameters of the freezing system are collected. In the second block, based on the previously collected data, the analysis of the freezer temperature is done. In the third block the calculation of coefficient of performance or *COP* for the compressor unit is made. In the fourth block, data analysis of the compressor *COP* versus operational parameters such as pressure in the condenser and ammonia vapor temperature after compressor is performed. In the fifth block, the data analysis between operational parameters is performed. The conclusions of results were written during the last block.

COP of a single-stage compresor is calculated by the following equation [21], [22]:

$$COP = \frac{h_1 - h_5}{h_2 - h_1}. \tag{2.6}$$

COP of a two-stage compressor is calculated by the following equation [21], [22]:

$$COP = \frac{h_1 - h_{10}}{h_2 - h_1 + \frac{(h_2 - h_9)(h_5 - h_3)}{h_3 - h_8}}. \tag{2.7}$$

The following graphs will analyze the *COP* of a two-stage and single-stage compressor when the various parameters related to compressor operation change.

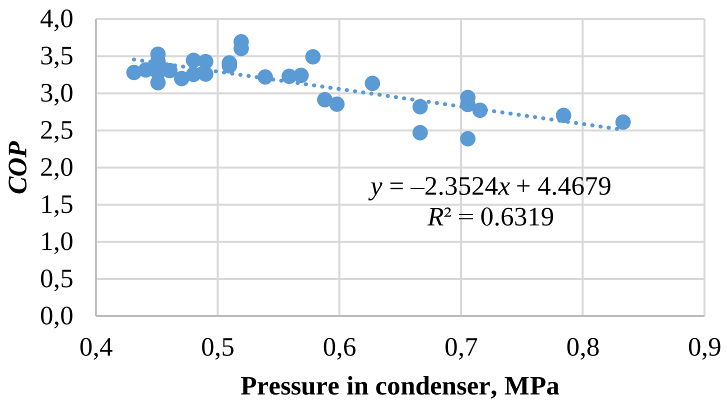

Fig. 2.22. Two-stage compressor *COP* depending on condenser pressure.

Taking into account the two-stage compressor operation data and the thermodynamic cycle, calculations of the compressor efficiency or *COP* were made (see Fig. 2.22). The results of calculations show that the two-stage compressor efficiency coefficient or *COP* ranges from 2.4 to 3.7. From the data shown in the figure it can be concluded that *COP* is affected by the pressure in the condenser – the higher the pressure in the condenser, the smaller is *COP*, and vice versa.

The correlation coefficient shows that there is a connection between the compressor efficiency and condenser pressure. Thus, the equation shown in the graph could be used to predict the efficiency of the compressor at a specific condenser pressure, where “*x*” denotes the pressure in the condenser but “*y*” the compressor efficiency or *COP*.

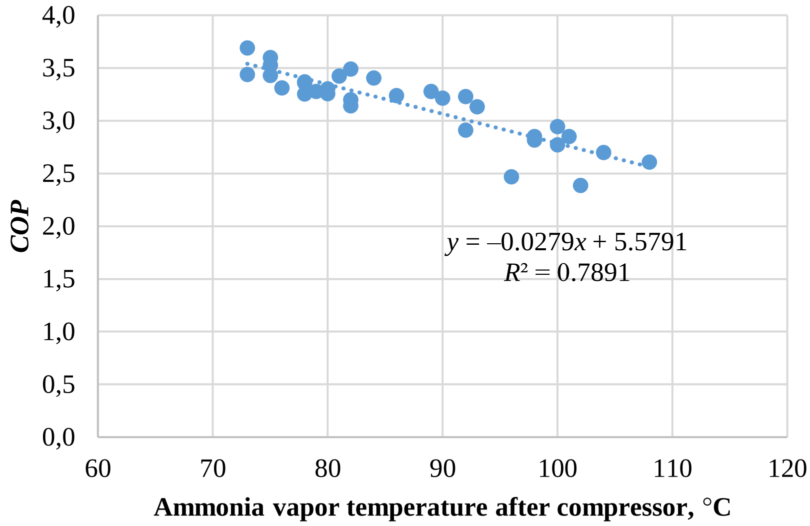

Fig. 2.23. Two-stage compressor *COP* depending on ammonia vapor temperature after compressor.

The graph (see Fig. 2.23) shows effect of the temperature of ammonia vapor after the compressor on the compressor *COP*. From the results, it can be concluded that the ammonia temperature after the compressor increases, whereas that of compressor *COP* decreases. This correlation is also confirmed by the correlation coefficient *R*. As *COP* decreases, electricity consumption increases to produce one unit of cold energy. Thus, the equation shown in the graph can be used to predict the efficiency of the compressor at specific ammonia vapor temperatures at the compressor, where "*x*" stands for ammonia temperature after the compressor, but "*y*" – for compressor efficiency or *COP*.

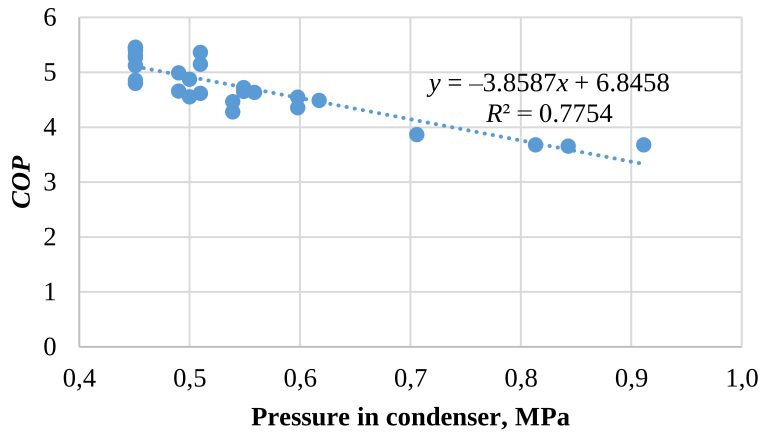

Fig. 2.24. Single-stage compressor *COP* depending on condenser pressure.

Based on the single-stage compressor performance data and thermodynamic cycle, calculations of compressor efficiency or *COP* were performed. From the results (see Fig. 2.24) of the calculations it can be concluded that the single-stage compressor efficiency coefficient or *COP* ranges from 3.7 to 5.5. From the data shown in the figure it can be concluded that *COP* is affected by the pressure in the condenser – the higher the pressure in the compressor, the smaller is *COP*, and vice versa.

The correlation coefficient shows that there is a connection between the compressor efficiency and condenser pressure. Thus, the equation shown in the graph can be used to predict compressor efficiency at a specific condenser pressure, where "*x*" denotes the pressure in the condenser but "*y*" compressor efficiency or *COP*.

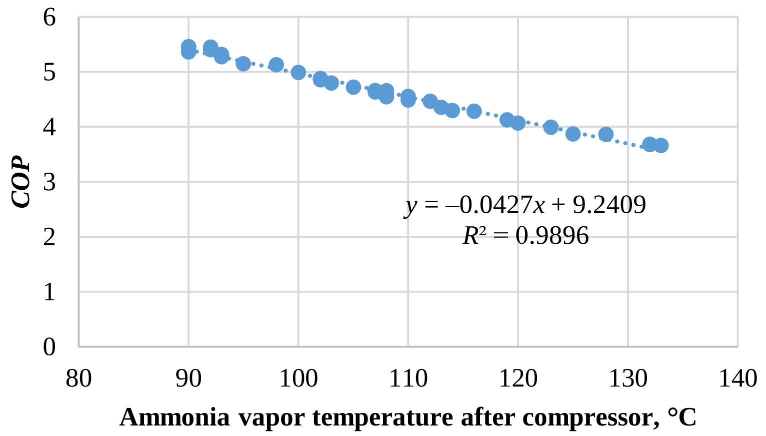

Fig. 2.25. Single-stage compressor *COP* depending on the ammonia vapor temperature after compressor.

The graph (see Fig. 2.25) shows the results of the effect of ammonia vapor temperature after the compressor on the compressor *COP*. From the results, it can concluded that when the ammonia temperature after the compressor increases, the compressor *COP* decreases. This correlation was confirmed by the high value of correlation coefficient *R*. As *COP* decreases, electricity consumption increases to produce one unit of cold energy.

2.7. Investigation of Fish Freezing Parameters Using Exergy Analysis

The study of the company's situation was conducted for the period from September 2017 until May 2018. The factory uses six freezers: two freezers are used for freezing fish at –32 °C; two freezers are used to store frozen fish at –18 °C to –20 °C; two freezers are used to store semi-finished products at a temperature of ~0 °C. The factory purchases fresh fish from local fishermen, but the missing amount of fish is purchased in frozen way from other suppliers. Fresh fish are initially frozen at –32 °C, then transferred to a freezer where frozen fish is stored. The frozen fish, in turn, are placed in the freezer for frozen fish immediately.

All freezers are operated by 5 two-stage compressors and 3 single-stage compressors. Usually one two-stage or/and one single-stage compressor is in operation. Single-stage compressors are used to provide the required temperatures in freezers where frozen fish and finished products are stored. Two-stage compressors, however, are used to maintain the freezer temperatures in which fresh fish are frozen.

Ammonia is used as a refrigerant in compressors, but local river water is used for cooling condensers and compressors.

The compressor performance is recorded in the journal. The following data is recorded every 2 hours:

1) ammonia temperature before and after the two-stage compressor stages, and flash chamber pressure;
2) ammonia temperature before and after one-step compressor;
3) water temperature before and after the compressor and condenser as well as ammonia condensation pressure;
4) freezer temperature;
5) outdoor temperature;
6) temperature of the ammonia vapor fed to the freezer evaporators.

Within the framework of the study, exergy efficiency as well as exergy destruction of the refrigeration system for freezing fish and parameters affecting exergy efficiency were analyzed.

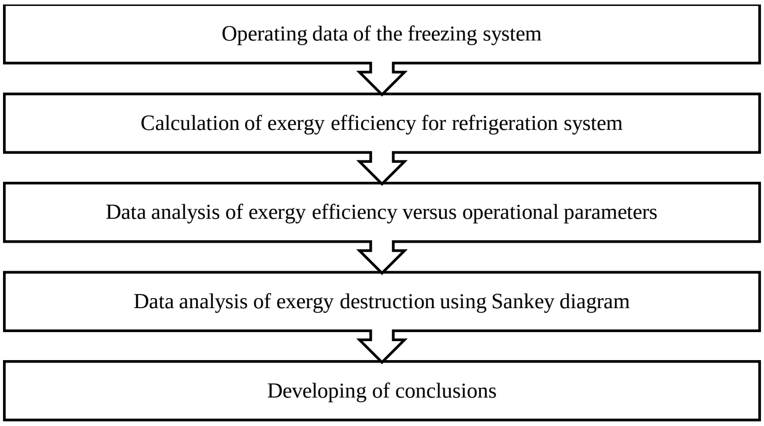

Fig. 2.26. Algorithm of exergy efficiency analysis for refrigeration system.

The algorithm consists of 5 blocks (Fig. 2.26). In the first block, data of the technical and operational parameters of the refrigeration system are collected. In the second block, calculation of exergy efficiency for the single-stage and two-stage compressor refrigeration system is made. In the third block, data analysis of the refrigeration system exergy efficiency versus operational parameters such as pressure in condenser and ammonia vapor temperature after compressor is performed. In the fourth block, data analysis of exergy destruction in single-stage and two-stage refrigeration system using *Sankey* diagram is performed. The conclusions of results were written in the last block.

The following graphs analyze exergy efficiency and losses in a sigle-stage and two-stage compressor refrigeration system.

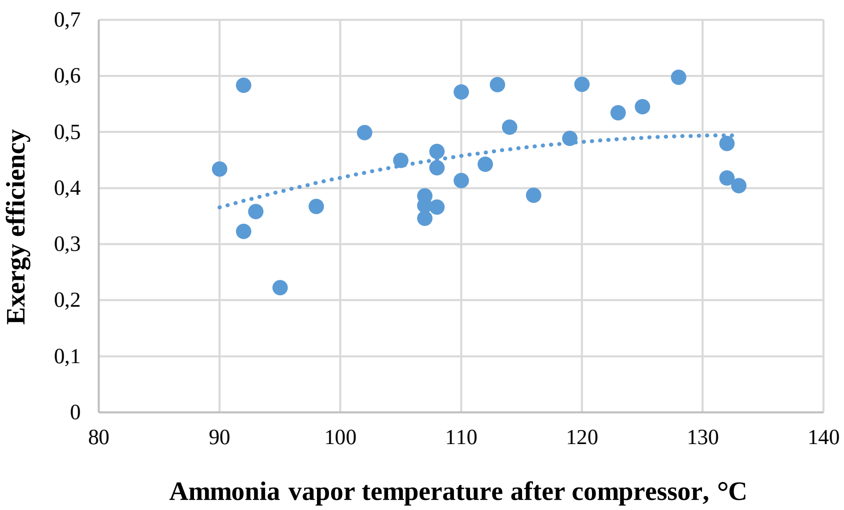

Fig. 2.27. Exergy efficiency of a single-stage compressor refrigeration system depending on ammonia vapor temperature after compressor.

Figure 2.27 shows information on changes in the exergy efficiency of single-stage compressor refrigeration system depending on the ammonia vapor temperature after the compressor. From the information presented, it can be concluded that the exergy efficiency increases with the increase of ammonia vapor temperature after the compressor. The increase in ammonia vapor temperature after compressor is explained by the amount of ammonia vapor sucked into the compressor, which is higher in the warmer months of the year than in the coldest months. The second reason for the ammonia temperature after the compressor increase is the increase in the temperature of the cooled water, which ensures the cooling of the compressor. Exergy efficiency reaches a maximum of 0.6 at ammonia vapor temperature of 128 °C. With ammonia temperatures above 128 °C, the efficiency of exergy decreases.

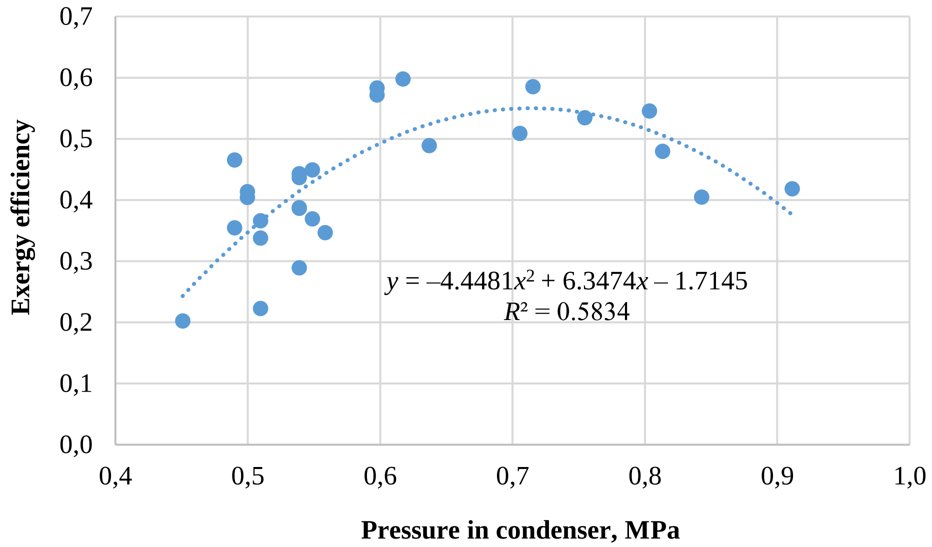

Fig. 2.28. Exergy efficiency of a single-stage compressor refrigeration system depending on the pressure in condenser.

Figure 2.28. shows information on changes in the exergy efficiency of a single-stage compressor refrigeration system depending on the pressure in the condenser. From the information shown, it can be concluded that the exergy efficiency increases with increasing pressure in the condenser to 0.72 MPa, but decreases above the condenser pressure of 0.72 MPa. The increase in pressure in the condenser can be explained by the increase in the water temperature of the condenser cooling. In contrast, the reduction in exergy efficiency when the condenser pressure exceeds 0.72 MPa is explained by the high temperature of the condenser cooling and the reduction of the ambient temperature. This situation is typical for the autumn months when the ambient temperature is lower than the water temperature used to cool the condenser. Exergy efficiency reaches a maximum value of 0.6 at a pressure of 0.62 MPa in a condenser.

Figure 2.29 shows information about the average amount of exergy and exergy destruction in the single-stage refrigeration system. The biggest exergy destruction takes place in a condenser followed by 15.85 % in evaporator and 15 % in compressor, while the smallest exergy destruction of 4.98 % takes place in the expansion valves. The amount of exergy in the refrigeration system is 39.6 %.

The amount of exergy destruction in system elements depends on the ambient temperature and entropy change during the processes in system elements. Taking into account that the ambient temperature cannot be changed, but entropy can be changed, it is necessary to choose the equipment or process providing modes that reduce the entropy increase.

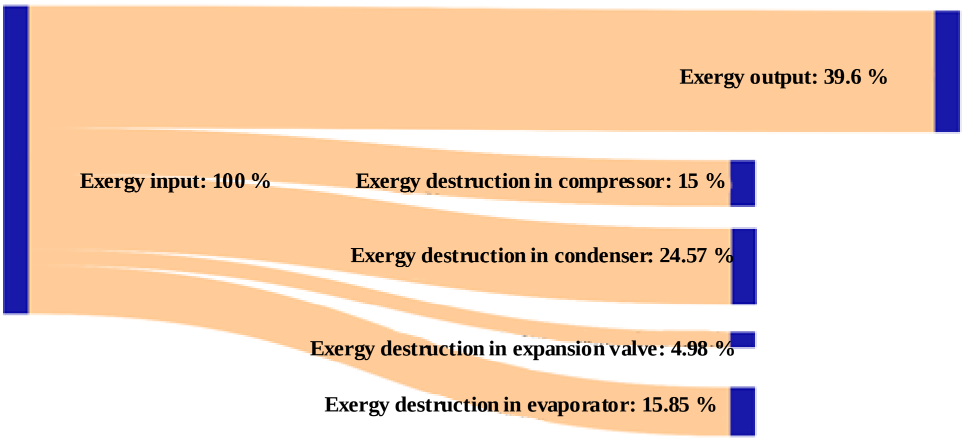

Fig. 2.29. Exergy destruction in single-stage compressor refrigeration system.

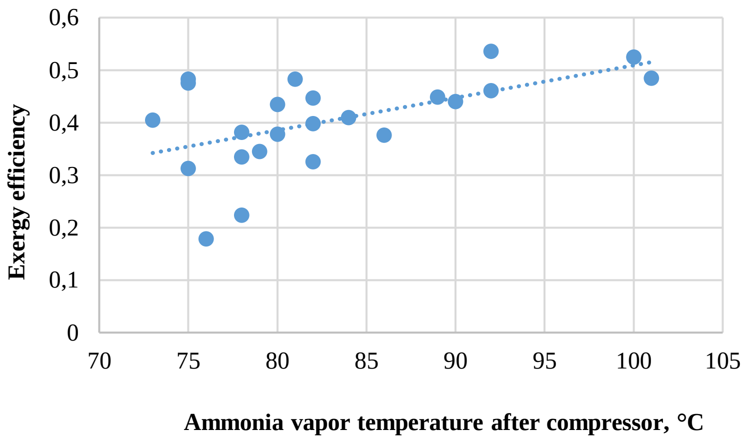

Fig. 2.30. Exergy efficiency of two-stage compressor refrigeration system depending on ammonia vapor temperature after compressor.

Figure 2.30 shows information on changes in the exergy efficiency of two-stage compressor refrigeration system depending on the ammonia vapor temperature after the compressor. From the information presented, it can be concluded that the exergy efficiency increases with the increase of ammonia vapor temperature after the compressor. The increase in ammonia vapor temperature after compressor can be explained by the amount of ammonia vapor sucked into the compressor, which is higher in the warmer months of the year than in the coldest months. The second reason for the ammonia temperature after the compressor increase is the increase in the temperature of the cooled water, which ensures the cooling of the compressor. Exergy efficiency reaches a maximum value of 0.54 at an ammonia vapor temperature of 92 °C.

Figure 2.31 shows information on the changes of exergy efficiency of two-stage compressor refrigeration system depending on the pressure in the condenser. From the information presented, it can be concluded that the exergy efficiency increases with increasing pressure in the condenser. Exergy efficiency reaches a maximum value of 0.54 at a pressure of 0.56 MPa in a condenser. The increase in pressure in the condenser can be explained by the increase in the water temperature of the condenser cooling. The condenser cooling water temperature reaches its maximum value in the warmer months of the year. Conversely, the low correlation between the efficiency of the exergy of the refrigeration system and the pressure in the condenser can be explained by the fact that other parameters, such as the ambient temperature, also affect the efficiency of exergy.

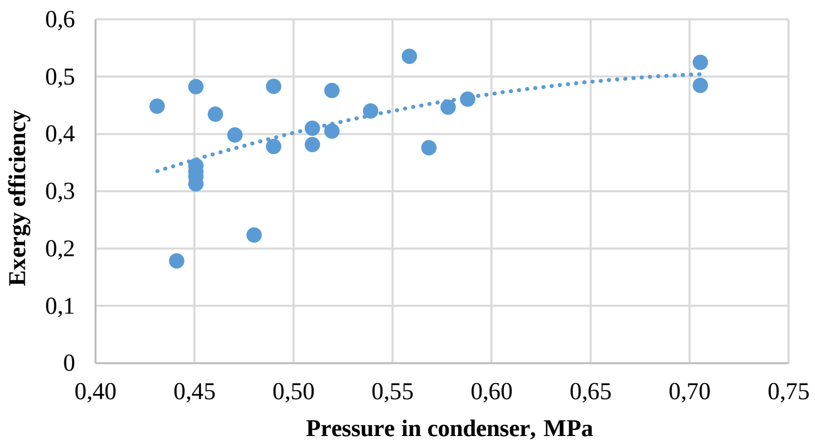

Fig. 2.31. Exergy efficiency of two-stage compressor refrigeration system depending on ambient temperature and evaporator temperature difference.

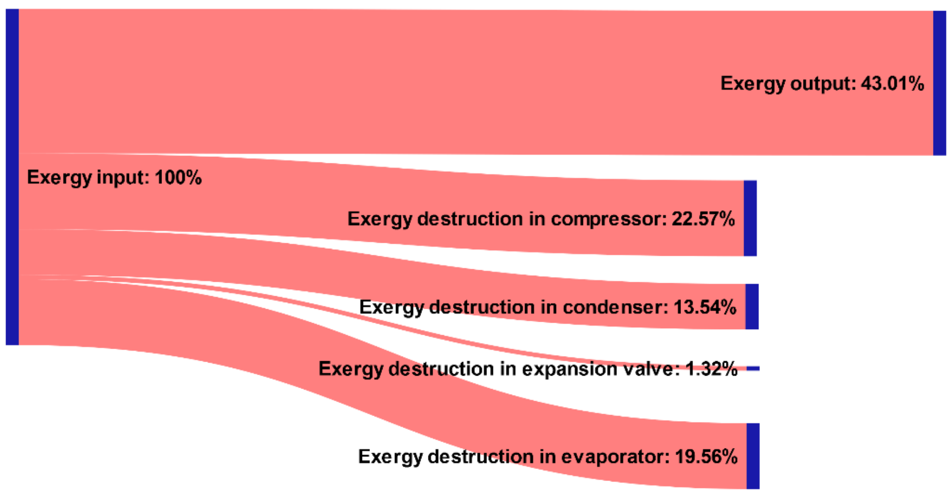

Fig. 2.32. Exergy destruction in two-stage compressor refrigeration system.

Figure 2.32 shows information about the average amount of exergy and exergy destruction in the two-stage refrigeration system. The biggest exergy destruction takes place in a compressor followed by 19.56 % in evaporator and 13.54 % in condenser, while the smallest exergy destruction of 1.32 % takes place in the expansion valves. The amount of exergy in the refrigeration system is 43.01 %.

The amount of exergy destruction in system elements depends on the ambient temperature and entropy change during the processes in system elements. Taking into account that the ambient temperature cannot be changed, but entropy can be changed, it is necessary to choose the equipment or process providing the modes that reduce the entropy increase.

CONCLUSIONS

1. Complex analysis of the efficiency of power systems is based on the use of two concepts – exergy and energy. A system that is thermodynamically balanced with the environment has no exergy. System exergy increases with the difference in numerical values of thermodynamic parameters between the thermodynamic system and the environment surrounding the thermodynamic system. The energy balance is used to identify and reduce energy losses, such as heat losses, as well as energy recovery opportunities. However, the energy balance does not provide information on the internal loss of energy or resources during the process, nor does it determine the quality of the various energy and material streams flowing through the system and passing out as products and waste. Exergetic analysis clearly indicates the loss of energy in the process and in the technological element in which the process takes place. The primary goal of exergetic analysis is to identify opportunities for exergy enhancement and the causes and true extent of exergy loss. Thus, the use of exergetic analysis in determining the efficiency of power systems provides a real opportunity to truly evaluate energy consumption efficiency.
2. Energy efficiency of different objects of power systems (heat supply, fish processing, pellet plants) is determined by using both energy and exergy balances. This approach, by using indicators such as coefficient of energy efficiency, coefficient of performance (for heat pumps, refrigeration / cooling systems), energy loss, coefficient of exergy efficiency, exergy loss (depending on the amount of energy loss), exergy degradation, makes it possible to develop a universal approach by using an analysis of the energy and exergy balances of the plants mentioned before and formulating ranges of use and interactions of these balances.
3. The objectives of the dissertation have been achieved because the results confirming the hypothesis have been obtained – when analyzing energy consumption efficiency, it is necessary to use both energy and exergy balances, determining their usage ranges and interactions in different power systems. These results are obtained as the result of a complex study of various power systems (heat supply, fish processing, pellet plants) and interaction of their energy and exergy balances. It improved understanding of the causes of power system losses and ways to reduce them, which in turn provides a theoretical basis for remedying errors and failures in practice, as energy and exergy balances are based on the internal structure and characteristics of energy, exergy amount in energy system, as well as energy and exergy exogenous changes in the power system.
4. During experimental research of the exergy factor using the data of the city of Latvia – Ludza – district heating system, the following results were obtained: average exergy factor during the calculation period is 0.17; as the heat load increases, the boiler output increases and the exergy factor increases; as the outdoor air temperature decreases and the supply and return temperatures of the heating networks increase, the exergy factor of the heating system increases. Comparing the exergy factor of the Ludza district heating system with the Danish and Swedish district heating systems at the same outdoor temperature, it can be concluded that the exergy factors of the Danish and Ludza district heating systems are similar, but the exergy factor of the Swedish district heating system is higher because the difference between supply and return temperatures is greater than in Danish heat supply system. Thus,

the exergy factor shows the amount of exergy in the heat energy supplied to the consumer. Low exergy factor is characteristic for those heat supply systems that are using low potential heat sources such as solar heat, deep cooling of boiler flue gas, and heat from industrial technological processes.

5. The energy and exergy efficiency of pellet drying process depending on the drying process parameters is analyzed in the research. The energy efficiency of the pellet drying process ranges from 23 % to 10 % and the exergetic efficiency – from 16 % to 1 %. The difference in the numerical values between exergy and energy efficiency is due to the fact that the exergy efficiency calculation takes into account not only the losses of energy entering the environment, but also losses occurring inside the system, such as a drying chamber and air dryer. Reducing the mass flow rate of pellet drying air increases energy and exergetic efficiency, since less heat flow is required for heat drying. As the air humidity level decreases before the dryer, energy and exergy efficiency increases, as drying air with less humidity is able to attract more moisture from the drying product.
6. During the research energy analysis of the freezing equipment was performed using the equipment coefficient of performance (*COP*), which shows the obtained cold energy per unit of electricity consumed. The analysis shows that the *COP* of the two-stage compressor ranges from 2.4 to 3.7 and from 3.7 to 5.5 for the single-stage compressor. The operation of both compressors is influenced by the condenser pressure and the ammonia vapor temperature before the condenser – as the ammonia vapor temperature and the condenser pressure increase, the compressor *COP* decreases. This increases the energy consumption required to produce one unit of cold energy. The pressure in the condenser and the ammonia vapor temperature before the condenser are affected by the temperature of the water used to cool the condenser and the compressors. As the cooling water temperature rises, the compressor's *COP* decreases and the power consumption increases.
7. The exergetic analysis of the freezing equipment was performed with the help of the following indicators – exergy efficiency η_{ex}; loss of exergy Ex_{zud}; and exergy disassembly $Ex_{noārd}$. The exergetic efficiency of the single-stage compressor reaches 60 % compared to 54 % for the two-stage compressor. The efficiency values are influenced by the ambient temperature, the temperature of the refrigeration chamber and the operating parameters of the unit – pressure and ammonia temperature after the compressor. The difference in exergy efficiency for single-stage and two-stage compressors is mainly determined by the temperature of refrigeration chamber, which in case of a single-stage compressor is –20 °C to –23 °C (fish storage), but in the case of two-stage compressor –32 °C to –34 °C (quick freezing of fish).
8. An in-depth analysis of the exergy changes of the elements of the freezing system was performed with the help of exergy losses. Exergy losses of the element include losses linked with energy loss exergy and exergy degradation. The amount of exergy loss in system elements depends on the ambient temperature and entropy increase during the process. The example of the analysis shows that in a single-stage unit, the largest exergy losses are in the condenser (25 %), followed by the evaporator (16 %), the compressor (15 %), and the throttle valves (5 %). In a two-stage compressor unit, the largest losses are in the compressor

(23 %), further in the evaporator (20 %), the condenser (14 %), and the throttle valves (1.3 %). The numerical values obtained in the analysis of the exergy loss indicate which elements of the equipment must first be subjected for the loss reduction.

9. One of the methods of energy consumption analysis is regression analysis of power system operation data. The paper assesses the current state of a fish processing company, which can be used as a baseline scenario for further optimization of the company aimed to reducing the company's energy consumption. Multivariate regression analysis can be used to evaluate how different products (independent variables) are affecting electricity consumption (dependent variables) during the production process. The resulting multiple regression equation assumes a specific power consumption under different production conditions. The resulting equation describes 75 % of the data analyzed (R^2 = 0.754) and it can be used as a baseline for further analysis.

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