RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Energy Systems and Environment

Ģirts VĪGANTS

LOW CARBON DISTRICT HEATING SYSTEMS

Summary of doctoral thesis

Riga 2015

RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Energy Systems and Environment

Ģirts VĪGANTS
Doctoral Program in Environmental Science

LOW CARBON DISTRICT HEATING SYSTEMS

Summary of doctoral thesis

Scientific supervisors

Dr.habil.sc.ing., professor
D. BLUMBERGA

Dr.habil.sc.ing., professor
I. VEIDENBERGS

Riga 2015

UDK 697.34(043.2)
Vī 323 l

Vīgants Ģ. Low carbon district heating systems.
Summary of doctoral thesis. Riga: RTU, 2015. – 47 pp.

Published in accordance with the decision of the Institute of Energy Systems and Environment No. 50, January 22, 2015.

This work has been supported by the European Social Fund within the project “Support for the implementation of doctoral studies at Riga Technical University”.

ESF
EIROPAS SOCIĀLAIS FONDS

EIROPAS SAVIENĪBA

ISBN 978-9934-542-02-2

DISSERTATION PROPOSED FOR DR.SC.ING. DEGREE IN ENVIRONMENTAL ENGINEERING AT RIGA TECHNICAL UNIVERSITY

This study is proposed for attaining the degree of Dr.sc.ing. in Environmental Engineering and will be defended on June 11, 2015 at 2:00 p.m. at the faculty of Power and Electrical Engineering, Āzenes iela 12/1, Room 115.

OFFICIAL OPPONENTS

Dr.sc.ing. Gatis Bažbauers
Riga Technical University

Dr.sc.ing. Andres Siirde
Tallinn University of Technology, Estonia

Dr.ing. Ingo Weidlich
Fernwärme-Forschungsinstitut/District Heating Research Institute, Germany

CONFIRMATION STATEMENT

I, the undersigned, hereby confirm that I have developed this dissertation, which is submitted for consideration at Riga Technical University, for attaining the degree of Dr.sc.ing. in Environmental Engineering. This study has not been submitted to any other university or institution for the purpose of attaining scientific degrees.

Ģirts Vīgants ……………………………… (signature)

Date: 11.06.2015.

The dissertation is written in Latvian and contains: an introduction, 3 chapters, conclusions, a bibliography, 33 figures, 3 tables, 81 pages and appended five papers. The bibliography contains 89 references.

TABLE OF CONTENTS

Topicality of the doctoral thesis

In recent years the European Union has published various directives and regulations determining and regulating increase in the proportion of renewable energy resources in primary energy resource balances as well as decrease in energy consumption due to increasing energy efficiency. The three most important of these directives, which will influence the development of national energy sectors in the long term, concern energy services, renewable energy resources and energy efficiency.

No less important are the short-term objectives in the energy and climate package, which must be achieved by 2020. This also confirms the importance of the issue of reducing greenhouse gas emissions, which determines the influence of the energy sector on global climate change. The development of a low carbon energy system with a minimal proportion of fossil fuels and maximally high energy efficiency is not only an innovative solution on the national level but also a matter of human survival.

An essential player in the energy sector in the Nordic and Baltic countries is centralised district heating, the operations of which are targeted by all of the above-mentioned European Union directives as well as the climate and energy packet. The efficiency of centralised district heating systems depends on the energy efficiency of all three of their components: the energy source, heat networks and the energy consumer.

Likewise of importance is the operational effectiveness of each separate component. The energy efficiency of the boiler house while operating at variable modes of operation, changes in the differing domestic heat consumption and also the broad range of heat network loss demand special attention. However, the most important benefit can be achieved if the analysis is aimed at the centralised district heating system (CDHS) as a unified whole. In order to evaluate and analyse the possibilities of increasing CDHS energy efficiency, not only is a method for the objective determining of operational effectiveness needed but also indicators that most precisely determine and evaluate the technological, economic, environmental and climatic aspects, which are based not only on an analysis of current district heating system operational experience but also allow the researcher to predict the potential decrease in primary energy resources.

Goal and tasks of the doctoral thesis

The goal of this thesis is to develop and approbate methods for evaluating existing and new technological solutions of district heating systems from the perspective of energy efficiency, cost and environmental protection. The following tasks have been set forth in order to achieve the goal:

1. analysis of the possibilities and results of integrating a flue gas condenser and heat pump into a district heating system;
2. development of an evaluation diagram for the operation of a boiler house with condenser;
3. creation of an energy management system at a system’s energy source by determining energy efficiency characterising indicators, benchmarks and changes in indices;
4. economic evaluation of the use of a flue gas condenser at a system’s energy source based on an analysis of operational data;
5. evaluation of a district heating system’s influence on the environment.

Methodology of studies

Two research approaches have been used in developing the study. The first approach concerns the creation of models and the modeling of the quantities studied. This pertains to the study of the integration of a heat pump into a district heating system and the study of the system's eco-intensity. The second approach is based on an industrial experiment, or, the statistical processing of the business' operational data using the correlation and regression analysis methods, thereby obtaining empirical equations that are used in the modeling of parameter changes. Wherever possible, the results of the modeling have been compared with the experimental data.

Scientific significance of the doctoral thesis

A complex study of the possibilities of increasing the energy efficiency of a district heating system that uses a flue gas condenser and heat pump has been performed. The influence of efficiency-increasing measures on the environment have been evaluated using eco-intensity indicators.

A new heat pump integration scheme has been developed for using a district heating system's return heat to partially cover consumers' heat load. A model has been created and the heat pump operations have been modelled in variable climatic conditions. A nomogram for the distribution of the boiler house's load between the boiler and the condenser has been developed and approbated, and this nomogram can be used to evaluate the current operations of a district heating system as well as to make predictions.

Practical significance of the doctoral thesis

Studies of increasing a district heating system's energy efficiency are an important step towards the efficient use of renewable energy resources in Latvia's energy sector. The results of the thesis have practical significance both on a national as well as regional and local level. A gas condenser can be installed in any boiler house burning wood chips in the effort of improving energy efficiency, and consumption of energy resources can be decreased by up to 20%.

The computer model provided can be used to evaluate the use of a heat pump; it evaluates the decrease in the district heating system's return water temperature and the increase in effectiveness of the flue gas condenser installed in the boiler house. Benchmarks for specific heat rate and specific incremental heat rate provided to the boiler house energy management system can be used to ensure the system's energy efficiency.

In total, the study results can be used to plan energy efficiency measures and to determine the influence of such measures on a district heating system's operations as well as to perform studies of system development projects and to evaluate indicators of the implementation and operation of systems, taking into account both the technical limitations and possibilities as well as an analysis of environmental and economic aspects.

Structure and description of the doctoral thesis

This thesis is based on five [1; 2; 3; 4; 5] main publications and an overview of other studies performed and published by the author. The goal of the overview is to expand the range of district heating system issues to be studied with other studies [6-12] performed and published by the author and to accent the interconnection of these studies. This thesis consists of an introduction and three chapters:

1. Overview of the literature;
2. Study methodologies;
3. Study results and analyses thereof.

In the introduction, the study goals and tasks are defined, the structure of the thesis is explained, and a short description of the author's studies is given that covers both the main publications and other studies by the author regarding the analysis of district heating systems. Chapter One provides an overview of the literature and focuses on the necessary studies regarding aspects of district heating system operations and the improvement thereof as examined in the main publications. Chapter Two examines the methodologies of the issues studied in the main publications. The results obtained in the study and the analysis thereof are presented in Chapter Three. Conclusions are presented at the end of the thesis.

An overview of the doctoral thesis author's studies of the centralised district heating system in the town of Ludza

Introduction to the overview of studies

Centralised district heating plays a main role in the Scandinavian and Baltic countries. In Latvia, centralised district heating currently covers 80% of the total energy consumption for heat supply. In order for such a system to develop sustainably, technological improvement of systems and a gradual transition to third- and fourth-generation systems is necessary. For this to happen, a complex evaluation of indicators characterising existing systems and possible improvements is necessary.

The RTU Institute of Environmental Protection and Heating Systems has performed studies of increasing the energy efficiency of centralised district heating systems. It has also developed or adapted various methods for the evaluation of centralised district heating systems that include the influence of technological solutions on the economically and environmentally friendly operations of a system. The evaluation models have been tested for the centralised district heating system in the town of Ludza and are shown in Figure 1.

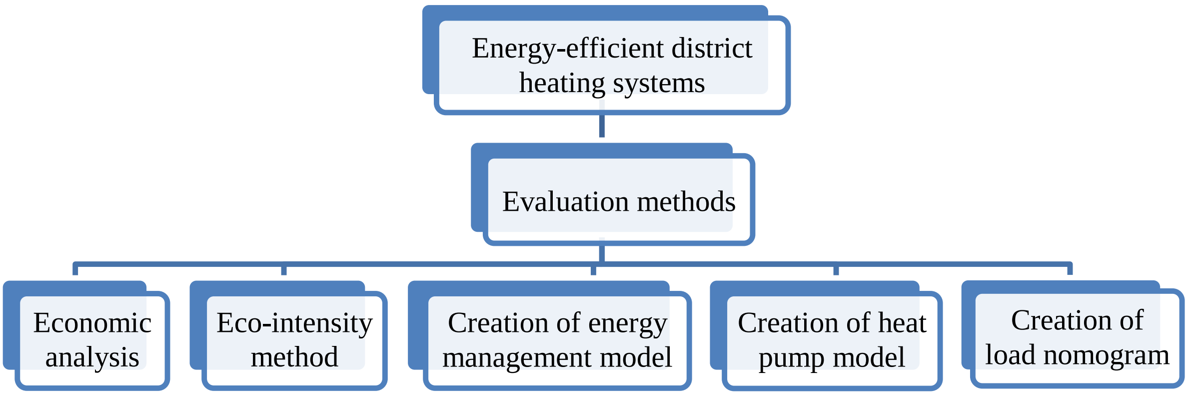

Fig. 1. Evaluation methods

Each district heating system is a complex whole of technological solutions consisting of separate elements that must be examined as a united system. It is a system whose effective operation depends on the development of economically justifiable and environmentally friendly technological solutions. The goal of this section is to provide a general overview of the complex evaluation of the district heating system, which is then examined in more detail in subsequent sections.

Short description of the solutions used

Influence of a decrease in the district heating system temperature schedule on operational indicators

Study [6] examines a universal method that can be used to calculate the optimal flow and temperature modes for centralised district heating networks that offer the lowest operation costs based on significant amounts of data gathered by SIA "Ludza Bio-Enerģija" regarding the operations of the Ludza municipal CDHS at various heat loads. An analysis of the results shows that decreasing the temperature can be considered an economically beneficial measure because the financial resources saved by the decrease in heat loss exceeds the expenses created by ensuring a more intensive heat carrier circulation.

Use of a flue gas condenser at a district heating system's source

The results show that a district heating system's energy efficiency can be increased by installing a flue gas condenser in the boiler house, thereby making fuller use of the heat released during fuel combustion [7]. The heat recovered with the aid of the condenser is used for primary heating of the heating network return water, and the condenser's efficiency depends on how effectively the heat transfer takes place on the energy consumer's side. This, as well as the boiler house temperature schedule, determines the temperature level in the heating networks. Regarding the flue gas condenser, its operation is significantly influenced by the heating network return temperature. The lower the return temperature, the more effective the vapour condensation from the flue gases and the greater the recovered phase transition heat. As the temperature of the return water increases, the condenser's heat capacity decreases because the heat transfer between the heating network and the condenser's water circuits in the network water heat exchanger is poorer. The water heated in the condenser is cooled less effectively in the network heat exchanger and is sprayed through the nozzles into the condenser at a higher temperature. At higher spray water temperatures, the dry heat transfer between the droplets and flue gases as well as the mass transfer worsens.

Installation of a condenser at a district heating system's heat source increases the system's energy efficiency and allows the consumer load to be covered with a smaller capacity boiler. It is important to determine the load distribution between the boiler and condenser at variable system operation conditions. Based on an analysis of data from the Ludza district heating system over the course of a heating season, study [2] examines in more detail the influence of the parameters of interaction between the condenser and the district heating system, network return temperature and boiler capacity on the condenser's efficiency. The study offers a nomogram to evaluate condenser effectiveness and distribute the heat load between the boiler and condenser during the heating season. Primary resource consumption is decreased by 11.8% during the heating season due to the installation of a condenser after the wood chip boiler.

The influence of heat losses and flue gas condenser effectiveness on a system's energy efficiency are analysed in more detail in study [9]. It shows that a system's efficiency is determined by changes in the relative ratio of condenser capacity and heat losses, the character of which differs depending on the outdoor temperature. A condenser's relative capacity increases quadratically as the outdoor temperature increases. The increase in relative losses is small at low outdoor temperatures, and further increases in outdoor temperature are linked with a distinct increase in relative heat losses. Changes in quantities are quantitatively described by curve gradients.

Integration of a heat pump in a district heating system

The energy efficiency of a district heating system can be increased in various ways: by optimising the system's operation parameters or by integrating new, innovative elements into the system. Among the latter are flue gas condensers and heat pumps. Study [1] examines the use of a high-temperature heat pump installed in the heating network return pipe to partially cover consumer load. It has calculated a heat pump installation diagram and conducted modelling of changes in the system's operational parameters during the heating season. The calculation model consists of equations of district heating system elements and the balance between the heat pump's energy and mass and empirical equations gained from the processing of the system operations' experimental data, which describe the network water flow as well as changes in the supply and return water temperatures during the heating season. The calculations show that the use of a heat pump can cover the load for a part of the consumers and, more importantly, lower the return temperature compared to a scenario in which there is no heat pump. This means that the temperature in the flue gas condenser's heat exchanger in the boiler house is lower and that the energy efficiency of the condenser increases.

Creation of an energy management model

As a result of the experimental study of boiler house operations, it is possible to create a database summarising indicator values and empirical correlations and curves describing the changes therein. The creation of such a database allows energy management measures to be introduced in order to increase the energy efficiency of the boiler house and critically evaluate current operation practice. Study [3] analyses energy management aspects of a wood chip boiler house based on operational parameters gathered over the course of many years. Specific heat rate and specific incremental heat rate indices, which are determined using measured boiler house operational data, are used to describe boiler house operations. Specific heat rate benchmarks are curves with a distinct minimum. The character of the curves is determined by idle fuel consumption and changes in boiler efficiency. The study examines issues related to the creation of a database and the realisation of constant energy management measures at the production process level.

Eco-intensity of district heating system operations

The eco-intensity of a district heating system's operations describes the ability to increase the quantity of heat energy produced by the boiler house, delivered to the heating networks and received by the energy consumer without increasing the consumption of fuel. Consumption of natural resources, environmentally harmful emissions and greenhouse gas emissions are all thereby decreased, which underscores the link between environmental solutions and energy efficiency. A study of district heating system eco-intensity has been conducted in paper [5]. The eco-intensity of a district heating system is characterised by the mutual interaction of parameters. The mathematical description of eco-intensity consists of a system of equations. Equations provide answers about the set of independent variables that are included in the eco-intensity evaluation model and help to make decisions about ways to optimise district heating system operations. In the study, eco-intensity is characterised by a decrease in the consumption of fuel.

Analysis of fuel diversification at the heat source. Potential of GHG decrease.

Paper [11] describes the mathematical model and algorithm developed by the author that compares and evaluates (from the economic and ecological aspect) various alternatives for the diversification of fuel in order to quickly and justifiably choose the most advantageous solution. The devised method has been tested on the boiler house in the village of Ādaži. When diversifying fuel in centralised district heating boiler houses, it is important to find not only economically optimal solutions but to also strictly evaluate the solution's influence on the environment and climate. This method has therefore been developed in such a way that it helps to evaluate and compare various types of fuel diversification from the economic as well as ecological aspect.

Economic analysis of the use of a fuel gas condenser at a district heating system source

The goal of study [4] is to analyse the cost of fuel in a small-capacity wood chip boiler house and the cost of condenser operation in an effort to evaluate the decrease in cost when a fuel gas condenser has been installed. The examined fuel cost chain consists of the actual cost of fuel, the hourly cost depending on capacity and the specific cost per unit of produced energy. The object of study is the heat source of the centralised district heating system in the Latvian town of Ludza, namely, a boiler house with a wood chip boiler that has had a direct-contact condenser installed. The analysis of the specific costs of the flue gas condenser shows that the condenser has a capacity benchmark above which financial savings can be noticed. As capacity falls below the benchmark, the condenser operates at a loss and its operating costs are greater than its income as determined by savings of wood chips. The analysis shows that during the nine months of the 2012-2013 heating season the condenser was operated with financial savings as well as without. The total evaluation consists of the balance between specific weighted gains and losses, which determines the specific weighted pure income earned during the time period. The economic effect of turning off the condenser during times of low capacity is also examined.

Exergetic analysis of a district heating system

Heat system analysis methods examined by the author have up till now been based on quantitative evaluations of flows and losses. They have not taken account that various types of energy have different exergetic qualities, which is evaluated according to the possibilities for its use. In order to cover consumer heat load, heat energy and electric energy are needed to deliver the heat to the consumer via pumps. Energy analysis methods examine the total energy in relation to the energy balance. Exergetic analysis methods use a more complete and unified characterisation of energy – exergy – whose electrical energy is higher than that of heat energy.

Study [12] offers a method for the calculation of a district heating system's exergy. The mathematical side of the district heating exergetic model consists of the exergy balance. The model has been approbated based on the Ludza municipal centralised district heating system. In order to evaluate the district heating system model, the exergy factors for the 2010–2011 heating system at various district heating system parameters have been determined, which have then been analysed and compared with district heating systems in other countries. Exergy losses in various district heating system elements have also been evaluated. The results show that an exergy analysis is a much more complete method of showing the analysed system's performance than a simple energy analysis.

Approbation of the study

Reports at conferences

1. Vīgants Ģ., Blumberga D. Modelling of the District Heating System's Operation. The 52nd International Scientific Conference of Riga Technical University, Section, “Environmental and Climate Technologies” – “Energy Resources 2011”, Riga, Latvia, October 12–13, 2011.
2. Vīgants Ģ., Ivanova P., Vīgants E., Veidenbergs I. Analysis of Diversification of Fuel in DH Sources. Potential of Reduction of GHG. The 13th International Symposium on District Heating and Cooling (DHC13), Copenhagen, Denmark, September 3–4, 2012.
3. Vīgants Ģ. Environmental Aspects of District Heating Systems. Environmental Science and Education in Latvia and Europe: Resources and Biodiversity, Ministry of Environmental Protection and Regional Development, Riga, Latvia, October 19, 2012.
4. Vīgants Ģ., Galindoms G., Veidenbergs I., Blumberga D. Energy efficiency of DH system with wood chip boiler houses and flue gas condensing unit. International Conference on Energy, Environment, Ecosystems, and Development (EEED 2013), Rhodes Island, Greece, July 16–19, 2013.
5. Ziemele J., Blumberga D., Vīgants Ģ. District heating systems performance analyses. Heat energy tariff. The 8th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES2013), Dubrovnik, Croatia, September 22–27, 2013.
6. Vīgants Ģ., Terehovičs E., Blumberga D., Veidenbergs I. Exergy Model for District Heating System Analysis, International Conference on Industrial Engineering and Management Science (ICIEMS 2013), Shanghai, China, September 28–30, 2013.

7. Vīgants Ģ., Veidenbergs I., Galindoms G., Vīgants E., Blumberga D. Analysis of Operation Mode for Complex DHS. International Scientific Conference Environmental and Climate Technologies 2013, Riga, Latvia, October 14–16, 2013.
8. Vigants Ģ., Galindoms G., Veidenbergs I., Vigants E., Blumberga D. Energy management of a wood chip boiler house with a gas condenser. The 27th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Turku, Finland, June 15–19, 2014.
9. Vigants G., Galindoms G., Veidenbergs I., Vigants E., Blumberga D. Efficiency diagram for district heating system with gas condensing unit. The International Scientific Conference on Environmental and Climate Technologies (CONECT 2014), Riga, Latvia, October 14–16, 2014.
9. Vigants G., Veidenbergs I., Vigants E., Blumberga D. Cost analysis of a wood chip boiler house with a gas condenser. The 7th International Conference on Applied Energy (ICAE2015), Abu Dhabi, United Emirates, March 28–31, 2015.

Publications by the author

1. Vīgants Ģ., Blumberga D. Modelling of the District Heating System's Operation. Environmental and Climate Technologies, 2011, Vol. 6, pp. 132–137.
2. Blumberga D., Vīgants E., Veidenbergs I., Vīgants Ģ., Vītoliņš V. Eco-Intensity Analysis for a Chip-Fuelled Boiler House. Journal of Environmental Engineering and Landscape Management, 2012, Vol. 20, No. 4, pp. 249–255.
3. Vīgants Ģ., Ivanova P., Vīgants E., Veidenbergs I. Analysis of Diversification of Fuel in DH Sources. Potential of Reduction of GHG. Proceedings of the 13th International Symposium on District Heating and Cooling, Copenhagen, Denmark, September 3–4, 2012, pp. 179–285.
4. Rošā M., Romagnoli F., Blumberga D., Vīgants Ģ. Small Scale District Heating Systems. Demand Side Management Effect. Proceedings of the 13th International Symposium on District Heating and Cooling, Copenhagen, Denmark, September 3–4, 2012, pp. 38–46.
5. Vīgants E., Blumberga D., Veidenbergs I., Vīgants Ģ., Rochas C. Experimental Research of Flue Gas Condensing Unit. Advances in Environment, Biotechnology and Biomedicine: Proceedings of the 1st WSEAS International Conference on Energy and Environment Technologies and Equipment, Zlin, Czech Republic, September 20–22, 2012, pp. 179–189.
6. Vīgants Ģ., Galindoms G., Veidenbergs I., Blumberga D. Energy efficiency of DH system with wood chips boiler houses and flue gas condensing unit. Proceedings of the 2013 International Conference on Energy, Environment, Ecosystems, and Development, Energy, Environmental and Structural Engineering Series, Rhodes Island, Greece, July 16–19, 2013, Vol. 12, pp. 168–171.
7. Vīgants Ģ., Terehovičs E., Blumberga D., Veidenbergs I. Exergy Model for District Heating System Analysis. Proceedings of International Conference on Industrial Engineering and Management Science, Shanghai, China, September 28–30, 2013, pp. 351–361.
8. Ziemele J., Vīgants Ģ., Vītoliņš V., Blumberga D., Veidenbergs I. District Heating Systems Performance Analyses. Heat Energy Tariff. Proceedings of the 8th Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik, Croatia, September 21–27, 2013.
9. Ziemele, J., Pakere, I., Talcis, N., Cimdiņa, G., Vīgants, Ģ., Veidenbergs, I., Blumberga, D. Analysis of Wood Fuel Use Development in Riga. Agronomy Research, 2014, Vol.12, No.2, pp. 645–654.

10. Vīgants, Ģ., Galindoms, G., Vīgants, E., Veidenbergs, I., Blumberga, D. Heat Pump Application for Efficient DH Systems. Conference Proceedings: 6th International Conference on Applied Energy, Taipei, Taiwan, May 30–June 2, 2014, Vol. 61, pp. 2168–2171.
11. Vīgants Ģ., Veidenbergs I., Galindoms G., Vīgants E., Blumberga D. Analysis of Operation Mode for Complex DHS. Conference Proceedings: Environmental and Climate Technologies 2013, Riga, Latvia, October 14–16, 2013, pp. 35–38.
12. Vigants G., Galindoms G., Veidenbergs I., Vigants E., Blumberga D. Energy management of a wood chip boiler house with a gas condenser. Proceedings of the 27th International Conference On Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Turku, Finland, June 15–19, 2014, Vol. 1, pp. 1464–1474.
13. Vīgants, Ģ., Galindoms, G., Veidenbergs, I., Vīgants, E., Blumberga, D. Efficiency Diagram for District Heating System with Gas Condensing Unit. Abstracts of 55th International Scientific Conference: Subsection: Environmental and Climate Technologies, Riga, Latvia, October 14–15, 2014, pp. 65–66.
14. Cimdina G., Slisane Dz., Ziemele J., Vitolins V., Vigants G., Blumberga D, Sustainable Development of Renewable Energy Resources Biomass Cogeneration Plant. Proceedings of the 9th International Conference Environmental Engineering, Vilnius, Lithuania, May 22–23, 2014.
15. Vigants G., Veidenbergs I., Vigants E., Blumberga D. Cost analysis of a wood chip boiler house with a gas condenser. The 7th International Conference on Applied Energy, Abu Dhabi, United Emirates, March 28–31, 2015.

1. RESEARCH METHODS

1.1. Description of Ludza centralised district heating system

1.1.1. Characteristics of the district heating system source

The Ludza boiler house has been operating since 2000 and uses wood chips for fuel, which are bought from local providers. The boiler house is equipped with a biomass combustion boiler after which a flue gas condenser (made and patented in Latvia) was installed in 2010 for further recovery of energy from flue gases.

Measured data from the boiler house's operations over the course of several heating seasons from 2010 to 2013 have been used for the analysis of the system.

Data have been measured to define the following parameters, upon which the district heating system's operations were then evaluated:

1. boiler capacity;
2. condenser capacity;
3. total boiler house capacity;
4. water temperature in the condenser circulation loop before and after heat exchanger;
5. supply and return temperature of network water;
6. electricity consumption in the boiler house;
7. electricity consumption of condenser;
8. monthly wood chip consumption.

Employees measure and record the data once every three hours from the automation and control unit as well as from the meters on the boiler and condenser. The condenser cools the flue gases to approximately 60 °C and heats the water that is used to preheat the heating system's return water. The film of condensation that appears on the heat transfer surface promotes the precipitation of particulate matter from the flow and the absorption of gaseous components. It has been found that particulate matter emissions can be decreased by up to 33–44%. A separator is used to separate the particulate matter that is collected. The water level in the separator rises due to the formation of condensate, and some of the water together with the particulate matter is drained off in the form of pulp. The condensate creates an acidic environment and NaOH is used to neutralise this environment. The acidic environment is created by the condensate's soluble oxides, which are found in the flue gases.

1.1.2. Characterisation of the district heating system's heat networks

The heating networks in the Ludza centralised district heating system are designed for steam, a gaseous heat carrier. This is because before 2000 heating in the town of Ludza was provided by mazut-burning boilers. The diameters of the heating network are small when compared with other centralised district heating systems. One main heating network pipe with an inner diameter of 0.263 meters leads out of the boiler house, and the length of this main heating network is 2029.5 meters, at the end of which the inner diameter is 0.07030 meters. The branches off the main heating network connect 108 objects that require heating: homes, childcare facilities, schools, hospitals and the Ludza town hall. The total length of the Ludza heating network is 9770 meters.

1.2. Integration of a heat pump into the district heating system

1.2.1. Connecting the heat pump

The issue of study is connected with insufficient heat supply to one group of consumers within the district heating system. The temperature of the heat carrier must be raised before is reaches the consumer group. This can be done by raising the temperature of the whole system at the boiler house exit or by setting up additional capacity to raise the temperature for the consumer group. A version for the use of a heat pump has been examined here. The study creates a diagram for connecting the heat pump and calculating the temperature changes within the district heating system that are caused by the heat pump. This diagram for connecting a heat pump to the district heating system is shown in Figure 1.1:

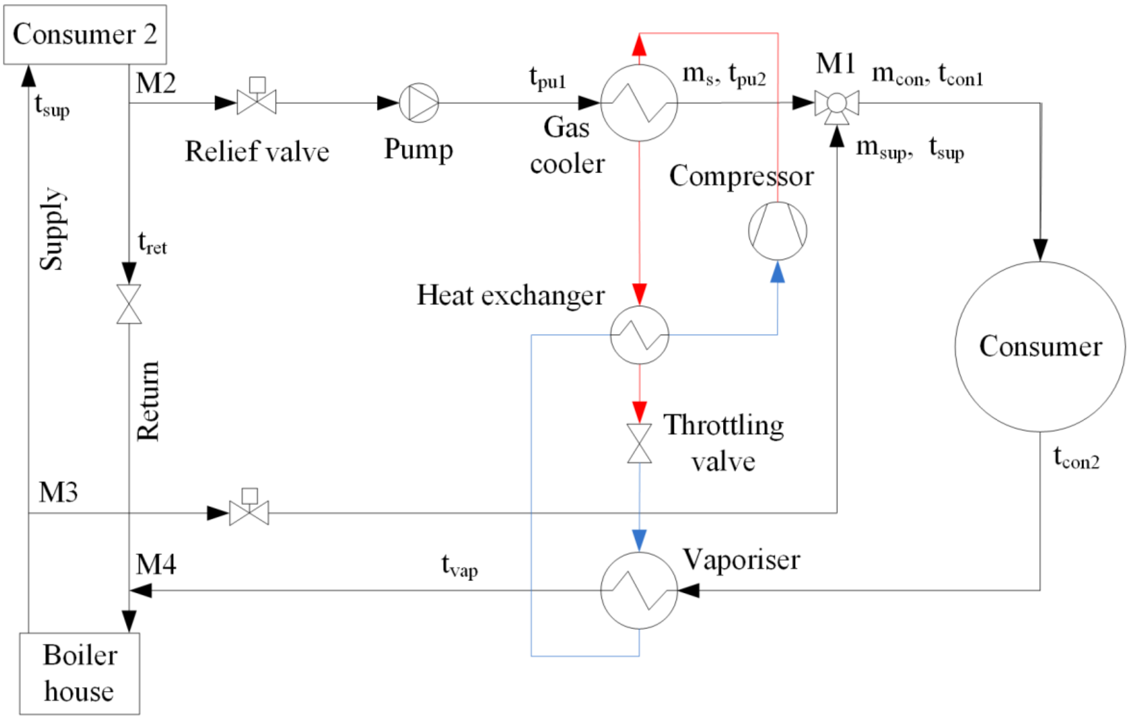

Fig. 1.1. Integration of a heat pump into a district heating system

The heat pump is connected to the heating network return and, by mixing in a portion of the supply network water, it is intended to ensure the necessary heat load to the consumer group. The mixing in of supply water is necessary in case the heat pump's capacity is not enough to cover the consumer group's load or in case the heat pump is unable to operate properly.

After Consumer 2 at node M2, the return network water is diverted and sent to the heat pump's gas cooler. The flow of the diverted return water is m_s. The portion of supply water m_{sup} is also diverted to node M3. Both flows come together at node M1 and create the consumer flow m_{con}. After the consumer, the heat carrier flow m_{con} flows through the heat pump vaporiser, after which the flow is introduced into the return heating network at node M4.

The task of the heat pump is to raise the water temperature before the consumer t_{con1} in such a way that consumers achieve the necessary indoor temperature in their homes when outdoor temperatures are low. This is done by mixing the portion of return water heated in the heat pump's gas cooler m_s with the portion of supply water m_{sup}. The sum of the flows m_{con} is a quantity that corresponds to the consumer's water flow and changes depending on the outdoor temperature. It is important to remember that flows m_s and m_{sup} are related quantities – as m_{sup} increases, m_s decreases and vice versa. In order for the gas cooler to heat the diverted return network water m_s, the heat pump receives heat from the vaporiser, which has been turned on in the consumer's return. The return water temperature t_{vap} is lower after the heat pump's vaporiser. This lessens heat loss in the return and increases the efficiency of the flue gas condenser installed in the boiler house.

1.2.2. Model of a district heating system with a heat pump

The calculation of the diagram for the integration of a heat pump into a district heating system creates a model that includes the empirical and analytical correlations and algorithm necessary for the calculations. The goal of the calculation is to determine the temperature of the diverted return network water after the heat pump's gas cooler t_{pu2}, the flow of the diverted water through the heat pump's gas cooler m_s, the return water temperature after the heat pump's vaporiser t_{vap}, the return water temperature after the consumer and the mixed-in supply water flow m_{sup}. The calculation assumes that the heat pump operations result in a water temperature before the consumer t_{con1} that is Δt_t °C higher than the supply network water temperature t_{sup}. The unique aspect of this calculation model is that it unites empirical equations characterising district heating systems that are obtained by processing and developing analytical expressions of experimental data that characterise the system's operations. The analytical correlations have been obtained by using equations of the diagram elements and the mass and energy balance of the nodes. The diagram's calculated algorithm, which consists of 16 blocks, is shown in Figure 1.2.

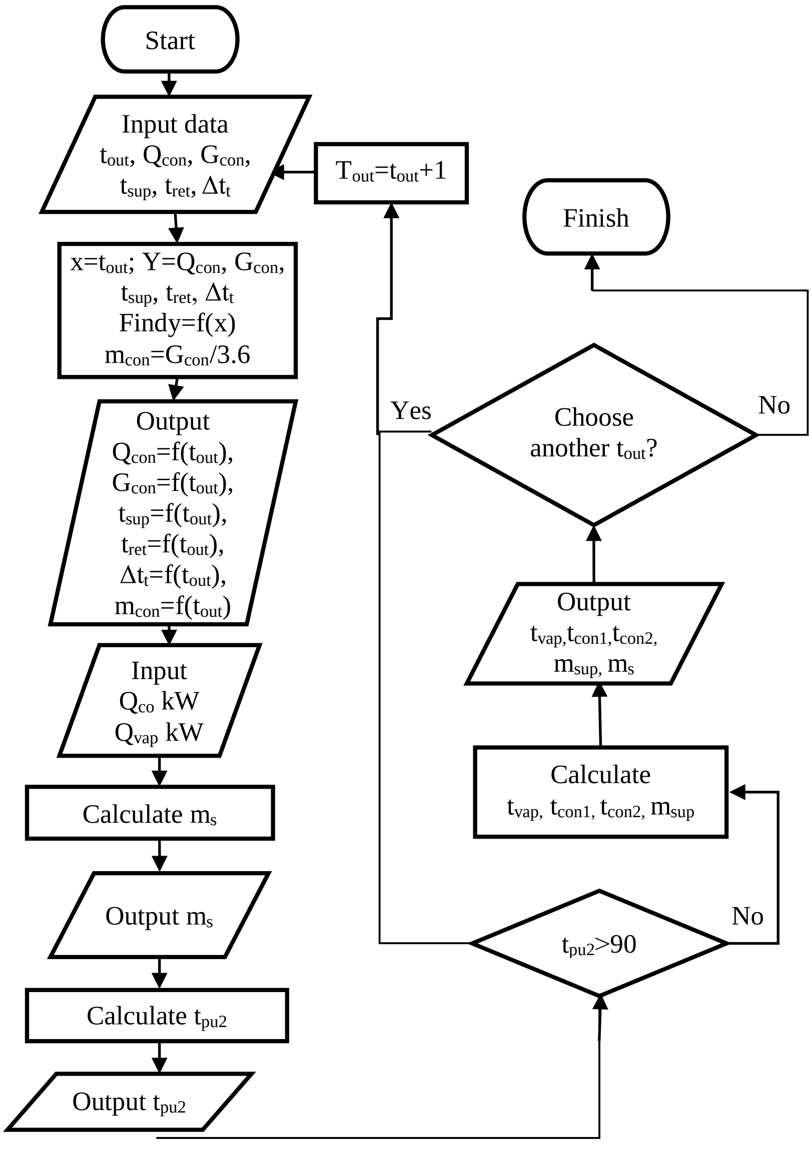

Fig. 1.2. Calculated algorithm of a heat pump

The mass and energy heat balances in node M1 and the heat balance of the heat pump's gas cooler are used to obtain an expression from the total heating network to determine the diverted supply water flow:

$$m_s = \frac{\frac{Q_{co}}{4.19} - \Delta t_t \cdot m_{con}}{t_{\sup} - t_{ret}}, \tag{1.1}$$

where

m_s – return water flow through gas cooler, kg/s;

Q_{co} – capacity of heat pump's gas cooler, kW;

Δt_t – increase in temperature before consumer, °C;

m_{con} – consumer's water flow, kg/s;

t_{sup} – supply network water temperature, °C.

The temperature of the diverted water after the heat pump's gas cooler is determined using an equation of the heat balance at node M1 in the diagram:

$$t_{pu2} = t_{\sup} + \Delta t_t \cdot \left(\frac{m_{con}}{m_s} \right) \tag{1.2}$$

The maximum possible water temperature after a high-temperature heat pump is around 90 °C. Therefore, the t_{pu2} temperature obtained in the calculations is compared with the permissible temperature and, if it is not higher than 90 °C, the calculation is continued. Otherwise, the calculation is begun again with a higher outdoor temperature. The outdoor temperature is changed in increments of 1 °C.

When using the consumer's heat balance equation, the water temperature after the consumer is calculated with the following expression:

$$t_{con2} = t_{\sup} + \Delta t_t - \frac{Q_{con}}{4.19 \cdot m_{con}}, \tag{1.3}$$

where

Q_{con} – consumer's heat load, kW.

The post-consumer water flows through the heat pump's vaporiser, where the water temperature decreases to t_{vap}. The following equation is used to calculate the water temperatures after the heat pump vaporiser:

$$t_{vap} = t_{\sup} + \Delta t_t - \frac{Q_{con} + Q_{vap}}{4.19 \cdot m_{con}}, \tag{1.4}$$

where

Q_{vap} – capacity of heat pump's vaporiser, kW.

As seen in Figure 1.1, at node M4 water with a temperature of t_{vap} mixes together with the network water after the second consumer and is further diverted to the boiler house. If t_{vap} is lower than the return water temperature t_{ret}, then the return water temperature in the boiler house decreases.

The necessary mix of supply water is determined from the material balance at node M1:

$$m_{\sup} = m_{con} - m_s \quad (1.5)$$

The water temperature supplied to the consumer is raised in cases of low outdoor temperature, and this is determined as:

$$t_{con1} = t_{\sup} + \Delta t_t \quad (1.6)$$

The calculation is performed for the whole range of outdoor temperature changes.

1.3. Method for creating a nomogram for a condenser

A nomogram, which determines what boiler house load can be covered with a boiler and what load can be covered with the help of a condenser, has been developed for the Ludza municipal district heating system source, which has been equipped with an 8 MW wood chip boiler with a direct-contact condenser. Boiler house operations have shown that at low outdoor temperatures the wood chip boiler's capacity can be increased to 10 MW with good-quality fuel. The study has been performed by analysing operational data from the Ludza district heating system during the 2012–2013 heating season with correlation and regression statistical analysis methods. The *Statgraphics Plus* programme has been used for the statistical data processing. The analysed data set contains 474 modes and 17 parameters. The goal of the data analysis obtained in the industrial experiment is to determine the set of statistically significant operational parameters that significantly influences the effectiveness of the condenser's recovery of heat as well as to determine a multi-regression equation binding the parameters and evaluate its adequacy.

In order to evaluate the condenser's operations, an indicator for the condenser's effectiveness has been chosen, which is defined as:

$$E_c = N_c \cdot \frac{100}{N_b}, \ \%, \quad (1.7)$$

where

N_c – condenser capacity, MW;

N_b – boiler capacity, MW.

The condenser effectiveness indicator shows what portion of the boiler capacity can be recovered by a deep cooling of the flue gases.

As the result of the statistical analysis, an equation has been obtained that connects the condenser effectiveness indicator with seven statistically significant independent variable parameters:

$$\begin{aligned} E_c = 7.84433 + 0.0793491 \cdot G_t - 1.82416 \cdot K_{sh} + 0.394416 \cdot K_{sv} - \\ -1.96617 \cdot N_b - 0.0255361 \cdot t_{g2} + 0.966587 \cdot t_{k2} - 1.07522 \cdot t_r \end{aligned} \quad (1.8)$$

The variance analysis shows that the independent variables are statistically significant to a confidence interval of 95%. Equation (1.8) explains 94.6 % of the E_c changes. The independent variables in the equation are:

N_b – boiler capacity, MW;

G_t – water flow in the heating network circuit of the network heat exchanger, m^3/h;

t_{g2} – temperature of flue gases after the flue gas condenser, °C;

t_{k2} – water temperature after the condenser and before the network heat exchanger, °C;

t_r – temperature of the return network water before the network heat exchanger, °C;

K_{sh} – water spray coefficient in the horizontal part of the condenser, $kg/kg_{s.g.}$;

K_{sv} - water spray coefficient in the vertical part of the condenser, $kg/kg_{s.g.}$

The range of variable parameter changes during the experiment is shown in Table 1.1.

Table 1.1.

Range of parameter changes

Parameter	G_t	K_{sh}	K_{sv}	N_b	t_{g2}	t_{k2}	t_r
Unit of measurement	m^3/h	kg/kg$_{s.g.}$	kg/kg$_{s.g.}$	MW	°C	°C	°C
Range	107–216	0.034–1.005	3.19–22.04	2.8–9.4	50–70	51–64	43.3–58.3

The following correlation is used to determine the water spray coefficient:

$$K_s = \frac{G_c \cdot \rho_w \cdot 1000}{L_{dg}}, \tag{1.9}$$

where

G_c – amounts of water sprayed through the nozzles in the horizontal or vertical part of the condenser, m^3/h;

L_{dg} – amount of dry flue gases, kg$_{s.g.}$/h;

ρ_w – water density, kg/m^3.

Spray coefficients K_{sh} un K_{sv} are chosen depending on whether the water is sprayed into the vaporisation section of the condenser's horizontal part or the condensation section in its vertical part.

1.4. Energy management of a wood ship boiler house with a flue gas condenser

The study is associated with developing a method for the creation of an energy management system for a small-capacity centralised district heating system and its approbation in the wood chip boiler house in Ludza. The energy management method includes an evaluation of the boiler house's energy efficiency based on operational data obtained from the boiler house and then processed. The mathematical processing of the data results in an empirical model that describes the changes in specific wood chip consumption depending on produced heat. That is the first benchmark. Equations characterising the benchmarks have been obtained for cases in which the boiler operates with and without a condenser. Seeing as energy management is a continuous process of the rational use of energy resources, when a system has reached the first benchmark we must consider what measures must be performed for the subsequent decreasing of fuel consumption. The provided method is also used for determining these measures.

The study has been performed by using the correlation analysis method to analyse the monthly operational data from the Ludza district heating system's boiler house during the 2011–2012 and 2012–2013 heating seasons. The measurements were taken with measuring equipment set up in the boiler house. Wood chip consumption is expressed in m^3 using the volume balance method; it is based on the difference between the amount of fuel bought and in stock according to the following formula:

$$V = P + (S - E), \tag{1.10}$$

where

V – fuel burned during the observed time period, m^3;

P – fuel obtained during the observed time period, m^3;

S – stocks of fuel at the beginning of the observed time period (measured with a tape measure), m^3;

E – stocks of fuel at the end of the observed time period (measured with a tape measure), m^3.

The fuel's lowest combustion temperature and density is determined in the laboratory. Each month, fuel samples are taken from each fuel provider. Following the analyses in the laboratory, values for the lowest average monthly combustion temperature and density are calculated. From this characterisation of the fuel, the monthly addition of fuel energy into the boiler is determined as:

$$B_f = V \cdot Q_{low}^h \cdot \rho \text{, MWh}_f\text{/month,} \quad (1.11)$$

where

V – monthly wood chip consumption, m^3;

Q_{low}^h – lowest combustion heat for wood chips, MWh/t;

ρ – wood chip density, t/m^3.

By dividing the monthly addition of energy into the boiler B with the number of hours per month, we arrive at the average monthly capacity of fuel P_f. Similarly, by dividing the energy measured by the meters with the number of hours per month we arrive at the average monthly MW boiler capacity P_b and the average monthly electrical capacity P_{el}.

The specific indicators for fuel temperature b_b and b_{bc} are determined by dividing the consumed fuel energy B with the corresponding measured heat energy produced by the boiler Q_b and the heat energy produced by the boiler condenser Q_{bc}. Specific electrical energy e_{el} consumption is determined by dividing the measured monthly electrical energy consumption E_s with the heat produced by the boiler Q_b. Thus, the specific indicator values are attributed to the heat produced by the boiler or the boiler and condenser. The results of the data processing are shown in Figure 1.3.

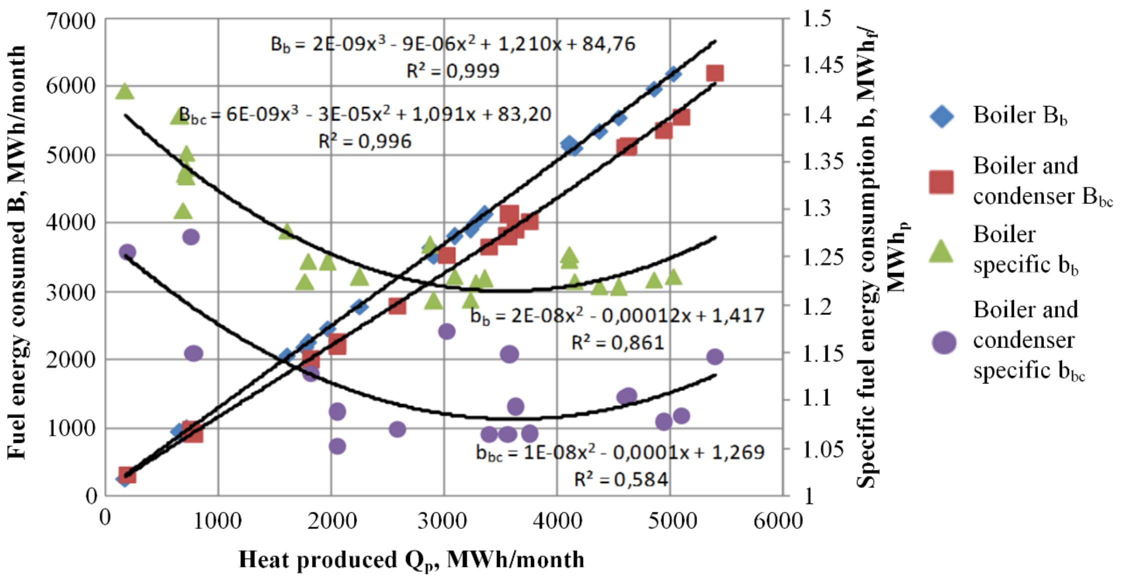

Fig. 1.3. Changes in fuel heat consumed in the wood chip boiler house and the specific fuel heat depending on the monthly heat energy produced by operating the boiler with and without a condenser

The curves in Figure 1.3 show the values of the corresponding parameters and changes therein as energy production in the boiler house changes. Empirical equations describing these parameter changes have been obtained, and they generally correlate well with the obtained data.

The square values R^2 for the correlation coefficient range from 0.86 to 0.99. The poorest correlation can be observed in the data regarding changes in the specific heat rate for a boiler with a condenser (R^2=0.58). The equations can be used for further data analysis. The obtained graphs describe the parameter benchmarks for the current situation, and these are necessary for effective energy management of the boiler house. If energy management measures are performed in either the boiler house or on the heat consumer's side, these parameter benchmarks will change and new graphs will have to be made. This can be done with the method offered here.

The boiler house is equipped with electricity meters, and these meters separately measure electricity consumption for a boiler house without a condenser E_{bh} and for a condenser E_{co}. Figures 1.4 and 1.5 show the changes in electricity consumption and specific electricity consumption.

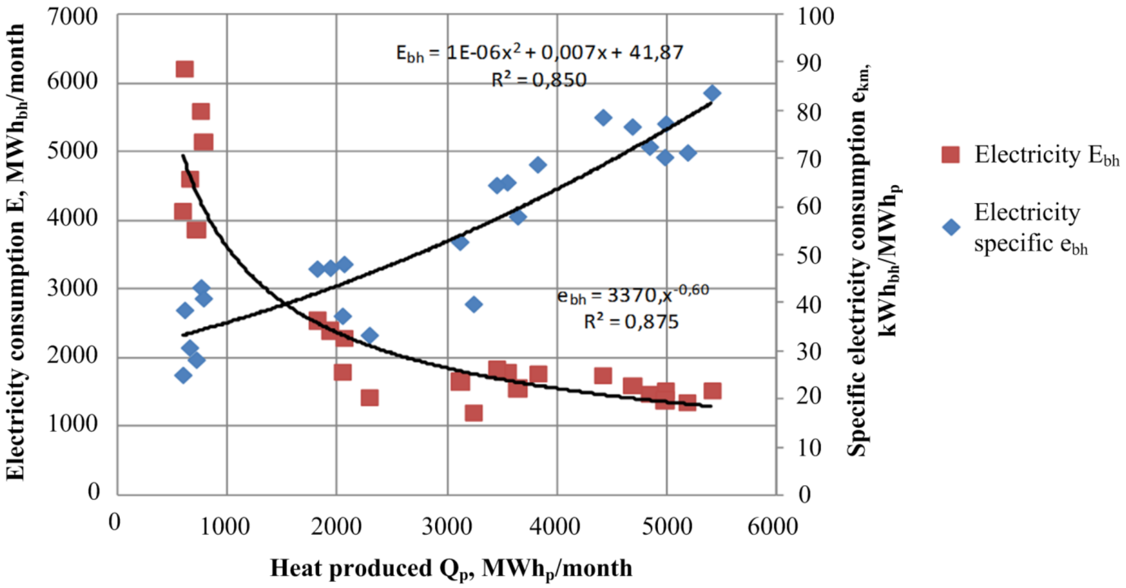

Fig. 1.4. Changes in a district heating system's electricity consumption and specific electricity consumption depending on the amount of heat produced per month

The graph shows good correlation of data, and R^2 is within the range of 0.85–0.87. The boiler house itself is the electricity consumer, and the graph does not include electricity consumption linked to network water pump operations. Equations describing electricity consumption can be seen in Figure 1.4.

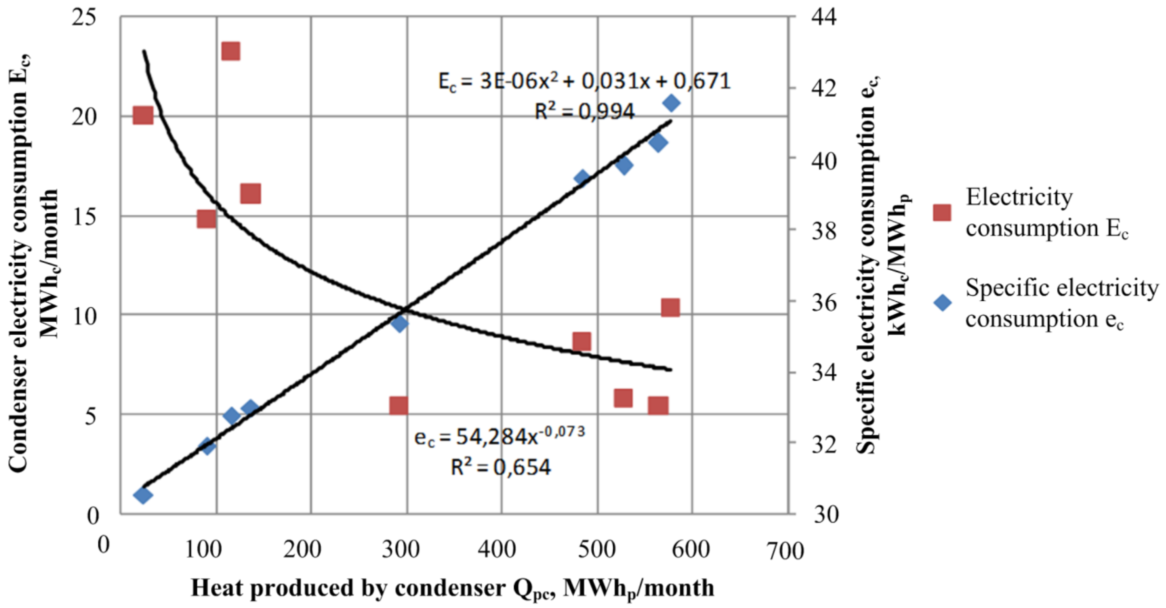

Fig. 1.5. Changes in condenser electricity consumption depending on heat produced

The boiler house parameter benchmarks can be determined for the whole boiler house or separately for each main heat production technology (wood chip boiler and condenser). The benchmarks for consumption B_{bc} and specific heat rate b_{bc} seen in Figure 1.3 describe the production of heat by the boiler and condenser together. But curves B_b and b_b in Figure 1.3 show only the boiler's heat production benchmark. The distributed benchmark curves seen in Figures 1.4 and 1.5 show electricity consumption related to heat production in the boiler and condenser. From the aspect of energy management, preference is given to the distributed benchmarks because they evaluate which system deviates from the defined benchmark. In practice, however, one must take into account what kind of operational data are measured in the boiler house and are available for analysis.

1.5. Economic analysis of the use of a glue gas condenser at a district heating system's source

The goal of the analysis is to perform a cost analysis of fuel and condenser operations at a small-capacity wood chip boiler house with the intention of evaluating a decrease in costs in the case of the installation of a flue gas condenser. The analysis examines the fuel cost chain: cost of fuel, hourly costs depending on capacity and specific costs per unit of produced energy.

1.5.1. Fuel costs for a boiler and a boiler plus condenser

The following have been obtained and used for the cost analysis of fuel used for energy production:

1. fuel consumption curve;
2. fuel costs curve;
3. specific heat rate curve;
4. specific heat rate cost curve.

The study has been performed by analysing the monthly operational data from the 2012–2013 heating season at the Ludza district heating system's boiler house. Measurements were taken from meters set up in the boiler house. Fuel consumption is expressed in m^3 per month of the balance of fuel bought and fuel remaining in stock. Once a month, the lowest combustion temperature for fuel from each provider is determined in a laboratory. Based on the character of the fuel and the amount of fuel consumed, the capacity introduced into the boiler (fuel input)

P_f MW_f is determined. Data from the business' monthly financial reports regarding boiler fuel and condenser operation costs are used for the cost analysis. The energetic aspects of the system's operations are examined in more detail in the energy management section. Fuel costs are determined by wood chip prices, which are shown in Figure 1.6.

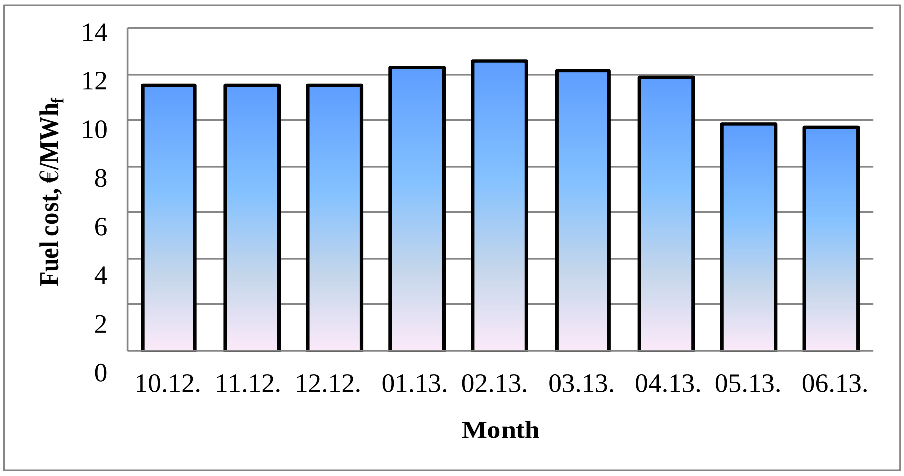

Fig. 1.6. Changes in wood chip prices at the Ludza boiler house

It is evident that prices fluctuate and are higher during the winter months. An average price value of c_f = 11.46 €/MWh_f has been used for further calculations. The wood chip price is determined per unit of fuel energy.

The system's input-output curve is used as a base for determining the fuel cost curve and for further specific fuel energy and cost calculations. The average monthly boiler P_b and boiler plus condenser P_{bc} capacity is determined by dividing the monthly produced energy as measured by meters Q_b and Q_{bc} with the number of hours per month. The graphs of correlations $P_f = f_1(P_b)$ and $P_f = f_2(P_{bc})$ form the input-output curves for a boiler and boiler plus condenser. The fuel cost curve is obtained by multiplying the fuel input capacity P_f by the fuel price c_f. Graphs of the curves can be seen in Figure 1.7.

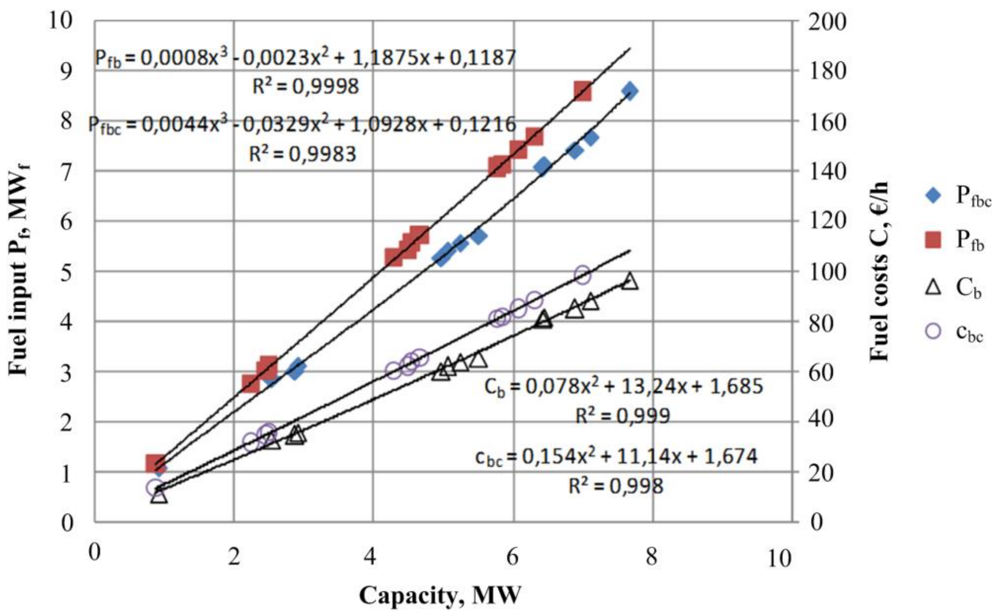

Fig. 1.7. Input capacity and hourly fuel costs depending on the system's heat capacity

The figure shows that as the system's capacity increases, hourly fuel costs also increase. The trend is understandable because, as generation capacity increases, so does fuel consumption. The data correlation analysis shows that fuel costs for a boiler without a condenser can be described with the following equation:

$$C_b = 0.078 \cdot P_b^2 + 13.24 \cdot P_b + 1.685, \text{€/h} \quad (1.12)$$

If the boiler house is operated with a condenser, hourly fuel costs are lower and can be determined thus:

$$C_{bc} = 0.154 \cdot P_{bc}^2 + 11.14 \cdot P_{bc} + 1.674, \text{ €/h} \quad (1.13)$$

The system's fuel consumption depending on generation capacity is determined by the fuel consumption curve. This curve differs from the fuel costs curve only in scale. The scale factor is the fuel price c_f. Equations (1.12) and (1.13) indicate non-linear changes in fuel costs, which leads one to believe that there might be economically more advantageous and less advantageous modes of operation.

Specific indicators ensure a more in-depth cost analysis. The specific heat rate indicators b_b and b_{bc} are determined by dividing the consumed fuel energy B by the measured heat produced by the boiler Q_b and the heat produced by the boiler plus condenser Q_{bc}. The specific indicator values determine how much fuel energy must be consumed per one unit of produced heat energy. Numerically, the same value is obtained by dividing the fuel input capacity P_f by the boiler capacity P_b or boiler plus condenser capacity P_{bc}. If so, then the system's fuel consumption curves can be used to determine the specific indicators. By knowing the the fuel energy unit price c_f, €/MWh$_f$, the fuel component price for a boiler c_{fb} or boiler plus condenser c_{fbc}, €/MWh$_p$ can be determined per unit of produced energy. The results of the quantity calculations are shown in Figure 1.8.

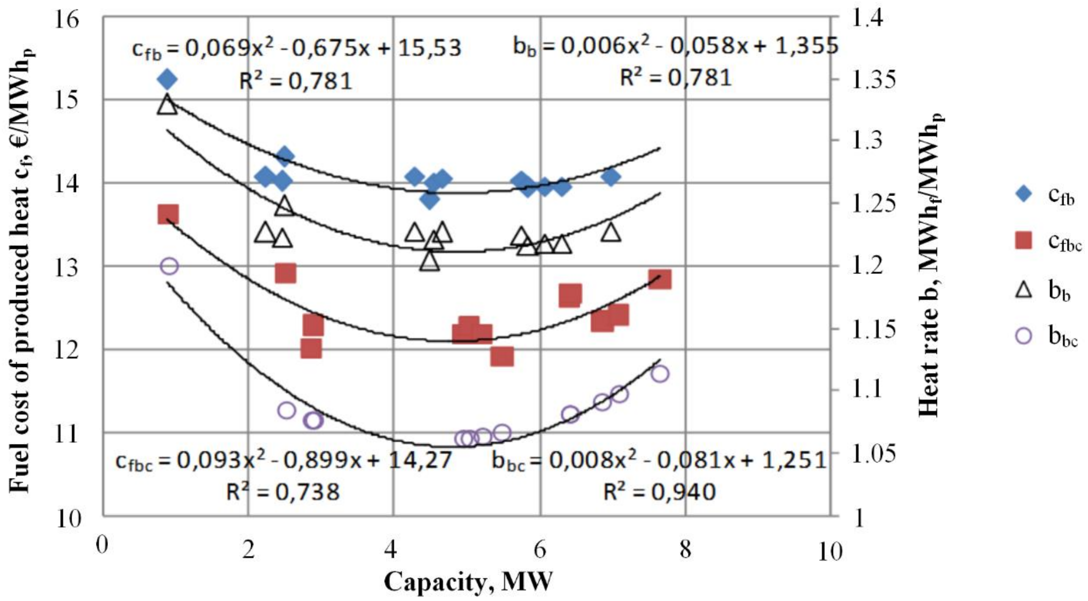

Fig. 1.8. Changes in specific fuel consumption and fuel costs depending on generated capacity

The character of the curve in Figure 1.8. indicates that minimums for both specific heat rate indicators and price per unit of produced heat can be observed at certain heat generating capacities. The equations describing changes, which are obtained in the data correlation analysis, are used to determine the fuel price minimum.

1.5.2. Condenser operation costs

When performing measures to increase the energy efficiency of a boiler house, it is important to know whether they will have a positive economic effect and how large this effect will be. Detailed data regarding operation costs are used in the analysis of the condenser. In order to perform this analysis, operational data from the condenser for nine months of the 2012–2013 heating season was collected and summarised. This data set was comprised of the results of direct measurements (produced heat, electricity consumption, water consumption, amount of ash caught in condenser) and data regarding fuel, electricity, sewerage, ash transportation and labour costs. Specific indicators were created for the data analysis in which income, costs and savings were applied to each unit of heat produced in the condenser MWh_c. The analysis examines the specific costs for electricity c_{el}, water and sewerage c_{ws}, labour and materials c_{lm} and ash disposal c_{ash}. The sum of the specific costs of separate positions form the total specific costs for operating a condenser:

$$c_{\exp} = c_{el} + c_{ws} + c_{lm} + c_{ash} + c_{am}, \text{€/MWh}_c \tag{1.14}$$

The financial savings obtained from using a condenser are savings c_{sav}, which are associated with the difference between wood chip economy c_{in} and the total costs c_{exp}. The condenser operations data obtained via direct measurements and calculations have been compiled in Table 1.2.

Table 1.2.

Condenser operations data

Items	**Unit**	**2012**			**2013**					
		Oct.	**Nov.**	**Dec.**	**Jan.**	**Febr.**	**Mar.**	**Apr.**	**May**	**Jun.**
Produced heat Q_c	MWh_c	137	116	577	563.8	484.2	529.9	291.5	90.6	23.9
Capacity P_c	MW	0.19	0.16	0.8	0.78	0.67	0.73	0.4	0.12	0.03
Income c_{in}	€/MWh_c	14.2	14.1	15.8	15.2	15.4	15.4	14.3	12.1	11.8
Expenses c_{exp}	€/MWh_c	17.93	20	6.14	6.62	7.28	6.82	10.13	26	79.8
Electricity c_{el}	€/ MWh_c	3.46	3.36	2.6	2.88	3.06	2.9	3.29	4.19	4.26
Water & sewerage c_{ws}	€/MWh_c	1.79	1.49	0.49	0.56	0.52	0.54	0.74	2.24	3.75
Labour cost & materials c_{lm}	€/MWh_c	0.21	0.25	0.051	0.052	0.06	0.055	0.1	0.32	1.23
Ash removal c_{ash}	€/MWh_c	0.21	0.41	0.08	0.144	0.168	0.154	0.24	0.75	0.57
Amortisation c_{am}	€/MWh_c	12.26	14.51	2.92	2.98	3.47	3.17	5.76	18.5	70
Savings c_{sav}	€/MWh_c	−3.73	−5.92	9.66	8.78	8.12	8.58	4.17	−13.9	−68

Changes in condenser operation cost elements depending on condenser capacity are shown in Figure 1.9.

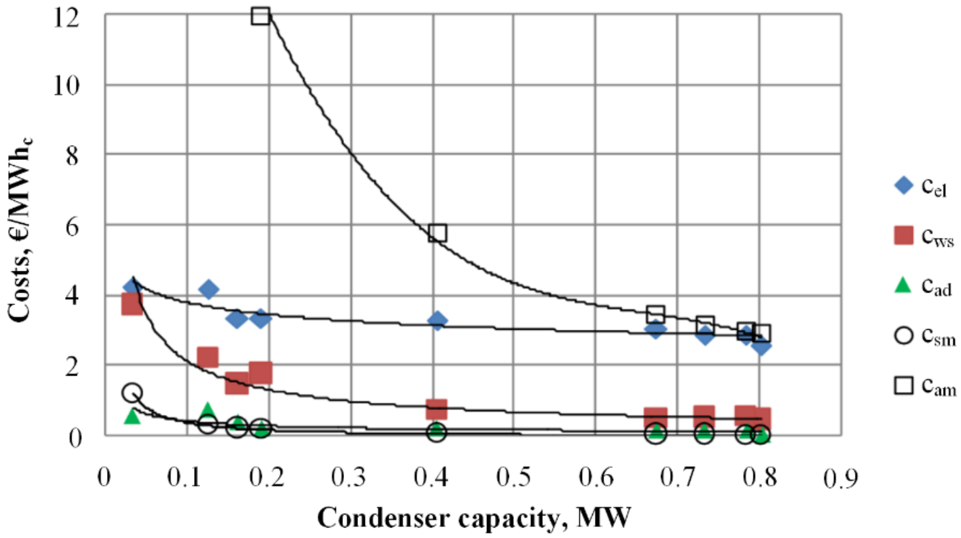

Fig. 1.9. Condenser operation costs depending on capacity

It can be seen that the changes in costs are steady and with no pronounced minimum. As condenser capacity increases, all of the specific costs decrease. At low condenser capacities, amortisation and electricity costs dominate and water and sewerage costs increase. At higher capacities, the specific electricity and amortisation costs even out.

1.6. Method for studying the eco-intensity of flue gas condenser use in a district heating system

1.6.1. Eco-intensity of district heating system operations

The eco-intensity of district heating system operations characterises the opportunities for increasing the amount of heat produced in a boiler house, delivered through heat networks and received by energy consumers without increasing the consumption of fuel. Natural resource consumption, environmentally hazardous emissions and GHG emissions thereby decrease, which underscores the link between environmental solutions and energy efficiency and eco-intensity. Operational eco-intensity depends on the efficient operation of district heating system elements (energy source, heat networks and energy users) in the system as a whole. Eco-intensity depends on the following technological, economic, environmental and management aspects of district heating system operations:

1. organisation of the combustion process in the boiler furnace,
2. quality of the energy resource used,
3. energy efficiency of the boiler system,
4. operational parameters of the heat networks,
5. professionalism of boiler house management,
6. economically advantageous installation and operational parameters for systems,
7. effective use of natural resources,
8. monitoring of harmful emission amounts,
9. controlling of GHG emission amounts.

The district heating system elements are illustrated in Figure 1.10; the figure also shows the positions for determining operational parameters for the system.

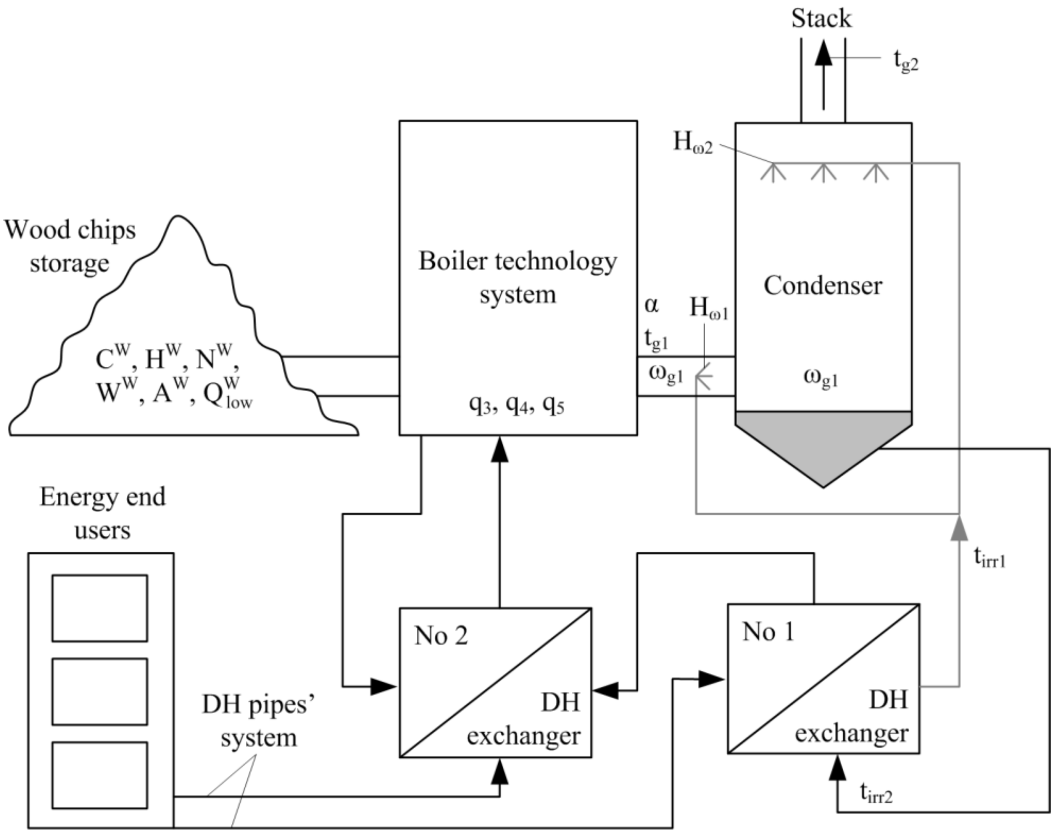

Fig. 1.10. Diagram of the integration of district heating system elements

The system consists of the following elements:

1. boiler systems with water preparation and purification systems as well as flue gas purification technologies,
2. in addition to the existing system, an innovative wood chip boiler house technology has been installed, namely, a gas condenser that consists of two linked sections for the deep cooling of flue gases,
3. a heat exchanger for the heating of network water with heat obtained from the gas condenser,
4. a heat exchanger for the heating of network water with heat produced in the boiler,
5. a heat network pipe system that connects the energy source with energy end users,
6. heat consumers who use the heat energy to heat their buildings and hot water systems.

The operational parameters for a district heating system are determined and evaluated from the standpoint of decreasing fuel consumption; then, their influence on the environment and climate change is determined.

The gas condenser is developed in such a way that the processes taking place inside it supplement one another and the conditions for heat and mass transfer are optimal. The optimal conditions for operating a condenser depend on the construction and operational conditions of the condenser itself as well as on the terms and effectiveness of operating the boiler system and the operational parameters of the district heating system.

1.6.2. Model for evaluating the eco-intensity of a district heating system

A district heating system's eco-intensity is characterised by the interaction between the parameters, and its mathematical description is formed by a system of equations. The equations provide answers regarding the set of independent variables, which are included in the eco-intensity evaluation model and allow the researcher to judge the kinds of optimisation possible for the district heating system.

In general cases, a complex system of four equations must be solved, the functional dependency of which is illustrated below. In this case, the eco-intensity is characterised by a decrease in fuel consumption:

$$\begin{cases} dB_1 = f\left(C^w, H^w, N^w, W^w, A^w, Q^w_{low}\right) \\ dB_2 = f\left(\alpha, t_{g1}, q_3, q_4, q_5\right) \\ dB_3 = f\left(t_{g1}, t_{g2}, t_{irr1}, t_{irr2}, \omega_g, H_{\omega 1}, H_{\omega 2}\right) \\ dB_3 = f\left(t_{ret}, t_{\sup}, G_{dh}\right) \end{cases} \quad (1.15)$$

where

dB – decrease in fuel consumption;

C^w, H^w, N^w, W^w, A^w – composition of fuel: carbon, hydrogen, nitrogen, moisture and ash content, respectively;

$Q_{low}{}^w$ – lowest combustion temperature for fuel;

q_3 – heat loss due to chemically incomplete combustion;

q_4 – heat loss due to mechanically incomplete combustion;

q_5 – heat loss in surrounding environment;

t_{g1} – flue gas temperature before gas condenser;

t_{g2} – flue gas temperature after gas condenser;

t_{irr1} – liquid temperature before nozzles;

t_{irr2} – liquid temperature after gas condenser;

ω_g – rate of flue gases through gas condenser, which can differ in the first and second sections;

$H_{\omega 1}$ – density of spray in first section of gas condenser;

$H_{\omega 2}$ – density of spray in second section of gas condenser;

t_{ret} – heating network return temperature;

t_{sup} – heating network supply temperature;

G_{dh} – flow of water through heating networks.

The decrease in fuel consumption is determined by:

$$dB = B_1 - B_2, \quad (1.16)$$

where

B_1 – fuel consumption in a boiler house with a gas condenser,

B_2 – fuel consumption in a boiler house without a gas condenser.

The first system equation (1.15) summarises the fuel quality parameters in a system of equations; the second summarises the indicators of boiler operation effectiveness; the third summarises the independent variables for gas condenser operations; and the fourth summarises the parameters regarding the regulation of heating networks. Heat loss through flue gases is determined as the flue gas parameters change (flue gas temperature behind the boiler system and air consumption coefficient). Therefore, both of these parameters have been separated out in the second equation, which must be considered input data for the characterisation of gas condenser operations: flue gas temperatures, rates, flue gas flow and other factors characteristic of a system’s energy efficiency.

The decrease in fuel consumption – if the produced heat and boiler efficiency coefficient are constant – due to an improvement in fuel quality can be evaluated as:

$$\Delta B_1 = \frac{Q_{prod}}{\eta \cdot \left(\frac{1}{Q^w_{low_1}} - \frac{1}{Q^w_{low_2}} \right)} , \tag{1.17}$$

where
η – boiler efficiency coefficient;
Q_{prod} – produced heat;
Q_{low1}^{w}, Q_{low2}^{w} – lowest combustion temperature for initial and improved-quality fuel.

Regarding wood chips, it is assumed that initially the fuel is moist and of low quality but that improved-quality wood chips correspond to EU standards and their moisture content does not exceed 25%. Equation (1.17) can be mathematically transformed to obtain the expression:

$$\Delta B_1 = \frac{k_1}{Q^w_{low_2} \cdot \left(\frac{Q^w_{low_2}}{Q^w_{low_1}} - 1 \right)} , \tag{1.18}$$

where
$k_1 = Q_{prod}/\eta$ – primary energy consumption.

The lowest combustion temperature for fuel depends on the fuel content, and it can be determined using Mendeleev's formula:

$$Q^w_{low_1} = k_C \cdot C^w_i + k_H \cdot H^w_i - k_{OS} \cdot \left(O^w_i + S^w_i \right) - k_W \cdot W^w_i , \tag{1.19}$$

where
$k_C = 339$ – carbon coefficient;
$k_H = 1031$ – hydrogen coefficient;
$k_{OS} = 109$ – oxygen and sulphur coefficient;
$k_W = 25$ – moisture coefficient.

The values for the fuel elements $C^w{}_i$, $H^w{}_i$, $O^w{}_i$, $S^w{}_i$ and $W^w{}_i$ are given in percentages. The higher the moisture content in the flue, the greater the fuel economy by lowering the moisture content to the standard value.

The decrease in fuel consumption due to changes in indicators of boiler operation efficiency (improvement) can be expressed with the following equation:

$$\Delta B_2 = \frac{Q_{prod}}{Q^w_{low} \cdot \left(\frac{1}{\eta_1} - \frac{1}{\eta_2} \right)} = \frac{k_2}{\eta_1 \cdot \left(1 - \frac{\eta_1}{\eta_2} \right)} , \tag{1.20}$$

where
η_1, η_2 – boiler efficiency corresponding to the beginning and end of the technological process;
$k_2 = Q_{prod}/Q^w{}_{low}$ – primary resource use indicator.

The following inverse balance equation can be used to determine boiler efficiency:

$$\eta_i = 100 - \left(q_{2i} + q_{3i} + q_{4i} + q_{5i} \right), \tag{1.21}$$

where

$q_{2i}, q_{3i}, q_{4i}, q_{5i}$ – heat loss corresponding to flue gases, chemically incomplete combustion, mechanically incomplete combustion and heat output in the surrounding environment.

Heat loss via the exiting flue gases is important and is determined with the following equation:

$$q_{2i} = \frac{1}{Q_{low}^{w}} \cdot \left[\left(c'_{CO_2} \cdot V_{CO_{2i}} + c'_{N_2} \cdot V_{N_{2i}} + c'_{H_2O} \cdot V^0_{H_2O_i} + (\alpha - 1) \cdot c'_{air} \cdot V_i^0 \right) \cdot \right.$$
$$\left. \cdot t_{g1_i} - c'_{air} \cdot V_i^0 \cdot t_{air_i} \right] \cdot \left(100 - q_{4i} \right), \quad (1.22)$$

where

c'_{CO2}, c'_{N2}, c'_{H2O}, c'_{air} – specific thermal capacity of gases and air;

V^0_{N2i}, V^0_{H2Oi}, V^0_i – volume of nitrogen, steam and air under stoichiometric combustion conditions;

V_{CO2i} – volume of three-atom gas;

t_{g1i} – flue gas temperature after boiler;

t_{air} – temperature of air feed for combustion.

When expressing gas volumes through the fuel content (1.22), the equation can be transformed thus:

$$q_2 = \frac{1}{Q_{low}^{w}} \cdot \left\{ \left\{ \left[K_{1C} \cdot c'_{CO_2} + K_{2C} \cdot c'_{N_2} + K_{3C} \cdot c'_{H_2O} + K_{4C} \cdot (\alpha - 1) \cdot c'_{air} \right] \cdot C_i^w + \right. \right.$$
$$+ \left[K_{1H} \cdot c'_{N_2} + K_{2H} \cdot c'_{H_2O} + K_{3H} \cdot (\alpha - 1) \cdot c'_{air} \right] \cdot H_i^w + \left[K_{1S} \cdot c'_{CO_2} + K_{2S} \cdot c'_{N_2} + \right.$$
$$\left. + K_{3S} \cdot c'_{H_2O} + K_{4S} \cdot (\alpha - 1) \cdot c'_{air} \right] \cdot S_1^w + K_{1N_2} \cdot c'_{N_2} \cdot N_i^w + K_{1W} \cdot c'_{H_2O} \cdot W^w -$$
$$\left. - \left[K_{2S} \cdot c'_{N_2} + K_{3H} \cdot c'_{H_2O} + K_{4S} \cdot (\alpha - 1) \cdot c'_{air} \right] \cdot O_i^w \right\} \cdot t_{g1_i} - \left(K_{4C} \cdot \alpha \cdot c'_{air} \cdot C_i^w + \right.$$
$$\left. \left. + K_{3H} \cdot \alpha \cdot c'_{air} \cdot H_i^w + K_{4S} \cdot \alpha \cdot c'_{air} \cdot S_i^w - K_{3O} \cdot \alpha \cdot c'_{air} \cdot O_i^w \right) \cdot t_{air} \right\} \cdot \left(100 - q_{4_i} \right), \quad (1.23)$$

where

$K_{1C} = 0.0187$; $K_{2C} = 0.07$; $K_{3C} = 0.00143$; $K_{4C} = 0.089$ – carbon coefficient;

$K_{1H} = 0.21$; $K_{2H} = 0.11528$; $K_{3H} = 0.266$ – hydrogen coefficient;

$K_{1S} = 0.007$; $K_{2S} = 0.026$; $K_{3S} = 0.00053$; $K_{4S} = 0.033$ – sulphur coefficient;

$K_{1N} = 0.008$ – nitrogen coefficient;

$K_{1W} = 0.0124$ – moisture coefficient.

The third equation of the equation system (1.15) describes the decrease in primary resources ΔB_3 using a flue gas condenser in the boiler house. The mathematical description of the flue gas cooling, steam condensation and liquid evaporation processes that take place simultaneously in the condenser is complex and is not given here. The condenser correlations are obtained experimentally and they describe empirical equations.

When determining a decrease in fuel consumption in the above-listed expressions, the heat produced was constant. Changes in this heat are determined by the expression:

$$Q_{prod} = c_{wat} \cdot G_{dh} \cdot \left(t_{out} - t_{ret} \right), \quad (1.24)$$

where

c_{wat} – specific thermal capacity of water;

G_{dh} – network water flow.

The return water temperature has a significant influence on fuel consumption – the lower the temperature, the greater the fuel economy ΔB_4.

1.6.3. Model for the evaluation of a boiler house's eco-intensity

The installation and operation of an economically beneficial system is linked to a need to decrease operation costs and increase a boiler house's efficiency. For example, the installation of a system for the deep cooling of flue gases in a boiler house is linked to investments of capital that can be paid for in three to ten years depending on the set capacity of the system and the type of system selected.

The Ludza municipal boiler house has a gas condenser that serves as an experiment site for researchers studying not only the heat and mass transfer process but also the effectiveness of such a system. The system has been designed to operate with or without filling and with the option of turning the nozzles on or off in one or another location as well as the possibility of changing the spray density parameters.

Changes in the eco-intensity of a boiler house's operations are determined by dividing the total heat produced by the boiler house over a certain period of time with the heat produced by the boiler over the same period of time:

$$\Delta q = \frac{(Q_c + Q_b)}{Q_b}, \tag{1.25}$$

where
Δq – eco-intensity of boiler house operations;
Q_c – heat produced with gas condenser;
Q_b – heat produced with boiler.

The changes in the eco-intensity of boiler house operations illustrate the possibility of increasing the amount of heat produced in the boiler house without increasing fuel consumption.

The boiler's specific load is determined by applying the boiler load to the set capacity of the boiler:

$$q = \frac{Q_{act}}{Q_{inst}}, \tag{1.26}$$

where
q – specific load of boiler;
Q_{act} – actual boiler load;
Q_{inst} – set capacity for boiler.

The examined correlations have been used to evaluate eco-intensity, which has been done in the results section below.

2. RESULTS AND ANALYSIS OF THE STUDY

2.1. Results of integrating a heat pump into a district heating system

2.1.1. Testing of the heat pump model for the Ludza district heating system

The approbation of the model has been performed in the Ludza municipal district heating system. The heat source for this system is a boiler house with two boilers: an 8 MW wood chip boiler for the base load and a peak load boiler that uses diesel fuel. A flue gas condenser has been installed after the wood chip boiler, which ensures heat recovery and also increases the boiler's energy efficiency.

The main networks separate into two branches after the boiler house. In one of these it is intended to install a heat pump and raise the temperature before the consumer by Δt_t in order to ensure the necessary heat load for the consumers when outdoor temperatures are low. The greatest increase in temperature is +4 °C at an outdoor temperature of –26 °C, and this gradually decreases as the outdoor temperature rises. The supply water temperature is no longer increased at outdoor temperatures of –4 °C or above and its value and changes correspond to the existing graph of changes in supply temperature. The current solution intends for the supply water temperature to be raised for the whole system at the boiler house exit. Such a solution is linked to greater heat losses in the networks. The model assumes that the capacity for the high-temperature heat pump gas condenser is 260 kW and that the capacity for the vaporiser is 190 kW.

In addition to the already examined energy and mass balance equations, empirical equations of the changes in system operational parameters are also needed to perform a modelling of the system. These are obtained by performing a statistical analysis of the operational data of the Ludza district heating system for the 2011–2012 heating season. Changes in the district heating system's supply and return network water temperatures depending on outdoor temperatures are shown in Figure 2.1.

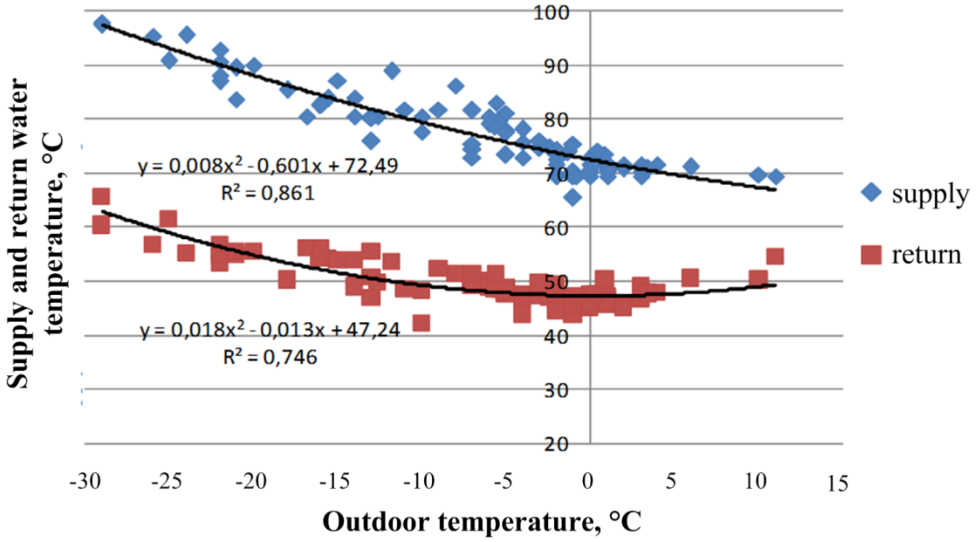

Fig. 2.1. Changes in the district heating system's supply and return temperatures over the course of a heating season

By performing a data correlation analysis, empirical equations for determining temperature changes have been obtained. The obtained correlations and correlation coefficient square values are shown in Figure 2.1.

Similarly, by processing the observation data, the study has obtained correlations for the changes in a consumer group's heat load:

$$Q_{con} = 0.02 \cdot t_{out}^3 - 0.273 \cdot t_{out}^2 - 50.41 \cdot t_{out} + 759.2\text{, kW} \tag{2.1}$$

the changes in water flow through the heating network branch:

$$G_{con} = -0.011 \cdot t_{out}^2 - 0.997 \cdot t_{out} + 25.7\text{, m}^3\text{/h} \tag{2.2}$$

and the changes in necessary temperature increase before the consumer:

$$\Delta t_t = -0.00017 \cdot t_{out}^3 + 0.00211 \cdot t_{out}^2 - 0.00061 \cdot t_{out} - 0.0148\text{, °C} \tag{2.3}$$

Flows m_{con} and G_{con} are linked by the correlation

$$m_{con} = \frac{G_{con} \cdot \rho_w}{3600}\text{, kg/s} \tag{2.4}$$

where
ρ_w – water density, kg/m^3.

Changes in the consumer group's heat load Q_{con} take into consideration the temperature increase before the consumer.

2.1.2. Modelling results and analysis

The modelling begins with a heating network route in which a heat pump and parameter entries will be installed. For each of these parameters, a correlation in the form of empirical equations as a function of the outdoor temperature is obtained. The capacities of the chosen heat pump gas cooler and vaporiser are entered, and the heating network parameters after heat pump installation are calculated. The modelling shows the required temperature after the heat pump gas cooler so that, as it mixes with the supply network water t_{sup}, the consumer's necessary water temperature t_{con1} is ensured. Because the permissible water temperature after the heat pump gas cooler t_{pu2} is limited (around 90 °C), the calculated necessary temperature is compared to the permissible heat pump temperature. If $t_{pu2} > 90$ °C, then the heat pump cannot be used and the consumer heat load must be fully covered by the boiler house by increasing the supply temperature there by Δt_t.

The temperature changes depending on outdoor temperature as obtained by the modelling are shown in Figure 2.2.

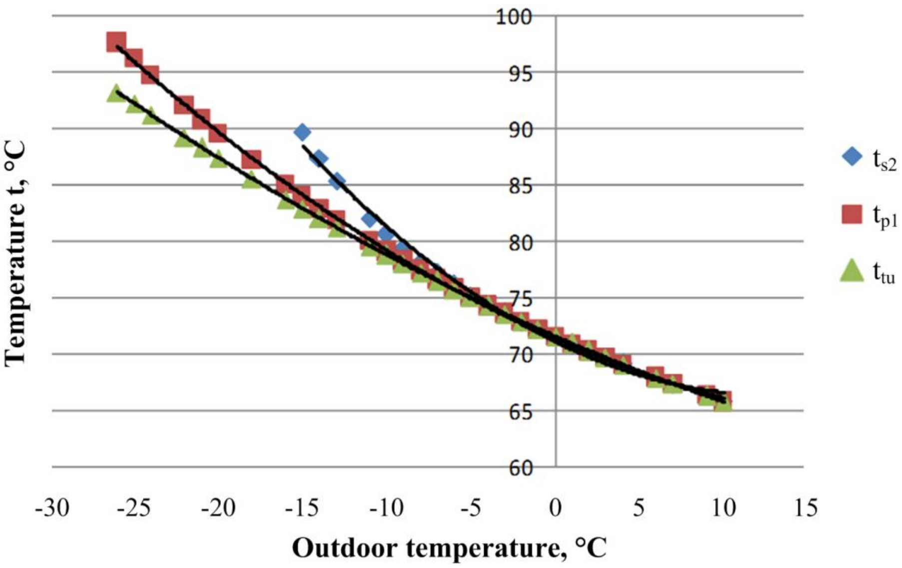

Fig. 2.2. Changes in heat carrier temperature before the consumer

The curves shown in the graph correspond to the water temperature t_{pu2} after the heat pump before it is mixed with the supply water in node M1, consumer water temperature t_{con1} and the temperature of supply water t_{sup} to be mixed in node M1. The analysis of temperature changes shows that when the outdoor temperature is low, the heat pump cannot be used to cover the consumer heat load and the temperature of the supply water at the boiler house exit must be increased. The participation of the heat pump in covering the consumer load is possible if the outdoor temperature is –16 °C or higher. If the outdoor temperature is –16 °C, the water temperature t_{con1} = 85 °C necessary for the consumer is obtained in node M1 by mixing water after the heat pump with a temperature of t_{pu1} = 90 °C with supply network water that is at a temperature of t_{sup} = 82 °C. It can be seen that, if the outdoor temperature is approximately –4 °C or higher, then the observed temperature curves coincide and there is no temperature increase before the consumer.

In order to cover the consumer heat load without heat carrier temperatures, the flows must be known. Changes in flows depending on outdoor temperature obtained as the result of the modelling are shown in Figure 2.3.

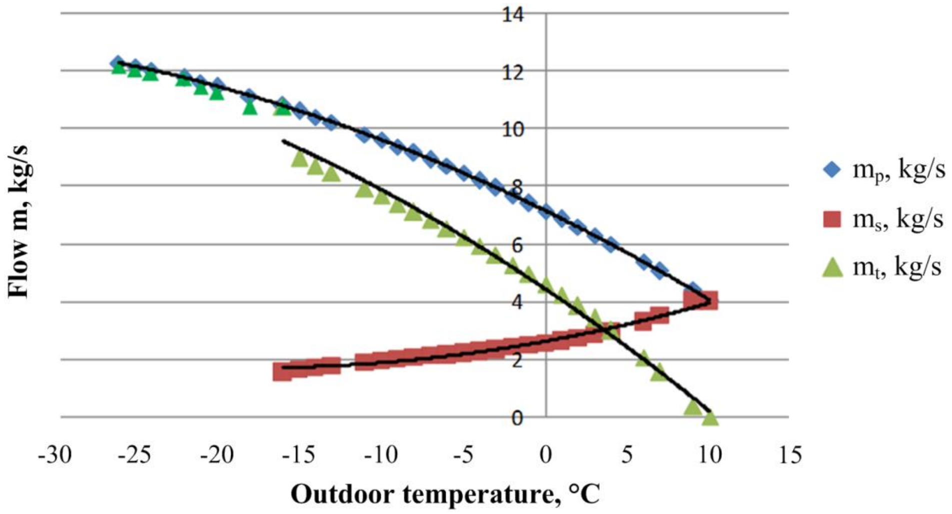

Fig. 2.3. Changes in flows depending on outdoor temperature

The graph shows the consumer's heat carrier flows m_{con}, flows through the heat pump gas cooler m_s, and changes in supply heat network flows m_{sup} depending on outdoor temperature. Flow m_s is the network water amount that is branched off of the heating network return and determines the amount of return heat used to ensure heat supply to a consumer group. This means that a greater flow through the heat pump is desirable. The flow is limited by the heat pump gas cooler capacity and the required temperature after the heat pump. As the outdoor temperature increases, the total flow m_{con} and the flow from the supply network m_{sup} decreases, but the flow through the heat pump gas cooler m_s increases. This means that the heat pump has an increasingly larger share in providing heat to the consumer. As stated earlier, the heat pump does not work at low outdoor temperatures (below –16 °C). This means that the entire consumer heat load is covered by the boiler house and $m_{con} = m_{sup}$.

Changes in heat carrier temperature after the consumer are shown in Figure 2.4. The graph shows the changes in heat carrier temperature after the consumer t_{con2} and the temperature after the heat pump vaporiser t_{vap} depending on outdoor temperature. The analysis shows that the temperature of the heat pump operating within the outdoor temperature interval after the vaporiser is lower than the return network temperature. This means that the use of a heat pump in a district heating system according to the proposed scheme lowers the return network water temperature. At low outdoor temperatures (below –16 °C) the network water temperature after the consumer group corresponds to the temperature t_{con2}.

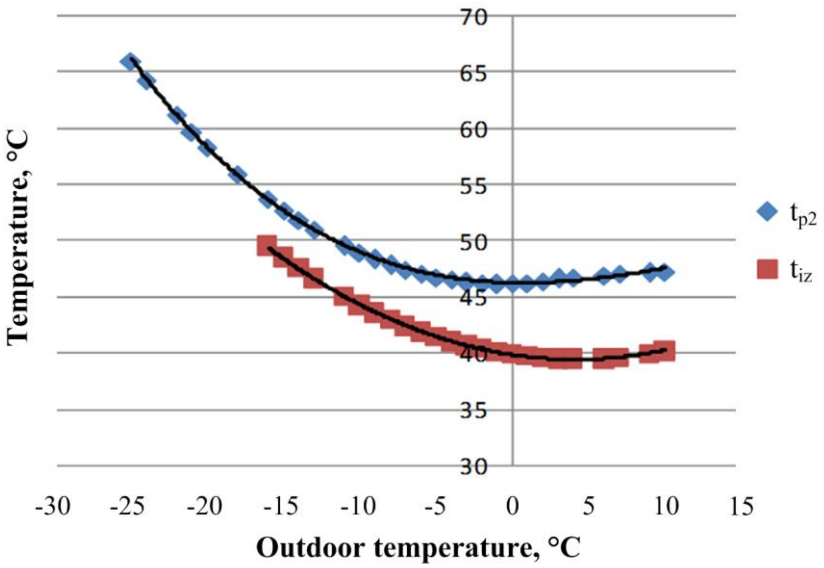

Fig. 2.4. Changes in heat carrier temperature after the consumer depending on outdoor temperature

The results of the performed analysis are in force if the initial assumptions are observed. The most significant of these is the provision that the heat pump operates with the nominal gas cooler Q_{co} and vaporiser Q_{vap} capacities. Theoretical and experimental studies of the use of a heat pump in a district heating system show that the heat pump COP changes within the range of 2.8…3.4 within the range of examined water temperatures.

2.2. Results of the creation of a condenser nomogram

2.2.1. Interrelationship between condenser parameters

The independent variable parameters characterising condenser operations can be divided into two groups: those that characterise the condenser itself (spray coefficient in the condenser's horizontal K_{sh} and vertical K_{sv} sections, flue gas temperature after the condenser t_{g2}, water temperature after the condenser and before the network heat exchanger t_{k2}) and those that characterise the interaction between the condenser and the district heating system (water flow through the network heat exchanger on the heating network side G_t, boiler capacity N_b and return temperature of heating networks t_r.

One of the most significant interaction parameters is the return temperature of heating networks. In order for condensation of water vapour from the flue gases to begin, they must be cooled to the dew point temperature. Further decreases in temperature determine how complete the condensation is and how complete the recovery of latent heat, therefore, how effective the condenser is. The dew point of flue gases is close to 65 °C. This is influenced by the moisture content of the flue gases and the amount of oxygen in them. In order for condensation to take place in the vertical section of the condenser, the temperature of the sprayed water must be lower. Cooling of the spray water takes place in the network heat exchanger with the help of the return water. The network water thereby performs a cooling function, and the effectiveness of the cooler is determined by the temperature of the return water. Changes in the condenser efficiency indicator depending on the return water temperature are shown in Figure 2.5.

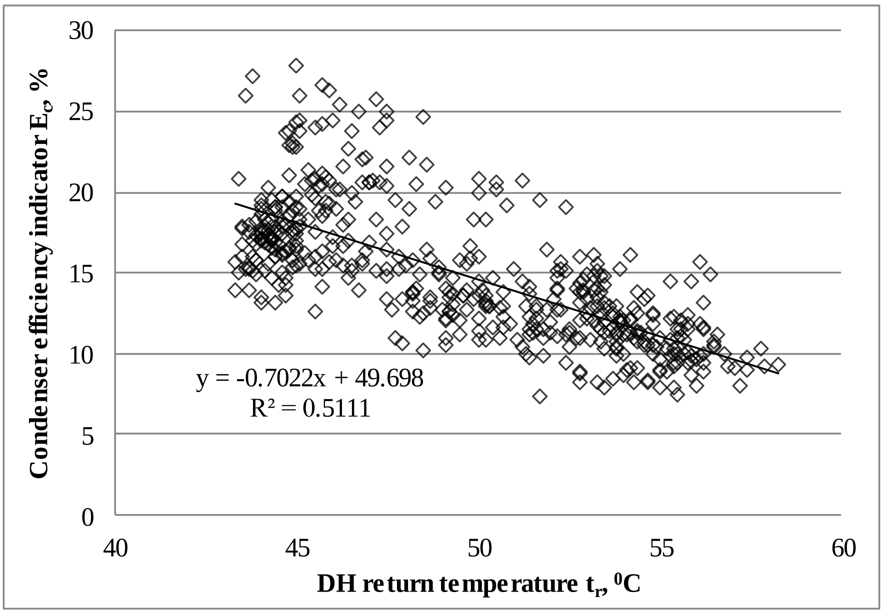

Fig. 2.5. Changes in the condenser efficiency indicator depending on the network return temperature

It can be seen that, by lowering the return water temperature by 1 °C, the condenser efficiency indicator value increases by 0.7%. The heating network return temperature is a variable quantity and is influenced by the outdoor temperature, the system's heat load, the type of regulation and also the operation of the consumer's heat node. The influence of so many variables explains the dispersion of data seen in Figure 2.5.

The boiler capacity must be changed in order to cover the variable load of a heating season. The measured boiler capacities and the corresponding indicator changes over the course of a heating season can be seen in Figure 2.6.

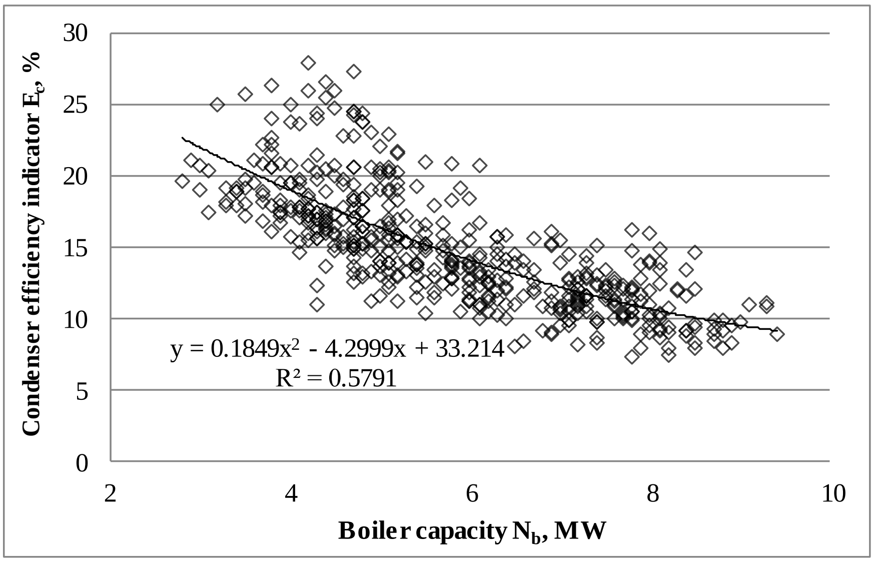

Fig. 2.6. Changes in condenser efficiency indicators depending on boiler capacity

An analysis of the district heating system data shows that as the boiler capacity increases, condenser capacity also increases. But in cases of larger boiler capacities, the relation of condenser capacity to boiler capacity is smaller percentage-wise than at small boiler capacities. As boiler capacity increases, the condenser efficiency indicator value decreases non-linearly and dispersion of data is observed. Changes in average indicator values are described by the following quadratic equation:

$$E_c = 0.184 \cdot N_b^2 - 4.299 \cdot N_b + 33.21 \quad (2.5)$$

A district heating system's operational modes are determined by outdoor temperature, and the necessary boiler capacity and network heat carrier parameters (water flow, supply and return temperatures) needed to cover consumer load are dependent on the outdoor temperature. Outdoor temperature is a significant, but not the only, factor dictating boiler capacity and the network return temperature. Changes in boiler capacity and return temperature observed over the course of a heating season depending on outdoor temperature are shown in Figure 2.7.

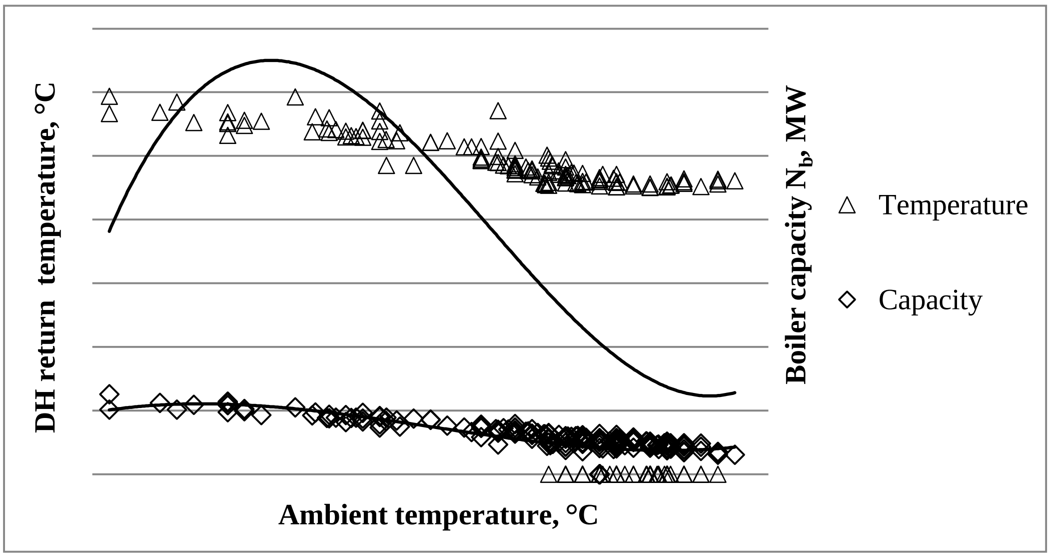

Fig. 2.7. Changes in boiler capacity and network water return temperature depending on outdoor temperature

It can be seen that changes in both parameters follow a similar path – as boiler capacity increases, network water temperature also increases. The decrease in the condenser efficiency indicator as boiler capacity increases (see Figure 2.6) can be explained with the higher return temperatures in the heating network. In order to ensure greater condenser capacity at very low outdoor temperatures, the return temperature of the heating networks must be lowered. This can be achieved by increasing the energy efficiency of consumer's buildings, lessening loss in the heating networks or, for example, using heat pumps in the condenser or heat network circuit.

2.2.2. Distribution of boiler and condenser load

Boiler houses with boilers that have had condensers installed cover the necessary load with the boiler and condenser combined. In order to evaluate the operation of both systems in covering the total boiler house load, the graph in Figure 2.8. has been developed.

The study has examined changes in boiler house capacity for four boiler house values: 3 MW, 5 MW, 7 MW and 8.5 MW. The graph corresponding to each capacity has been obtained from experimental data by selecting the characteristic capacity within a range of ±0.1 MW. Thus, for example, 3 MW capacity is described by data whose boiler capacity values range from 2.9 MW to 3.1 MW. The condenser capacities and efficiency values corresponding to each characteristic boiler capacity create experimental points through which the line has been drawn. If the condenser is turned off, then its efficiency is 0 and the boiler house capacity is determined by the boiler capacity. It can be seen that the lines are of differing slopes and form a beam-set. An efficiency indicator value was calculated for each experimental point by using the multi-factor regression equation (1.8). The points show good congruence, and the regression equation can be used to create graphs.

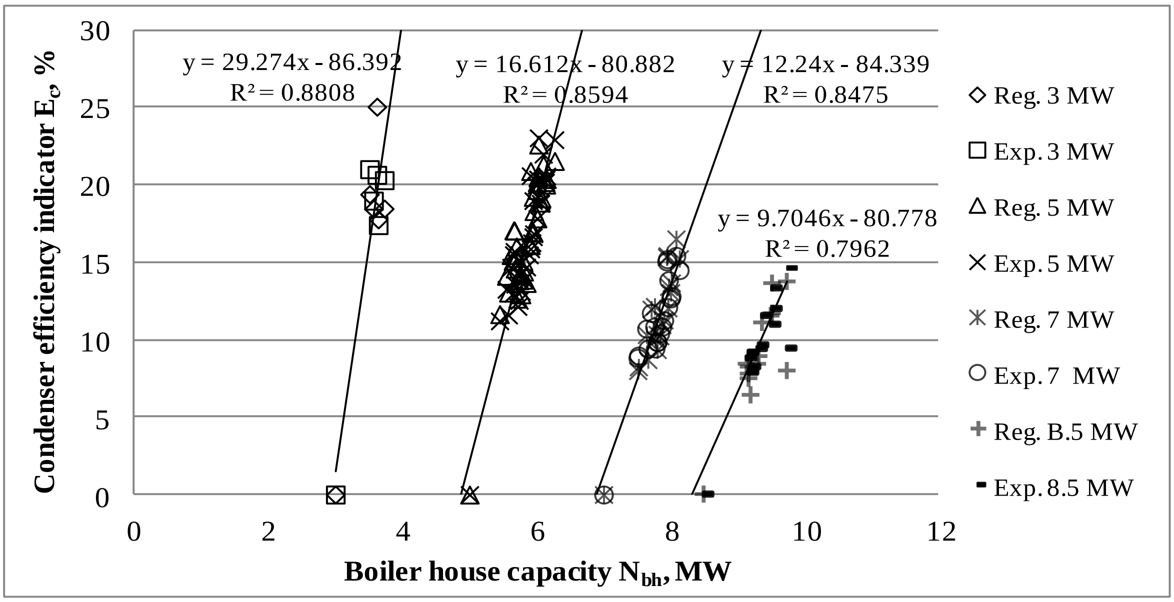

Fig. 2.8. Influence of boiler and condenser in covering boiler house load

In order to portray the mutual dependence of changes in boiler capacity, boiler house capacity and the condenser efficiency indicator, the nomogram in Figure 2.9 has been created. The nomogram consists of a beam-set in which each line corresponds to a boiler capacity within the range of 3 MW to 10 MW in increments of 1 MW. By using equation (2.5), the average condenser efficiency indicator value for each boiler capacity has been determined. Changes in the indicator depending on boiler capacity are characterised by the curve depicted in the nomogram. Points 1 and 2 can be seen in the nomogram, which help to explain its use. If boiler house capacity at position 1 is 6.8 MW, then line 1–2 crosses the average condenser efficiency curve at position 2 at an indicator value of 12.5%. A line corresponding to a boiler capacity of 6 MW runs through position 2. This means that the boiler house capacity is ensured by a boiler with a capacity of 6 MW and a condenser with a capacity of 0.8 MW.

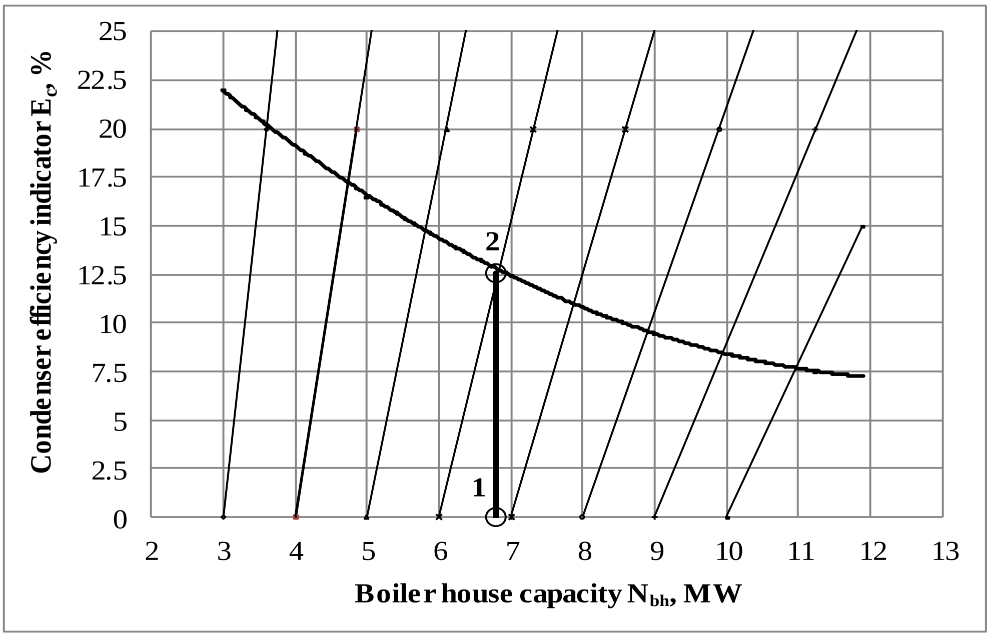

Fig. 2.9. Nomogram for boiler house capacity distribution between the boiler and condenser

Boiler house capacity is determined by the consumer heat load recalculated to the boiler house exit. Changes in load during the heating season are characterised by the graph of load duration seen in Figure 2.10 (upper curve).

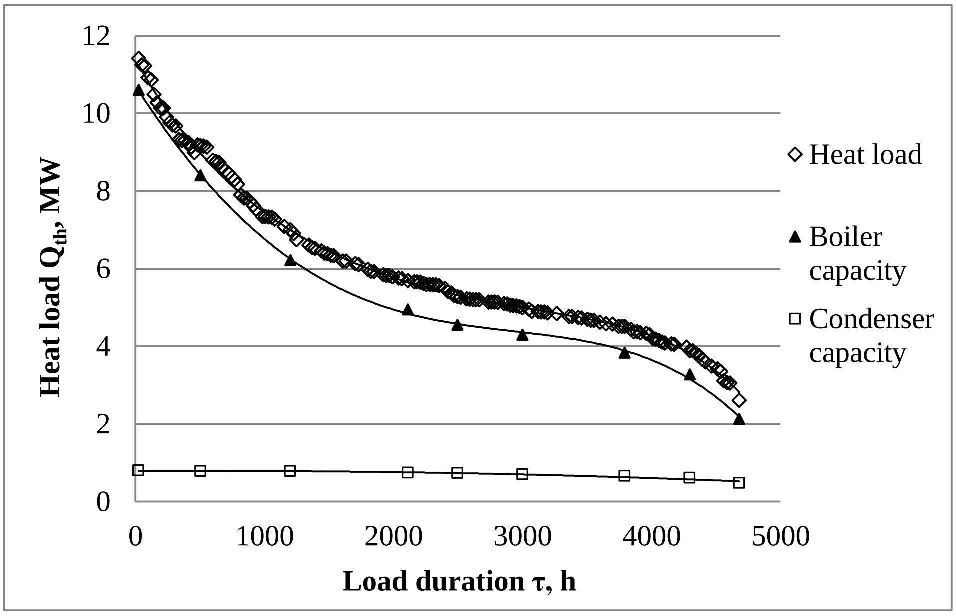

Fig. 2.10. Distribution of boiler house load if a condenser has been installed

By using the nomogram in Figure 2.9, it has been determined what part of the load is covered by the boiler and what part by the condenser. Changes in boiler and condenser loads over the course of the heating seasons are shown in Figure 2.10.

By knowing the boiler house, boiler and condenser capacities and their durations, researchers can calculate the total energy produced by the boiler and condenser, just the boiler and just the condenser over the course of a heating season. The results of this calculation are shown in Figure 2.11.

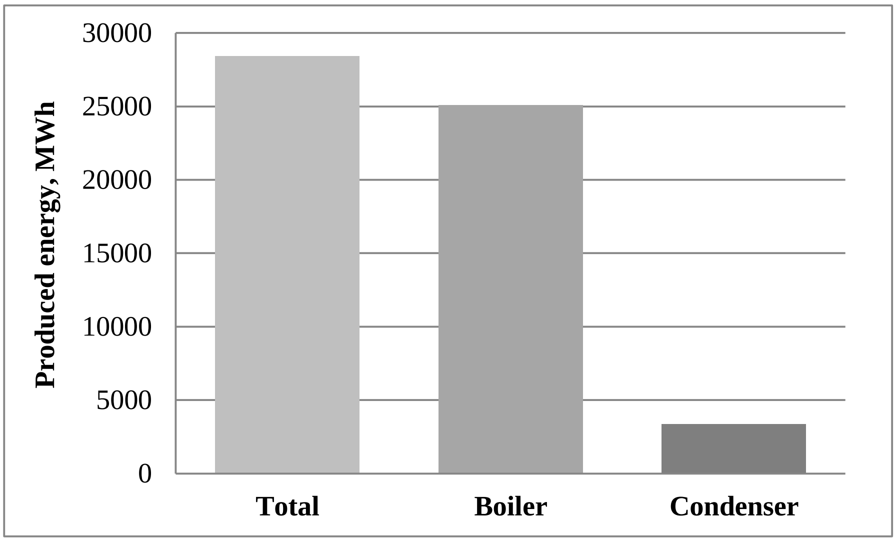

Fig. 2.11. Energy produced by the whole boiler house, boiler and condenser over the course of a heating season

An analysis of the results shows that the installation of a condenser results in energy savings of 11.8% over the course of a heating season.

2.3. Results and analysis of the study of the energy management of a wood chip boiler house with gas condenser

In examining the benchmark curves in Figure 1.3 of the heat rate depending on heat produced by the boiler and boiler plus condenser, it can be seen that the curves are not linear and can be described by cubic equations. This is significant for the further processing and analysis of the data. Changes in the heat rate of a boiler without a condenser are determined by the equation:

$$B_b = 2E-09 \cdot Q_b^3 - 9E-06 \cdot Q_b^2 + 1.21 \cdot Q_b + 84.76, \text{ MWh}_f/\text{month} \quad (2.6)$$

In the equation, Q_b is the heat produced in the boiler MWh_b/month. Changes in the entered heat if the boiler and condenser operate simultaneously can be described as:

$$B_{bc} = 6E-09 \cdot Q_{bc}^3 - 3E-05 \cdot Q_{bc}^2 + 1.091 \cdot Q_{bc} + 83.2, \text{ MWh}_f/\text{month} \quad (2.7)$$

The argument Q_{bc} is the heat produced in the boiler and condenser MWh_{bc}/month. If there is no load (x = 0), the conditional idle heat rate can be obtained from equations (2.6) and (2.7). In graphic terms, this quantity is depicted as a point on the Y axis. The quantity is conditional because the system cannot operate in such a mode. It is evident from the equations that the values for idle heat rate are close and approximately 84 MWh_f/month.

Specific heat rate benchmarks are curves with a distinct minimum whose values for a boiler and a boiler plus condenser correspond to b_b = 1.22 MWh_f/MWh_b and 1.07 MWh_f/MWh_{bc}. The character of the curves is determined by the idle heat rate and the boiler efficiency coefficient changes within the observed range of heat production. The boiler efficiency coefficient decreases at low boiler capacities; it increases and reaches its maximum at capacities that are approximately 0.65...0.8 of the nominal and remains constant or decreases slightly (depending on the type and technical condition of the boiler) as boiler capacity increases to the nominal or above. This means that the boiler's energy efficiency is directly linked to the heat rate benchmarks. This is also proven by the lower specific heat rate values in cases of a boiler with a condenser. The use of a condenser lessens the boiler's heat loss through the exiting flue gases and thereby increases its energy efficiency. From the point of view of energy management, it is evident that by performing the energy efficiency measure of installing a condenser after a wood chip boiler the minimum specific heat rate decreases from 1.22 MWh_f/MWh_b to 1.07 MWh_f/MWh_b.

Changes in the boiler house's electricity and specific electricity consumption can be seen in Figure 1.4. The data reflect electricity consumption in a boiler house without a condenser and in the heating networks. The idle electrical capacity of the boiler house is 60 kW and is 170 kW at maximum heat production. Specific electricity consumption decreases as the amount of heat production increases from e_{bh} = 80 kWh_{bh}/MWh_p at minimum production and reaches the lowest benchmark of e_{bh} = 20 kWh_{bh}/MWh_p at maximum production.

Changes in the condenser's electricity and specific electricity consumption, which are seen in Figure 1.5, have their own features. These are linked to the higher specific electricity benchmark e_c = 34 kWh_{bh}/MWh_p, compared with the boiler house benchmark e_{bh} = 20 kWh_{bh}/MWh_p, at maximum heat production. This means that electricity consumption per unit of heat produced by the condenser is greater than the heat produced by the boiler.

In addition to the specific heat rate b, the specific heat rate increase indicator δ is also used in an analysis of the energy efficiency of energy sources. This indicator can also be used to evaluate an energy source's influence on the environment. Just as for the specific heat rate, its unit of measurement is MWh_f/MWh_p. By definition, the specific incremental heat rate is the incremental fuel heat necessary for the supplementary production of 1 MW of capacity. The specific heat rate b and the specific incremental heat rate δ can be determined by using the heat consumption curve. The heat consumption curve describes the changes in fuel heat's input capacity P_f depending on the boiler capacity P_b or boiler plus condenser capacity P_{bc} and is shown in Figure 2.12.

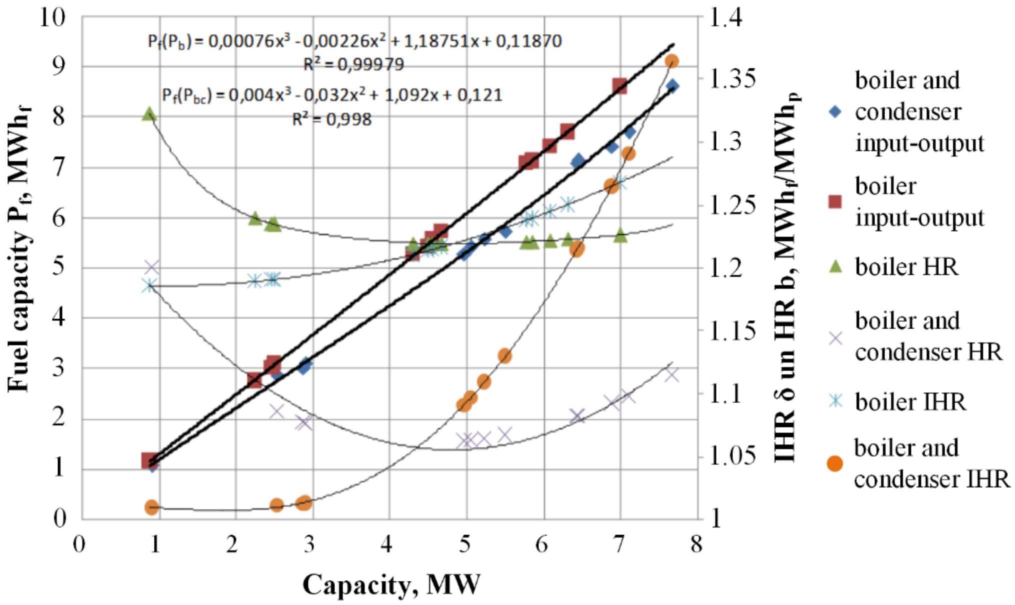

Fig. 2.12. Characteristic indicators of boiler and boiler plus condenser operations

The heat rate curve for a boiler is described by the equation:

$$P_f(P_b) = 0.00076 \cdot P_b^3 - 0.00226 \cdot P_b^2 + 1.1875 \cdot P_b + 0.1187, \text{ MW}_f \quad (2.8)$$

where
P_b – boiler capacity, MW.

The mathematical expression for the heat rate curve for a boiler plus condenser is determined as:

$$P_f(P_{bc}) = 0.004 \cdot P_{bc}^3 - 0.032 \cdot P_{bc}^2 + 1.092 \cdot P_{bc} + 0.121, \text{ MW}_f \quad (2.9)$$

where
P_{bc} – boiler and condenser capacity, MW.

By using the heat rate curves, the specific heat rate for a boiler b_b or for a boiler plus condenser b_{bc} is determined as $P_f(P_b)/x$ or $P_f(P_{bc})/x$. The corresponding equations for the calculations are:

$$b_b(P_b) = 0.00076 \cdot P_b^2 - 0.00226 \cdot P_b + 1.1875 + \frac{0.1187}{P_b}, \text{ MWh}_f/\text{MWh}_b \quad (2.10)$$

$$b_{bc}(P_{bc}) = 0.004 \cdot P_{bc}^2 - 0.032 \cdot P_{bc} + 1.092 + \frac{0.121}{P_{bc}}, \text{ MWh}_f/\text{MWh}_{bc} \quad (2.11)$$

In order to determine the expressions for specific incremental heat rate δ calculations, the first derivatives of expressions (2.8) and (2.9) must be determined:

$$\delta_b = \frac{dP_f(P_b)}{dP_b} = 0.00228 \cdot P_b^2 - 0.00452 \cdot P_b + 1.1875, \text{ MWh}_f/\text{MWh}_b \quad (2.12)$$

$$\delta_{bc} = \frac{dP_f(P_{bc})}{dP_{bc}} = 0.0132 \cdot P_{bc}^2 - 0.0659 \cdot P_{bc} + 1.0927, \text{ MWh}_f/\text{MWh}_{bc} \tag{2.13}$$

Expressions (2.10) to (2.13) have been used to calculate the specific heat rate b and the specific incremental heat rate δ, and the results are shown in curve form in Figure 2.12. It can be seen that the b and δ curves cross at a certain point and there the quantity values are equal. A minimal specific heat rate can be found at the meeting point of these curves. Comparing different types of boiler and boiler plus condenser operation modes, it can be seen that in the case of condenser use there is a new point of intersection for curves b and δ at which the minimum specific heat rate is lower. This means that an energy efficiency measure has been performed – a condenser has been installed after the boiler, new benchmarks b and δ have been determined, and the system can be operated with greater energy efficiency. If the boiler house has one boiler and heat production increases, then the boiler capacity will be greater than optimal and the specific heat rate will be the determining factor. If the boiler house has several working boilers and an increase in load is distributed among them, the specific incremental heat rate is the determining factor and the load must be increased for the boiler whose δ is smaller. The provided method is used to determine b and δ benchmarks for a new system.

2.4. Results of the economic analysis of the use of a flue gas condenser in a district heating system source

2.4.1. Analysis of fuel costs for a boiler with condenser

The specific fuel heat indicator per unit of produced heat and the changes in specific fuel costs depending on the heat-generating capacities are non-linear with a distinct minimum. Equations describing the changes in price per unit of produced heat have been used to clarify the capacity values for the curve minimums seen in Figure 1.12. The equation for changes in fuel price for a wood chip boiler is:

$$c_{fb} = 0.069 \cdot P_b^2 - 0.675 \cdot P_b + 15.53, \text{ €/MWh}_p \tag{2.14}$$

and for a boiler plus condenser it is:

$$c_{fbc} = 0.093 \cdot P_{bc}^2 - 0.899 \cdot P_{bc} + 14.77, \text{ €/MWh}_p \tag{2.15}$$

The minimum of the function is determined by equating its first derivative with zero:

$$\frac{dc_{fb}}{dP_b} = 0 \quad \text{un} \quad \frac{dc_{fbc}}{dP_{bc}} = 0 \tag{2.16}$$

The values for generating capacities determined by correlations (2.16), at which fuel cost minimums per unit of produced energy are observed, are P_b^{min} = 4,89 MW and P_{bc}^{min} =4,83 MW. It can be seen that these values practically correspond and the observable difference is within the range of 1.2%. A system working at a capacity of approximately 5 MW will have lower fuel costs per unit of produced heat.

Capacity, and therefore the cost minimum, is determined by two factors: the influence of the conditional idle mode and changes in the boiler's efficiency. As the boiler capacity increases, the influence of the idle mode becomes relatively smaller than it is at smaller capacities. The boiler's efficiency, in turn, increases as boiler capacity increases and asymptomatically reaches the maximum value and then remains constant or decreases slightly.

2.4.2. Cost analysis of condenser operations

The goal of the analysis is to evaluate whether the use of a condenser leads to economic savings, how large this savings is and whether it applies to the entire range of condenser capacities. The changes in specific total expenses c_{exp}, income c_{in}, and economic savings c_{sav} linked to condenser use depending on condenser capacity are shown in Figure 2.13.

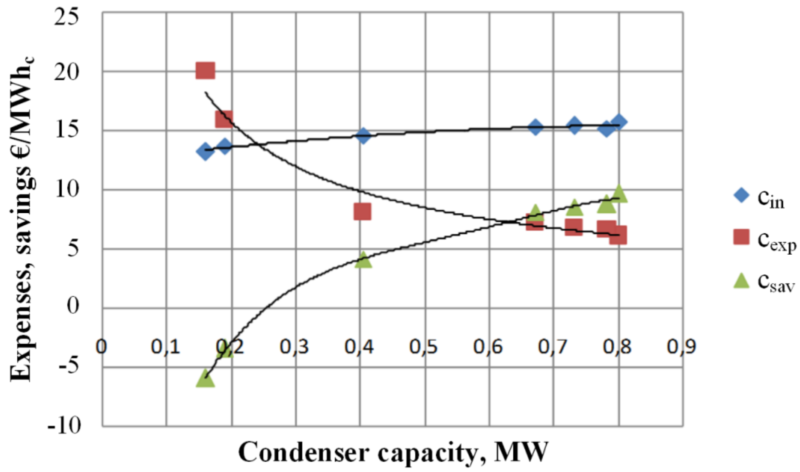

Fig. 2.13. Expenses and savings of condenser use depending on capacity

The analysis shows that by operating the condenser at a capacity greater than 0.25 MW an economic savings can be observed, which increases as the capacity increases to 0.8 MW and reaches 10 €/MWh$_c$. A capacity of 0.25 MW is the limit value below which there is no economic effect. As capacity falls below 0.25 MW, the condenser operates at a loss and its operational expenses are greater than its income, which is determined by the wood chip economy.

As seen from the data, during the nine months of the 2012–2013 heating season the condenser was operated both with and without an economic effect. The total evaluation is provided by the balance of savings and losses, which determines the pure income gained in the studied time period:

$$c_{net} = \sum_{i=1}^{i=9} \frac{Q_{c_i}}{Q_{sum}} \cdot \left(c_{in_i} - \left(c_{el_i} + c_{ws_i} + c_{lm_i} + c_{ashi} + c_{am_i}\right)\right), \text{ €/MWh}_c, \quad (2.17)$$

where

i – number of months during the studied time period;

Q_{sum} – heat recovered by the condenser during the studied time period, MWh$_c$.

Using the data from the table, the evaluated specific weighted income per unit of heat produced by the condenser is 5.74 €/MWh$_c$. Economic losses are linked to condenser operation and amortisation costs. The question arises of whether it is not more advantageous to turn off the condenser at low condenser capacities and allow the flue gases to exit directly through the chimney? If the condenser is turned off, there will be no operational costs, however, amortisation costs will remain. In such a case, the specific weighted pure income is calculated as:

$$c^*_{net} = \sum_{j=1}^{j=5} \frac{Q_{c_j}}{Q_{sum}} \cdot \left(c_{in_j} - \left(c_{el_j} + c_{ws_j} + c_{lm_j} + c_{ash_j} + c_{am_j}\right)\right) - \sum_{k=1}^{k=4} \frac{Q_{c_k}}{Q_{sum}} \cdot c_{am_k}, \text{ €/MWh}_c, \quad (2.18)$$

where

j – months in which condenser is operated;

k – months in which condenser is turned off.

The calculations show that if the condenser is operated only at capacities of over 0.25 MW and is turned off at lower capacities, the specific weighted pure income is 4.79 €/MWh$_c$, which is 16.5% lower than if the condenser is operated non-stop. The analysis shows that it is also advantageous to operate the condenser at lower capacities during months when the savings do not cover operational costs.

2.5. Results of the eco-intensity analysis of the use of a flue gas condenser at a district heating system source

2.5.1. Results of the experiment of boiler house operations

The data determined during the industrial experiment included the parameters for boiler house operations, which depend on the consumer heat load, which is determined by the behaviour of the energy users as well as by climatic conditions and the district heating system's operational conditions. The results of the experiment that are linked with the determination of the eco-intensity of operating a gas condenser without filler are illustrated in Figures 2.14 and 2.15.

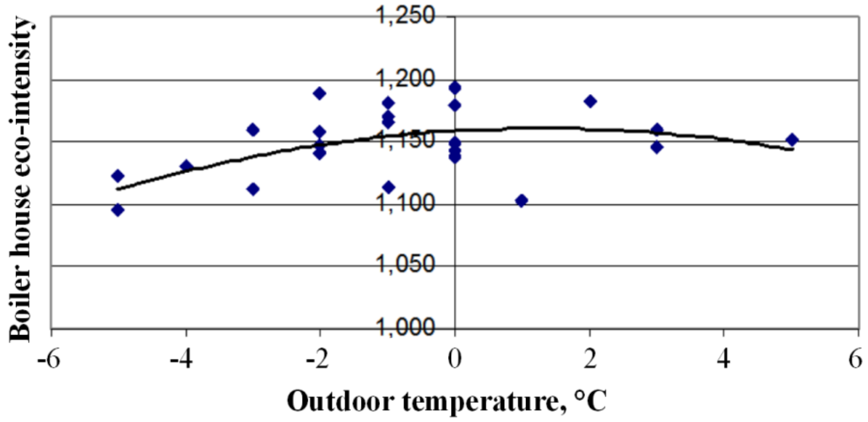

Fig. 2.14. Eco-intensity of boiler house operations depending on outdoor temperature

As seen in Figure 2.14, the eco-intensity of boiler house operations decreases if the outdoor temperature falls. This happens for several reasons, the most important of which is the divergence of an empty gas condenser without filler from its optimal operational parameters: increase in flue gas rate and temperature.

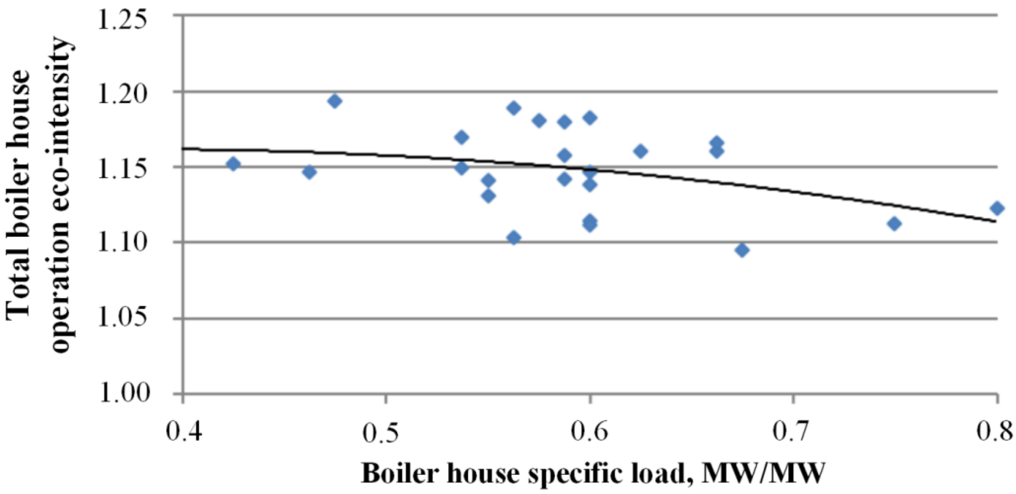

Fig. 2.15. Eco-intensity of boiler house operations depending on specific boiler load

This consideration is confirmed by the analysis of another parameter that influences the intensity of boiler house operations, namely the specific load of the boiler house. The influence of this load on the eco-intensity of boiler house operations is indicative of the fact that the greater the boiler house load, the lower its eco-intensity, the less it is possible to receive heat in the gas condenser per unit of boiler capacity, as seen in Figure 2.15.

This confirms the above-mentioned hypothesis that when the outdoor temperature decreases, boiler house load increases, fuel consumption increases, and greater amounts of flue gases are created.

2.5.2. Results of the analysis of the eco-intensity of a district heating system

Any district heating system is a complex whole of technological solutions of its separate elements that must be examined as a united system, a system whose effective operation depends on the creation of economically well-grounded and environmentally friendly technological solutions. Indicators for the operation of a condenser as one element of this system can be seen in Figure 2.16.

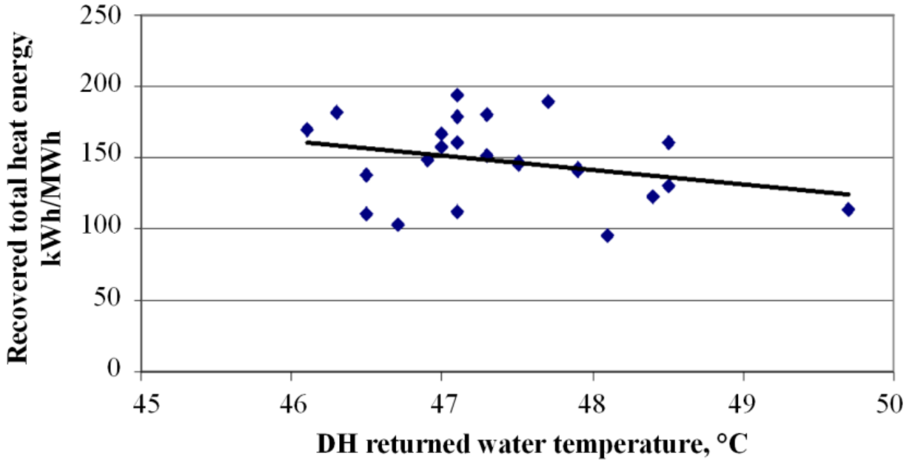

Fig. 2.16. Heat recovered in a gas condenser depending on the temperature of the district heating system's return water

As seen in Figure 2.16, the correlation analysis shows that the experimental data correlate weakly with the empirical model (line). Nevertheless, a clear trend is seen in which the specific heat obtained in the gas condenser is greater if the heating network return temperature is lower and vice versa, that the amount of heat obtained falls as this temperature increases. This confirms the above-mentioned opinion that the fuel savings depends on the operation of the entire system as a whole, of which the gas condenser is one element. The system's operations, in turn, depend on the energy efficiency of the energy users connected to the district heating system as well as the water rates and flow parameters in all of the heat network elements, including the heat exchangers in the buildings' heat nodes. In order to increase the amount of heat obtained in the gas condenser, it is necessary to lower the heat network return temperature, which can be done by modelling the system's regulation modes as well as performing energy efficiency measures on the part of the consumers.

The increase in eco-intensity of the operations of a boiler house plus gas condenser can also be evaluated from the point of view of decreasing the amount of nitrogen oxide emissions. This happens for two reasons:

1. fuel consumption decreases and the total amount of nitrogen oxide emissions from the boiler house chimney decreases,
2. partial absorption of some of the nitrogen oxide components takes place via the spray liquid: 10% of the total amount of NO_x is absorbed by the spray liquid.

CONCLUSIONS

1. The study provides a scheme for the integration of a high-temperature heat pump into a municipal district heating system to use network return heat to partially cover consumer load.
2. A model has been created and calculations performed for changes in a district heating system's parameters in the case of the use of a heat pump as the outdoor temperature changes over the course of a heating season. The model includes mass and energy balance equations for the scheme's nodes and elements as well as empirical correlations describing the system. The modelling has clarified that the use of a heat pump is possible if the outdoor temperature is not lower than –16 °C. The district heating system's return water temperature drops as the result of heat pump use, which raises the effectiveness of the flue gas condenser installed in the boiler house.
3. The statistical analysis of the district heating system data has resulted in a multi-factor regression equation that links the condenser efficiency indicator with statistically significant independent variable parameters. The equation's independent variable parameters can be divided into two groups: those that describe the condenser itself and those that describe the interaction between the condenser and the heat supply system. The main interaction parameters are boiler capacity and the heating network return temperature.
4. The dew point of flue gases is close to 65 °C. The temperature of the sprayed water must be lower than this in order for vapour condensation to take place inside the condenser. The cooling of the sprayed water is done in the network heat exchanger with the help of the return water. The network water thereby performs the function of a cooler, and the effectiveness of this cooler is determined by the temperature of the return water. The analysis shows that by lowering the temperature of the return water by 1 °C the condenser effectiveness indicator value increases by an average of 0.7%.
5. A nomogram is provided that depicts the variable mutual dependence of boiler capacity, boiler house capacity and the condenser effectiveness indicator. With the help of this nomogram the distribution of the boiler house load between the boiler and the condenser can be determined. The nomogram has been approbated in the analysis of the Ludza municipal district heating system's operations. It has been determined that over the course of a heating season the boiler has produced 88.2% of the total produced heat and 11.8% has been produced with the help of the condenser. This means that condenser use results in an 11.8% savings of primary resources.
6. The study has used specific heat rate and specific incremental heat rate indicators (which have been determined using measured data from boiler house operations) as energy management benchmarks for the characterisation of boiler house operations and management. It has been shown that the most optimal boiler capacity is observed at the point of intersection between the benchmark curves. If the boiler house has one boiler and heat production increases, then the boiler capacity will be greater than optimal. In such a case, the determining quantity is the specific heat rate. A different situation arises if the boiler house has several working boilers and an increase in load is distributed among them. Then the determining factor is the specific incremental heat rate and the load must be increased for the boiler whose specific incremental heat rate is smaller.
7. The curve showing the cost per hour for operating the boiler shows that the changes are not linear and the operating modes are not all equally economically advantageous. By evaluating the changes in specific fuel costs it is seen that the boiler has operation modes with minimal specific fuel costs. The character of the curves is determined by

idle fuel consumption and changes in boiler efficiency. An equation describing these changes determines the most economically advantageous boiler capacities operating both with and without a condenser.

8. A detailed analysis of the flue gas condenser's specific expenses shows that by operating the condenser at a capacity greater than 0.25 MW a significant economic savings is observed, which increases as the capacity increases to 0.8 MW and reaches 10 €/MWh$_c$. A capacity of 0.25 MW is the limit value below which there is no economic effect. As capacity falls below 0.25 MW, the condenser operates at a loss and its operational expenses are greater than its income, which is determined by the wood chip economy. During the nine months of the 2012-2013 heating season the condenser was operated both with and without an economic effect. The specific cost-benefit balance provides an evaluation of the whole studied time period. The evaluated specific pure gains per unit of heat recovered by the condenser is 5.74 €/MWh$_c$. This means that the use of a condenser has on the whole provided an economic effect over the period of time studied.
9. Operation of a wood chip boiler house that has been equipped with a gas condenser depends on the operation of the entire district heating system as as whole. An evaluation of the effectiveness of the system's operations with the help of eco-intensity (which includes the influence of technologies on decreasing natural resource consumption) provides a full analysis of the possibilities of increasing efficiency by recognising factors that influence changes in eco-intensity. Such factors are: outdoor temperature, specific boiler house load, heat network return temperature. The influence of these factors on eco-intensity is varied – as outdoor temperature falls and boiler house load increases, eco-intensity decreases. But eco-intensity increases as the heating network return temperature is decreased. A decrease of return temperature by 1 °C decreases wood chip consumption by 0.02 m^3 per MWh of produced heat.