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RIGA TECHNICAL UNIVERSITY

Egīls Dzelzītis

APPLICATION OF ALTERNATIVE ENERGY TRIGENERATION FOR BALANCING OF LOADS AND SUSTAINABLE QUALITY ASSURANCE IN SMART ENERGY NETWORKS

Summary of the Doctoral Thesis

RTU Press
Riga 2021

RIGA TECHNICAL UNIVERSITY

Faculty of Electrical and Environmental Engineering
Institute of Industrial Electronics and Electrical Engineering

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Doctoral Student of the Study Programme "Computerized Control of Electrical Technologies"

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Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 28 December 2021 at 10.00 p.m. in Microsoft Teams meeting.

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DECLARATION OF ACADEMIC INTEGRITY

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

Egīls Dzelzītis ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction; 7 chapters; Conclusions; 50 figures; 3 tables; the total number of pages is 95. The Bibliography contains 135 titles.

CONTENTS

ANNOTATION

The object of the research is micro-grids in district heating systems (DHS) in Riga and Ogre, the end consumers of the thermal energy from these systems (the passive building: Ogre Central Library).

Targets of the national Energy and Climate Plan of Latvia for 2030.

The aim of the Doctoral Thesis is to design the energy management model for micro-grids with passive buildings and ecological trigeneration by using renewable energy resources.

The Doctoral Thesis comprises the introduction and seven chapters in which the research results regarding balancing of the end consumer loads by thermal network power, considering the use of ecological trigeneration in the renewable energy micro-grids, as well as the experimental part based on the renewable energy micro-grid of Ogre Central Library, the evaluation of the results, the conclusions, the information resources (literature review) are presented.

The applications of the patents protecting the technical solutions of the Doctoral Thesis have been submitted to the Patent Office of the Republic of Latvia.

In Chapter 2 the creation of mathematical model for cooling the rooms of the building and the evaluation of the model designed are presented.

In Chapter 3 the research results regarding the options to improve the dynamic properties of individual energy supply phases (permanent air distribution within the maintaining limits in the room, based on the identification of the heat exchange process possible and maintained by the Coanda effect, by creating pulsations of the heat carriers) are presented.

In Chapter 4 improvement of interaction of the distribution networks of different energy types is described based on the use of the smart energy consumption meters.

In Chapter 5 a graph-analytical method for selection of air processing technology is presented, based on selection of the processing vector with the least possible energy consumption.

In Chapter 6 the creation of the digital twin of the DHS phase is described and the application of the patent regarding the usage of the digital twin for management of the DHS thermal energy resources is explained.

In Chapter 7 the strategy of creating renewable resource energy communities (microgrids) has been described.

1. INTRODUCTION

General part

1. *National energy and climate plans*.

In accordance with the Management Regulation which has been effective since December 2018, the EU member countries have a duty to report their contribution to the Energy Union according to the national energy and climate plans (NECPs), which comprise a 10-year period and are updated regularly. The first NECPs cover the time period from 2021 to 2030.

The long-term goal of the NECP is to promote climate-neutral economic growth by improving energy safety and the wellbeing of the society in a sustainable, competitive, cost-effective, and safe way based on the market principles.

In order to achieve such long-term goal, it is necessary to:

1) promote effective use of resources as well as their self-sufficiency and diversity;

2) ensure significant decrease in consumption of resources, especially fossil and non-sustainable resources, and at the same time transition towards sustainable, renewable and innovative use of resources, ensuring equal access to the energy resources for all groups of the society.

3) stimulate development of such research and innovation that promotes the development of sustainable energy sector and mitigation of climate change.

In order to achieve the goals defined by the EU and the international commitments, in each member country NECPs are developed based on:

• commitments expressed in the Paris Agreement of the United Nations Framework Convention on Climate Change for 2030 related to climate change mitigation: to reduce the total greenhouse gas (GG) emissions of all EU member states by at least 40 %, compared to 1990, in a cost-effective way by 2030 [5];

• the EU "Roadmap towards competitive economy with low level of carbon dioxide emissions 2050" – in 2050, the EU is ready to reduce within its territory total EU emissions by 80–95 %, in comparison to the level in 1990 in order to shift to competitive economy with low level of carbon dioxide emissions [6];

• the EU strategic plan "A clean planet for all – European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy" – in 2050, the EU is ready to achieve "climate neutrality" [7].

2. *The desirable situation in Latvia in 2030 (NECP of the Republic of Latvia).*

- In the fund of buildings, the average thermal energy consumption for heating is by 30 % lower than in 2020.
- At least 2000 multi apartment houses and at least 5000 private houses are renovated, non-emission renewable energy resource (RER) technologies are installed in them or they are connected to the district heating supply (DHS).
- Increase of energy efficiency in state and municipal buildings is ensured.

At the moment Latvia is in the third place in Europe behind Iceland and Lithuania regarding the number of population (%) to whom thermal energy is provided by DHS. Implementation of measures of more rapid increase of energy efficiency in DHS is hindered by lack of investment volume, limited capabilities of the municipalities to take a loan, as well as the slow speed of the capital turnover growth in DHS modernisation processes. By carrying out renovation of complex system (production=transfer=consumption), it is possible to optimize the process of energy production and to reduce thermal energy losses in the transfer systems.

Additional actions in order to achieve the desirable situation in 2030:

- Promote energy autoproduction and self-consumption in order to make individual thermal energy production efficient and non-emission technology usage applied in it.
- Make the tax system greener and improve attractiveness of energy efficiency and RES technologies, where excise duty on fuel and natural resources tax (DRN) are assessed and evaluation of tax incentives and phasing out of energy subsidies is done.
- Involve the society in the energy production.
- Involve the inhabitants in the energy production by installing larger volume of energy production equipment for self-consumption.
- Promote economically justified energy autoproduction, self-consumption and renewable energy communities.
- Expand the circle of persons involving in electrical energy production in unified local networks (micro-grids, energy islands).

The interactions of the building information model (BIS) are as follows:

1) modern construction structure;
2) innovative materials for construction;
3) 3 D moulding and related production;
4) autonomous construction;
5) enhanced reality;
6) big data and leading analysis;
7) wireless monitoring and networked equipment;
8) cloud and real-time interface;
9) 3 D scanning and photogrammetry;
10) building information modelling (BIM) [15].

Interactions 5 to 8 are related to the Doctoral Thesis, which are further investigated in the *Institute of Electrical and Electronics Engineers* (*IEEE*).

IEEE is a professional association of electronics and electrical engineers, its aims are to educationally and technically improve electronic engineering, telecommunications, computer engineering and related disciplines [16].

Future progress outline in the view of *IEEE* was presented in the guest lecture by Professor Rik W. De Doncker "*Further Advantages in Electrical Grids with DC Technology*" in the Institute of Industrial Electronics and Electrical Engineering of RTU (Fig. 1) [17].

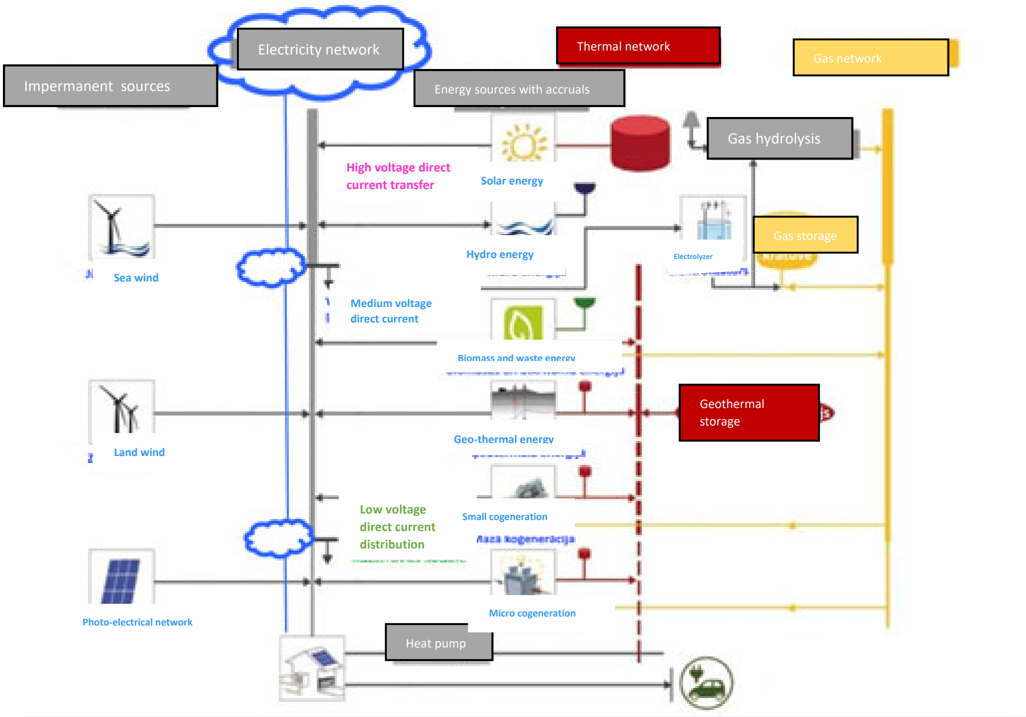

Fig. 1. Interaction of smart direct current networks with diversified local electrical energy generators.

Technical options and current tasks for smartification of energy distribution networks are as follows:

1) distributed production of electrical energy and thermal energy, creation of micro-grids;
2) energy accumulation;
3) diversification of electrical energy and thermal energy sources (solar energy, wood, hydrogen), use of trigeneration;
4) capabilities of industrial electronics in achieving CO_2 neutrality.

Topicality of the work

Several doctoral theses have been presented at the Pomotion Council “P-14”, in which research on electrical-technological processes was carried out on improving management of these processes. The authors of these works are researchers Pēteris Apse-Apsītis, Aleksandrs Suzdaļenko, Anatolijs Zabašta, Genādijs Zaļeskis, Rodions Saltanovs, and Gints Poišs. The works were presented in the time period from 2013 to 2021.

However, in order to improve and advance the energy supply, the following must be carried out:

1) research on cooling at the end consumers which are involved in the energy supply network;
2) digital twins for thermal supply systems should be designed;
3) basic principles for ecological trigeneration management should be formulated;
4) development of ecological trigeneration management strategy;
5) development of recommendation for improving dynamic properties of individual stages in energy supply automated regulation systems.

Novelty

Improving the performance of energy supply systems, including renewable energy micro-grids with eco-generation by adapting to the dynamic load of passive buildings. Patent applications:

1. Application regarding LR patent No. LVP2020000012 "Automated temperature adjustment system and technique for rooms in order to make consistent air distribution". Inventors: E. Dzelzītis, A. Krūmiņš, A. Prozuments. Application date: 28.02.2020.
2. Application regarding LR patent No. LVP2020000045 "Equipment and technique for increasing efficiency of sewerage water recovery system". Inventors: E. Dzelzītis, K. Grīnbergs. Application date: 16.06.2020.
3. Application regarding LR patent No. LVP2020000070 "Automated management system and technique for temperature regulation of return flow in thermal supply network". Inventors: E. Dzelzītis, N. Talcis. Application date: 13.10.2020.

For the patentable engineering novelty "Usage of sewage heat potential to provide microclimate in a building", the Golden Award was granted (inventors Egīls Dzelzītis and Kaspars Grīnbergs) at the 8th International Inventions and Innovations Exhibition "MINOX 2020", in Riga, on 30 and 31 October 2020.

The aim of the work

1. To develop an energy management method for micro-grids with passive houses and ecological trigeneration, using renewable energy resources for ecological trigeneration.

2. Development of smart energy metering system, considering interaction of different energy distribution networks.

Practical significance

The justification is developed for the energy community (micro-grid) work with ecological trigeneration and passive houses complying with section Energy Communities of draft Energy Law.

The Doctoral Thesis has been developed within the framework of the National Research Programme No. VPP-EM-INFRA-2018/1-0003.
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Financing number: VPP-EM-INFRA-2018/1-0003
Acronym: VPP-2018-ENERGY
Ministry of Economics of the Republic of Latvia, project "Development trends of Latvian gas infrastructure, challenges and solutions (LAGAS)"

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CHAPTER 2. DATA COLLECTING ANALYSES AND DATA AGGREGATION MODEL FOR COOLING MANAGEMENT IN THE END CONSUMERS OF THE ENERGY SYSTEM

2.1. 6R2C Creation of the mathematical model for cooling modes

Based on *ISO 13790:2008*, the model *6R2C* is developed for building cooling modes. The model is created in *MatLab* environment, it consists of two sub-models: *6R2C* model and air handling unit (*AHU*) model.

AHU model is very significant so that real *AHU* equipment may be simulated, parameters of which change dynamically due to changes of parameters of outdoors and indoor spaces. This model is designed corresponding to the real *PN4* zone *AHU* equipment which is used in the building. *AHU* operation:

1. Depending on the outdoor temperature, it determines the necessary set-point of the room temperature.
2. It compares the set-point of the room temperature with the measured room temperature value in *AHU* output and with PID regulator adapts the dropping air-flow temperature in order to achieve the room temperature set-point. The minimal and the maximal values are limited, in this case − from 14 °C to 26 °C.
3. *AHU* model is checked to see whether it is possible to increase or decrease the value of inflow air temperature by using the recuperator. Efficiency of the recuperator in this ventilation system is 61 %. Efficiency of the recuperator is calculated by using Formula (2.1):

$$\mu t = [t2 - t1]/[t3 - t1], \qquad (2.1)$$

where

μt – heat transfer efficiency;

$t1$ – outdoor air temperature before the heat exchange;

$t2$ – inflow air temperature before the heat exchange;

$t3$ – exhaust air temperature.

The temperature value is obtained from *IoT* sensors which give feedback in real-time. It is assumed that in the summer mode the inflow temperature is no less than 14 °C, which is achieved by cooling, but not higher than the outdoor temperature or the possible temperature after the recuperator depending on which temperature is higher.

The necessary energy volume for heating the air, with the recuperator, to the desired inflow air temperature which is regulated by PID regulator, is estimated by modelling.

2.2. *Evaluation of 6R2C* model for cooling

In order to evaluate results of the created model, *ASHRAE CVRMSE* (average square error variation coefficient) method is used. As a result of the evaluation by *CV RMSE* of consumption per day in the period from 8 August to 8 September a value of 28.62 % was obtained. Such deviation is considered a good result because according to *ASHRAE* guidelines this value should be <30 %, so that it could be used for determining energy base line.

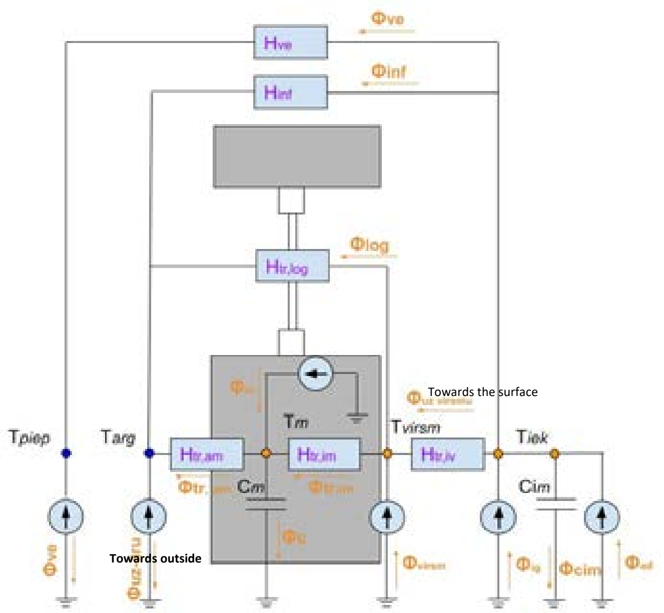

Fig. 2.1. 6R2C – a model of six resistors and two capacitors.

(Measurable parameter *T*, temperature °C; character constants of the model: *H* – thermal conductivity, w/K; *C* – heat capacity, J; ϕ – heat gains from equipment, J).

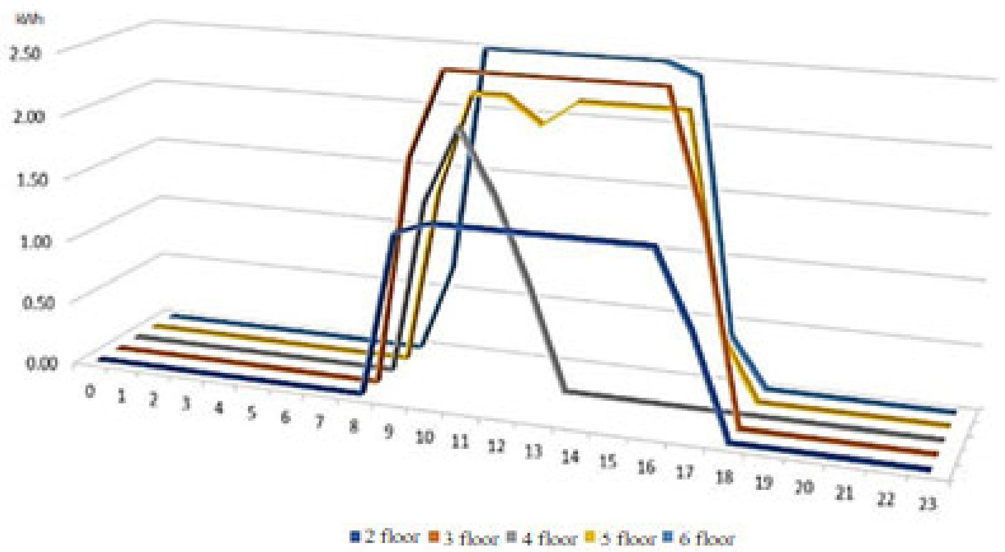

Fig. 2.2. Electrical energy consumption of lighting systems in the trial building from the second to the sixth floor.

During the day of the experiment the blinds were closed, and in the rooms the artificial lighting was used all day. *PN4* zone is on the south side of the building; therefore, closing the blinds (also improving comfort of people who work in the room) reduces the sun radiation impact and the electrical energy consumption for cooling. In the morning period when the solar radiation has the highest impact on the windows of the building (from 8 am until 12 am), the lighting system consumed is 38.2 kWh (the rooms were 100 % occupied). The total consumption of the cooling equipment (24 h) during the day of this experiment (23.08.2018) was 323.1 kWh. Comparing the obtained results of the cooling equipment consumption with other methodologically “similar” days (solar radiation, air temperature and speed of wind), it is evident that in other days it additionally consumes: 12 kWh – 14.08.2018; 50 kWh – 15.08.2018; 34 kWh – 16.08.2018; 46 kWh – 17.08.2018; 36 kWh – 18.08.2018.

The same tendency was observed also on days that are not similar. With the help of the mathematical model, it is possible to obtain also the average room temperatures of the *PN4* zone, thus it is possible to compare them with the measured values from *LoRa* sensors in both rooms and the ventilation block output. It should be taken into account that the ventilation block is turned off at night. The differences between the values may be explained by the fact that the combined *6R2C* simulation model of the ventilation exhaust does not take it into account, but the energy transfer between the walls and the rooms is occurring.

CHAPTER 3. POSSIBILITIES OF IMPROVING ENERGY EFFICIENCY PERFORMANCE OF INDIVIDUAL STAGES IN THE MANAGEMENT SYSTEMS OF THE ENERGY DISTRIBUTION NETWORKS

3.1. Human comfort level in the energy saving simulation model of the office building

During designing and construction of the nearly zero buildings the main goal is to use the available energy resources more effectively. It may be achieved by using the available technical solutions which are technically possible, economically justified and acceptable also from the environment and social perspective. Meanwhile, such solutions should not change the usual comfort conditions of humans [2] – [10].

The possible improvements in energy supply of buildings:

- By increasing energy efficiency of individual elements of the energy supply.
- By increasing energy efficiency of individual elements of the system.
- By balancing load profile of the end consumers with performance of the energy sources.

One of the main ways to increase efficiency of thermal energy equipment in future is to improve heat exchange equipment, which may be implemented by introducing efficient heat transfer intensification methods.

By carrying out heat transfer intensification, the heat volume is increased which is transferred through the heat exchanger surface allowing to achieve more favourable ratio between the heat transfer and the volume of the pumped heat carrier.

The experimental studies carried out regarding alternating fluxes in ventilation channels and heaters [11] – [16] prove that the flow pulsations may significantly impact hydrodynamics and heat transfer.

Therefore, numerical studies were done regarding the impact of the pulsating heat carrier flow, which arrives to the panel heater, on its thermal power, and the impact of thermal power pulsation also on the human comfort level.

The numerical modelling was carried out by the software complex of *SolidWorks* / FlowSimulation CAD / CFD / *HVAC* [17].

Due to complexity of the numerical solution of the task and in order to reduce calculation time, it was decided to use a simplified three-dimensional model of the office room, excluding the impact of furniture.

The accuracy of the solution was evaluated based on the convergence results of thermal power of a *P11* type panel radiator installed in the room model, comparing to the thermal power declared by the producer.

3.2. Maintaining the comfort level of employees in the office building in the energy saving simulation model

Numerical calculation results showed that for the heating stationary mode the thermal power Q_0 of the radiator in the office room is 820 W. This value is by 5 % less than the known full scale technical features of *P11* type radiator, whereas the value is within the limits of the estimated error.

In the case of periodically pulsating fluid in the radiator, its thermal power Q (t) changes in the course of time. Q/Q_0 changes in time t are shown in Fig. 3.1. The interrupted line corresponds to the stationary process with V_0 = 0,4 m/s, the uninterrupted line – to the unstationary heat transfer process. The graph shows that when the heat carrier speed changes in the radiator, the thermal power, in comparison with the stationary mode, may change in average by 10 %, the thermal power both increasing and decreasing.

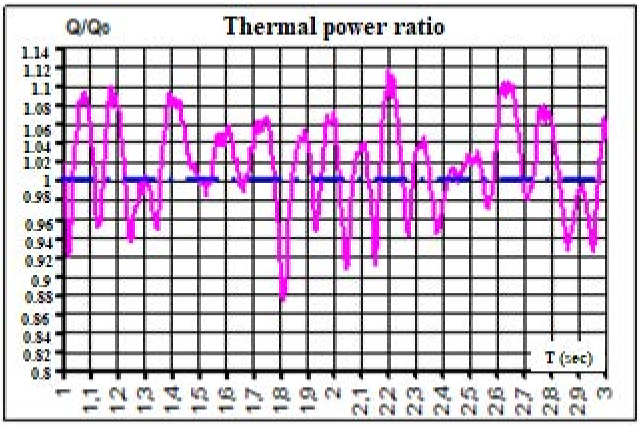

Fig. 3.1. Changes of thermal power ratio Q/Q_0.

The changing temperature in the room has been studied. The temperatures are assumed in the points with the corresponding coordinates in the space – x, y, z. The room under consideration was theoretically divided into three zones: zone 1 – the zone where pipes for heating forward flow and return flow are located; zone 2 – the radiator zone; zone 3 – the zone in which persons are situated, there are no heaters; the top of the wall features an aperture for ventilation.

The estimates showed that in zone 1, in relation to the stationary mode the fluid flow pulsations do not impact the work temperature T °C significantly. Zone 2 is characterised by temperature increase in average by 20 % because pulsating thermal power changes produced by the radiator occur. Compared to the stationary mode, a decrease of the operating temperature by an average of 20–25 % was observed in zones 2 and 3.

The temperature comparison T/T_0 graph is presented in Fig. 3.2. The work temperature T_0 °C refers to the stationary mode and T °C refers to the pulsating flow mode in the radiator. The X axis marks numeration of points which correspond to the coordinates in the space – x, y, z.

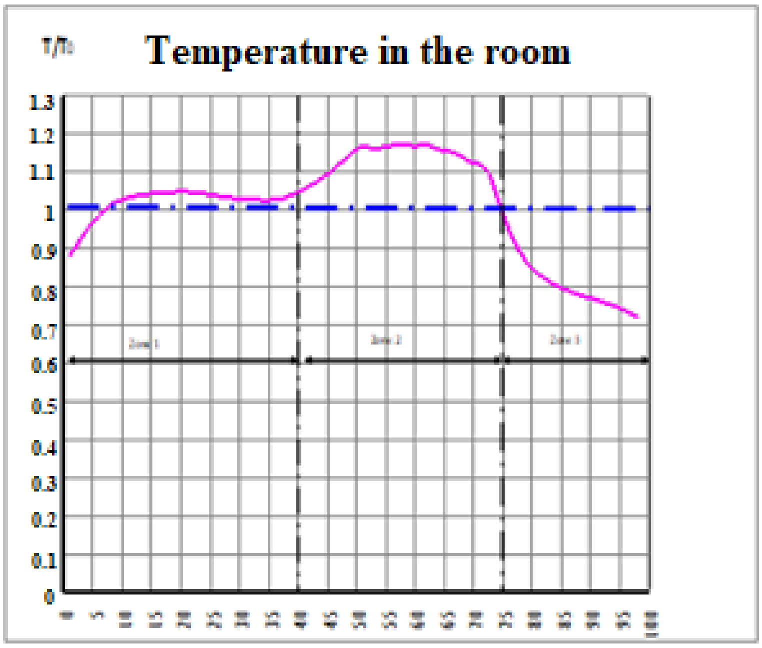

Fig. 3.2. Temperature comparison graph T/T_0.

The model of Prof. Ole Fanger, which is the basis of standard ISO 7730, is applied to the evaluation of comfort conditions. Human wellbeing is determined by the heat balance in the body. In the process of the numerical calculation, the environmental parameters, for instance, the average radiation temperature Tr as well as the temperature Ta, air speed and humidity were determined. It allows to forecast the heat perception by the people in the room – the average valuations forecasted (AVF) by the people in the room. The visualized average valuation forecasted in the room is represented in Fig. 3.3.

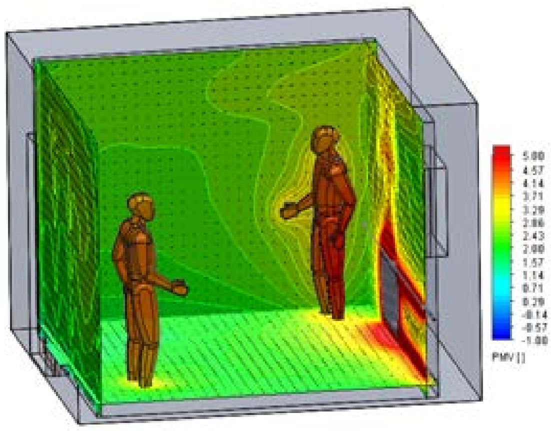

Fig. 3.3. The heat perceptions of the average valuation forecasted.

In Fig. 3.3 the maximum *AVF* value is +5 and it is located outside the calibrated scale from –3 to +3, that is, the human condition at the radiator may be evaluated as “very hot”. For the second person, that is, in the zone between “warm” and “hot”, that is, from +2 to +3.

In case of unstable heat carrier flow regime, the AVF value by the person near the radiators reaches +6. It happens due to increase of the radiator heat dissipation.

CHAPTER 4. MONITORING OF THE ESSENTIAL PARAMETERS OF THE INTERACTION BY THE ENERGY SUPPLY SYSTEMS

4.1. Necessity for smart metering of energy consumption in distribution networks of different energy types

Necessity for the use of smart metering devices for gas consumption in Latvian natural gas market is relevant:

- Requirements regarding implementing smart meter systems are laid down in the directive *2009/73/EK*.
- Requirements of energy efficiency.
- Reduction of unauthorized consumption of natural gas.
- Calculation according to the permitted load included in the draft regarding the distribution system tariff.
- Opening of the Latvian natural gas market [18], [19].

With the opening of the natural gas market in Latvia, it is necessary to provide an operational and accurate information distribution system regarding the volume of natural gas consumed, as well as to carry out forecasting for maintaining the balance of the gas supply system of the natural gas. In several studies [18], [19] it is acknowledged that the smart system with the smart meters improves both data metering and efficiency of the system operation.

4.2. Interaction of the gas and electrical energy markets

European decarbonization scenarios 2030 and 2050 present the analysis of interaction of the gas and electrical energy supply systems [20], [21].

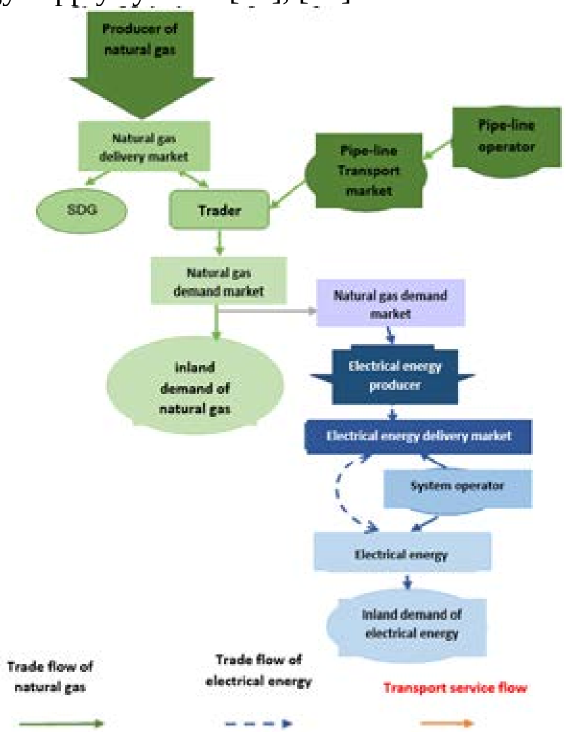

Fig. 4.1. Interaction of the gas and electrical energy markets.

Necessity for in-depth investigation regarding the system interaction was exacerbated by the events of 9 February 2012. At that time the cold wave had impact on France, increasing the demand for electrical energy by 100 GW. Usually, the required extra energy in such cases is ensured by the import from Germany. Taking into account the moratorium of the Germany in relation with the nuclear energy after the Fukushima emergency, the nuclear plants that usually export electrical energy to France were closed, and the load was transferred to the natural gas. However, regarding that the Germany was in lack of natural gas, the export of electrical energy to France was limited.

The interaction model is considered both systems which are connected with the gas-fired power plants. Fig. 4.1 shows the link of the producers, traders, operators of the liquefied natural gas and pipeline operators in the gas market.

All these participants react to the natural gas demand in the market. Increase of the renewable energy production will reduce necessity for natural gas units; nevertheless, the gas stations will be an advantage in order to support production and distribution of the renewable energy.

4.3. Smart metering advantages

Usage of smart meters ensures a number of advantages which may be divided into several groups.

1. According to the technical parameters of the equipment:
   - More precise, dynamic and safer metering of the consumed volume.
   - Effective management of all the group of meters, when receiving the alarm (temperature, manipulations, accumulator, air in the pipe).
   - Remote reading.
   - Option to choose different communication solutions for data transmission (sending information via mobile or radio communications, using optical cables or wireless signal).
2. According to the usage efficiency in the natural gas distribution system:
   - Remote automated data reading saves resources of the system operator, minimizing the physical technical maintenance of the meters (readings, suspension/renewal of the natural gas supply, physical condition verification of the equipment, etc.).
   - Efficient and fast identification of natural gas leakage or other technical problems in the gas pipe-line system.
   - Prevention of possible natural gas stealing, by identifying untypical load that does not correspond to the natural gas consumption profile.
   - Facilitating forecasting of the natural gas consumption for system optimization, obtaining precise data on the used volume as laid down by the Cabinet Regulation No. 78 [22].
   - Improvement of the customer service (adding and analysis of consumption readings, operative control and reading of data).
   - Option to differentiate (segmentation and profiling) customers based on obtained data regarding gas consumption.
   - Option to pay in advance for the natural gas used.
   - Option to remotely and quickly disconnect the natural gas without entering the object as laid down by the Cabinet Regulation No. 78, including the option to suspend the natural gas supply (in case of non-payment) and/or terminate the contract.
   - Option to optimize system servicing in emergency cases, by disconnecting the natural gas supply, as well as to fulfil duties of the system operator to restrict the gas delivery as determined by the Cabinet Regulation No. 312 (19 April 2011) “Procedures for the Supply of Energy Users and Sale of Heating Fuel During Declared Energy Crisis and in

Case of Endangerment to the State".

- Option to obtain precise information on the gas pipe-line system which allows to calculate the loss in detail.
- Option to install smart metering system in the control measurement spots.

3. According to energy efficiency and convenience of use for the end consumers:
   - Obtaining of precise information in electronic format on the natural gas consumed.
   - Obtaining of information on the consumed volume in real time, allowing the customers to change the energy usage scenario and save energy resources.

CHAPTER 5. BALANCING OF LOADS OF THE END CONSUMERS OF THE ENERGY DISTRIBUTION SYSTEMS

The dynamic programming allows to run technological processes if they occur in evenly distributed energy field. However, when selecting the energy consumption field for air processing, it should be taken into account that the energy consumption is determined by the available air processing technologies. Therefore, for the technologies selected in order to design universal management algorithms it is possible to use a tuneable finite automaton synthesis theory [23], [24]. It is possible to programme synthesized algorithms in the design phase based on outdoor air condition diagram on the base of the microprocessor [25].

Overviewing opportunities to implement technological equipment management, several evaluation phases of information aggregation should be carried out.

1. The design of the management system structure in the course of which individual functional blocks and their mutual connections should be created. In the course of the design, it must be based on general programme architecture principles of embedded microprocessors [26], taking into account also recommendations for their verification [27].
2. Selection of microprocessors so that it would be possible to embed them into the developed management system architecture [28], [29].
3. Programming option of the selected microprocessor for work algorithm reprogramming, adopting suitable equipment [30] – [32] and creating interfaces suitable for air processing technology [33], [34].

In order to obtain displacements of the point characterizing the outdoor air condition to the required point of the influx air condition along the trajectory which is beneficial from the energy consumption point of view, it is possible to use the dynamic programming [20], [33]. Then the air processing is considered a deterministic process for resource distribution.

The recurrence function, which describes the condition achieved by the influx air in the considered step, is as follows:

$$F_i\,(I) - \min[g(\Delta 1_i) + f_{i-1}(I_i - \Delta I_i)],\ 0 < \Delta I_i < I_i, \qquad (5.1)$$

where

I_i – i-step enthalpy;

ΔI_i – enthalpy change, implementing the step from i-1 to i;

$f_i(I)$ – function of enthalpy change (the minimum energy consumption, transferring into condition I_i with steps i ΔI_i);

$f_{i-1}(I_i - \Delta I_i)$ – the minimum energy consumption, transferring into condition $I_i - \Delta I_i$ with steps $i-1$;

$g(\Delta I_i)$ – function of energy consumption (the energy consumption – increasing the enthalpy by ΔI_i).

Multi-step process of air processing is presented in Fig. 5.1.

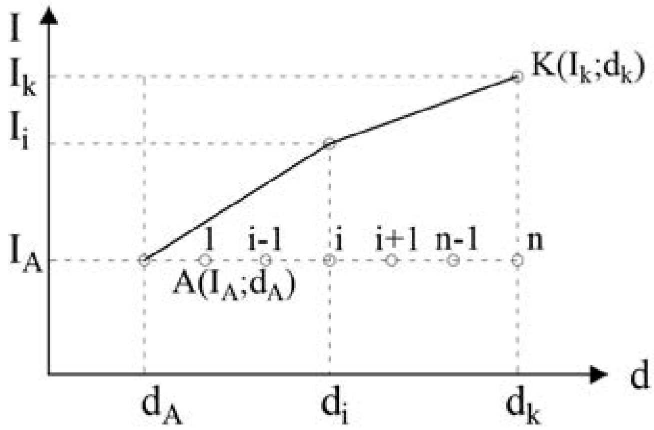

Fig. 5.1. *I-d* representation of air processing procedure, step by step, in the diagram.

5.1. Graph-analytical methodology for ESS balancing management, considering the dynamic loads of the end consumers

The method of the adjustment analysis of the graph-analytic functional units, by arranging the technological parameter-inducing inputs to the final automat in a series of input sizes, permits the resulting binary intercom positions to be described in separate software blocks that can also be implemented on the basis of the micro-circuits.

The above described provides the possibility to create work channels of the functional blocks in form of a separate user interface, visualising, where necessary, the management process in a separate information panel, demonstrating the essential technological zones of the energy distribution system and the parameters of the adjustment circles.

By defining the graph of the set-value change in time, an analytical infographic of the function value estimate may be received, modelling different consumption of energy based on weather forecasts of various timeframes.

The functional blocks are programmed in the format of final automat without memory, providing for each combination of each influx size a definite combination of output sizes. The graphic representation of the management system algorithm of the select air processing technology consists of related functional blocks. A functional block may also carry out a computation of functional relations, for example, by defining the outdoor air condition limit in which it is beneficial to increase the outdoor air volume to be processed. The outdoor air condition zone in which it is beneficial to increase the volume of the processed air (Fig. 5.2) is hatched. Fig. 5.2 presents the air processing technological procedures – recirculation, heating, power, adiabatic humidification and characteristics of the room load. The placement of the line segment A-A is determined by the humidity content behind which the air volume to be processed should be increased.

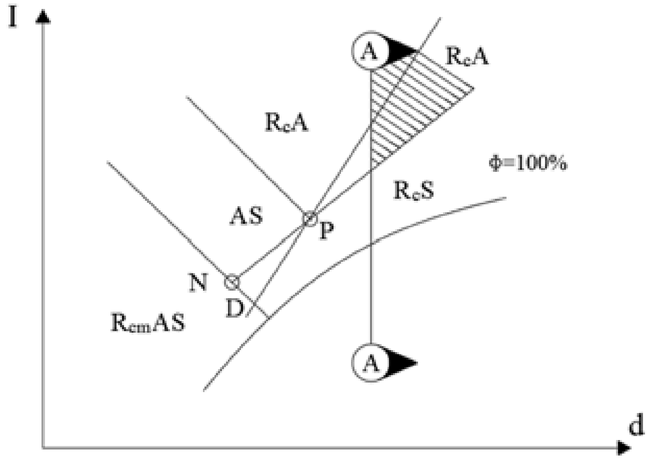

Fig. 5.2. The outdoor air zone in which it is beneficial to increase the volume of the air to be processed.

The developed methodology ensures the following sub-tasks for analysis:

1) the selection of the air processing technology in micro-climate conditioning systems of the end consumer according to the outdoor air condition and additional information on the condition of the equipment in which the air processing is carried out, and the selected technology; on the basis of the obtained information in binary form the final automat without memory executes the management algorithms of the ESS end consumer equipment [22], [36];
2) improvement of adjustment quality in the adjustment circles of technological processes [36];
3) increase of ESS performance by reducing energy consumption in technological processes with additional management software blocks [36];
4) increasing of ESS reactivity by placing sensors of individual parameters directly in the technological process; information from these sensors, handling in the adjusted management software blocks [37];
5) evaluation of the thermodynamic condition of the outdoor air for reducing the processed air [38].

CHAPTER 6. DESIGN OF THE DIGITAL TWIN FOR THE DISTRICT HEATING SUPPLY SYSTEM MANAGEMENT

At the moment many district heating supply systems are classified as the third-generation district heating supply systems in which usually the forward flow and return flow water temperatures are respectively in the range from 80 °C to 110 °C and from 40 °C to 50 °C [39]. In the latest studies [40], [41] it is found that even with relatively low forward flow water temperatures (slightly over 50 °C), it is possible to ensure requirements of the consumers in Central European and Northern European countries.

The difference between the water temperature in forward flow and return flow (ΔT) usually changes during the year. In the research [94] it is established that in Denmark during the heating season there is correlation between ΔT and the air temperature (ΔT). Trends identified in the investigation [37] show that when the T_{out} values increase, ΔT decreases if $T_{\text{out}} < 10\,°\text{C}$. Regarding higher T_{out} values the data are not systematized, they cover wide range of values (from 0 °C to 50 °C), and correlation at temperatures $T_{\text{out}} > 10\,°\text{C}$ does not exist. The operation of district heating supply systems differs in Denmark and Latvia; therefore, it was decided to carry out research with the aim to find out the relation between ΔT and T_{out} in the thermal energy stations in Latvia.

Taking into account the practical aspects of the problem, it would be desirable to determine the statistically significant difference between ΔT and T_{out} during all the heating season. It is possible to clarify this relation by using the equation of regression (correlation):

$$y = f\left(x, a_1, a_2, ..., a_n\right), \tag{6.1}$$

where $f\left(x, a_1, a_2, ..., a_n\right)$ is a function selected by the user, the air temperature T_{out} is the independent variable and the temperature difference between the forward flow and return flow water temperature ΔT is the dependent variable. Coefficients $a_1, a_2, \dots a_n$ are calculated by using the respective optimization model. The most popular method is the least squares method with which the following function is minimized:

$$Q = \sum_{i=1}^{N} \left[y_i - f\left(x_i, a_1, a_2, \ldots, a_n\right) \right]^2, \tag{6.2}$$

where $(x_i, y_i), i = 1,2, \dots, N$ are experimental points. In Equation (6.2) the apparent problem is solved by *Matlab*. Different functions are chosen – $f\left(x, a_1, a_2, ..., a_n\right)$. It is established that for the approximation of the data given in Fig. 6.2 (as well as data of other studies) it is best to use the second-degree polynomial.

$$y = a_0 + a_1 x + a_2 x^2. \tag{6.3}$$

Boiler house "Gobas" with a capacity of 20 MW was built in 1999. It is the automated boiler house; its operation temperature regime is from 70 °C to 115 °C. For thermal energy production mainly, the natural gas is used, but in emergency situations diesel fuel may be also used as a heating fuel. The average thermal energy volume transferred in the network within the five-year period is 20,422.49 MW. The regression analysis for the boiler house "Gobas" is presented in the Fig. 6.1.

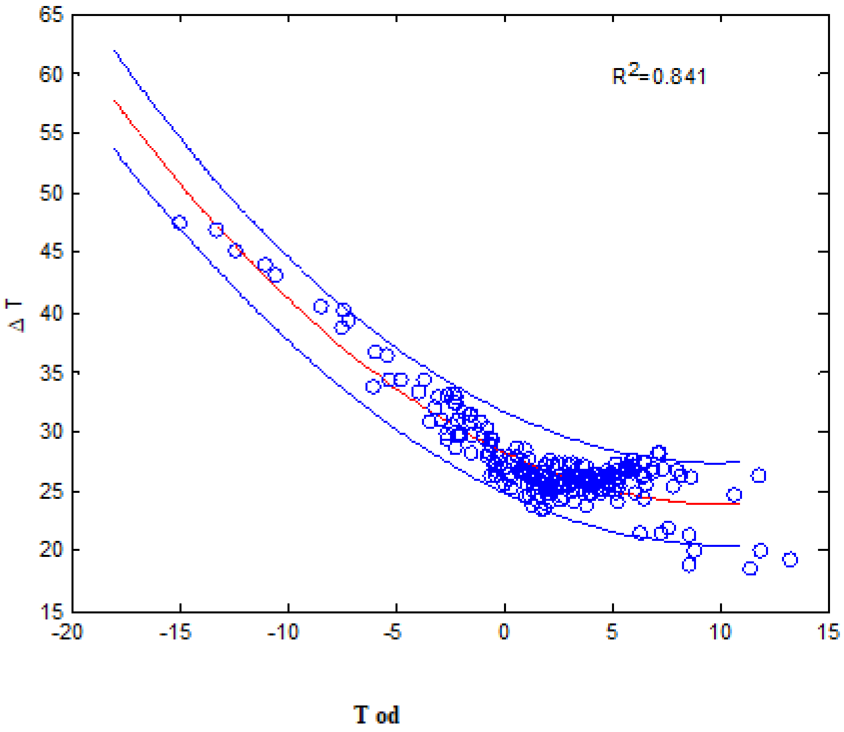

Fig. 6.1 The second-degree polynomial approximation in the thermal energy network during the heating season (the digital twin of the system): in the phase of the acceptable parameter deviations.

In the thermal supply network, the temperature difference in the local system inlet is maintained by the network pump and the pressure difference regulator, whose regulating actuating's are created in the programmable regulator based on the polynomial approximation. Fig. 6.1 shows the second-degree polynomial approximation in the network during the heating season, where the results of the regression analysis provide that the second-degree polynomials approximate the relation better between the temperature difference (ΔT) forward flow/backward flow and outdoor air temperature ($T_{\bar{a}rg}$).

CHAPTER 7. STRATEGY OF CREATING RENEWABLE RESOURCE ENERGY COMMUNITIES WITH RENEWABLE ENERGY ECOLOGICAL TRIGENERATION

7.1. Options to include passive house in the renewable resource energy community (micro-grid)

According to normative requirements for energy management – Energy Law or draft Cabinet Regulations – energy management implementation must be carried out according to *ISO50001:2018* "Energy management systems. Requirements with Guidance for Use". Implementation of the energy management may be carried out in an individual enterprise or administrative territory. The analysis of the data provided by energy management should lead the energy balance towards improving the energy balance of an individual company or administrative territory, achieving in the first phase a zero-energy balance for the minimal energy consumption possible, further, by organising the renewable energy generation, achieving that the energy produced by itself exceeds the energy consumed. Then it is possible to overview usefulness of creating the energy community [40] in order to create a collaborative model with the existing energy distribution networks.

The technical solutions for the energy community (micro-grid) management are presented in several patents that are known to the author, in which:

- with the preferable model of energy consumption, the different regulation strategies and technologies of energy production and transfer are compared [42];
- configuration and parametrization options of energy management systems on the basis of the available energy digital twin set of the end consumer are provided [43];
- thermal supply system with hydraulically separated inner engineering systems of the buildings is described; in the system it is possible to separate the heat carrier in layers in the thermal energy accumulator; the memory device follows the accumulator stratification and conducts the thermal energy supply to consumers from different layers [44];
- there is a local energy distribution for harmonized sharing by bonding and conducting "lack of energy" chains with "energy source" chains, fulfilling the requirements of limiting CO_2 emissions [45];
- Reuse of the thermal energy, energy accumulation and reduction of emissions in places where thermal energy is gained from waste waters of the populated area [42];
- Energy accumulation system for creating several forms of energy for consumption, taking into account that the available energy types should supplement each other [43].

7.2. Conditions for the strategy of the renewable energy micro-grid management

The task of the performance calculator (PC) is to forecast the potential of the thermal heat process, to calculate thermal inertia, and to forecast the operation regime of the equipment. Provided that the sewage temperature drops, its consumption reduces, it is necessary to precisely estimate the thermal potential of the available sewage, thus changing the operation parameters of the equipment.

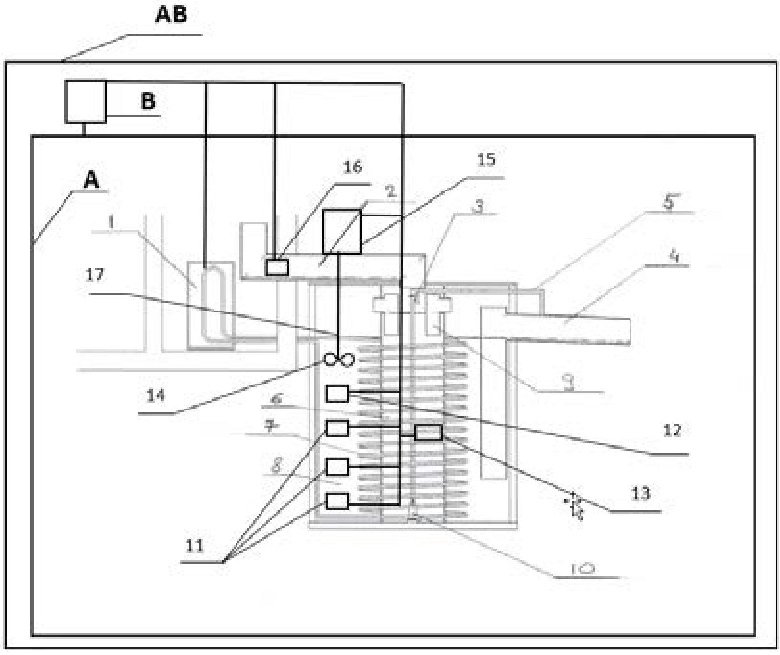

Fig. 7.1. Sewage tank with thermometers placed in three levels.

Fig. 7.1 presents the sewage tank with thermometers placed in three levels so that it is possible to follow the thermal exchange process direction. It changes depending on the operation mode – heating or free cooling. The available thermal potential in the tank always depends on its temperature, flowing in the tank, in which according to the estimate it is expected that the outflowing sewage temperature must not be lower than laid down in the Cabinet Regulation No. 34 "Regulations Regarding Discharge of Polluting Substances into Water". The PC calculator must warn for decreasing thermal potential, adapting the equipment operation to the reduced power mode. Power reduction is necessary only in such cases when according to the analysis of the parameters the increase of the thermal potential is not forecasted, with the condition that the thermal potential decrease is temporary when the necessary thermal reserves in the accumulation tank are being used. Depending on the thermal volume demanded from the heat pump, it is necessary to calculate the volume of the inflowing waste water. The PC makes an estimate for the inflowing waste water changes in order to forecast the possible changes in consumption within one hour. In order to determine the waste water volume which flows into the tank, an electricity meter will be installed on the supply pump. Dividing the consumption in one hour with the power, the pump output may be determined and, consequently, the waste water volume in m^3 pumped in the tank.

If the condition is satisfied that the instantaneous power is less than the thermal potential in the tank, calculating it per volume of the waste water and the inflow temperature to the cooling limit of +7 °C, the output of the circulation pump of the heat carrier remains unchanged in the volume of the heat required by the building. If the thermal potential in the tank is sufficient, whereas the heat consumption of the building increases, the flow valve opens to the additional heat exchanger circle, thus increasing the heating surface area which allows transferring larger volume of energy. If the instantaneous heating power of the building exceeds the thermal reserve calculated for the tank, taking into account the variable amount of the sewage input, the calculator, according to the thermal potential calculation, reduces the flow of the heat carrier through the circuit of the sewage heat exchanger in the sewage tank.

PC calculation depends on the forward flow temperature of the heat carrier. The higher the sewage temperature, the higher the thermal potential and sewage cooling reserve to the specified +7 °C. The lowest temperature of the heat carrier must be forecasted so that the tank is not cooled under the set values. It means that when the temperature at the tank inlet is dropping, the curve of the circulation pump flow-through will be reduced until an appropriate flow-through rate is adjusted, which may ensure the set temperature schedule with a temperature difference between the forward flow and the return flow of 4 °C, provided that the outlet temperature from the heat pump of the heat carrier is not lower than +4 °C.

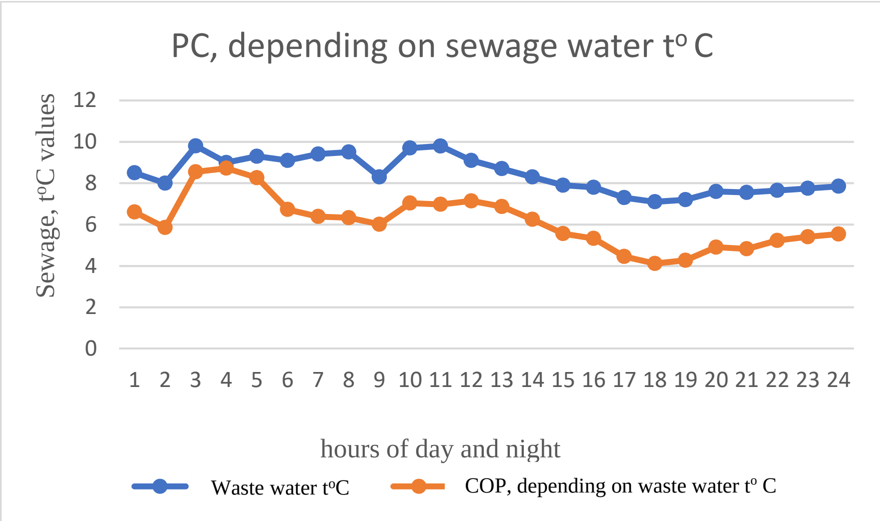

Fig. 7.2. Sewage temperature impact on COP values.

Fig.7.2 shows that due to the volume and temperature of the sewage intake, the curve of PC values changes.

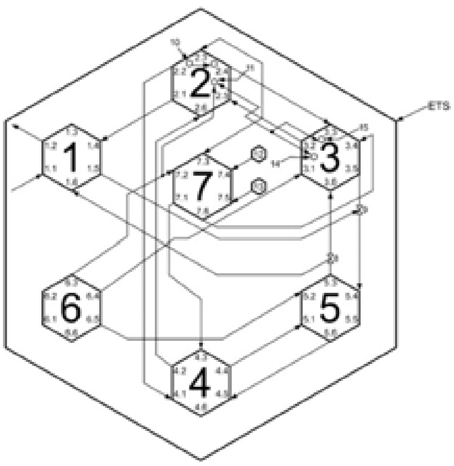

Fig. 7.3. The ecological trigeneration connection diagram.

The ecological trigeneration system (ETS) includes:
1) sewage system energy transformation equipment for cooling of the passive houses included in the energy community (micro-grid);
2) the end consumer of the thermal energy in the energy community (micro-grid) – a passive house;
3) the cooling system of the passive house;
4) thermal energy storage (accumulator);
5) heat pump;

6) electrical energy generation system of PV panels with DC/AC inverter.

The first inlet of ETS is connected to the urban sewerage network, the second inlet – to the sewerage system outlet of the end consumer network (passive house) (2) of the energy community (micro-grid) and the facilities in which the inlet is connected to the mixer valve at the thermal circle of the heat pump (5). The sewage system, the first outlet of the energy transformation equipment is connected to the urban sewerage network, while the second outlet connects to the first inlet of the cooling system (3) of the end consumer (passive building) (2). The first outlet (4) of the end consumer (passive building) (2) is connected to the second inlet of the energy transformation plant (1) of the sewage system, the second outlet is connected to the second inlet of the cooling system (3), while the outlet (3) is connected to the first inlet of the heat accumulator (4). The first inlet of the end consumer (passive building) (2) is connected to the first inlet of the room cooling system (3), while the second outlet is connected to the first inlet of the system (4).

The second inlet of the room cooling system (3) is connected to the electrical energy generation system of PV panels with DC/AC inverter (6) for the first outlet. The first outlet of the heat storage (accumulator) is connected to the third inlet of the end consumer (passive building), the second outlet is connected to the second inlet of the heat pump (5). The heat pump (5) circle is connected in its second outlet to the second inlet of the heat storage (accumulator) (4) and the heat pump (5), while the second outlet (4) of the heat storage (accumulator) is connected to the third inlet of the heat pump (5) (i.e., to the heat network) (evaporation), in the circle inlet. The second outlet of the electric energy generation system of the PV panel system with DC/AC inverters is connected to the central inlet of the heat pump (5) (to the compressor engine).

The known ecological trigeneration system in the energy community (micro-grid) with a passive consumer of energy (Patent application: LVP2020000045 16.06.2020; F24D 11/00; F25B 27/00 "Equipment and method to increase efficiency of sewerage water recuperation system") is supplemented with electrical energy generation system of PV panels in which DC/AC inverter is included, in order to execute power supply to the engineering system network of the energy community (micro-grid). However, the volume of the generated electrical energy is determined by the sun radiation intensity which is changing during the 24 h of the day (Fig. 2). Such day and night distribution of solar energy does not let the available solar energy potential to be used fully, in the evening hours when there is still OCB working time in the passive building, the electrical energy generated by the PV is insufficient to operate the OCB engineering systems. An indoor air quality and outdoor temperature correlation block (7) is added to the ecological trigeneration system in order to achieve better use of the solar power potential. This block performs adjustment of settings for the indoor air quality, mainly indoor air temperature, when the outdoor temperature changes.

The indoor air quality (IAQ) and the outdoor temperature correlation block inlet (4) is connected to the electric energy generation system of the PV panels and the outlet to the inlet fan of the ventilation system. The rotation speed control unit performs a correlation of IGK and outdoor temperature according to the recommendations of ANSI/ASHRAE Standard 55 "Thermal environmental conditions for human occupancy."

7.3. The control strategies in the renewable energy community (micro-grid) with ecological trigeneration

Looking at the perspectives of application of the energy control methods and techniques in the renewable energy community (micro-grid) with ecological trigeneration, it may be concluded that the local management system with an embedded microprocessor is the most appropriate for this sphere and data volume.

Analysing the application areas of microprocessors [40] it is concluded that “the most visible use of microprocessors is alternating current in the electric powered drive with minimum number and dimensions of the reactive elements, as well as high conversion quality”. This statement has also been confirmed in further practical investigations [42], [43]. These findings are also supported by guidelines recommended in the fields of heating (including also heat supply), cooling, freezing and air conditioning [44], which help engineers to understand the individual system regulators included in the system, the system equipment and their linkage for designed system performance. The working sequence is important for regulators operating in the network in order to ensure smooth network operation [45]. An overview of the challenges today in home information systems is presented in the interview with Chris Benson, Chairman of ASHRAE Technical Committee 1.4 Control Theory and Application [46]. In the mentioned sources it is concluded that the usage options of microprocessors in the renewable energy resource micro-grid require an additional assessment based on the current rules and the technological process managed in the micro-grid.

In the renewable energy micro-grid, the heat for heating and hot water needs in the building is provided by means of a thermal recovery system of waste waters. Indoor cooling is provided from the waste water in the free cooling mode. The electrical energy providing the technology of these processes is generated from the sun, the author of the Doctoral Thesis has named this concept as ecological trigeneration or eco-trigeneration.

Fig. 7.4 illustrates the waste water consumption of an existing building (which is converted [..] into a recoverable thermal unit), the expected cooling demand, the demand for hot water for the building and the benefit from the electrical power generated by 30 m^2 of solar panels. Fig. 7.4 shows the interaction of the energy demand for the building in July. Solar radiation in summer covers a great share of the electrical energy demand for the building. This means that by regrouping resource usage habits in the course of the day it is possible to provide the building with a low-cost renewable energy.

It is possible to provide thermal energy for preparing hot water in the morning time with the waste water thermal recovery equipment, provided that the waste water in the tank contains a sufficient volume of heat that has not been consumed in the previous evening. Solar radiation is sufficient from 4:00 am – 9:00 am in order to satisfy hot water heat demand for the operation of the heat pump and the circulation pumps. If the waste water potential in the waste water tank from the waste waters generated by the building is insufficient, it is possible to supply the waste water from the urban network in order to compensate the lack of energy. At 9:00 am – 12:00 am when occupants of the building go to work, waste water consumption is declining (hence the need for hot water), but demand for indoor cooling is increasing at this point. Indoor cooling initially shall be provided by the B side of the heat pump, to an extent that covers the hot water demand. As the solar activity increases, cooling capacity is growing, the thermal energy output by the heat pump is increasing accordingly on the A side. It is not economically justified to place large thermal accumulators in the building, therefore, at 12:00 am – 4:00 pm indoor cooling should be provided in the free cooling mode, including from the urban waste water network, because the demand for hot water in the building is low, consequently, there is no need to operate the heat pump, so that there is no waste of accumulated thermal energy, which has no economic justification. From 4:00 pm – 8:00 pm demand for hot water in the building increases, respectively, the heat pump works preparing hot water and transmitting A side heating energy in the accumulator of the building and B side ensures cooling of the building indoor (if there is a lack of thermal and cooling power, waste water is supplied from urban networks for energy compensation). In such operating mode the waste water is not cooled in the storage tank, allowing the waste water thermal resource to be used at the end of the day from 8:00 pm to 12:00 pm after the solar radiation when it serves to prepare the hot water. This is a way how to produce the energy required for the building during summer period in the ecological trigeneration cycle.

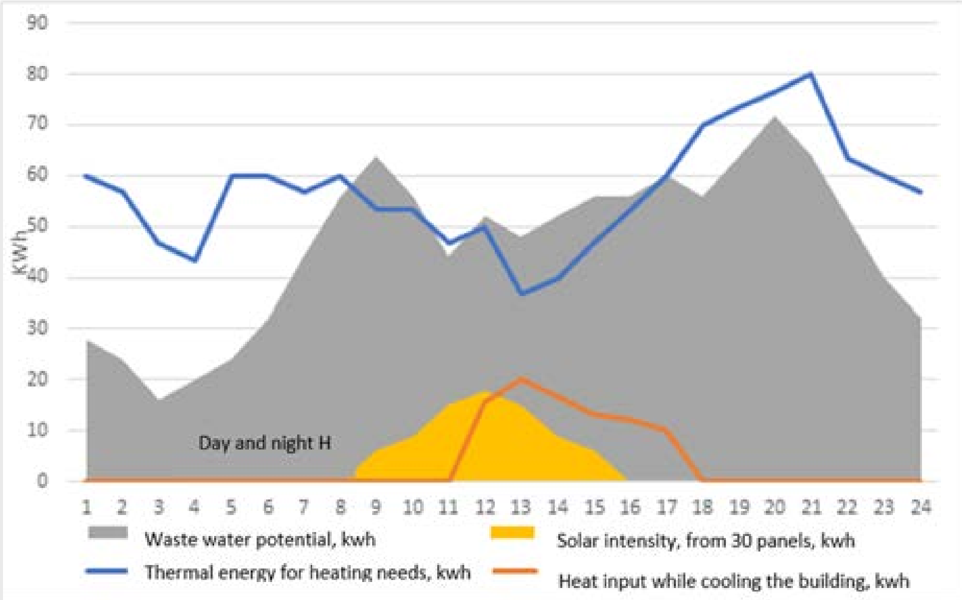

Fig. 7.4. The expected energy consumption in the building in summer.

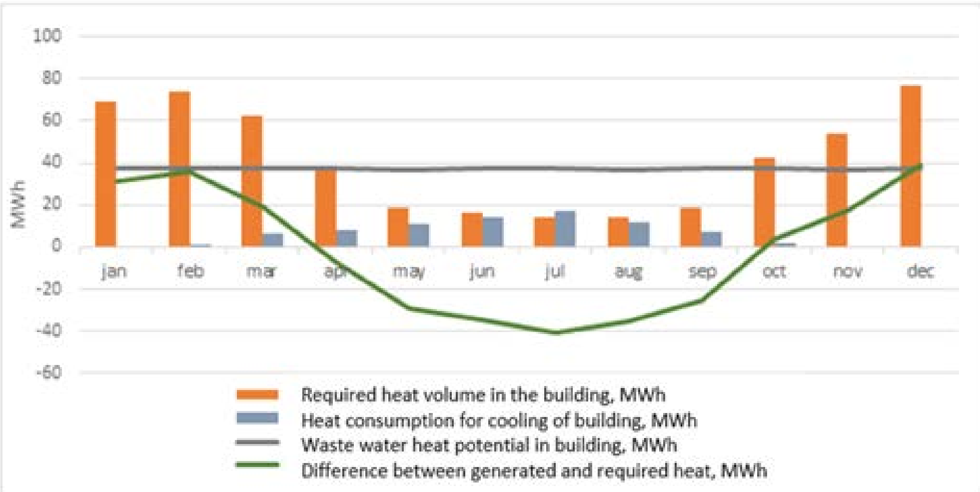

Fig. 7.5. The expected energy consumption in the building in a year.

Fig. 7.5 does not include a solar activity energy curve, but it still reflects the amount of energy produced and demanded in the building. A complex of ecological trigeneration equipment would make it possible to reduce energy costs and CO_2 emissions.

CONCLUSIONS

1. Safe, affordable for the consumers, environmentally friendly, sustainable and consistent energy supply of cities, populated areas, buildings and industrial objects is only possible from different types of energy distribution networks concurrently.
2. The energy efficiency and the performance of management dynamics of each individual energy distribution network are determined by a combination of performance in its individual stages.
3. In order to achieve high efficiency of the interaction between energy distribution networks and the energy communities (micro-grids), the degree of openness of each individual system and community to the interaction is significant so that the load of the end consumers of the energy is reduced.
4. The model 6R2C created based on ISO 13790:2008, Energy Performance of Buildings provides the closest match with real measurements for cooling the rooms of the end consumers.
5. In order to create microclimate in the room of the end consumers, creation of concurrent and consistent air distribution and intensification of heat exchange processes are essential.
6. For mixed energy supply, energy consumption metering is important with the exchange of information between the producer and the consumer in continuous duplex mode, i.e., smart metering.
7. The designed graph analytics method for analysis of the air-processing technology carries out investigation of operations according to ISO-OSI layer 6 of Open Systems Interconnection.
8. For the verification of a digital district heating twin, the main criterion is 1 °C decrease in the return flow temperature in energy units and costs.
9. In energy communities (micro-grids), the passive buildings should be included in order to increase the energy rationality of these communities.
10. The assessment of usage of the ecological trigeneration should be limited by the overheating permitted for passive building.

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