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

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MODULAR SOLAR AND PELLET COMBISYSTEM FOR APARTMENT BUILDINGS. EXPERIMENTAL RESEARCH AND OPTIMIZATION

Summary of thesis

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Experimental system has been developed in framework of the European Economic Area financial mechanism program "Environmental Policy and Integration of Latvia" subproject "Compact Solar and Pellet Module".

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DISSERTATION PROPOSED FOR ACHIEVING DR.SC.ING. DEGREE AT RIGA TECHNICAL UNIVERSITY

This study is proposed for attaining the degree of Dr.sc.ing. in Environmental Engineering and will be defended on 6 September 2012 at the RTU faculty of Power and Electrical Engineering, Kronvalda Boulevard 1, room 21.

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CONFIRMATION STATEMENT

Hereby I confirm that I worked out the present promotional study, which is submitted for consideration at Riga Technical University for achieving Dr.sc.ing. degree. This promotional study is not submitted to any other university for achieving scientific degree.

Aivars Žandeckis …………………………….

Date: ………………………

Promotional study is written in Latvia, containing an introduction, five chapters, conclusions, bibliography, 52 figures, 123 pages in total. Bibliography contains 72 titles.

CONTENTS

Background and Current Situation

The energy sector plays a vital role in the development of every country. Sustainable energy policy provides a guarantee for stable economic growth and protects the local market from rapid energy price fluctuations.

One of the leading discussions concerning the energy sector in the European Union is related to energy efficiency in the building sector. To successfully fulfil the declared energy policy targets in this fieldenergy consumption must decrease in existing buildings, and stricter regulations on the construction of new buildings must be introduced. In both objectives, the greatest attention is given to the integration of renewable energy resources, and the increase in efficiency of fossil fuel transformation technologies.

European Commission Directive 2009/28/EC sets an ambitious but reachable target – to raise renewable energy share of gross final energy consumption in European Union to 20% by 2020. The Latvian target within the directive is to reach 40% renewable energy share of gross final energy consumption.

A number of financial support mechanisms have been implemented to stimulate a reduction in energy consumption and the use of renewable energy sources in the residential sector.

The measures which have been implemented to date are only the first step in the development of the sector and the fulfilment of the directive's target.

Objectives

The general objective of this thesis is to develop a renewable energy solution for the heating of medium sized apartment buildings in Latvian climatic conditions. The solution must be entirely based on the use of solar energy and biomass.

To achieve the objective of the study, the following tasks were carried out:

- defining the boundary conditions for development and the realisation of a renewable energy-based heating solution;
- developing a concept for the foundation of a modular combined solar and wood pellet system, that provides a compact modular design, an opportunity to achieve a high degree of system assembly in the factory site and hydraulic connection with the possibility to combine solar panels, a wood pellet boiler, accumulation tanks, and heating and hot water load bearing function in one system.
- forming a deterministic mathematical model of a combined system for computer simulation software;
- choosing alternative technical solutions for a combined system based on economic optimization and benchmark definition for the further optimization of the real system.

- founding a pilot industrial combined system and model validation using monitoring results;
- optimisation of combined system operation parameters based on processing and analysis of laboratory experiments, monitoring and dynamic simulation results, using benchmarks, specific solar energy consumption (FSC), regression analysis, and the method of steepest ascent.

Research Methodology

This research is developed within the European Economic Area Financial Mechanism programme "Environmental policy integration program in Latvia" subproject "Compact solar and granular model", European Commission European Regional Development Fund Programme "Central Baltic INTERREG IV A Programme 2007-2013" subproject "Ecohousing" and in cooperation with two Latvian industrial companies and one engineering company.

The research methodology of this promotion work is divided into two interconnected parts. A modular combined solar and pellet system concept design for the apartment building heating and the development of a dynamic simulation model for TRNSYS environment for the economic optimization of different technological alternatives.

Development of the experimental system for heating of apartment building, system monitoring and optimization. The simulation model was validated by the results of the system operation monitoring. The optimisation of the combined system was based on monitoring, simulation and laboratory experiments, using benchmarks, fractional solar consumption (FSC), multiple nonlinear regression analysis and generalized reduced gradient (GRG2) method.

Scientific Novelty

As a result of this research work, a combined solar and wood pellet systems deterministic simulation model in TRNSYS environment was developed and, on the basis of monitoring results of the experimental system, validated. Boundary conditions for a combined solar and wood pellet system have been defined. The system optimization was based on the following methodologies:

- benchmark and target function definition
- economical optimization of different technical solutions for the system using simulation results;
- several series of combustion experiments were carried out using a pellet boiler with a smaller capacity in laboratory conditions. Results of those experiments were used for the assessment of installed pellet boiler modes and the optimization of the combustion process.

- developed optimization algorithm for system operation parameters, that includes dynamic simulation, multi-parameter nonlinear regression analysis, Marquardt and generalized reduced gradient method (GRG2) methods.

Optimization resulted in a non-linear regression equation, which describes economic benefits from the use of solar collectors, depending on the parameter changes. Specific solar energy consumption method (FSC) was used for the quantitative evaluation of the experimental system performance and optimization measures.

Several ideas about solar energy use possibilities, specifically concerning summer houses and apartment buildings, that were developed during the study were patented.

Practical Application

This thesis is of great practical importance, which comes from the participation of a number of industrial partners and companies in the development of the pilot system. The system design and optimization were carried out within two research projects and project results were widely presented in the scientific community and society.

This work has various target groups:

- residents of apartment buildings – in this thesis an experimental system, that serves as an example of an entirely renewable energy-based building heating system was developed. Results of this work can be used as a benchmark for the performance evaluation of similar projects, optimization methods can be used for the optimization of different solar and wood pellet systems.
- installers and distributors of equipment – methods for the economical evaluation of different technological solutions have been offered in this work, as well as various methods for the selection and optimization of system components and operation parameters.
- equipment manufacturers – this target group includes local wood pellet boiler and modular boiler manufacturers. Within this thesis, a variety of methods for evaluating technical solutions, optimizing of the boiler control algorithms, performance improvement, and emissions reductions were used.
- municipalities – a designed combined system can serve as an example or model for the eradication of different heating problems in an apartment building.
- representatives of legislation institutions and investors - results of the thesis are useful to evaluate the support mechanisms and potential for the use of renewable resources, especially in the sector of apartment buildings. This study highlights the need for the renovation of apartment buildings.

Approbation

The results of this study have been available in the respective informative sources and have been discussed on:

1. 47th RTU Students scientific and technical conference with report „Mazo koģenerācijas staciju darbības analīze" – 2006. – 18-28 April. – Riga;
2. 48th RTU Students scientific and technical conference with report „Katla bilances un energoefektivitātes noteikšana Ādažu katlu mājā" – 2007. – 27-28 April. – Riga;
3. 49th RTU Students scientific and technical conference with report „Granulu degšanas efektivitātes izpēte" – 2008. – 18-19 April. – Riga;
4. 49th RTU Students scientific and technical conference in session „Tehnogēnās vides aizsardzības zinātniskās problēmas" with report „Granulu katla darbības energoefektivitātes izpēte" – 2008. – 9-10 October. – Riga;
5. seminar within the framework of the COFITEK project with presentation „Biomasa kā kurināmais" – 2008. – 31 October. – Riga;
6. 49th RTU international scientific conference, in session „Climate technologies" with report „Slāpekļa oksīdu un energoefektivitātes saistības izpēte granulu katlos" – 2008. – 15 October. – Riga;
7. international seminar Baltic Economic Forum with report „Analysis of Wood Fuel Flow in Latvia" – 2008. – 3-4 November. – Riga;
8. BioNorm2 International Conference on Wood Fuel Standards. Combustion with report „Results of wood pellets combustion testing in Latvia" – 2009. – 6 August. – Riga;
9. international seminar "Current and future woody biomass for energy – Monitoring use and understanding technology" in framework of the BioNorm2 International Conference on Wood Fuel Standards with poster presentation „Bionorm II – Pre-normative research on solid biofuels for improved European standards" – 2009. – 15-16 September. – Riga;
10. RTU annual conference "Innovations and New Technologies" with poster presentation „Slāpekļa oksīdu samazināšanas metodes granulu katlos" – 2009. – 23 September. – Riga;
11. RTU annual conference "Innovations and New Technologies" with poster presentation „Periodiskās darbības Saules enerģijas modulis" – 2010. – 23 February. – Riga;
12. seminar „Cīņa ar enerģijas vampīriem: kā ietaupīt uz iekārtu izslēgšanas rēķina" with presentation „Mērījumu veikšana: pasaules prakse un Latvijas pieredze" – 2010. – 8 September. – Riga;
13. 51st RTU scientific conference, session „Environmental Engineering" with report „Methods of nitrogen oxide reduction in pellet boilers" – 2010. – 12 October. – Riga;
14. seminar „Saule un biokurināmais. No A līdz Z" with presentation „Biomasas apkures katli" – 2010. – 7 December. – Riga;

15. closing conference for European Economic Area financial Mechanism, Program's project "Environmental policy and integration of Latvia" with presentation „Kompakts saules un granulu modulis" – 2011. – 14 April. – Riga;
16. seminar „Zema enerģijas patēriņa ēka Latvijā" with presentation „Kompakts saules un granulu modulis, daudzdzīvokļu ēkā Siguldā, Krišjāņa Barona ielā 2. Pasākumu plānošana, darbu norise un sasniegtie rezultāti" – 2011. – 20 July. – Riga;
17. 6^{th} Dubrovnik conference „Sustainable development of energy, water and environment systems" in session "The interaction between heating technologies and renewable energy systems" with report „Solar, pellet combisystem for apartment buildings" – 2011. – 25-29 September. – Dubrovnik;
18. 52^{th} RTU scientific conference, in session „Climate technologies" with report „Saules siltuma izmantošanas iespējas daudzdzīvokļu ēkās Latvijā" – 2011. – 12 October. – Riga;
19. 52^{th} RTU scientific conference, in session „Climate technologies" with report „Gaisa padeves un kurināmā sastāva kontrole ar mērķi samazināt NO_x emisijas mazas jaudas biomasas apkures katlos" – 2011. – 12 October. – Riga;
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21. international seminar within the framework of the „Ecohousing" project with presentation „WP2: Progress in the project activities - Presentation in the project „Ecohousing" – 2011. – 11-13 October. – Riga;
22. seminar „Zinātnieku un uzņēmēju kontaktbirža" with presentation „Kompakts saules un granulu modulis" – 2011. – 20 October. – Riga;
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28. international seminar within the framework of the „Ecohousing” project with presentation „Monitoring and optimization of the solar combisystem” – 2011. – 9-10 February. – Riga;
29. international seminar within the framework of the „Ecohousing” project with presentation „Fuel combustion tests analysis” – 2011. – 9-10 February. – Riga;
30. seminar „Ēku energoefektivitāte un ekoloģiskie aspekti” with presentation „Praktiski risinājumi biomasas un saules enerģijas izmantošana daudzdzīvokļu ēku siltumapgādē kompleksā ar ēkas renovāciju” – 2012. – 28 March. – Riga;

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Structure and Volume of the Paper

Promotional study is written in Latvia, containing an introduction, five chapters, conclusions, bibliography, 52 figures, 123 pages in total. Bibliography contains 72 titles.

1. EXPERIMENTAL PROTOTYPE OF THE SOLAR COMBISYSTEM FOR AN APARTMENTBUILDING

In this section boundary conditions and the concept of the hydraulic scheme for an experimental prototype of a combined solar and pellet system is described.

1.1. Boundary conditions for project realization

For the development of an experimental prototype, the following boundary conditions were set:

- the system must be compact and modular. Its installation must be possible in buildings without free space in the basement or attic. Time consuming and expensive building of additions cannot be required;
- a wood pellet boiler must be used as an auxiliary source of energy;
- the system must be able to coverhot water and space heating loads for the apartment building. The proper organization of the preparation of hot water (HW) is the main condition for the effective use of solar energy;
- the combined system must include all components for heat production, storage and distribution. No additional place in the building for any system components, except solar collectors and pipelines can be used;
- the selection of alternative technical solutions for the system must be based on the results of economical optimization;
- the solar and pellet combisystem must be able to compete with conventional fossil fuel heating technologies;
- the renovated or newly built apartment buildings are more appealing for the installation of a combined solar and pellet system. Otherwise, it is more profitable to invest money in energy efficiency measures.

On the basis of the results of several studies and project partners' experience and suggestions, some more specific boundary conditions were set:

- a container-type boiler house with standard transportation sizes (6000×2900×3100 mm) must be used for the installation of the system;
- a limited boiler-house size allows for the use of pellet boilers with a capacity up to 150-200 kW, which in turn limits the potential range of consumers. The total energy consumption of 450 to 600 MWh year could be set as a threshold;
- the use of a container boiler house will allow for the installation of the system components on a factory site. Significantly reducing the time and costs of installationon site;
- the energy gained from solar collectors and the pellet boiler must be accumulated in a joined volume;
- the external heat exchanger must be used for space heating needs, it allows work to be completed effectively with all - high, medium and low - temperature heating systems;

- the consumer's hot water load can vary from 0 kW to 100 kW and up, so external a heat exchanger must be used and hot water recirculation load taken into account;
- the system should be built using flat plate solar collectors. This technology is chosen because it has lower capital and maintenance costs;
- the combined solar system must be designed to match Northern Europe climate conditions.

The hydraulic concept of the system was developed taking into account the previously defined boundary conditions.

1.2. Exploration algorithm for the developed experimental system

Development, optimization, and analysis of the experimental system was completed according to the algorithm in Figure 1. The algorithm consists of 2 stages: activities before and after the installation of the combined system.

The first stage of the algorithm includes a feasibility study, followed by the setting of boundary conditions. In subsequent phases of the algorithm an apartment building suitable for boundary conditions wassoughtand characterized by heating, hot water preparation and recirculation loads. Technological equipment and solutions were selected on the basis of acquired data. The hydraulic concept of the system was developed taking into account the specifics of heating systems in existing buildings.

All predefined parameters were used to develop the simulation model of the combined system. The simulation results were used to define the benchmark for optimal system performance, as well as for the determination of project compliance within the boundary conditions.

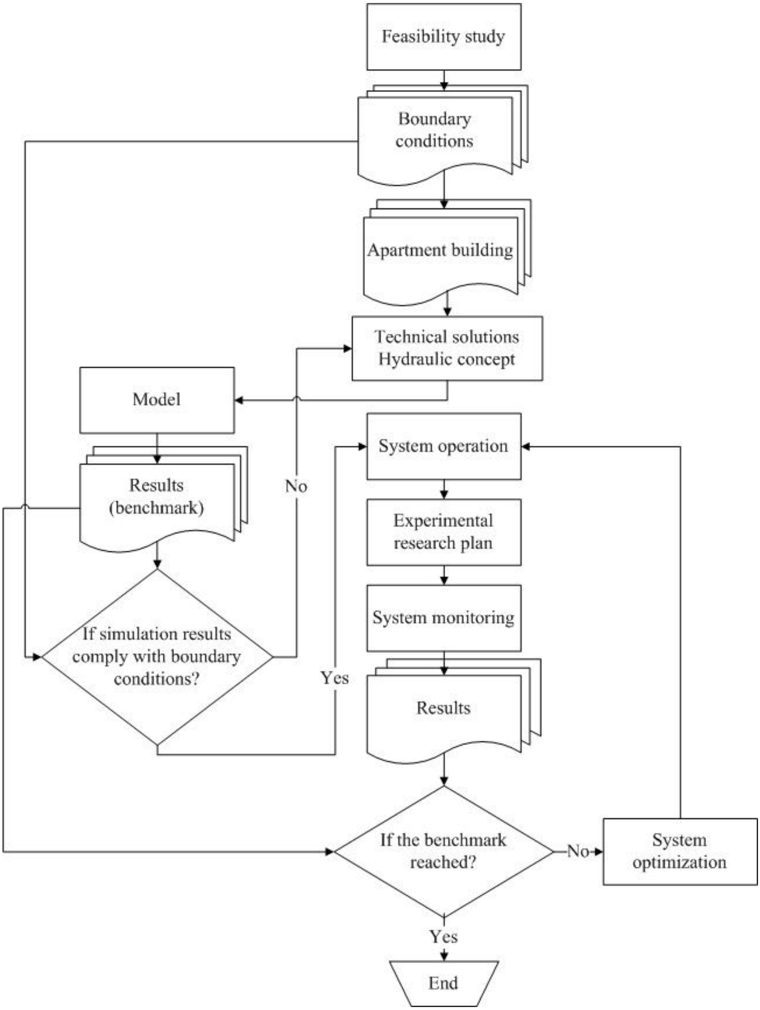


Figure 1. Exploration algorithm for the developed experimental system

The second stage of the algorithm begins at the moment when the system starts. This stage includes an analysis of the system performance and optimization. The system operation was monitored continuously. Monitoring results were used to evaluate system performance and compare it with the previously defined benchmark. The development and evaluation of optimization measures were carried out using a simulation model and results fromnumerical, laboratory and industrial experiments.

1.3. Hydraulic concept of the solar and pellet combisystem

The hydraulic concept of the system consists of five main components: solar collectors with hydraulic loops, pellet boiler, heat accumulation tank, district hot water (DHW) and space heating (SH) loops. See Figure 2.

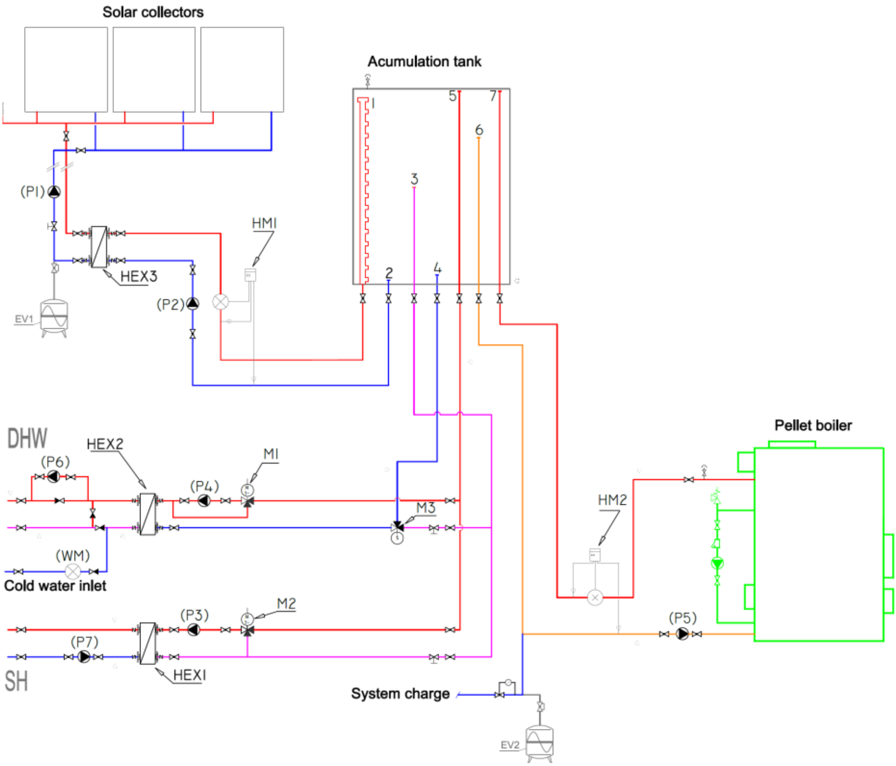


Figure 2. Hydraulic concept of the solar and pellet system
(HEX1 – heat exchanger for space heating, HEX2 – heat exchanger for DHW preparation, HEX3 – solar heat exchanger, M1 – DHW mixing valve, M2 – SH mixing valve, M3 – DHW return three way valve)

The hydraulic concept is designed to perform five functions within the system: DHW preparation and recirculation, space heating, accumulation and utilization of solar thermal energy, utilization and accumulation of heat energy from the pellet boiler.

2. MODELLING OF THE SOLAR COMBISYSTEM

The deterministic mathematical simulation model of the solar and pellet combisystem was developed in the environment of a transient and dynamic process simulation program TRNSYS 16.1 (*Transient Simulation Tool*).A working principle of the computer program is based on the mathematical description of every individual component of the system and solving the model.

2.1. TRNSYS model of the solar and pellet combisystem

The established layout of the computer model's system is shown in Figure 3. The layout corresponds to the hydraulic concept presented in Figure 2. The developed model is flexible and can be used for simulations of various technical solutions and heat loads of consumers.

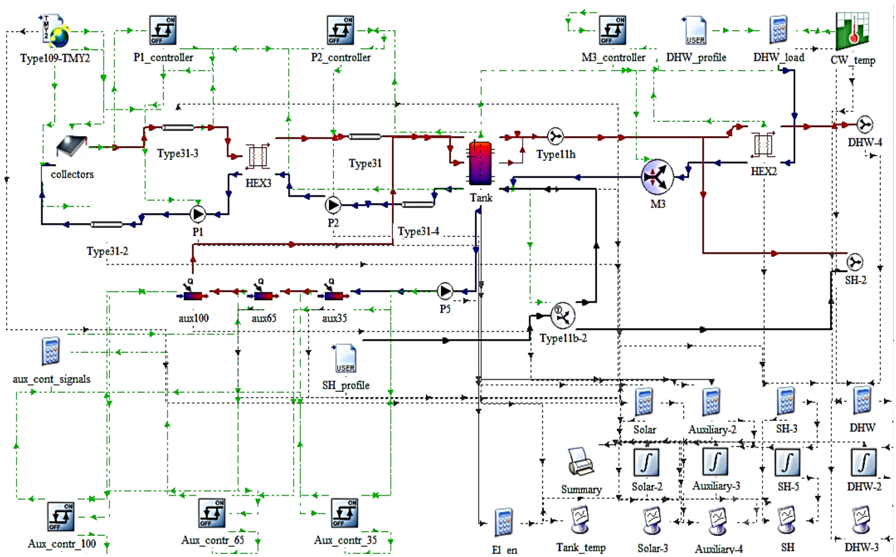


Figure 3. Layout of the TRNSYS model of the solar and pellet combisystem. Developed in TRNSYS Studio environment

Based on the results of numerical experiments, the reference system and benchmark were defined. Also, economical optimization for different technical solutions and an increase in performance of the experimental system were achieved.

2.2. Validation of the simulation model

Validation was carried out using monitoring results, actual operational and performance parameters of the experimental system. One week was defined as a validation period. Outdoor air temperature, amount of global solar irradiation on horizontal surface, mass flow rate of consumed DHW, calculated DHW recirculation and space heating loads are used as an input data for the validation process. Absolute values and the difference between monitoring and simulation results are summarized in Table 1.

Table 1

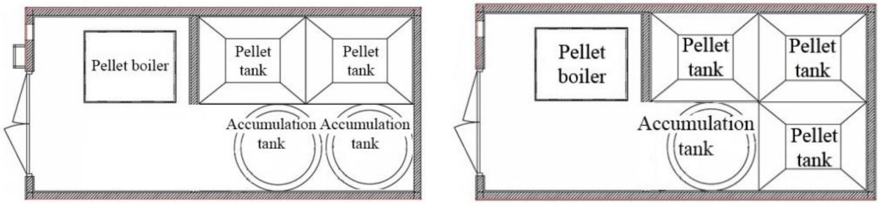
Comparison of the monitoring and simulation results

Parameter	Monitoring, °C or MWh	Difference, %
Accumulationtank		
Temperature atthe top part of thetank	71,4	+ 0,6
Temp. in the upper half part of the tank	39,4	- 0,5
Temp. in the lower half part of the tank	37,0	- 5,1
Temperature at the bottom of the tank	33,6	- 4,5
Pellet boiler		
Supply temperature to boiler	75,7	- 3,4
Return temperature from boiler	67,5	- 1,9
Solar collectors		
Supply temp.to collectors'secondary loop	50,2	- 8,0
Return temp.from collectors'secondary loop	38,0	- 7,9
Consumer side		
Supply temperature to hot water loop	56,3	+ 1,4
Supply temperature to space heating loop	38,3	+ 0,3
Consumption of heat energy		
Heat energyfor DHW preparation	0,807	+ 4,2
Heat energyfor DHWrecirculation	0,623	+ 4,0
Heat energyfor SH	2,790	+ 3,3
Total consumed (without losses)	4,220	+ 3,6
Heat production		
Heat energy gained in boiler	4,132	+ 3,4
Heat energy gained in collectors	0,125	+ 3,2
Totalgained heat energy(with losses)	4,257	+ 3,4

The internal energy balance of the simulation model showed 0.3 % difference between heat energy gained and consumed within the system. Heat losses from the accumulation tank were added to the consumed heat energy.

2.3. Selection of different technical solutions

At the selection of technical solution stage, two alternatives with different amounts and total volume of accumulation tanks were considered, see Figure 4. For each alternative, the optimum area of solar collectors was identified.



A. B.

Figure 4. Different layouts for accumulation tanks in boiler house (A. 2.35 m^3 accumulation volume and 12 m^3 for pellet storage, B. 4.7 m3 accumulation volume and 8 m^3 for pellet storage)

Both alternatives are technologically feasible, therefore economic optimization could be carried out. The results of the annual system simulation were used to evaluate economic indicators of both solutions.

The target of economic optimizations is to choose an alternative (by both accumulation tank volume and area of solar collectors) with the lowest heat energy costs. Capital costs ($E_{th.cap}$) and exploitation costs ($E_{th.expl}$) were set as components for the target function of thisoptimization. See formula 1 and 2.

$$\min\left\{E_{th.cap} = f\left(I_{c.eq}, n_c, I_c, n_t, I_t, n_{pel.t}, I_{pel.t}, n_{ye}, Q_{th}\right)\right\} \quad (1)$$

$$\min\left\{E_{th.expl} = g\left(Q_c, Q_{th}, I_{pel}, \eta_b, q_{net}, I_{transp}, m_{pel.t}, Q_{c.el}, Q_{b.el}, E_{el}\right)\right\} \quad (2)$$

Where,

$I_{c.eg}$ – expenses for the solar part of the system (except collectors and the tank), Ls;
n_c – amount of solar collectors, pieces;
I_c – expenses for solar collector, Ls;
n_t – amount of heat accumulation tanks, pieces;
I_t – expenses for heat accumulation tank, Ls;
$n_{pel.t}$ – amount of storage tanks for pellets, pieces;
$I_{pel.t}$ – expenses for storage tanks for pellets, Ls;
n_{year}– period of operation, years;
Q_{th} – heat energy consumption, MWh per year;
Q_c – solar heat energy gain, MWh per year;
I_{pel} – price for pellets, Lst^{-1};

η_b – efficiency of pellet boiler, - ;
q_{net} – lower calorific value of pellets, $MWht^{-1}$;
I_{transp} – expenses for transportation of pellets, Ls;
$m_{pel.t}$ – capacity of storage tank for pellet, t;
$Q_{c.el}$ – specific electricity consumption of solar pumps, $MWh_{el}MWh_{th}^{-1}$;
$Q_{b.el}$ – specific electricity consumption of pellet boiler, $MWh_{el}MWh_{th}^{-1}$;
E_{el} – electricity tariff, $LsMWh_{el}^{-1}$.

The change of capital costs for each alternative depending on the total area of installed collectors is shown in Figure 5.

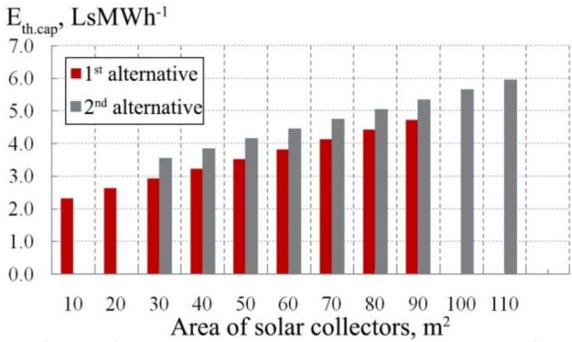


Figure 5. Change of capital costs for each alternative depending on the total area of installed solar collectors

Change of exploitation costs for each alternative depending on the total area of installed collectors is shown in Figure 6.

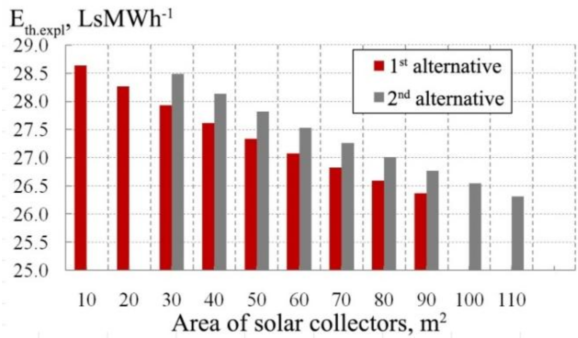


Figure 6. Change of exploitation costs for each alternative depending on the total area of installed solar collectors

The changes of heat energy costs (E_{th}) and heat energy gained in solar collectors (Q_c) for each alternativewas analysed. See Figure 7.

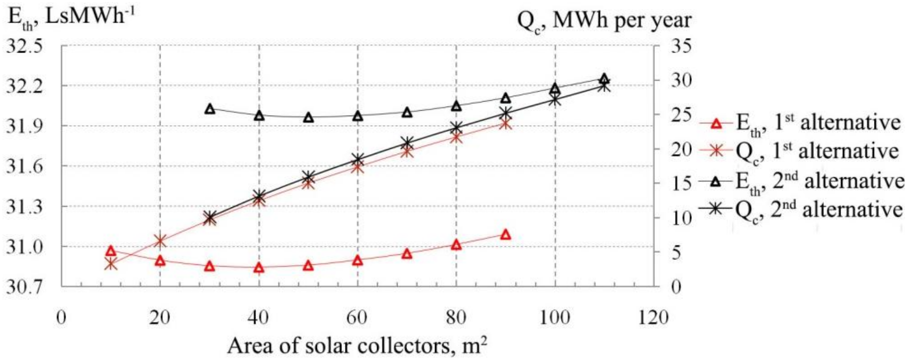


Figure 7. The changes of heat energy costsand energy gained by collectors for each alternative in the function of the total area of solar collectors

Results of analysis shows that the alternative with 1 accumulation tank, 3 pellet storage tanks and 40 m^2 solar collector is economically the most profitable for the installation of the experimental system.

2.4. Justification of arrangement for solar collectors

The annual system simulation was applied to determinate the optimal angle and orientation for the installation of thesolar collectors. The relative thermal performance of collectors was set as an optimization function, where the independent variables were installation angle and azimuth, see Figure8.

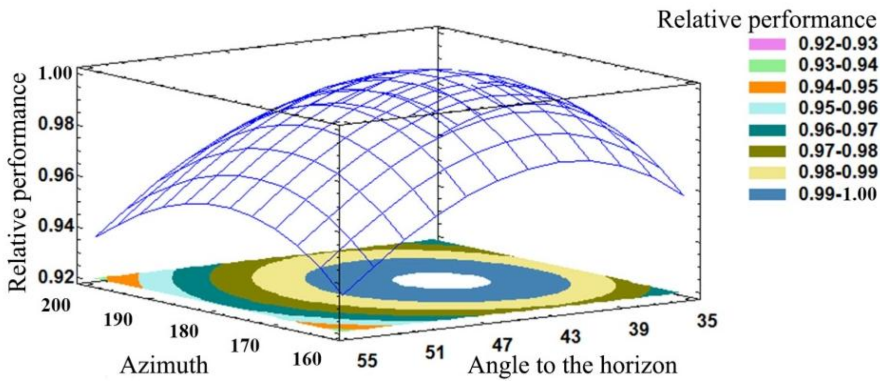


Figure 8. Relative thermal performance of collectors in the function of installation angle and azimuth.

Based on the results of the analysis it was concluded that the optimal solution for the installation of solar collectors are: 45 ° angle to the horizon and 0 ° degrees azimuth angle.

3. MONITORING OF THE SOLAR COMBISYSTEM

The experimental prototype of the combined solar and pellet system was installed at the apartment building Kr. Barona Street 2, in Sigulda (N 57° 09.410 E 024° 52.194). The complex building renovation was carried out in parallel with the installation of the system. The experimental system was designed to cover the heat load ofthe fully renovated building. The technological solution with one 2.35 m^3 accumulation tank (see Figure 4), 100 kW pellet boiler and solar collectors. A total area of 42 m^2 was used.

Monitoring was started after the installation of the experimental system. The monitoring scheme is shown in Figure 9.

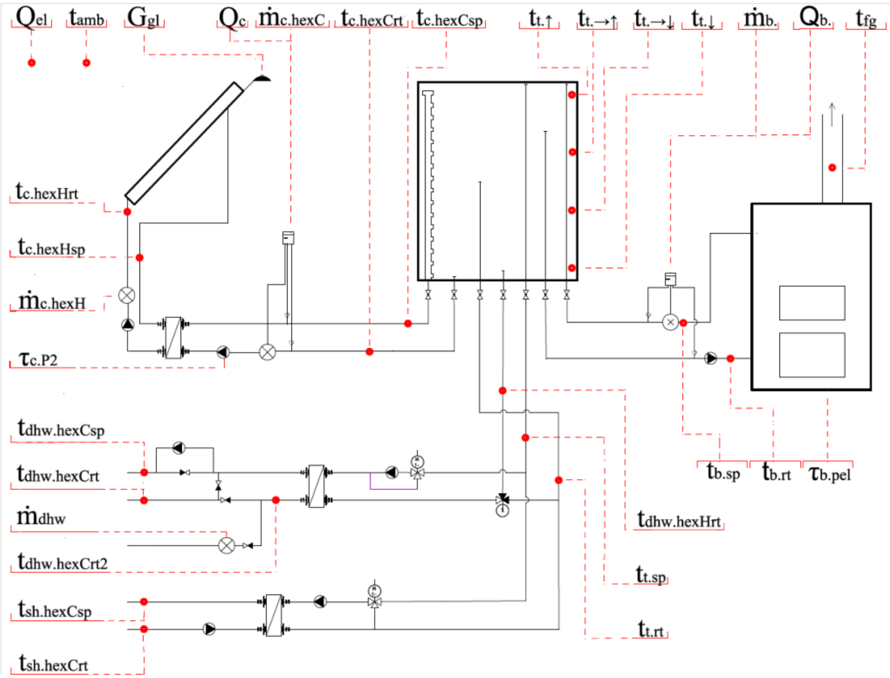


Figure 9. Monitoring scheme of the experimental system

The definition of potential optimization measures and tasks was summarized within the research monitoring data. Based on the monitoring results, theperformance of the system was analysed and compared with the defined benchmark.

4. OPTIMIZATION OF THE SOLAR COMBISYSTEM

Within the research, a complex system optimization was carried out, including the optimization of control algorithms, combustion process, operation parameters etc. The performance of the experimental system in the function of the flow rate in DHW recirculation loop was analyzed. Later, the optimization of the recirculation flow rate was carried out.

The seasonal boiler control algorithm was developed in order to reduce a temperature levelin the system and to prevent the overheating of the heat accumulation tank. As a result, in comparison with the reference system, the average temperature of the heat accumulation tankat the top of the section during the heating season decreased by 5.2 K season and by 7.3 K in summer time. The heat energy gained in collectors (Q_c) increased by 10.6 %, fractional energy savings ($f_{sav.th}$) and extended fractional energy savings ($f_{sav.ext}$) increased by 0.4 and 0.3 percentage –points accordingly.

To determinate the effect of the amount of combustion air on the boilers performance, laboratory combustion experiments with a 25 kW pellet boiler were carried out. The boiler testing stand at RTU Environment Monitoring Laboratory was used in the experiments. See Figure 10.

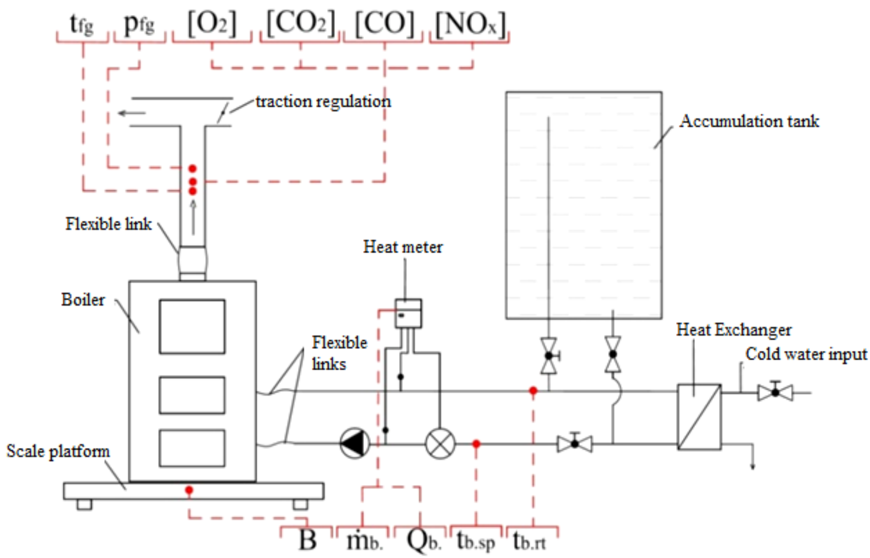


Figure10. The scheme of the laboratory boiler testing stand

By using two pellet samples, 13 experiments were carried out. The results show that there is a clear optimum between the O_2 concentration in flue gases and boiler power efficiency and CO emissions and losses with the flue gases, see Figure11.

All these correlations can be described with polynomial functions. The highest boiler efficiency was achieved with 5.6% O_2 in flue gases, and the lowest CO emissions with 7.8% O_2.

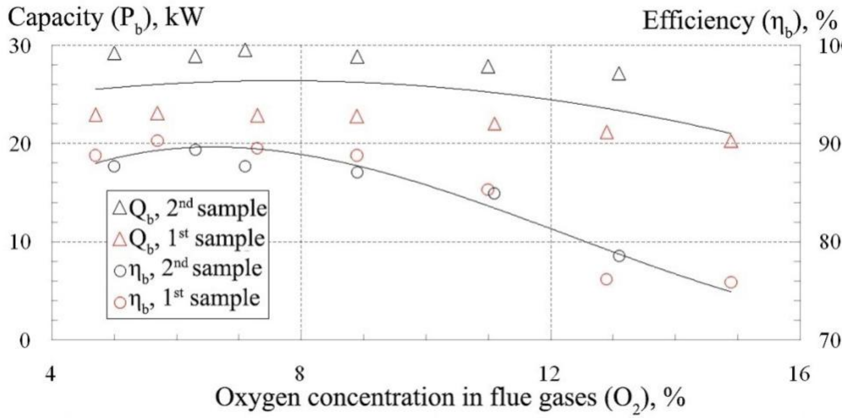


Figure 11. Laboratory experiments with 25 kW boiler. Boiler power (P_b) and efficiency (η_b) in function of O_2 concentration in flue gases

The results of the monitoring of the combined system show an increase of O_2 concentration in flue gasses, when the boiler works at the power modes of 65 kW and 35 kW. During the measurements, changes in CO concentration and chemical heat losses in the flue gasses (q_b) depending on O_2 concentration in the flue gasses were determined, see Figure12.

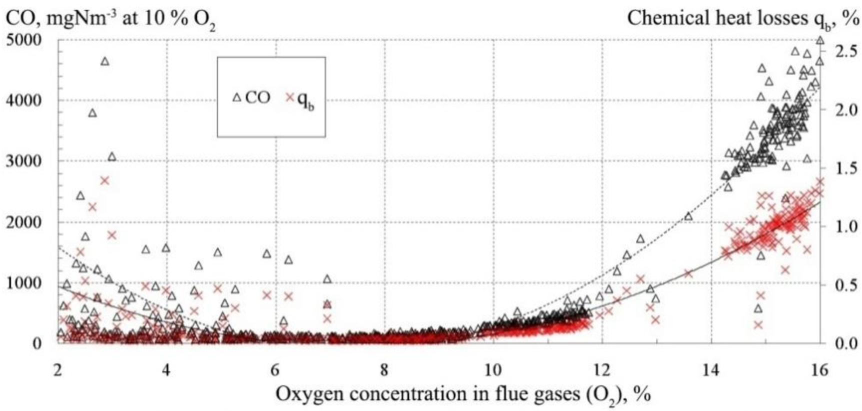


Figure 12. CO concentration and chemical heat losses in the flue gasses (q_b) in function of O_2 concentration

By the modification of the control algorithm, the amount of air supplied to the furnace was reduced. As a result, heat losses with flue gasses (q_a) were reduced by 1.6% and chemical losses (q_b) by 0.17%. That allows an increase of $f_{sav.th}$ and $f_{sav.ext}$, by 2%-points and 1.8%-points accordingly.

Within the research performance of the system, in function of the flow rate in the DHW recirculation loop ($\dot{m}_{dhw.rec}$) was analysed. It was stated that the flow rate is the main factor determining temperature at the bottom of the tank (t↓) and the performance of the collectors, see Figure 13.

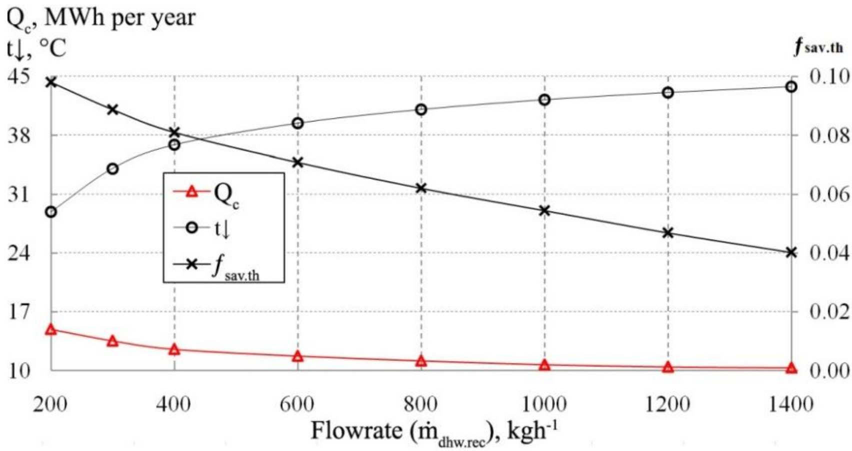


Figure 13. Solar energy gains (Q_c), fractional thermal energy savings ($f_{sav.th}$) and temperature at the bottom of the tank (t↓) in function of the flow rate in the DHW recirculation loop ($\dot{m}_{dhw.rec}$)

By reducing the flow rate in the DHW recirculation loop from 1400 kgh^{-1} to 295 kgh^{-1} an increase of 31% or 3.21 MWh per year in heat energy gained by the collector was achieved. The heat energy consumption for DHW recirculation decreased by 20 % or 5.12 MWh per year. Taking into account the reduction of the consumed heat energy $f_{sav.th}$ and $f_{sav.ext}$ values increased by 9.6%-points and 9.5%-points accordingly.

In this work, the methodology for the optimization of the operational parameters (OP) was developed. The developed methodology is based on the TRNSYS simulation model and the use of a multi-parameter non-linear regression analysis. The proposed algorithm for optimization methodology is given in Figure 14. The algorithm consists of the following steps:

- defining and mathematical expression of target functions;
- calculation of benefits for the reference system, defining of threshold values;
- dynamic simulation using random sampling of operating parameters between feasible ranges;

– multi-correlation analysis between the outputs from computer simulations and the randomly sampled operational parameters;
– optimization of the regression equation using generalized reduced gradient method (GRG2) in order to identify an optimal combination of parameters with maximal or minimal target function;
– refining simulations with reduced ranges around the optimized values;
– optimization of regression equation for the reduced range and stating of an optimal combination of operation parameters.

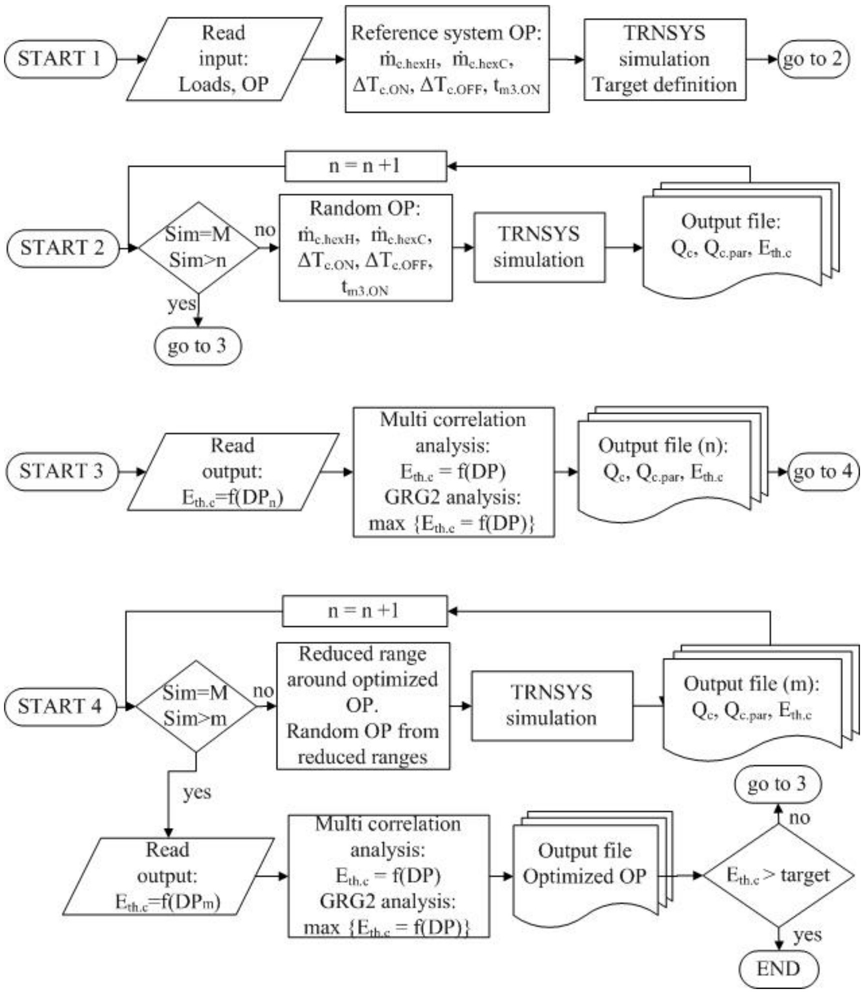


Figure 14. Algorithm developed for optimisation of OP

The methodology was approbated, by the optimization of the following operation parameters for the experimental system:

- flow rate in the primary collectors loop ($\dot{m}_{c.hexH}$);
- flow rate in the secondary collectors loop ($\dot{m}_{c.hexC}$);
- upper dead band temperature, solar controller ($\Delta T_{c.ON}$);
- lower dead band temperature, solar controller ($\Delta T_{c.OFF}$);
- activation temperature of the valve M3 ($t_{M3.ON}$).

Benefits from solar energy ($E_{th.c.}$) expressed in monetary units have been set as a target function for optimization, see Equation 3.

$$\max \{E_{th.c}=f(t_{c.\Delta t.ON}, t_{c.\Delta t.OFF}, \dot{m}_{c.hexH}, \dot{m}_{c.hexC}, t_{M3.ON})\} \quad (3)$$

Benefits are calculated according to Equation 4.

$$E_{th.c}=\frac{Q_c \cdot I_{pel}}{\eta_b \cdot q_{net}} + \frac{Q_c \cdot I_{transp}}{\eta_b \cdot q_{net} \cdot m_{pel.t}} + Q_c \cdot Q_{b.el} \cdot E_{el} - Q_{c.el} \cdot E_{el} \quad (4)$$

At first, 100 simulations were randomly performed, from a predefined large range and selected values of OP. The accurate results were processed in the program STATGRAPHICS Centurion 16.1.15 in order to obtain a second-degree polynomial regression equation (Marquardt method). The obtained regression equation is optimized using the generalized reduced gradient method (GRG2) within the SOLVER environment and the combination of the optimal operational parameters was stated. The procedure was repeated by reducing a range of possible values, and by running 50 additional simulations.

As a result of the optimization, the following combination of the OP was obtained: $\dot{m}_{c.hexH}$ = 514 kgh^{-1}, $\dot{m}_{c.hexC}$ = 447 kgh^{-1}, $\Delta T_{c.ON}$ = 7 K; $\Delta T_{c.OFF}$ = 2 K, $t_{M3.ON}$ = 29 °C.

The values for the obtained operation parameters were integrated into the operation of the experimental system. Changes in benefits ($E_{th.c}$) depending on the flow rate in both collector loops are reflected in Figure15.

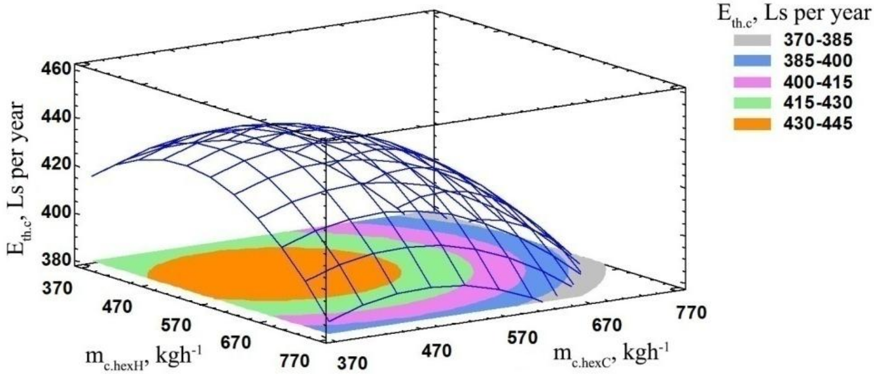


Figure 15. Changes in benefits ($E_{th.c.}$) depending on flow rate $\dot{m}_{c.hexH}$ and $\dot{m}_{c.hexC}$. At $\Delta T_{c.ON} = 8$ K, $\Delta T_{c.OFF} = 2$ K and $t_{M3.ON} = 28$ °C

Changes in benefits from solar collectors ($E_{th.c}$) depending on the setting of the controller ($\Delta T_{c.ON}$ and $\Delta T_{c.OFF}$) are shown in Figure16.

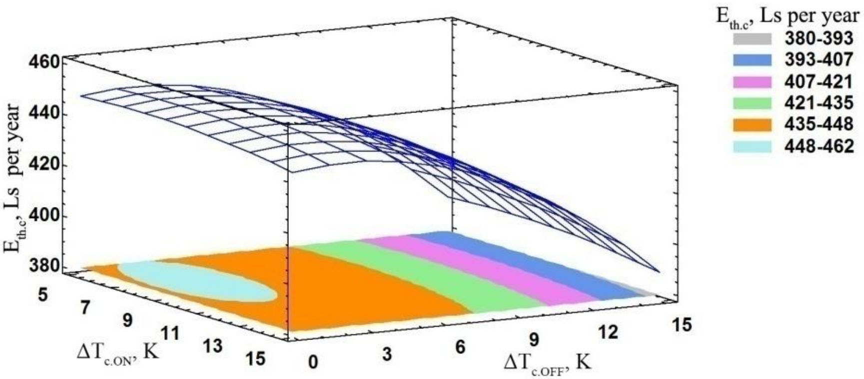


Figure 16. Changes in benefits ($E_{th.c.}$) depending on upper ($\Delta T_{c.ON}$) and lower ($\Delta T_{c.OFF}$) dead band temperature. At $\dot{m}_{c.hexH} = 519$ kgh^{-1}, $\dot{m}_{c.hexC} = 481$ kgh^{-1} and $t_{M3.ON} = 28$ °C

All developed optimizations tasks were implemented in the experimental system. Results of the optimization for the experimental system and simulation model are reflected in Figure 17.

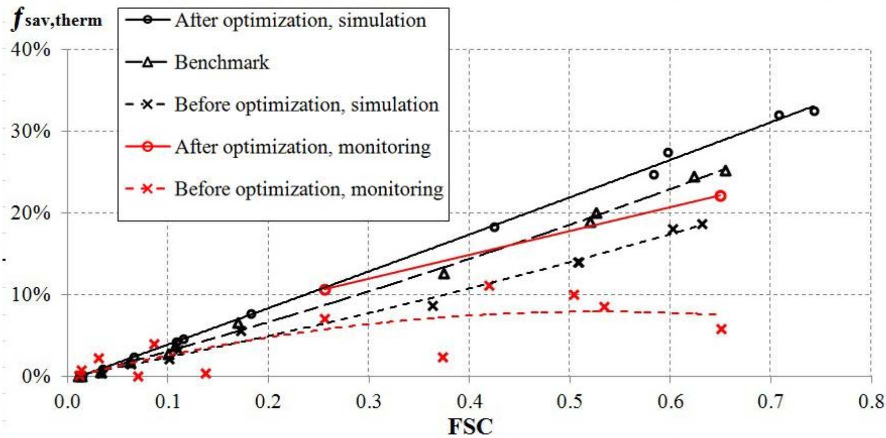


Figure 17. Optimization results of the experimental system and the simulation model. Changes within the fractional solar consumption (FSC) and fractional thermal energy savings ($f_{sav.th}$).

In comparison with the reference system, the optimized simulation model achieved an increase of $f_{sav.th}$ by 8.5 %-points and $f_{sav.ext}$ by 8.2 %-points on a yearly basis.

CONCLUSIONS

1. This work defines the boundary conditions for the development of a solar combisystem fully-based on the use of renewable resources and designed for heat supply purposes of apartment buildings. The boundary conditions determine modular and hydraulic concepts of the combisystem, the appropriate choice of technical solutions and apartment buildings.

2. The concept of the solar and pellet combisystem contains the following independent variables: free available space for pellet boiler installation, total volume of heat accumulation and pellet storage tanks.

3. The deterministic mathematical model of the solar and pellet combisystem is described using technical and operational parameters. The parameters are validated in TRNSYS program environment using the monitoring results of the experimental system. For the validation period, one week was chosen. The developed simulation model describes the experimental system and the validation results fit into predefined marginal intervals: ± 10% for the mean values of dynamic parameters, ± 5% for the total amount of gained and consumed energy and ± 1% for the internal energy balance of the model. The developed simulation model is applicable for analysis and optimization of similar solar combisystems.

4. Based on the combisystem simulation results, the following benchmarks are defined: fractional solar consumption (FSC) – 0.15, fractional thermal energy savings ($f$sav.th) – 0.051 and extended fractional thermal energy savings ($f$sav.ext) – 0.05. Defined benchmarks are used for analysis and optimisation of the experimental combisystem.

5. The selection between various technical solutions is based on economic optimization. The optimization criteria are the lowest components of the operating and capital costs. The optimization target functions are based upon the following independent variables: amount and expenses for solar collectors and components of the solar system, amount, cost and capacity of storage tanks for pellets, amount and cost of heat accumulation tanks, the operation period of equipment, total heat energy consumption, solar energy gains, price for wood pellets and lower calorific value of pellets, boiler efficiency, costs for the transportation of pellets, electricity tariff and electricity consumption of pumps in collector and boiler loops. Based on the results, the optimal solution single heat accumulation tank and 40 m2 solar collectors were chosen.

6. The methodology for the optimization of the system parameters that was developed within this work allows for determining the optimal combination of performance parameters with minimal computational effort. The methodology

takes into account mutual effects of operating parameters and is particularly suited for the analysis and optimization of complex systems. Algorithm of optimization methodology includes the simulation of the system performance in TRNSYS environment, multi-parameter nonlinear regression analysis and the use of a generalized reduced gradient method for the optimization of the regression equation. The developed method was approbated for the optimization of five operating parameters in the experimental combisystem.

7. In this thesis, three types of experimental data are analysed: numerical, laboratory and industrial on-site. Based on the results of the analysis, several statistical models are developed. The models describe the functionality between the following parameters in certain diapasons:
   - the performance of the solar collectors in function of the collector's orientation (160 – 200 º of azimuth) and installation angle (35 – 55° range);
   - the efficiency of the solar loop in the function of the temperature in the bottom of the tank (10 – 70 °C);
   - the temperature in the bottom of the tank, heat energy consumption for hot water recirculation, energy gain from the collectors and $f_{sav.th}$ changes in function of flow rate in the hot water recirculation loop (200 – 1400 kgh^{-1} range);
   - the change in capacity, efficiency, heat losses and CO emissions depending on O_2 concentration (4.7 – 14.9 %) in flue gasses of the laboratory 25 kW pellet boiler;
   - amount of CO emissions and heat losses in the function of O_2 concentration in the flue gasses of the on-site 100 kW wood pellet boiler (2.1 – 16 % range);
   - the benefits of using the solar collectors depending on the following operating parameters: the flow rate in the primary and secondary loops of the collectors (371 – 700 kgh^{-1}), the temperature difference for the activation (2 – 15 °C) and deactivation (1 – 14 °C) of solar pumps and the temperature for activation of the M3 three-way valve (20 – 40 °C).

8. The developed optimization tasks significantly increased the performance of the solar combisystem. In comparison with the reference system, the optimized simulation model achieved an increase of $f_{sav.th}$ by 8.5 %-points and $f_{sav.ext}$ by 8.2 %-points on a yearly basis. By the reduction of the flow rate in the hot water recirculation loop an increase of 3 %-points of fractional energy savings (FSC) was achieved. Based on two months monitoring data, it can be concluded, that the benchmark and performance of the simulation model can be achieved in the experimental system.