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DOCTORAL THESIS

Summary

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OPTIMIZATION OF TRIGENERATION SYSTEMS WITH RECIPROCATING INTERNAL COMBUSTION ENGINES AS PRIME MOVERS, WITH APPLICABILITY ON DIFFERENT TYPES OF BUILDINGS IN BUCHAREST

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1 INTRODUCTION

This doctoral thesis is structured in six chapters and has three major objectives: analysis of the operation of energy production systems through the trigeneration technology with reciprocating internal combustion engines (RICE), study the applicability of these systems on buildings with different energy needs and bringing of new contributions to optimizing the operation of these systems.

The bibliographic study in order to carry out the scientific research project proposed in the thesis included a number of 107 scientific papers (articles, case studies, courses) completed in the first year of the doctoral cycle. Some of these papers dealt with topics that although did not cover exactly the scope of the proposed topic (example: co / tri generation with turbines, Rankine cycle analysis, statistical works on algorithms, some optimization models, economic criteria for evaluating co / tri generation, specific technologies for refrigeration) helped to understand the field and to outline the approach to the topic.

In the first chapter of the thesis, after an overview of the classical systems of thermal and electrical energy production and modern cogeneration and trigeneration systems, a comparison is made of the efficiencies offered by the literature between these different types of technologies. Also in this chapter are presented various trigeneration systems configured by researchers and consumption prediction profiles. The field of research is identified and the research method is established during the thesis.

In the second chapter of the thesis are enunciated the general equations that lead the processes within a trigeneration plant and the particular equations that led to the construction of hourly energy profiles for a residential consumer - block of flats. It is proposed the mathematical model for simulating 3 modes of operation of RICE-s in a cogeneration system based on the variation of thermal efficiency with partial load (PL) of engines. The mode of commissioning of the prime movers within the proposed system is analyzed.

Chapter 3 - Experimental study - took place at the cogeneration plant which distributes thermal and electric energy in the urban network of Buzău. The information in the database, statistically processed, made it possible to determine an equation of linear variation of the overall efficiency of the part-load system. Following the analysis of the efficiency values obtained from the simulation of the operation with the mathematical model from the previous chapter, in the considered optimal operating mode, comparisons were made and conclusions were issued regarding: real plant efficiencies (10 years old), specified efficiencies in the literature and the yields given by equipment manufacturers in the data sheets.

In order to study the applicability of trigeneration systems with RICE-s on buildings with different energy needs, it was necessary to build with the greatest possible accuracy the energy profiles of consumption for the 4 distinct categories of consumer, proposed. A bottom-up calculation algorithm from consumer to producer was approached. **Chapter 4** proposes a diagram of a trigeneration system with reciprocating internal combustion engines and absorption chiller with H_2O-LiBr solution in which are highlighted: the area of energy produced by cogeneration, the area of energy supplied and the residential consumption energy area. Hourly energy profiles are built for the average day of each calendar month, profiles named after the 3 mentioned areas of the trigeneration system, respectively:

- consumption energy profiles;
- provided energy profiles;
- produced energy profiles.

Hourly profiles of heat type thermal consumption for domestic hot water (DHW) preparation, heating, ventilation by air heating, hourly profiles of cold type thermal consumption for air conditioning and ventilation by cooling were built and presented graphically for the block of flats. air and hourly profiles of electricity consumption for utilities: DHW, heating, ventilation, air conditioning, lighting and household appliances.

Following the sizing according to the thermal requirement, motors of 4 different nominal capacities were chosen and the overall yields were calculated in each case with the linear equation determined following the experimental study.

Chapter 5 analyzes the adaptability of the proposed trigeneration system to different categories of consumers by extending the energy profiles built in Chapter 4 to 3 other types of consumer buildings and after improving the prediction equation in Chapter 3 of the variation of overall efficiency with partial operating load. The same hourly energy profiles were built following the algorithm from the residential consumer condominium type but applying the particularities of each consumer to an office building, a hospital building and a commercial space. Chapter 5 presents comparative graphical analyzes between the hourly energy profiles of the 4 types of consumers. The maximum energy consumptions on each utility of the 4 categories of consuming buildings are compared.

The research was completed with the optimal selection of the number of heat engines and the rated heat of the engine for a trigeneration system in the conditions of strong variation of energy consumption from one category of consumer to another. The final subchapter 5.6 presents a method for optimizing the choice of the number of heat engines required for each type of consumer and the optimum rated thermal load of the engine, in sizing conditions according to the heat demand.

At the end of the thesis, **chapter 6**, the conclusions are presented, the main personal contributions made and some aspects regarding the practical applicability of the research carried out are mentioned. From the research perspective, one can consider the analysis of systems with thermal engines in different climatic zones, the study of state-of-the-art thermal equipment or the influence of two- or three-stage absorption installations in combination with internal combustion heat engines.

1.1 COMPARISON BETWEEN ENERGY GENERATING SYSTEMS

In the field of energy generating systems, trigeneration technology is a step forward in cogeneration, referring to the simultaneous generation of electricity, useful heat and cooling from a single fuel source [1]. The possibilities of configuring a trigeneration system are practically unlimited, the complexity of such systems resulting precisely from the multitude of production equipment, heat transfer and recovery equipment. The practical advantage of a trigeneration system over a cogeneration system is that it can provide a utility for thermal energy in the form of heat, produced during the cooling season - summer, energy that from residual heat, most often dissipated in the atmosphere , becomes useful heat in the generator of the refrigeration machine with absorption and ensures the air conditioning of the spaces. The heat in the trigeneration systems is recovered from the primary source: engine, turbine, steam generator, heat pump or boiler, with the help of exchanger type equipment, heat recuperators. The boilers are also used as peak sources to cover the peak loads of the consumer. The refrigeration equipment for air conditioning is: refrigeration machines with compressor, absorption refrigeration machines, heat pumps, air conditioners (split or multisplit type).

This thesis will focus on trigeneration systems that have as primary source the thermal engine with internal combustion, in Otto cycle, powered by natural gas and as a source of cold production the refrigeration system with absorption with LiBr-H2O solution.

If in the case of separate generation systems by classical methods the overall efficiency of separate production of heat and electricity is, according to the literature, approx. 58% [2], in the case of cogeneration the overall efficiency reaches approx. 85% [2]. In the case of trigeneration, the overall efficiency reaches, according to the literature, 87 ÷ 90% [3] by using heat, mainly from flue gases, in absorption chillers.

Table 1.1 presents some of the commonly used energy generating systems, the efficiencies achieved and the types of energy they provide.

Table 1.1 Efficiencies and energies provided by generating systems

Generator System	CCA Conventional steam power plant	ITG gas turbine plant	STAG combined cycle steam	CCA gas with supercritical parameters	CT fuel gas	CT lichid combustibil	CT fuel solid	CT low pressure steam	CT medium steam pressure	CT condensing gas	COGENERATION	TRIGENERATION
η_{el}	35,3%	39,3%	58%	48,3%							30%	35%
η_{th}					90%	89%	80%	90,5%	91%	94%	55%	55%
η_{global}											85%	90%
Electric	✔	✔	✔	✔							✔	✔
Heat					✔	✔	✔	✔	✔	✔	✔	✔
Cooling												✔

Regarding the efficiencies of cogeneration systems with internal combustion engines, they record values of electrical efficiencies that tend to 45% and of thermal efficiencies that can reach 48% [4].

BIBLIOGRAPHY STUDIED

In the field of configuration of trigeneration systems, A. Piacentino et al. [1], in April 2015, studies 3 configurations: 1 - internal combustion engine with a one-stage absorption chiller and a storage tank, 2 - internal combustion engine with a 2-stage absorption chiller plus electric chiller and a storage tank, 3 - gas turbine (or micro gas turbine) with a two-stage absorption chiller plus electric chiller and a pressurized superheated water storage tank.

Viknesh Andiappan and Denny K.S. Ng [5], in April 2016, makes an analytical scheme for determining the type and size of equipment needed for the trigeneration system, able to indicate the active and stand-by units within the plant.

KF Fong and CK Lee [6] in December 2014, analyze the energy performance of 3 types of heat engines in the trigeneration plant: diesel engine, natural gas engine and gasoline engine, compared to the conventional chilled water cooling system .

Mahesh N. Shelar et al. [7], 2015, realizes the energetic and exergetic analysis of a trigeneration system with diesel engine and absorption chiller in two systems: 1. the heat from the engine cooling water circuit is transmitted to the absorption chiller in one stage and the heat from the gases combustion is transmitted to the chiller with 2-stage absorption; 2. The heat from the engine cooling water circuit together with the heat from the flue gas circuit are transmitted through the heat recuperator in a single chiller with one-stage absorption.

Regarding the reciprocating internal combustion engine, Sepehr Sanaye et al. [8], in August 2007, I analyze 3 types of cogeneration systems having as primary source gas turbine, diesel heat engine and natural gas heat engine. The authors elaborate several mathematical relations regarding the thermal efficiency (in the case of the naturally powered engine and the one powered by the turbocharger), the mass flow of fuel, the energy recovered from the cooling water for the engines and the enthalpy of the flue gases. One of these mathematical relationships and the experimental findings of researchers on the margin of deviation from that relationship, as well as the correlation with the specifications given in the data sheets of engine manufacturers by rated power, is the basis for starting and developing thermal engine efficiency. operating at partial load, presented in ch. 2.2.3 of the thesis - Operating modes of heat engines.

Denilson Boschiero do Espirito Santo [9] and Xiling Zhao et al. [10], both in February 2014, analyze the annual energy and exergetic efficiency of trigeneration systems with internal combustion engines in connection with absorption chiller and absorption heat pump.

Regarding the cold production equipment, Pedro A. Rodriguez-Aumente et al. [11], in November 2011, are concerned about providing the necessary cold for a large office complex (50,000 sq m) in Madrid in the face of the major imbalance between summer and winter load.

Valerie Eveloy et al. [12], in February 2014, develops the idea of cooling with compressed air absorption chillers introduced into the combustion chambers of gas turbines used in the extraction of liquefied natural gas in the Middle East.

Mahesh Shelar and G. N. Kulkarni [13], in November 2015, make a comparison between two diesel engine trigeneration systems, the first with an absorption chiller and an auxiliary boiler and the second with an additional vapor compression chiller.

The optimization of trigeneration systems, within the studied scientific papers, is achieved simply objective or multi-objective and aims to meet certain energy performance criteria or economic criteria.

Hoseyn Sayyaadi [14], in October 2008, performs multi-objective optimization of a cogeneration system with genetic evolutionary algorithms and finds the optimal set of Pareto solutions (80/20) to fulfill 3 objective functions: exergetic efficiency, total cost rate and objective called "thermoenvironmental" - the impact on the environment.

M. A. Lozano et al. [15], in September 2009, presents a model that allows to determine the optimal mode of operation corresponding to obtaining the minimum cost (in € / kWh) of the final products of a simple trigeneration system - natural gas internal combustion engine, auxiliary boiler, chiller with one-stage absorption, electric chiller (with mechanical vapor compression).

Liwei Ju et al. [16], in June 2016, performs the multi-objective optimization of a hybrid system with renewable energies controlled by an automation system (DERs CCHP distributed energy resources).

1.2 CONSUMPTION PROFILES IN THE RESEARCH LITERATURE

Regarding the consumer, the calculation of the annual primary energy consumption of the building is performed using the calculation relations from the Romanian methodology Mc 001/2006 - Methodology for calculating the energy performance of buildings. Apart from the Romanian methodology Mc 001/2006, there are various methods in the scientific articles in the literature for predicting the annual energy consumption of buildings. These methods use simple mathematical algorithms to solve the nonlinearity of energy consumption data for large data sets [17], [18], [19] or hybrid mathematical algorithms for predicting the results of nonlinear statistical problems, for modeling complex relationships between inputs and outputs, or for managing large data sets [20], [21].

The “bottom-up” or consumer-to-source approach technique requires a multitude of parameters and input values. The model must be calibrated with measured data and systematic errors may occur when calculating for a large group of buildings [22], [23]. The "interior point method" is used in reference [19] to make a model for predicting indoor temperature and energy consumed at time "t + d" versus time "t".

Another method used in predicting the annual need for heating and cooling is the "degree-days method". The “degree-days method” also refers to Mc 001/2006 which describes a graphical method for determining the heating period using the “equilibrium temperature”, ie the outside temperature for which the inputs used equal the heat losses of the building. The calculation methodology recommends, in case the climatic data are not available, the use of the values indicated in the SR 4839 standard, referring to “Number of degrees-days” [23]. "Thermo-electric analogy" uses for the prediction of energy consumption to the consumer balance relations in temperature nodes based on the electrical-thermal similarity. The electric intensity is similar to the thermal flux, the electric sources are similar to the inputs, the electric capacitors are similar to the thermal capacities, the electric resistances are similar to the thermal resistances and in the nodes of the electric network we can imagine the temperatures.) [24].

The consumer profile is built and classified in the scientific literature based on the purpose of using energy in the consumption profile for heating, ventilation, air conditioning, a.c.m. and electric.

The analyzes are conducted by types of consumer: residential (single-family, multi-family type houses, blocks of flats), services (offices, schools, hospitals, commercial spaces), industrial (technological), etc.

Another type of classification is made by the amount of annual energy consumed [25] (eg up to 200 MWh / year of electricity), by operating scenarios [26] (operation of a data center) or by the time of predominant consumption recorded [27] (day, morning, afternoon).

Consumer behavior towards the use of energy was the criterion for establishing consumption profiles in the reference [28] (profiles called: “family”, “conscious”, “technician”, “comfort”), and in the reference [29] it even refers to a psycho-social profile related to the consumer's attitude towards energy efficiency. In references [30], [23], [31] and [32] the consumption profiles are established according to the consumer's location (in the street canyon / autonomous house; in different climatic zones on the territory of a state or in isolated areas, near the border) .

There are also in the literature classifications of consumption profiles according to energy supplier [33] (city heating network supplier, electricity network supplier, hydraulic energy at the place of consumption), depending on the percentage of use of consuming equipment [26] (use of servers 25%, 50%, 75% and 100%), depending on the operating regime of the installations [34], [35], [31], [36], (continuous / intermittent, working day / weekend, winter vacation / summer season) or according to the legal regime of the user [37] (public buildings; domestic / non-domestic in ANRE regulations).

What does not exist in the research literature or is difficult to meet is a complex "tool" that integrates all types of energy consumption customized to several categories of consumers. There are no studies on how to transfer this energy consumption from the final consumer to the basic source of a trigeneration system. The profiles encountered are generally small-scale or do not combine absolutely all types of utilities, being rather specialized on one or two of them, or treat a certain type of buildings without reaching the diversity of consuming building typologies. The development of such complete and complex profiles is a difficult and cumbersome task that is done by in situ measurements, by applying calculation methodologies or by accessing databases when consumption bills are available. The range of energy profile characteristics depends on a multitude of factors such as outdoor climatic conditions, indoor comfort conditions, consumer behavior, building envelope, installation systems and technologies used in the production of utilities, etc. The elaboration with the highest possible accuracy of some energy consumption profiles for the different types of consumers is very useful for the energy suppliers at the consumption forecast in the served area. Consumption energy profiles help investors when deciding to implement a trigeneration system. Also, the correct knowledge of consumption profiles, both in terms of quantity and proportions between the two energy requirements: thermal and electrical, is useful when sizing and choosing the equipment of the basic source and other components of the system.

The experimental study took place in two stages.

The first stage took place at the trigeneration plant that serves the headquarters of an economic operator. In this stage, a visualization and understanding of the operation of a trigeneration system was made, with the particularities of the thermal engines and of the other component equipments within the power plant. Important information and clarifications were obtained from the specialized personnel who manage the operation of the plant.

The second stage took place at the cogeneration plant of an economic operator that serves the heat supply network of a city in Romania, with 129,368 inhabitants. In this location, after viewing and understanding the objective, the operating scheme and the information received from the system operator, the values recorded in the daily database for 2012 were obtained and analyzed.

The purpose of the experimental study was to simulate the operation and to experimentally deduce the operating efficiency of a co / trigeneration system. The thermal, electrical and global yields deduced will prove to be different from the values indicated in the catalogs and data sheets and slightly different from the values indicated in the literature (in descending order).

Modeling the functioning of the system was the next step in the experimental study. We first developed a numerical model based on the equation of thermal efficiency at partial load of Sanaye S. et al. [8], on the equation of variation of the efficiency of the ASHRAE electric generator, 2008 [38] and on the method of calculating the energy requirements and the efficiencies of cogeneration systems from SR EN 15316 [39]. The numerical model was built to establish the optimal mode of operation of the heat engines within the plant, according to the indications of the operators in the two experimental stages. The operating mode 3 for the engines was indicated as optimal, respectively "simultaneous" operation at the same loading loads without the intervention of the boiler.

This first mathematical model was calibrated by applying values from the database (metered values) and improved by statistical analysis methods. Finally, a linear variation equation was developed that determines the overall efficiency characteristic of the system depending on the partial or nominal operating mode of the base source motors. In an attempt to improve the global yield prediction model and observing the exponential character of the equations issued by other researchers, the second exponential equation was obtained from the values of the point cloud modeled from the experimental data.

The analysis of the coupled consumer-production system operation could be done by studying in depth the consumption demand, respectively the energy consumption profiles.

Hourly energy profiles built on the basis of hourly average outdoor temperatures for Bucharest and on the basis of the specifications in the technical regulations (manuals, norms, methodologies) for a residential building, was the next important step in finding answers to questions asked at the beginning of the research. Hourly thermal and cold consumption in the form of heat and hourly electricity consumption for consumer utilities were determined. The calculation, called by some researchers "bottom-up", continued with the elaboration of hourly energy profiles of the energies supplied between the production system - the trigeneration plant - and the consumer, after which it was driven in the plant to the basic source - the heat engine internal combustion. The energy profiles that arrived at the source in the plant were called energy profiles produced in cogeneration mode. The calculation was made following the thermal requirement, the electrical requirement being ensured as a consequence of the sizing according to the thermal requirement, according to the indications in the technical data sheet of the chosen engine manufacturer.

The adaptability analysis consisted in building hourly energy profiles for 3 other types of different consumer buildings: offices, hospital and shopping complex. The calculation algorithm was followed from the residential consumer but with the application of the particularities of each type of consumer (flows, specific temperatures, number of people, operating hours, dimensional characteristics of buildings, different factors and coefficients mentioned by the calculation methodology, etc.). . Graphic comparisons and tabular comparisons were made between the 4 types of consumers. Conclusions were issued and recommendations were deduced regarding the adaptation of the trigeneration technology with internal combustion heat engines and absorption chillers to the 4 types of consumers studied.

The optimal selection aimed at maximizing the functions of the overall efficiency of the system following the criterion of selection of basic source equipment in terms of:

- the optimal nominal thermal load for the energy profile produced in cogeneration regime;
- the optimal number of heat engines to meet the profile of energy produced in cogeneration.

The objective function established was to maximize the overall efficiency of the system in the conditions of a variable thermal load to the consumer.

2 MODELING

The modeling of the processes that take place in a trigeneration system involves two aspects: the modeling of the production system and the modeling of the consumer.

2.1 SCHEME OF THE TRIGENERATION SYSTEM

In **Fig. 2.1** is presented the scheme of a trigeneration system with 3 internal combustion thermal engines provided with electricity generation modules (G1, G2, G3). The peak source (or additional heat generator), used to meet the load peaks, consists of two boilers (Cz1, Cz2). The fuel for the boilers and for the combustion chambers of RICE-s is natural gas. Heat recovery from the internal combustion engine is done with the help of plate heat exchangers mounted on two circuits: the cooling water circuit of the engine housing, with a temperature regime of 90 ÷ 80 ° C and the flue gas circuit, with a regime of temperature 560 ÷ 120 ° C.

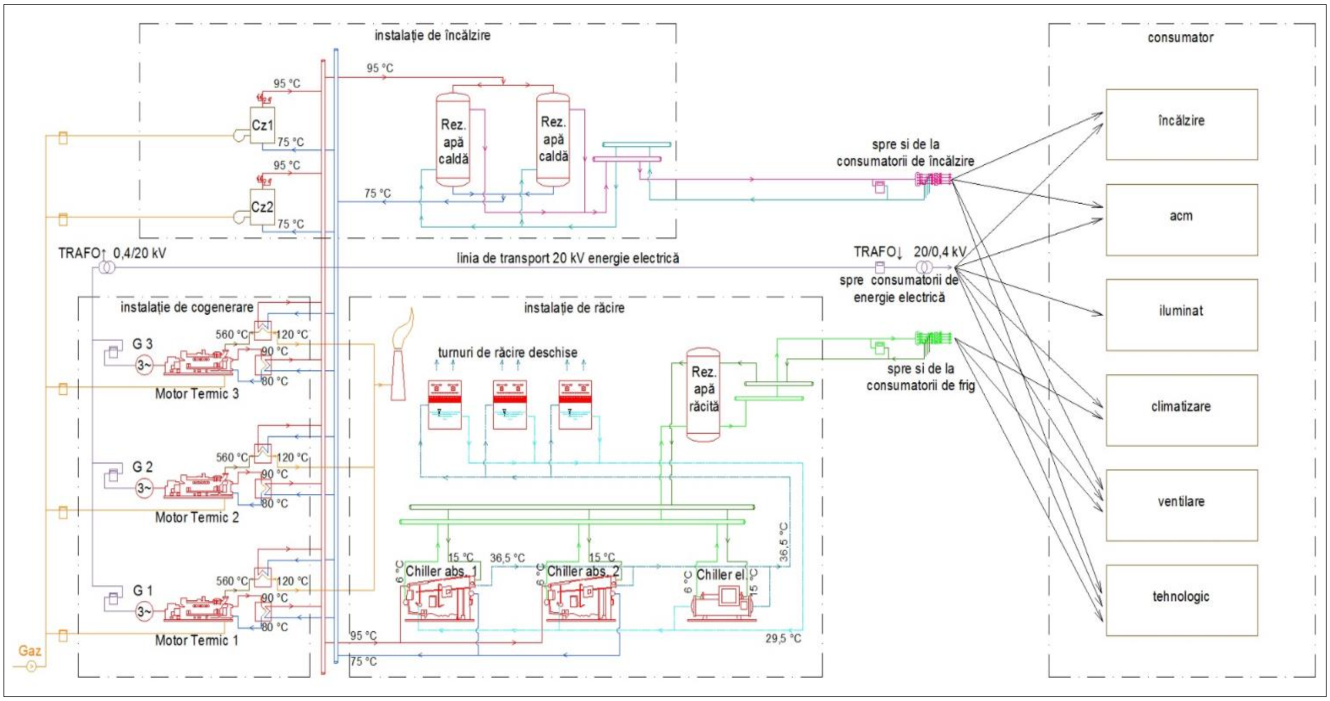

Fig. 2.1. General scheme of a trigeneration system with RICE-s and absorption chillers

2.2 MODELING OF THE PRODUCTION SYSTEM

Chapter 2.2.2 presents, for a general cogeneration system and for a trigeneration system, the contour energy balance equations, known from the literature. Also in chapter 2.2.2 are presented the balance equations of energy flows for: the heat engine, the electric generator, the heat boiler, the plate heat exchanger, the hot / cold water storage tank and the absorption chiller.

Internal combustion engines have the great advantage that they can operate at partial loads that can drop to 50% of their rated capacity, without significantly affecting their efficiency. At loads below 50% of rated capacity, heat engine manufacturers recommend stopping the engine for efficiency reasons and replacing it with a lower capacity heat boiler or other power source. In order to study the flexibility of this efficient technology, starting from the ways of starting the engines and aiming to obtain the maximum overall efficiency (thermal + electric), a simple cogeneration scheme with 5 internal combustion thermal engines is proposed, Fig. 2.2 [40].

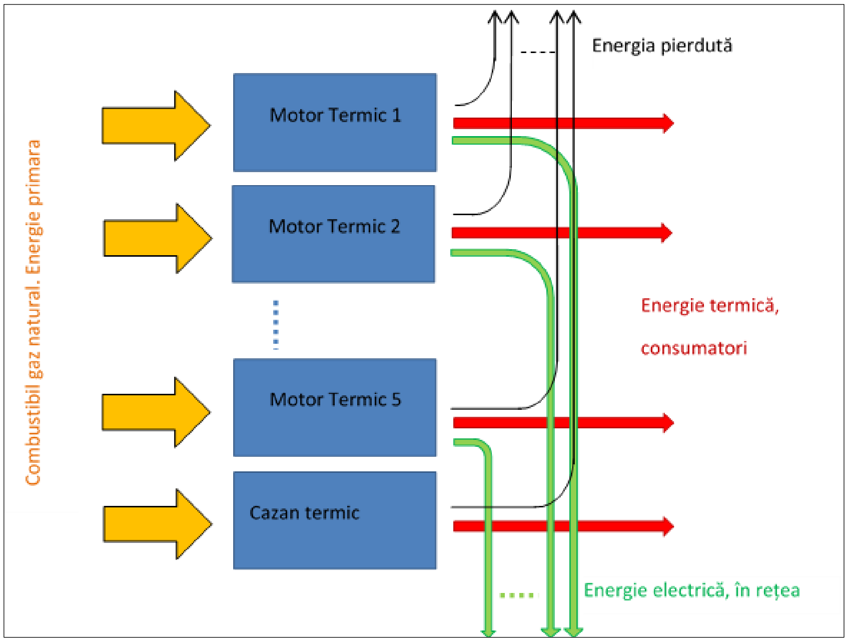

Fig. 2.2. Scheme of energy flows in a cogeneration plant (source G. Mărcuș et al. [40])

There are several possible modes of operation of heat engines within a cogeneration / trigeneration system. From these operating possibilities, 3 modes of operation were chosen and analyzed in the research, [40] for the cogeneration plant shown schematically in **Fig. 2.2**:

- **mode 1** of operation, in which the thermal engines M1, M2, M3, M4, M5 come into operation in a **cascade**, consecutively and each motor continues to operate at its nominal load, 100%, once this nominal load is reached. The boiler takes over the load sequences after the capacity of 100% of the previous engine is exceeded until the minimum requirement of 50% for the next engine scheduled to start is met;
- **mode 2** of operation, in which the heat engines come into operation **alternately** together with the heat boiler equalizing the load between them, at each new input of an engine; practically at the moment of entering the second motor, both M1 and M2 will start operating at 75% partial load;
- **mode 3** of operation, in which the heat engines operate **simultaneously**, equally dividing any value of the heat load exceeding 50% of the nominal capacity of the engine, without the need for the intervention of the heat boiler; practically after M1 reaches 100% and the consumer would require a consumption equal to 1.01 of the rated load, both M1 and M2 engines will start operating at 50.5% partial load. The boiler is used only at very low loads (less than 50% of engine capacity) and at peak loads exceeding the total capacities of the 5 engines.

Equations for the calculation of the partial operating load have been established for the 3 operating modes. The equations for determining the partial load of the boiler in modes 1, 2 and 3 were also determined.

The thermal efficiency of engine "i" is calculated with the equation Sanaye S. et al. [8] on the variation of thermal efficiency at partial load. The efficiency of the electric generator is calculated with the equation ASHRAE, 2008 [38] regarding the variation of the efficiency of the electric generator with partial load. The useful electric power is calculated with the linear interpolation method from the methodology for calculating the energy requirements and system efficiencies of SR EN 15316 [39].

The analysis was performed on 5 MWM TCG 2020 type engines, powered by natural gas, with a nominal thermal capacity of 1675 kW, with a nominal thermal efficiency of 45.7%, according to the manufacturer's data sheet. The rated electrical power of the motor is 1500 kW, with a nominal electrical efficiency of 40.9%. The overall efficiency of the MWM TCG 2020 engine (electric + thermal) is 86.6%.

Conclusions:

1. Regarding the total thermal efficiency of the engines considered without the peak source, the simultaneous operation mode 3 offers the maximum total thermal efficiency, 45.79%, operating at partial loads between 85.77% and 91.47%, over several intervals load versus module 1 or wider load ranges than module 2 [40];
2. The overall efficiency (electric + thermal) of cogeneration, considered without the range of loads in which only the peak load operates and no electric power is generated, records values between 82.08% and 88.19% for cascade and alternating operating modes (mode 1 and mode 2) and between 82.08% and 87.14% for simultaneous operating mode (mode 3) with better start-up efficiencies for mode 2 [40];
3. La o analiză mai atentă modul de operare simultană (mod 3) oferă un avantaj suplimentar prin cantitatea de energie electrică utilă furnizată. Dacă, de exemplu, în modurile cascadă și alternant (mod 1 și mod 2) la o sarcină egală ca valoare cu de 1,4 ori capacitatea nominală a motorului se generează o putere electrică utilă dată doar de primul motor funcționând la sarcina nominală (100%, restul de 0,4 din sarcină fiind preluată de cazanul termic), adică 1500 kW electrici, în modul 3 se vor genera 2100 kW electrici utili, furnizați de motoarele primul și al 2-lea funcționînd fiecare la sarcini parțiale de 70%, [40].

2.3 MODELING OF THE CONSUMER

Compiling consumption profiles for 4 different types of consumers in Bucharest, dividing consumption by categories of energy consumed (thermal, electrical, refrigeration) and transmitting energy to the source, sizing a trigeneration system according to thermal needs and analyzing the adaptability of these types of systems technological were the main concerns of the research thesis.

In calculating the primary energy consumption of the building, the calculation equations from the methodology in force were used, Mc 001 / 2-2006 - Methodology for calculating the energy performance of buildings, Part II - Energy performance of buildings in buildings [41].

Chapter 2.3.1 presents the general equations for calculating energy consumption for satisfying the utilities in the consumer building, according to the Mc 001 methodology, respectively for calculating the following consumptions:

- Consumption of thermal energy for the preparation of domestic hot water (a.c.m.);
- Consumption of electricity required for circulation pumps in the a.c.m preparation plant;
- Consumption of thermal energy for heating the building;
- Consumption of electricity for the distribution in the building of the heating agent;
- Consumption of electricity for lighting;
- Consumption of thermal energy for air conditioning of building spaces;
- Electricity consumption for air circulation in the air conditioning system;
- Electricity consumption for air circulation in the ventilation installation;
- Consumption of thermal energy necessary for heating the ventilated air, in winter;
- Consumption of thermal energy required to cool the ventilated air, in summer.

3 EXPERIMENT

3.1 DESCRIPTION OF THE COGENERATION SYSTEM

The scientific research process within the doctoral thesis continued in January 2018 with the experimental part carried out at the cogeneration plant of an economic operator in Buzau. The cogeneration system of the economic operator supplies the city network with thermal agent for heating and for the preparation of domestic hot water and electricity. The system was put into operation in June 2008. The functional scheme comprising the main equipments of the cogeneration system in Buzău is presented in **Fig. 3.1.**

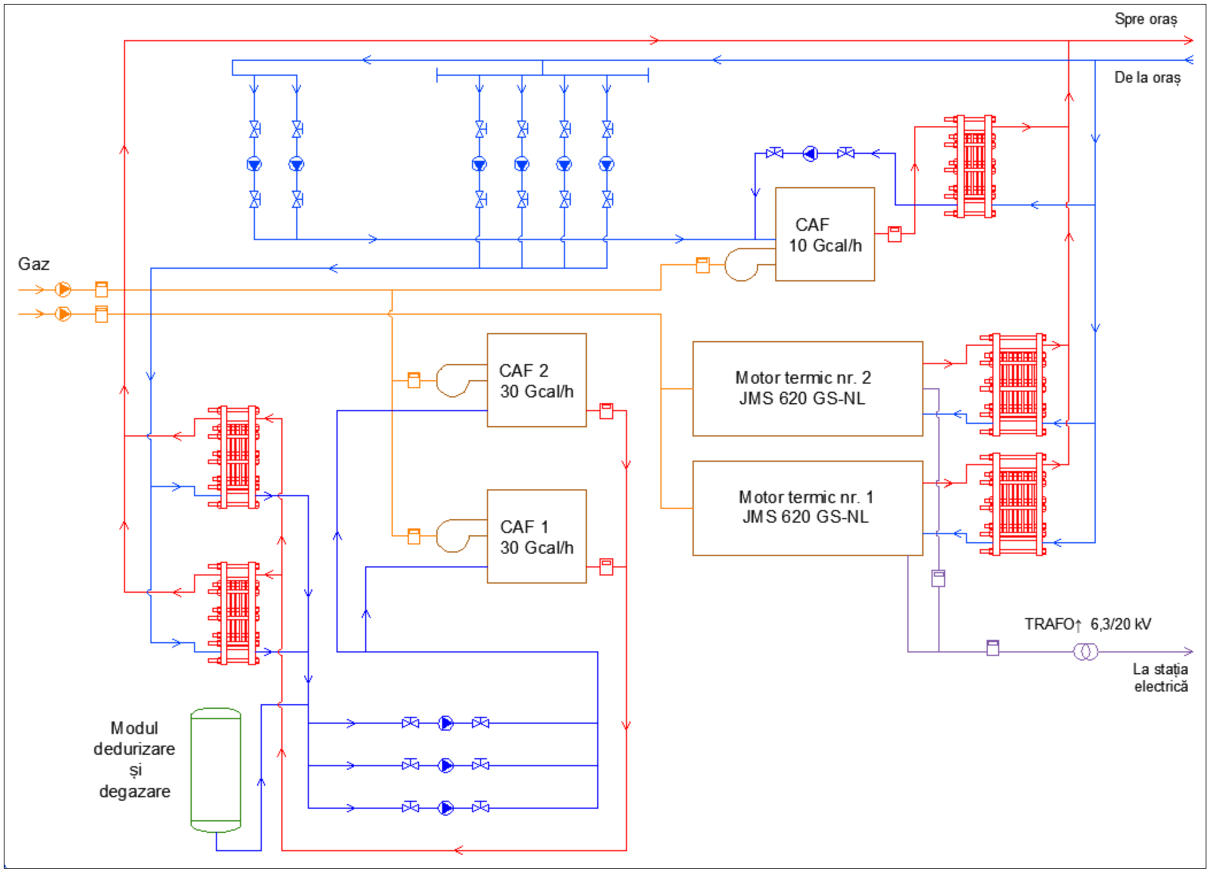

Fig. 3.1. Scheme of the Buzau cogeneration system

The cogeneration system is composed of:

- two reciprocating internal combustion engines;
- two electric generators;
- 5 plate heat exchangers;
- two boilers (CAF-s).

3.2 DATABASE PROCESSING

During the experiment, the access to the database of the cogeneration system from Buzău was received and we received the information and data necessary for the continuation of the scientific research. Two types of data were procured: monthly statements for 6 years, 2012 ÷ 2017 and daily statements for the entire year 2012.

The daily situations from 2012, used in the thesis, include the daily operating hours of each of the 2 engines, the daily quantities of natural gas in m3 consumed by the system, the daily quantities and hours of electricity in MWh produced by each electric generator, the daily quantities of thermal energy in MWh produced cumulatively by the 2 engines and the overall efficiencies of the system.

The numerical model configured in the paper [40] in mode 3 of **simultaneous** operation at the same loading loads without the intervention of the thermal boiler, is applied to the engines in the Buzau cogeneration system. The model uses the daily time step during 2012. From the Buzau database were taken the metered data for: the cumulative thermal energy production of the two engines (M1 and M2) in MWh / day and the daily operating hours of each engine, the individual electricity production of each motor in MWh / day and the overall daily efficiency. In simultaneous operation, at the same partial load, M1 and M2 share the hourly heat output equally during the day's operating hours. When dividing the thermal energy production, we introduced the condition of not exceeding the nominal thermal power of the motor from the technical data sheet - 3070 kW. It is observed that in the months of Oct., Nov. and dec. the thermal boiler (CAF) also comes into operation to ensure the peak heat demand requested by consumers. For each engine was calculated, after dividing the thermal output, the partial operating load (PL), the individual thermal efficiency at partial load and the individual electrical efficiency at partial load, the useful energies: thermal, electrical, total. The numerical model also calculated the energy lost by the system and the fuel energy of the cogeneration system. Finally, the total thermal efficiency and the overall efficiency (thermal + electrical) of the system were calculated, called **modeled efficiencies**. Database efficiency (BDBs) are also called **real efficiencies**.

LINEAR VARIATION OF EFFICIENCIES

With the help of the "trendline" function, Excel, the curves closest to the values representing the point cloud of the daily efficiencies (thermal, electrical or global) defined for the different partial operating tasks of the cogeneration system were drawn. Thus, the tendency of the set of values of thermal, electrical or global efficiency in the case of increasing the loading load (partial) of internal combustion heat engines was observed.

Calculation hypothesis

The partial daily operating load of the cogeneration plant, PLCOG (2MT + CAF) was calculated, assuming an optimal sizing of the plant, ie it was assumed that the nominal daily thermal load of the plant (at 100% capacity) is equal to the sum of the nominal thermal powers of the 2 engines during a day (24 hours) plus the power of a thermal boiler that should cover ½ the load of an engine, 1,535 MW, (the real power plant has, in an oversized way, two 35 MW CAFs).

The variations of **the modeled thermal efficiency**, **the modeled electrical efficiency** and **the global modeled efficiency** (thermal + electric) were represented graphically depending on the partial operating load of the cogeneration system. The trendline of the point cloud was drawn and the linear equations of the regression lines for each graphical variation resulted.

In **Fig. 3.2** is the graph of variation of the global modeled efficiency of the cogeneration plant depending on the partial operating load of the cogeneration system. The trend line of the point cloud was drawn and the linear equation of the regression line, equation 3.1, resulted.

$$\eta_{gl} = 0,1553 \cdot PL_{COG} + 0,6708 \qquad (-) \qquad 3.1$$

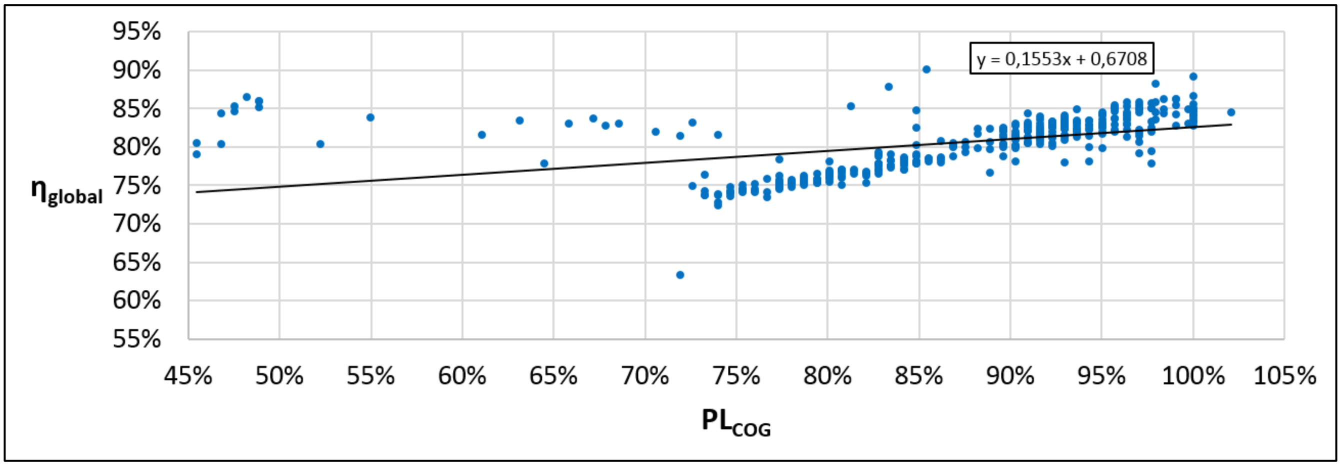

Fig. 3.2. The daily variation of the global modeled efficiency with the partial load of the system

For the purpose of processing in the direction of a distribution of the point cloud as close as possible to the normal distribution, the points that appeared dispersed were removed 'manually' from the value graph of the modeled thermal efficiency (the red dots were called 'thermal outliers values', 'electrical outliers values' and 'global outliers values') and the new graphs of the remaining values were drawn. The linear equations of the regression lines for the modeled thermal efficiency, without 'thermal outliers values', the modeled electrical efficiency without 'electrical outliers values' and the modeled global efficiency without 'global outliers values', were determined.

Fig. 3.3 presents the graph of the partial load variation of the modeled global efficiency from which the 'global outliers values' were removed.

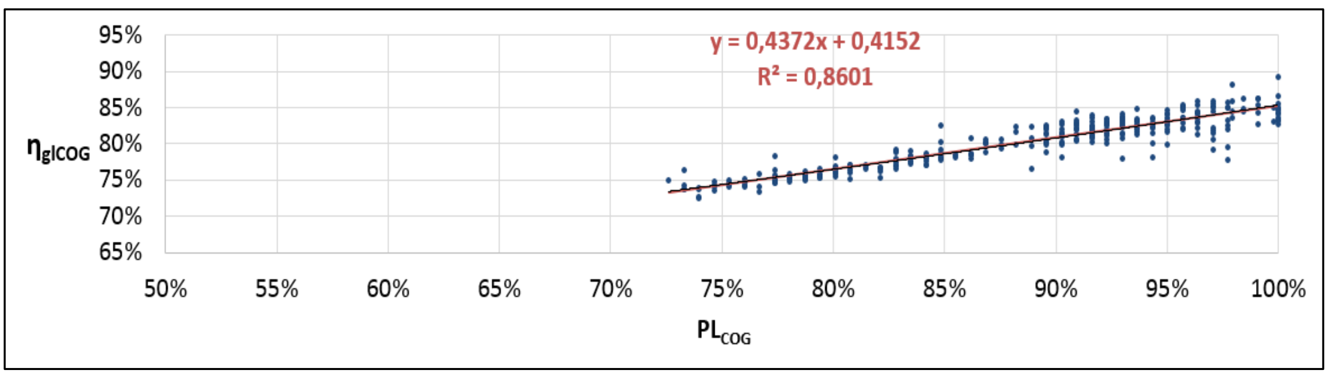

Fig. 3.3. Variation of modeled global efficiency without 'global outliers values' with partial load

The equation of the variation of the modeled global efficiency without 'global outliers values' depending on the partial load is:

$$\eta_{glCOG} = 0{,}4372 \cdot PL_{COG} + 0{,}4152 \qquad (\text{-}) \qquad 3.2$$

EXPONENTIAL VARIATION OF EFFICIENCIES

The equation obtained in ch. 3.2.2 of the thesis represents a linear variation of the efficiency with the partial load. During the bibliographic study it was found in the work of Sepehr Sanaye et al. [8], the equation describing the variation of the thermal efficiency at partial load as a function of the nominal thermal efficiency and of the partial load. The equation is applicable to supercharged (turbo) engines with rated loads between 50 and 6000 kW. The authors note that the equation showed a deviation of up to 10% from the experimentally values obtained from databases. It was observed that the respective equation is of exponential type, with the variable partial load (PL) at the exponent of the power of the number 'e'. In an attempt to improve the statistical prediction model, the possibility of obtaining also an exponential equation with the values of point cloud representing the modeled global efficiency was investigated, after eliminating the 'global outliers values'. A second equation was built with the Excel solver:

$$\eta_{glCOG} = 0{,}4926 \cdot e^{0{,}5498 \cdot PL_{COG}} \qquad (-) \qquad 3.3$$

The graph in **Fig. 3.4** presents the daily variation of the modeled global efficiency with the partial load of the system of two RICE-s, with the trend line in the case of the exponential variation.

Equation 3.3 has a slightly improved coefficient of determination, R2 = 0.8642 compared to that of the linear equation, R2 = 0.8601. 86.42% of the values of the partial load, PLCOG, determine the values of the global efficiency, ηglCOG. The forecast of the global yield value chain improves slightly in the sense of approximating the predicted values to the modeled values. The proximity of the modeled values from both directions is observed, ie when the values of the first equation are lower than the values of the modeled yield, the value obtained with the 2nd equation (exponential type) is higher / closer (ex: first day value) and when the values of the first equation are higher than the values of the modeled yield the value obtained with the 2nd equation is smaller / closer (ex: last day value, maximum value).

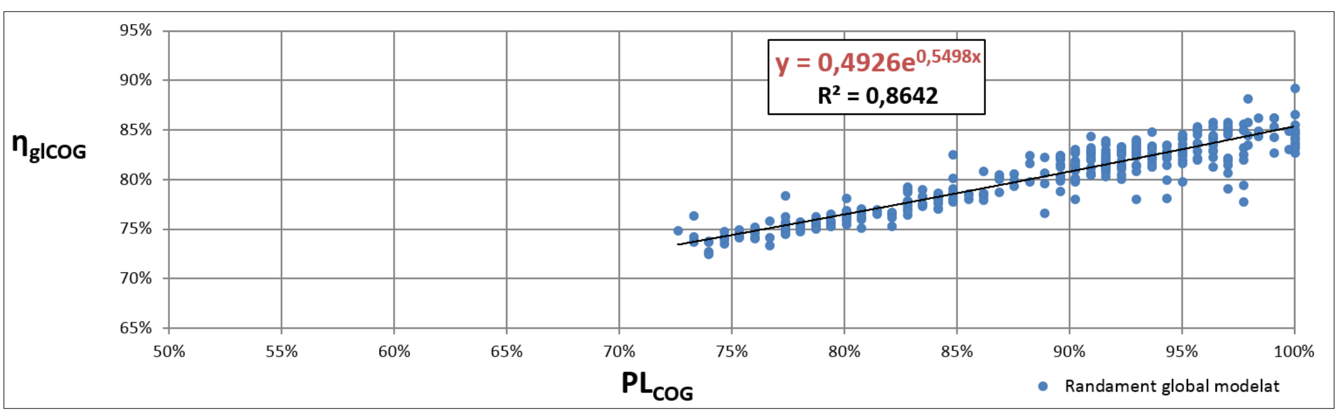

Fig. 3.4. The exponential variation of the modeled global efficiency with the partial load

3.3 COMPARISON OF THE EXPERIMENTAL EFFICIENCIES WITH THE EFFICIENCIES MENTIONED IN THE LITERATURE

Next, the variation of the daily global efficiency from the Buzau database, η_{BDB}, (also called real efficiency) was compared with the modeled global efficiency, $\eta_{gl}COG$, by multiple regression (modeled efficiency). The comparative graph between the values of the modeled global efficiency and the values of the global efficiency from the Buzau database is presented in **Fig. 3.5**.

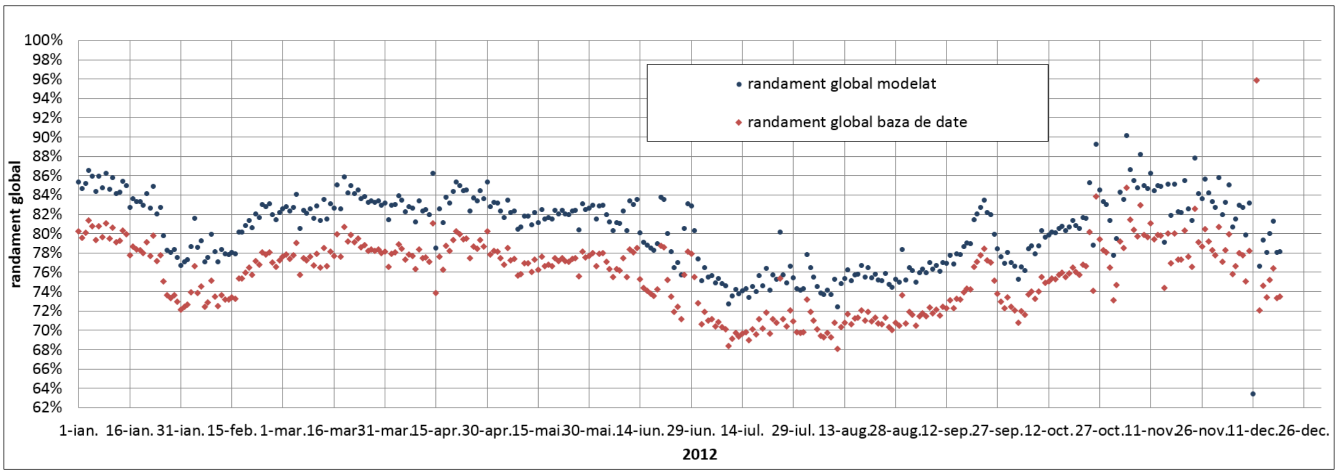

Fig. 3.5. Comparative variation between daily modeled global efficiency vs. experiment

It was observed that, in general, the modeled global yield characteristic faithfully follows the path of the global yield characteristic from the database but with uniform variation and **higher values by 4.34 ÷ 5.40%.**

3.4 SYSTEM MODELING CONCLUSIONS

The numerical model built within the analysis of the yields of the cogeneration system having as primary source the internal combustion engines required the taking into account of several possibilities of engine operation, which appeared progressively in discussion during the study. Several lines of calculations and tests resulted, some resulting in incorrect results that had to be corrected. Although the model does not deal in detail with the aspects related to the electric efficiency of heat engines (the second component of the overall efficiency) it had to be improved by applying linear interpolation in the method of calculating the electric useful power, as stipulated in EN 15316 [39].

In the case of aspects related to the efficiency of thermal boilers, research was done on the technical data provided by 7 manufacturers of such equipment which dismantled the erroneous perception that the efficiency of boilers would increase with the load. In the technical data provided at different loads (partial loads), generally between 40% and 100%, the efficiency values of the boilers are higher at the lower load. The maximum efficiency of a thermal equipment does not automatically equate to its operation at rated load. It was observed that in the case of internal combustion heat engines this is obtained at a partial load (PL) located around the range of 85% ÷ 91%. The graphical analyzes and the study of the obtained results led to the conclusion that mode 3 of operation - simultaneous operation of the motors at the same loading loads, without the intervention of the boiler - is the most advantageous mode of operation, with high values of global efficiency over longer intervals. load and with higher electrical production, decisive in the case of pursuing an important electrical requirement along with the thermal one.

This mode 3 of operation was applied to the cogeneration plant in Buzau and to the database collected from the economic operator. The comparison between the overall yields obtained in the model and the overall yields resulting from field measurements and metering led to a graphical analysis, to the obtaining of the equations of variation of yields and to a series of important conclusions presented in the article [42]. An analysis of the behavior of the overall efficiency in the conditions of the variation of the parameters of the absorption cooling installation was carried out in the article [43]. It was observed that, in general, the global yield characteristic of the model follows the route of the global field yield characteristic but with uniform variation and higher values by 4.34 ÷ 5.40%. The analysis of the values of global efficiency and thermal energy delivered to the consumer resulted in a less efficient behavior during the summer months compared to the winter period. This is a strong argument in favor of implementing trigeneration technology.

The numerical model built to analyze the yields of the cogeneration system is a preferable method to use approximate values or estimated values. The mathematical model will be extended, improved and calibrated on a trigeneration system, in the following chapters, after which the optimization possibilities for 4 different types of consumer buildings in Bucharest will be finally analyzed.

4 ANALYSIS OF THE OPERATION OF THE TRIGENERATION SYSTEM

4.1 RESIDENTIAL CONSUMER

The analyzed block of flats is located in Cernauti Street no. 50, pp. D8, sc. 1, Sect. 2, Bucharest. The block of flats is a building with a height of Ug + Gf + 4F, having a regular shape in plan, consisting of a single section of staircase, separated by a seismic joint from the neighboring staircase. The staircase section has a length of 27.00 m and a width of 16.00 m. The block of flats has a number of 19 apartments, these being considered medium conventional apartments (apmc), with an area of 60 m2 and a number of 2, 8 people per apartment.

I. CONSUMPTION ENERGY PROFILES

For the residential type consumer, the daily hourly consumption profiles (thermal and electric) for the average day of each month by utilities were identified:

1) consumption profile a.c.m. thermal - represents the hourly thermal energy consumption for domestic water heating;

2) consumption profile a.c.m. electric - represents the hourly electricity consumption necessary for the circulation pumps from the a.c.m distribution installation;

3) thermal heating consumption profile - represents the hourly thermal energy consumption for space heating;

4) electric heating consumption profile - represents the hourly electricity consumption necessary for the circulation pumps in the heating installation;

5) electricity consumption profile for lighting and appliances;

6) profile of thermal consumption for air conditioning, for cooling the spaces of the residential type of consumer;

7) profile of electricity consumption air conditioning - represents the hourly electricity consumption for air circulation in the air conditioning system;

8) ventilation thermal consumption profile for heating the air in the ventilation system, in winter;

9) ventilation thermal consumption profile for cooling the air in the ventilation system, summer;

10) ventilation electricity consumption profile - represents the hourly electricity consumption for air circulation in the ventilation system;

Each consumption profile for the residential type consumer in turn involves one, two or three categories of energy consumed: electricity, thermal energy for heating, thermal energy for cooling (cold), provided by the consumer trigeneration system, **Fig. 4.1.** The blue label indicates the type of profiles developed in each step.

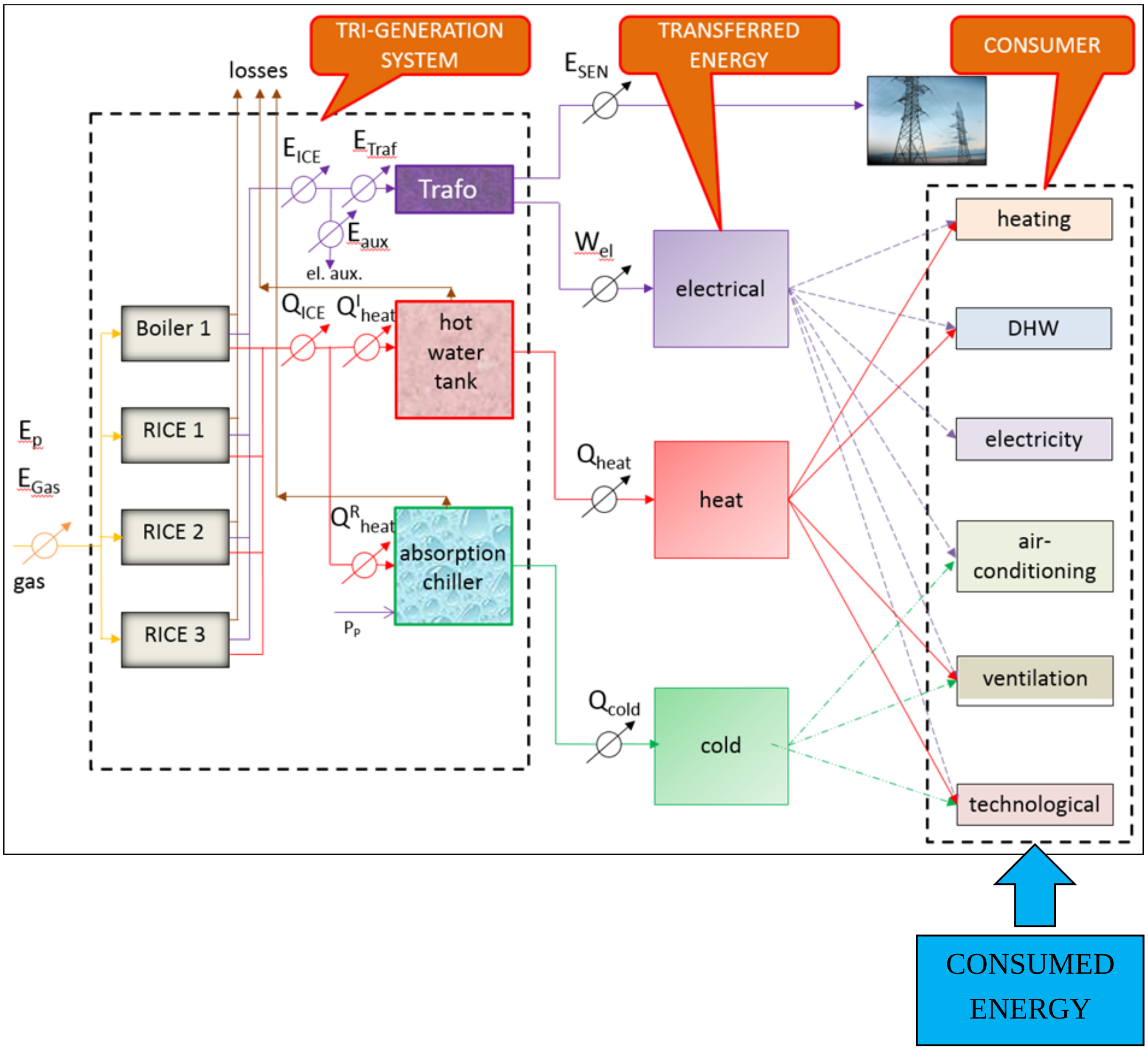

Fig. 4.1. Scheme of the trigeneration system, highlighting the energy consumed

II. PROVIDED ENERGY PROFILES

The trigeneration system will produce and transfer to the residential consumer 3 types of energy: electricity, thermal energy in the form of heat for heating and thermal energy in the form of cold for cooling. The three profiles of the supplied energies resulted from the sum of the hourly consumptions calculated and presented in the previous subchapter. Were built:

1) Hourly profile of energy supplied in the form of heat;

2) Hourly profile of energy supplied in the form of cold;

3) Hourly profile of electricity supplied.

The diagram in **Fig. 4.2** highlights the energies provided by the production plant to the consumer. The blue label indicates the type of profiles developed in each step.

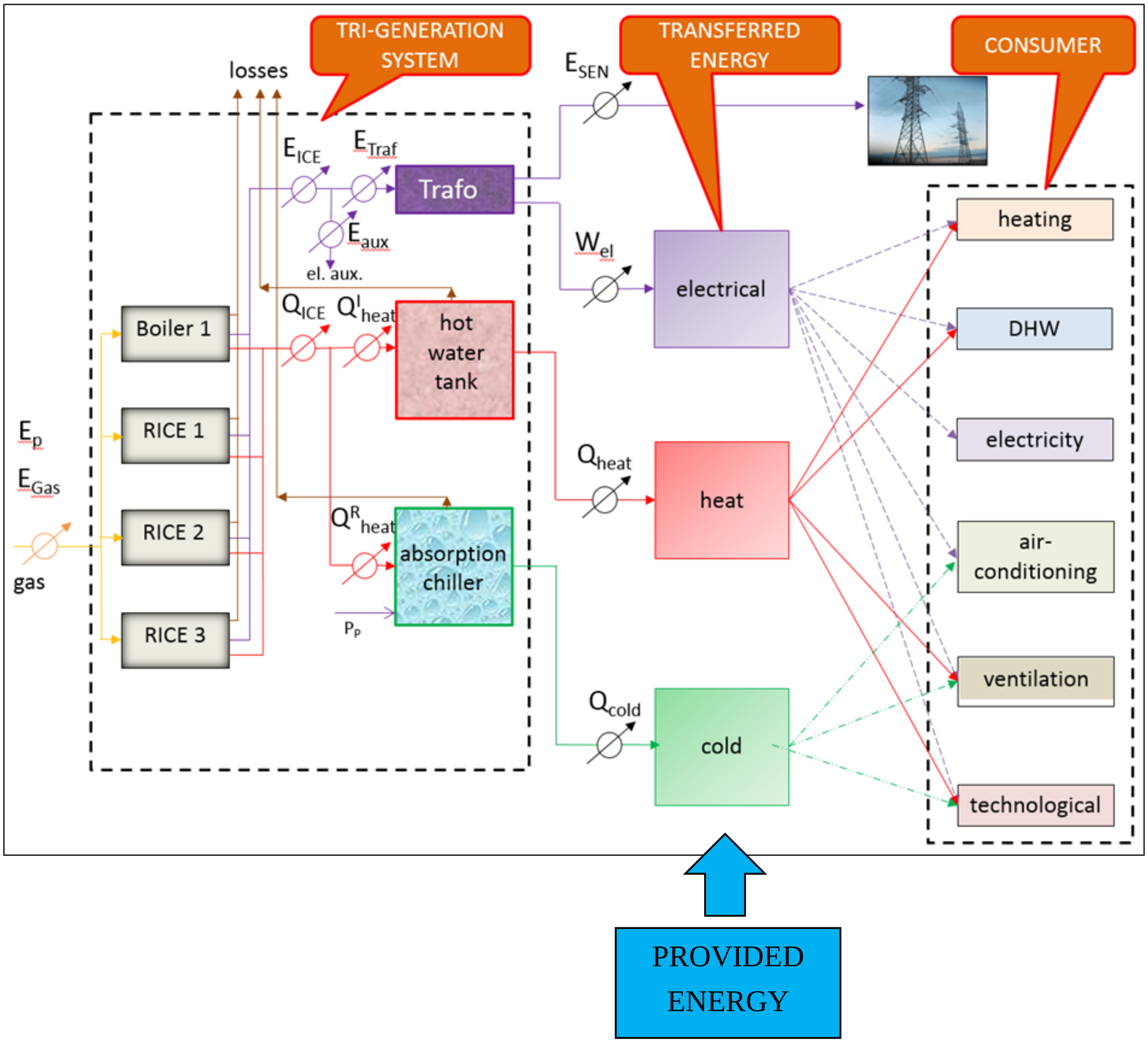

Fig. 4.2. Scheme of the trigeneration system, highlighting the energies provided

III. PRODUCED ENERGY PROFILES

The prime movers of the trigeneration system - RICE-s - will produce and transfer to the residential consumer 2 types of energy produced in cogeneration: electricity and heat.

The heat produced by heat engines, QMT, is divided during the cooling period - summer - into the heat needed to produce cold for air conditioning, QChill, in the absorption system - chiller - and the heat accumulated in the hot water tank, QRez, necessary for water preparation hot for consumption. During the heating period - winter - the heat produced by heat engines, QMT, is distributed to the heat tank - hot water - in the form of accumulated heat, QRez, at a temperature of 95 ° C, necessary for both space heating and preparation of hot water for consumption.

The electricity produced by the electric generators, EMT, of the heat engines has two components auxiliary electricity, Eaux, and the electricity which is transformed into the electric voltage transformer, ETraf. Auxiliary electricity represents the own internal consumption of the trigeneration system for the operation of pumps, fans, solenoid valves, electrical automation equipment, etc. The electricity of the transformer comes out of the production system and is transported to the consumer apartment block, Wel, and the surplus produced, W_{SEN}, is delivered to the electricity grid of the National Energy System (SEN), depending on the ratio of production and required by the consumer. The diagram in **Fig. 4.3** highlights the energies produced in the Q_{MT} and E_{MT} cogeneration regime from the contour of the production plant. The amount of hourly energies produced in cogeneration mode will be found by continuing the 'bottom-up' calculation meaning. The sizing of the system followed the thermal needs of the consumer. The heat required by the motors will result from the sum of the heat required by the chiller with the heat required by the hot water storage tank. Depending on the thermal capacities of the internal combustion engines selected according to the thermal needs of the consumer and according to the specifications of the manufacturer's data sheet, the production of electricity from the trigeneration plant will result. Subsequently, by a reverse calculation (from producer to consumer) it will be established the surplus electricity that will be delivered in SEN, W_{SEN}.

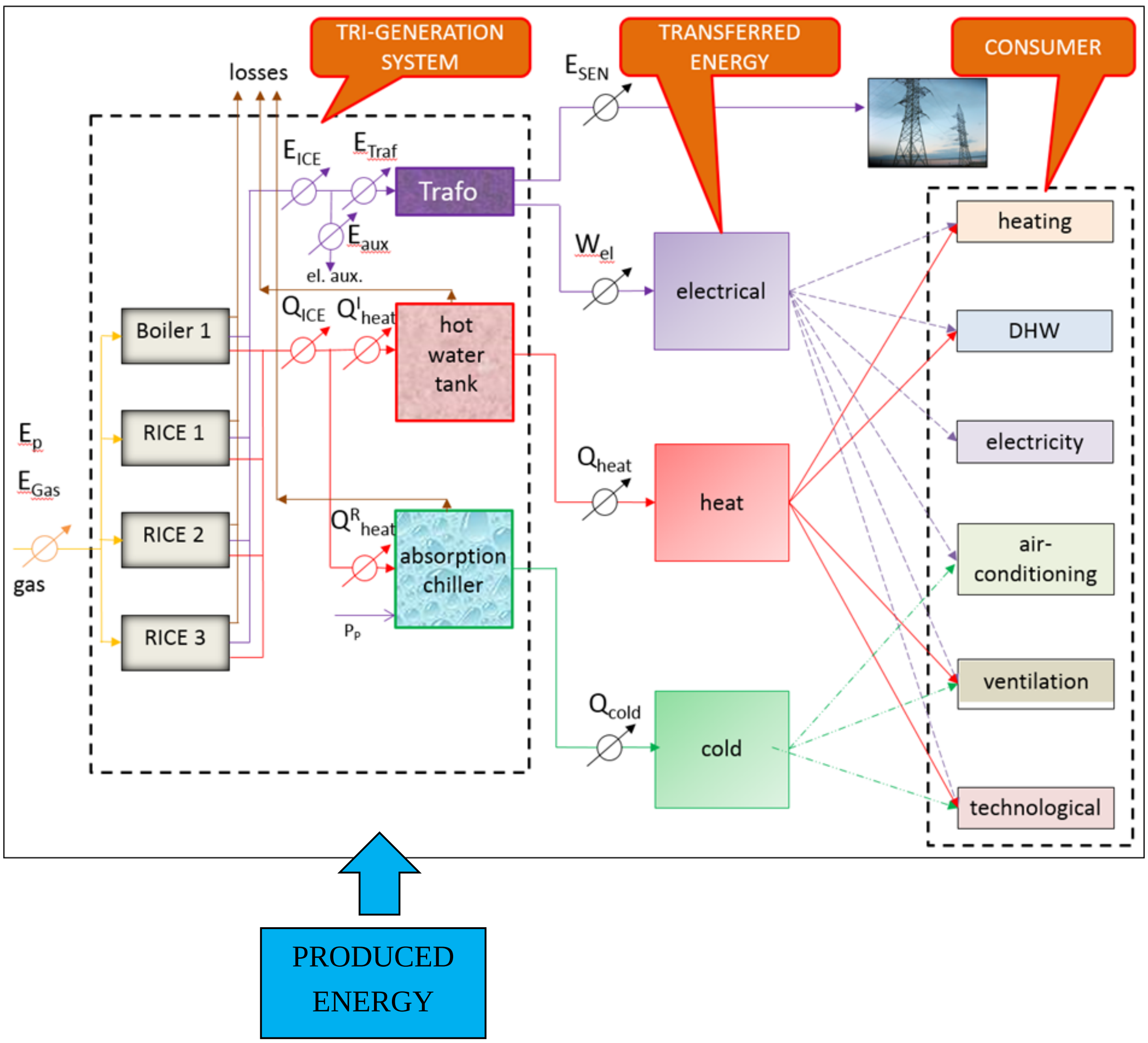

Fig. 4.3. Scheme of the trigeneration system, highlighting produced energies

Were built:

1) Hourly energy profile produced in cogeneration mode for absorption chiller;

2) Hourly energy profile produced in cogeneration regime for the hot water tank;

3) Profile of total thermal hourly energy produced in cogeneration, **Fig. 4.4.**

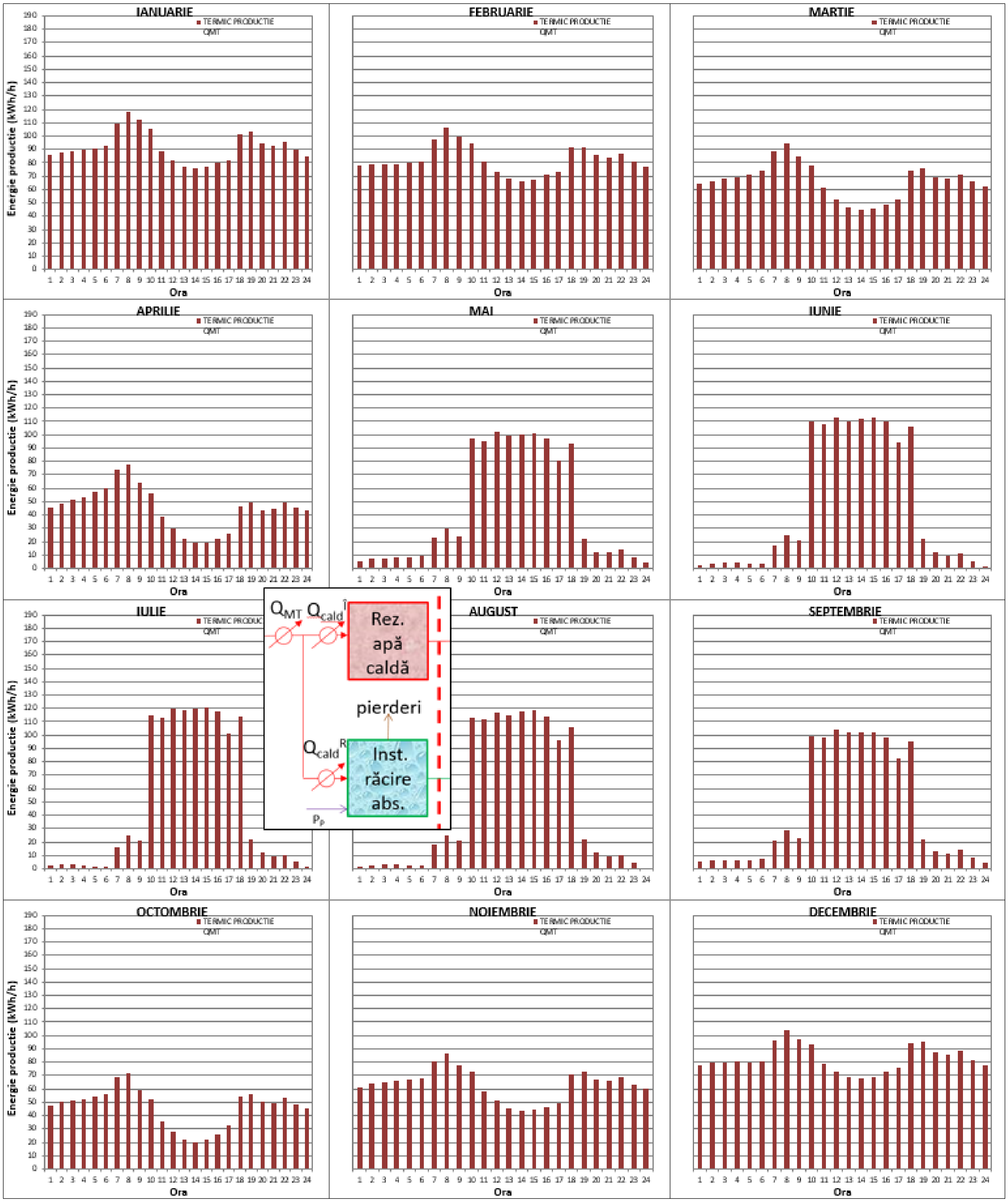

Fig. 4.4. Hourly profiles of total thermal energy produced in cogeneration, residential

Following the calculation of the total thermal energy values that need to be produced in cogeneration for the residential type consumer and the sizing of the system according to the thermal requirement based on the recommended hourly cogeneration coefficient, $\alpha cog = 0.5$ [3], two MAN E2676 E engines were chosen, with a rated thermal output of 86 kW and a rated electric power of 140 kW. The system operates in mode 3 of operation - **simultaneously**, at the same load without the intervention of the boiler, according to [40]. Based on the mathematical model built in the paper [40], applied to the trigeneration system for the residential consumer and using the data from the specification sheet, the total hourly electricity produced by the two heat engines, E_{MT}, is calculated.

Analysis and conclusions

The percentage differences in global efficiency in operation between these partial loads are around 8 percent. In this case, the demand for heating medium at certain time intervals requires the engines to be stopped in order not to operate below the recommended capacity. Only the boiler will operate on these time intervals. During the time intervals when only the boiler will operate, there will be no electricity production and we cannot talk about cogeneration. The operation of the system will be similar to the operation of a classic system of separate production, the efficiency will be only the thermal efficiency of the boiler and we can not raise the issue of an global efficiency as defined in chap. 2.2.1 of the thesis - SPECIFIC INDICES, there is no electrical efficiency. The values of the global efficiency of the trigeneration system configured for the residential consumer, having as prime movers two reciprocating internal combustion engines MAN E2676 E of 86 kW, are between a minimum of 52.50% and a maximum of 72.20%. Maximum global efficiency, higher than 75%, are obtained in the summer months at noon, when the cold load for air conditioning is high to maximum. It is observed that the global efficiency of the trigeneration system increases when the load required by the consumer is higher.

For the construction of the electricity profiles supplied to the S.E.N. a reverse calculation was processed from the engines of the production system to the consumer. It resulted from the calculations of the auxiliary electricity in the hypothesis that the electricity consumed inside the system (production hall) at the pumps that transport the heat to the hot water tank and to the chiller, Eaux, is equal to the sum of electricity calculated at the consumer profiles. for circulation pumps of the heating system, the pumps of the DHW preparation system and chiller pumps during operation. The hourly energy profiles for the electricity transformed into Transformer, E_{Traf}, was obtained by subtracting the auxiliary electricity, E_{aux}, from the total hourly electricity produced by the two heat engines, E_{MT}. The hourly electricity produced by the electric generators of the two heat engines MAN E2676 E of 140 kW electric from the trigeneration system configured for the residential consumer, after decreasing the auxiliary (internal) consumption of the production plant, is higher than the hourly requirement of electricity of the block of flats, respectively is higher than W_{el}, calculated in chapter 4.1.3.3 of the thesis - *Hourly profile of electricity supplied*. Therefore, the surplus production will be delivered to the National Energy System and the hourly energy profiles of the average day of month will result from the calculations for the electricity supplied to the National Energy System.

IV. PRIMARY ENERGY PROFILES

Fuel energy

Motorul termic cu combustie internă MAN E2676 E este alimentat cu gaz natural. Pentru București gazul natural provenit din zăcămintele bazinului județului Prahova are puterea calorifică inferioară: PCi=9,1667 kWh/Nm^3. Alcătuirea profilului orar energetic al combustibilului – gaz metan – consumat de sistemul de trigenerare a fost construit prin adaptarea ecuației variației randamentului global modelat ecuația 3.12 stabilită în cap. 3.2.2, la sistemul format din două motoare termice. Cu relația de calcul a variabilei sarcină parțială de funcționare s-a calculat randamentul global al sistemului de trigenerare și a rezultat apoi energia orară a combustibilului consumat. În modelul matematic s-a observat că perioadele de activare a cazanului termic corespund în modul de operare cu perioade de oprire a ambelor motoare termice, corespunzând unor sarcini termice cerute de consumator foarte mici (sub 40 de kW termici ceea ce reprezintă mai puțin de 50 % din sarcina nominală termică a unui motor, $40\ \text{kW} < 0{,}5 \cdot 86\ \text{kW}$).

Energia primară

The calculation of the primary energy consumed by the trigeneration system is done by multiplying the fuel energy by the conversion factor into primary energy, according to Mc 001, [34]. For the trigeneration system with two engines MAN E2676 E, configured for the residential consumer, in **Fig. 4.5** are represented the hourly energy profiles of the average monthly day, for the energies produced in cogeneration: thermal Q_{MT} and electrical E_{MT}, for energy losses P and for primary energy E_p.

Conclusions

On the basis of the consumed, provided and produced energies profiles, the operation of trigeneration technology was analyzed on a residential small consumer, by choosing a small capacity engine, with a rated thermal input of 86 kW and a rated electric power of 140 kW. The operation was simulated in **simultaneously** mod of operation - at the same load, without the intervention of the boiler. The global hourly efficiency of the system reaches values that tend towards a maximum of 78.55%, clearly superior to the separate production of energies by the classical method, 58% [2]. The minimum hourly global efficiency obtained in during the simulation is low, 52.50%, below the efficiency of the classical solution. The average hourly global efficiency, for the hours in which at least one of the engines is operating, is 62.86%. Hours at low capacity during the night in May, June, July, August and September, as well as mid-day in the transition months: April and October cause to stop the engines and only operate the boiler. The boiler does not produces electricity and therefore the efficiency values were not considered being co / trigeneration; during these time intervals the analysis would become only about the efficiency of a classical source. During operation, the consumer's demand imposed periods in which only one of the two engines was working.

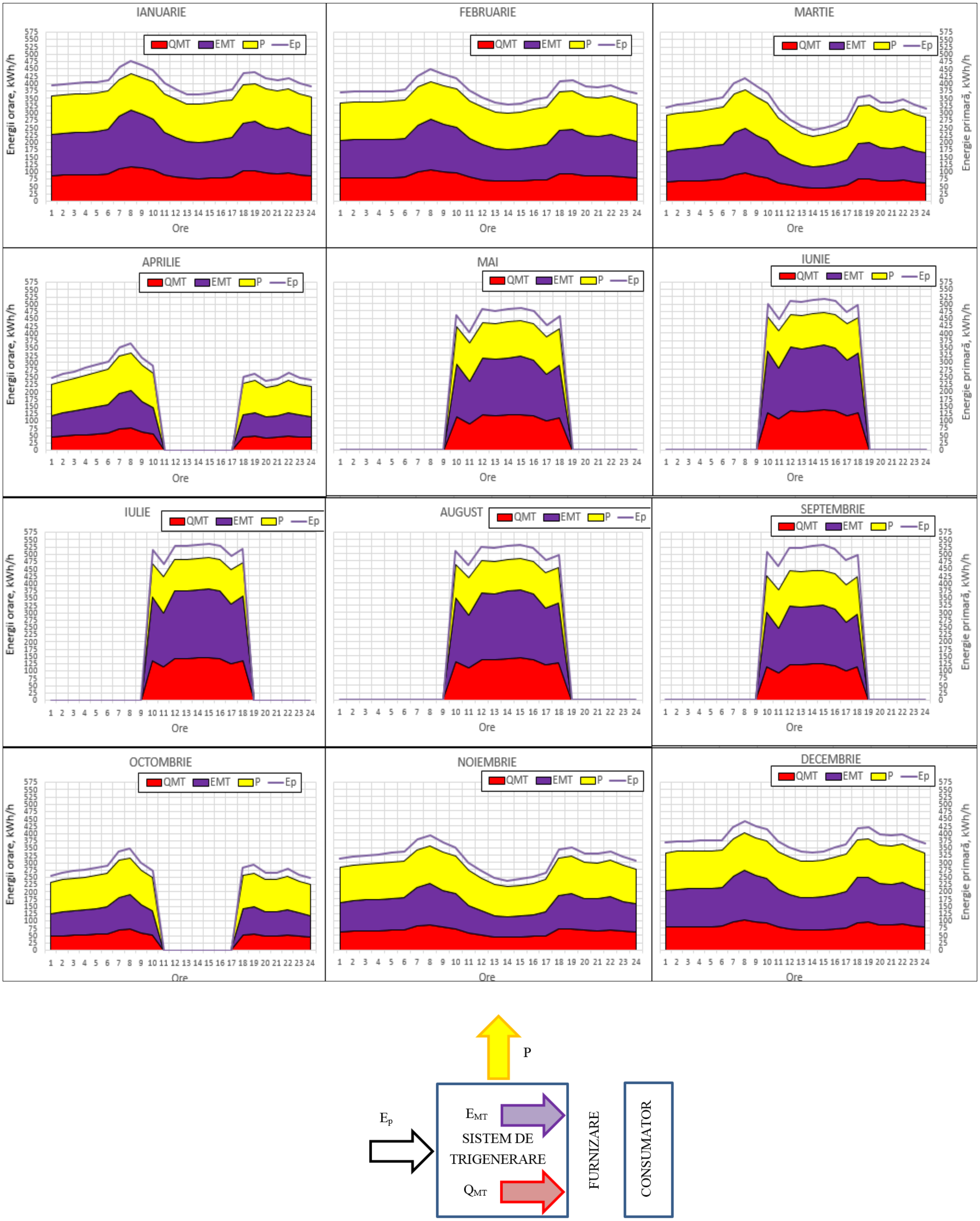

Fig. 4.5. Hourly profiles of produced energy in cogeneration, losses and primary energy

5 ANALYSIS OF THE ADAPTABILITY OF THE THERMAL ENGINE TRIGENERATION SYSTEM TO DIFFERENT CONSUMERS

5.1 CONSUMER DESCRIPTION

In order to meet the objectives set and pursued in the thesis, the construction of 3 other types of energy profiles for consumers completely different from the residential one was continued. The differences consisted not only in different dimensions of the consuming building but also in different areas of activity carried out with different specific flows, different number of occupants, different temperature regimes. The variety of the typology of the analyzed consumers will lead to the appreciation of the adaptability of the trigeneration technology with thermal engines and to the demonstration of its flexibility. The following were analyzed in Chapter 5, together with the residential consumer:

- office building;
- hospital building;
- commercial space.

The office building consumer is an administrative building in the city of Otopeni, str. Aurel Vlaicu, no. 11. The building has a height of GF + 2F and was built in 2007.

From a constructive point of view, the building is characterized by:

- destination of the building: offices;

- height regime: GF + 2F;

- total volume of the building: 38403 m3;

- useful area: 4416.9 m2;

- climatic zone II - represented by the external calculation temperature θe = -15 ºC;

- wind zone II, characterized by the calculation speed of the wind 0.20 m / s.

The hospital consumer is the building of the Craiova County Emergency Clinical Hospital - Corp C2, from Tabaci Street no. 1, Craiova, Dolj County, building owned by Dolj County Council.

From the point of view of the typology of civil buildings, the hospital is characterized by:

- territorial - urban area;

- conformation and location on the lot - independent building, without attached buildings;

- height-environment regime: Ug + Gf + 4F;

- climatic zone II - represented by the external calculation temperature θe = -15 ºC;

- wind zone II (by theoretical hypothesis), characterized by the calculation speed of the wind 0.20 m / s.

For the modeling of the hospital consumer a theoretical hypothesis was created: the real physical building is located in Bucharest (wind zone II).

The commercial space consumer is the ‘Le Fontane’ building from Str. Traian Popovici no. 79-91, Sector 3, Bucharest, mixed-use building (residential, office and commercial). Only the commercial area was taken into account from the analyzed building. The building is provided on the ground floor with 7 commercial spaces, an area with meters and two areas for storing bicycles, the floor area above the basement being 881.0 m2. On the ground floor, the commercial spaces have a height of 5.30 m + 0.90 m (consisting of false ceiling, slab and soundproofed upper floor). The building was built in 2011.

5.2 PARTICULARITIES OF ENERGY PROFILES FOR RESIDENTIAL, OFFICES, HOSPITAL AND COMMERCIAL CONSUMERS

For the construction of hourly energy consumption profiles for consumers such as office buildings, hospitals and commercial spaces, the same methodology was used and the same calculation algorithm was used, with the same equations as for the residential consumer, with the particularizations imposed by technical regulations.

Table 5.1 shows the main parameters of the hourly energy profile for DHW (domestic hot water). use for each type of consumer.

Table 5.1. DHW parameters for each type of consumer

Consumer	N_p	q_c	t_{ac}	$\Delta\theta$ ac - ar
	(pers)	(l/day,pers)	(h/h)	(K)
residential	53	70	0,6	50
office	260	5	0,2	
hospital	100	115	0,6	
	84	5	0,2	
commercial	134	10	0,2	

Table 5.2 shows the main heating parameters used for each type of consumer.

Table 5.2. Heating parameters for each type of consumer

Consumer	θ_i	H	t_H	f_{Sch}	f_{Abgl}	b	C_{P1}	C_{P2}
	(K)	(W/K)	(h/h)	(-)	(-)	(-)	(-)	(-)
residential	20	2637,12	1	1	1	2	0,9	0,1
office	20	2994,68				2		
hospital	22	1666,35				2		
commercial	18	2222,70				1		

In **Fig. 5.1** are presented comparatively, for January, the thermal consumption for heating of the 4 categories of consumers.

Table 5.3 shows the main electrical parameters calculated and used for each type of consumer.

Table 5.3. Electrical parameters by types of consumers

Consumer	P_{sp} (kW)	S_u (m^2)	k_u (-)	P_i (kW)	P_a (kW)	t_u (h)
residential					107,25	
office	0,160	1812,30	0,90	289,968	260,971	2047,5
hospital		2253,80	0,66	206,880	136,541	4700
commercial	0,0875	881,00	0,80	77,087	61,670	4230

In **Fig. 5.2** are presented comparatively, for July, the electricity consumption for lighting and sockets (appliances, equipment as appropriate) of the 4 categories of consumers studied.

Table 5.4 shows the main air conditioning parameters used for each type of consumer.

Table 5.4. Air conditioning parameters for each type of consumer

<table>
<tr><th rowspan="2">Consumer</th><th>H_T</th><th>H_V</th><th>θ_i</th><th>θ_e</th><th>θ_{intr}</th><th>P_{sp}</th><th>n</th><th>N_h</th></tr>
<tr><th>(W/K)</th><th>(W/K)</th><th>(K)</th><th>(K)</th><th>(K)</th><th>(W/m^3,h)</th><th>(h^{-1})</th><th>(h)</th></tr>
<tr><td>residential</td><td>1984,55</td><td>652,57</td><td>25,5</td><td rowspan="4">variabilă</td><td>23,5</td><td>0,42</td><td>5</td><td rowspan="4">0,3÷0,6</td></tr>
<tr><td>office</td><td>2844,42</td><td>1139,94</td><td>26</td><td>24</td><td>0,56</td><td>6</td></tr>
<tr><td>hospital</td><td>1064,12</td><td>10794,9</td><td>25,5</td><td>23,5</td><td>0,56</td><td>8</td></tr>
<tr><td>commercial</td><td>851,82</td><td>4728,38</td><td>25</td><td>23</td><td>0,35</td><td>7</td></tr>
</table>

Table 5.5 shows the main ventilation parameters used for each type of consumer.

Table 5.5. Ventilation parameters for each type of consumer

<table>
<tr><th rowspan="2">Consumer</th><th colspan="2">θ_{intr}</th><th>θ_e</th><th>CAI</th><th>G_p</th><th>G_s</th><th>τ</th><th>η_{vent}</th></tr>
<tr><th colspan="2">(K)</th><th>(K)</th><th>(-)</th><th>(m^3/h,pers)</th><th>(m^3/h,m^2)</th><th>(h/h)</th><th>(-)</th></tr>
<tr><td rowspan="2">residential</td><td>cooling</td><td>24</td><td rowspan="8">variable</td><td rowspan="2">2</td><td rowspan="2">25</td><td rowspan="2">2,52</td><td rowspan="2">0,4</td><td rowspan="8">0,7</td></tr>
<tr><td>heating</td><td>22</td></tr>
<tr><td rowspan="2">office</td><td>cooling</td><td>24</td><td rowspan="2">2</td><td rowspan="2">25</td><td rowspan="2">2,52</td><td rowspan="2">0,4</td></tr>
<tr><td>heating</td><td>22</td></tr>
<tr><td rowspan="2">hospital</td><td>cooling</td><td>23,5</td><td rowspan="2">1</td><td rowspan="2">36</td><td rowspan="2">1,8</td><td rowspan="2">0,4</td></tr>
<tr><td>heating</td><td>24</td></tr>
<tr><td rowspan="2">commercial</td><td>cooling</td><td>23</td><td rowspan="2">2</td><td rowspan="2">25</td><td rowspan="2">2,52</td><td rowspan="2">0,5</td></tr>
<tr><td>heating</td><td>20</td></tr>
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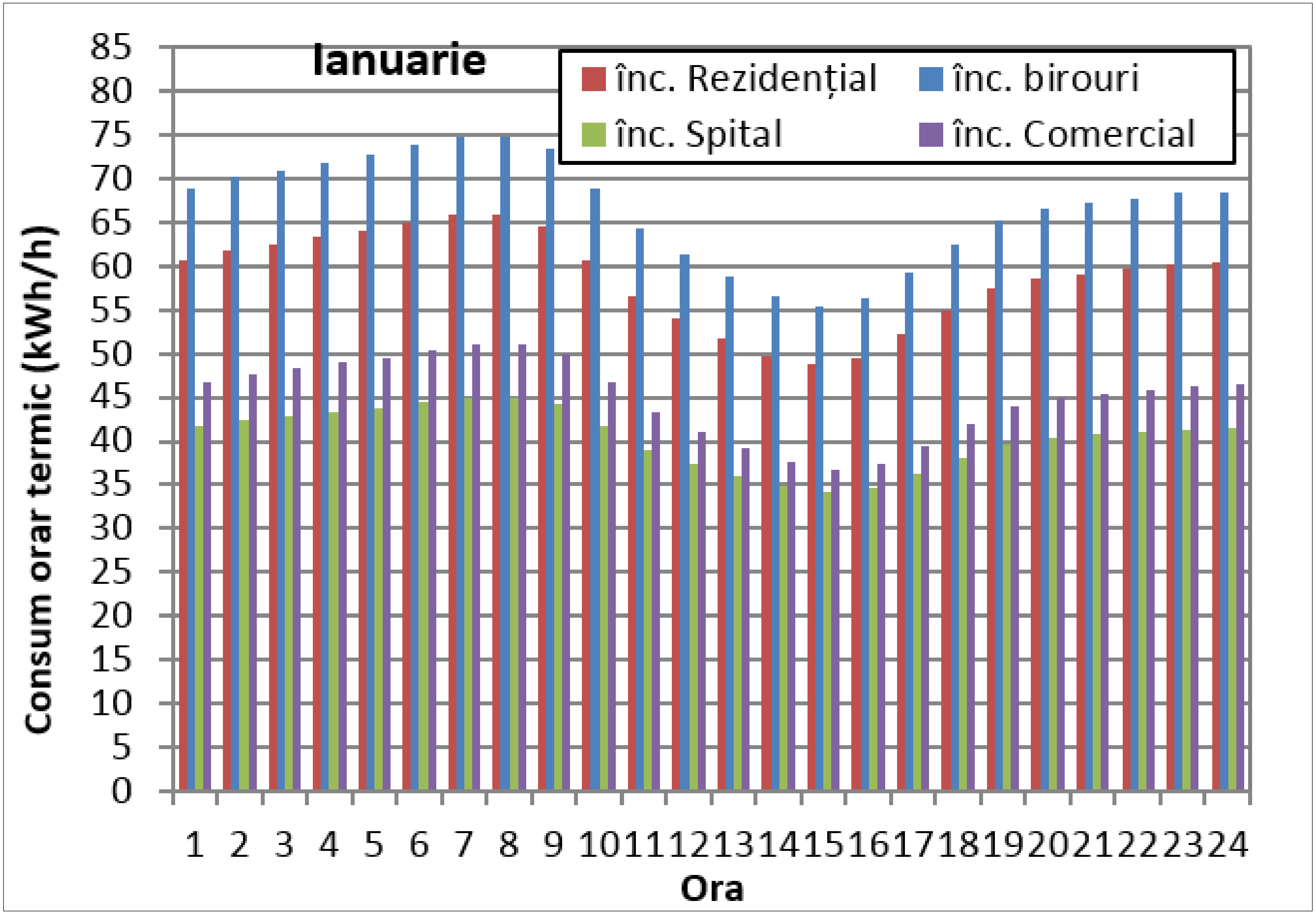


Fig. 5.1. Comparative thermal energy consumption for heating

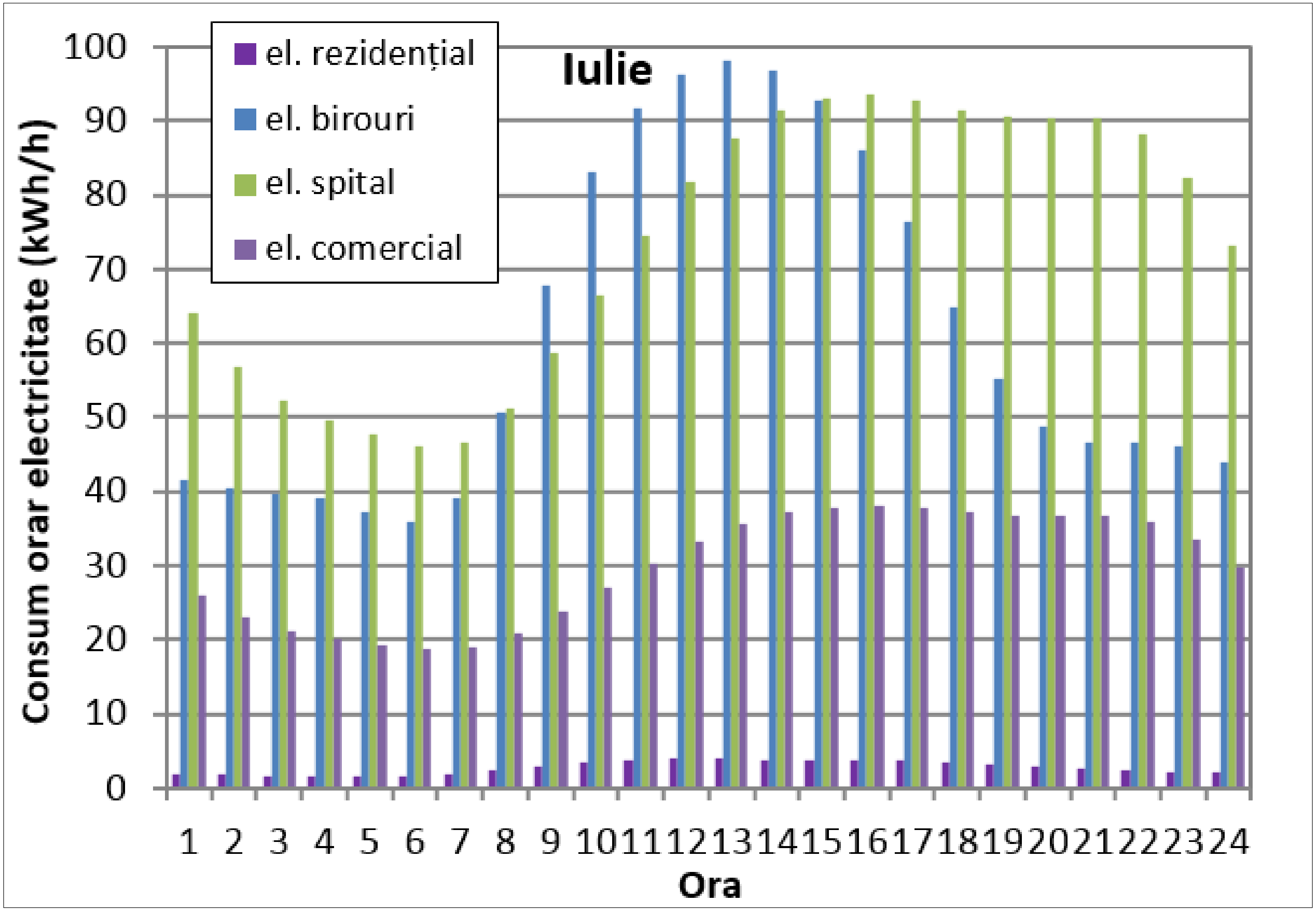


Fig. 5.2. Comparative electricity consumption (lighting + sockets)

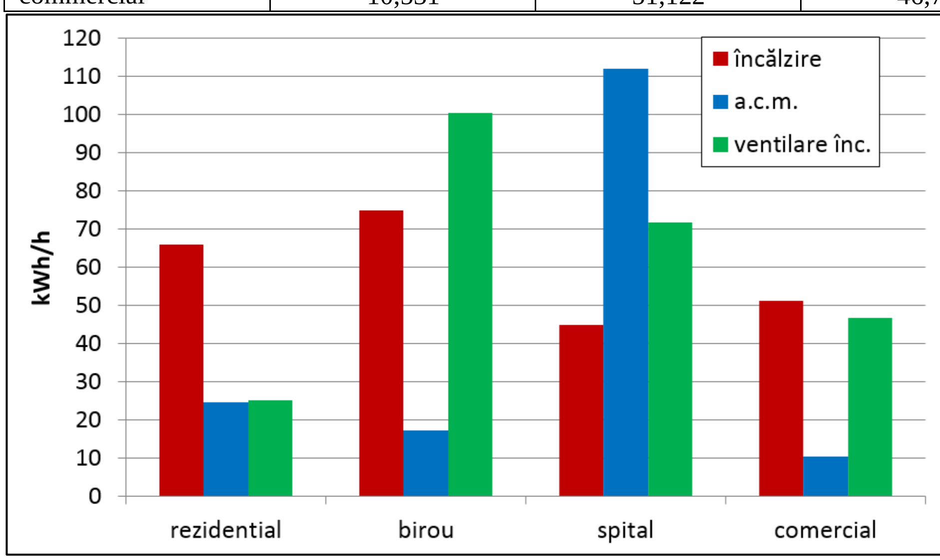
5.3 PROVIDED ENERGY PROFILES TO DIFFERENT CONSUMERS

HEAT PROVIDED

By summing the hourly consumption of thermal energy in the form of heat for DHW preparation, for space heating and for ventilation by air heating, the hourly profiles of the provided energy in the heat form, Q_{cald}, for office, hospital and commercial were made. **Table 5.6** presents the maximum values of hourly consumption for each utility consuming energy in the form of heat and the maximum hourly values of energy supplied in the form of heat, in kWh / h, for each type of consumer. **Fig. 5.3** compares hourly energy consumption for utilities that use energy in the form of heat.

Table 5.6. Comparative table of maximum heat consumption by utilities and provided heat

Consumer	$Q_{acm,oră}$ (kWh/h)	$Q_{inc,oră}$ (kWh/h)	$Q_{vent,inc,oră}$ (kWh/h)	Q_{cald} (kWh/h)
residential	24,683	65,928	25,172	115,783
office	17,265	74,867	100,418	192,550
hospital	112,020	44,991	71,742	228,753
commercial	10,531	51,122	46,798	108,450



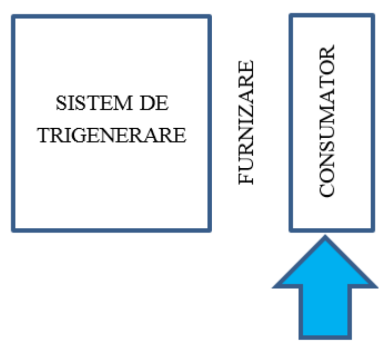


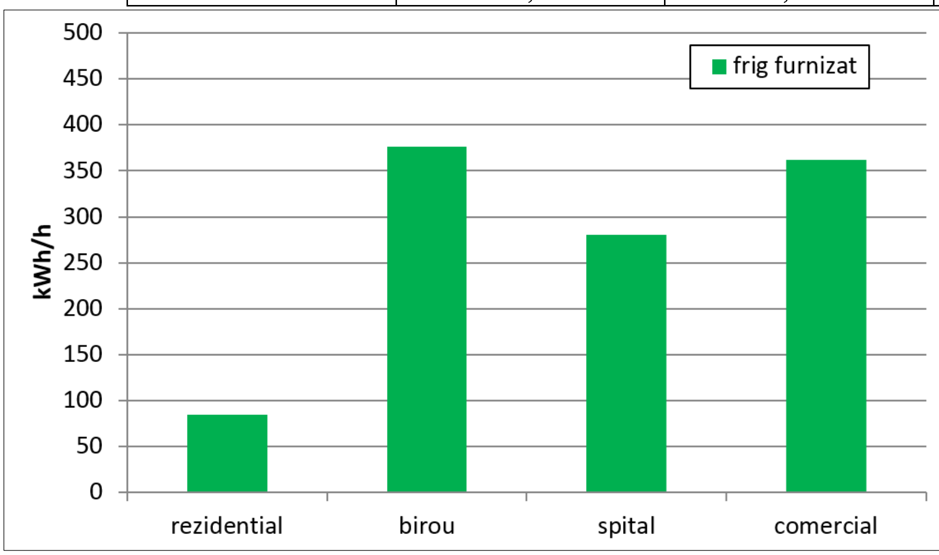
Fig. 5.3. Comparison of maximum hourly heat consumption by utilities

COOLING PROVIDED

By summing the hourly consumption of thermal energy in the form of cold for air conditioning and ventilation by cooling the air, the hourly provided energy profiles, in the cooling form, Qfrig, for office, hospital and commercial consumers were made. **Table 5.7** presents the maximum values of hourly consumption for each utility consuming energy in the cooling form and the maximum hourly values of energy provided, in kWh / h, for each type of consumer. **Fig. 5.4** compares the cold provided, by consumers.

Table 5.7. Comparative table of maximum cold consumption by utilities and cooling provided

Consumer	$Q_{clim,oră}$ (kWh/h)	$Q_{vent,rac,oră}$ (kWh/h)	Q_{frig} (kWh/h)
residential	81,055	3,776	84,831
office	361,586	15,065	376,651
hospital	268,945	11,257	280,202
commercial	352,355	9,454	361,809



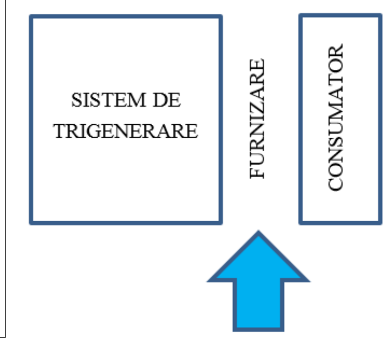


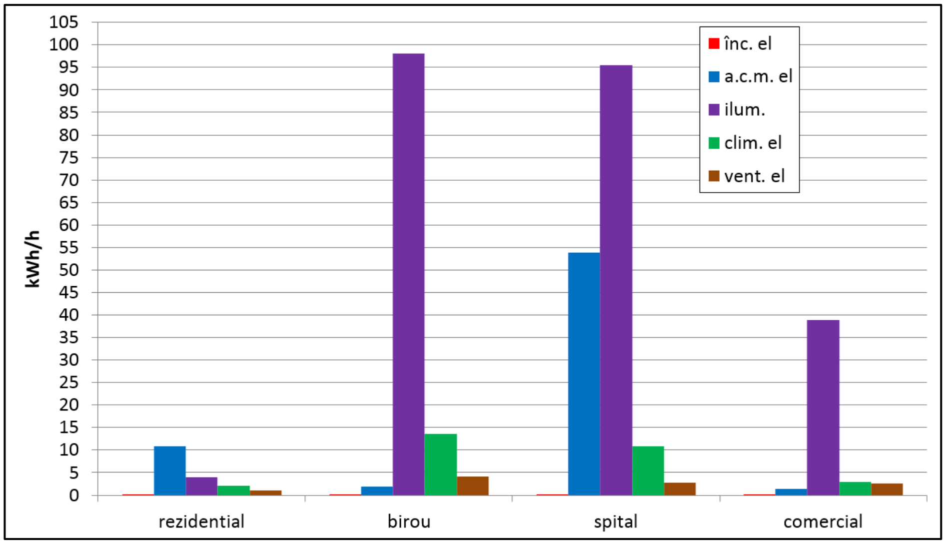
Fig. 5.4. Comparison of maximum hourly cold provided

<u>ELECTRICITY PROVIDED</u>

By summing the hourly electricity consumption for the a.c.m. preparation system, for heating, lighting and appliances, air conditioning and ventilation, the hourly profiles, monthly averages, of the supplied electricity, Wel, for office, hospital and commercial consumers were made. **Table 5.8** presents the maximum values of hourly consumption for each electricity consuming utility and the maximum hourly values of electricity supplied, in kWh / h, for each type of consumer. **Fig. 5.5** compares the hourly energy consumption for utilities that use electricity.

Table 5.8. Comparative table of maximum electricity consumption by utilities and provided electricity

Consumer	$W_{înc,oră}$ (kWh/h)	$W_{acm,oră}$ (kWh/h)	$W_{il,oră}$ (kWh/h)	$W_{clim,oră}$ (kWh/h)	$W_{vent,oră}$ (kWh/h)	W_{el} (kWh/h)
residential	0,212	10,846	3,972	2,022	1,013	18,019
office	0,238	1,892	98,096	13,519	4,040	117,786
hospital	0,105	53,782	95,570	10,793	2,687	162,937
commercial	0,129	1,315	38,818	2,955	2,542	45,759



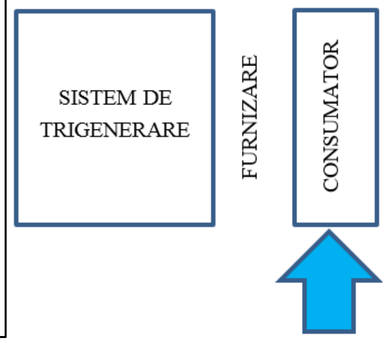


Fig. 5.5. Comparison of maximum hourly electricity consumption by utilities

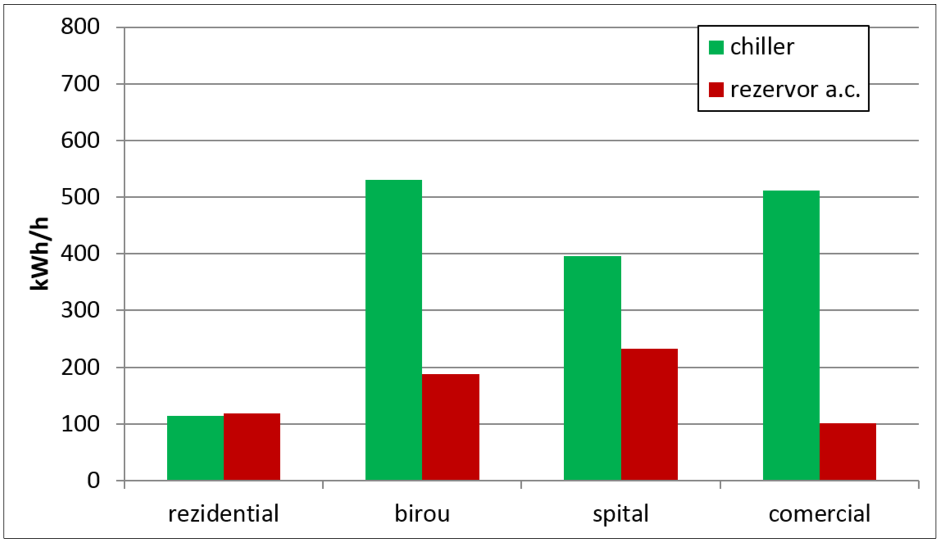
5.4 PRODUCED ENERGY PROFILES IN COGENERATION

HOURLY PRODUCED ENERGY PROFILE IN COGENERATION FOR ABSORPTION CHILLER AND HOT WATER TANK

The hourly profiles of heat, Q^{R}_{cald}, which must be produced to supply the absorption chiller kettle in the case of office, hospital and commercial consumers were calculated and realized. The hourly profiles, monthly averages, of the hourly energy in the form of heat, $Q^{Î}_{cald}$, which must be produced to supply the hot water tank for office, hospital and commercial consumers were calculated and realized. **Table 5.9** shows the maximum hourly values of energy in the form of heat required to be produced to supply the chiller and hot water tank to consumers and the maximum hourly values of thermal energy produced in cogeneration, in kWh / h, for each type of consumer. **Fig. 5.6** compares the hourly heat produced in cogeneration mode required for the chiller and hot water tank of each consumer.

Table 5.9. Comparative table of the maximum values of heat required for the chiller and hot water tank and the total produced heat in the cogeneration

Consumer	Q^{R}_{cald} (kWh/h)	$Q^{Î}_{cald}$ (kWh/h)	Q_{MT} (kWh/h)
residential	114,767	118,146	232,913
office	530,965	187,932	718,897
hospital	396,589	233,422	630,011
commercial	512,379	100,793	613,171



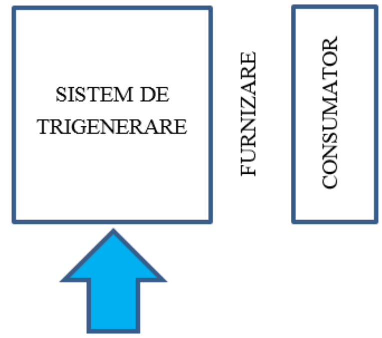


Fig. 5.6. Comparison of the maximum hourly produced heat in cogeneration, required for the hot water tank and the chiller

5.5 OPERATION WITH DIFFERENT THERMAL CAPACITIES OF THE ENGINES

In ch. 4.1.4.4 of the thesis, following the calculation of the total thermal energy values produced in cogeneration for the residential consumer, based on the hourly consumption profiles for the average day of each month, a trigeneration system consisting of two identical RICE-s was dimensioned , MAN E2676 E, with a rated thermal input of 86 kW and a rated electric power of 140 kW. In an attempt to find the optimal nominal thermal capacities under the given conditions, 3 other types of internal combustion and simulated engines operating in the same mode 3 of **simultaneous** operation were selected for the residential type consumer:

- MAN E3262 E engine;
- MAN E2676 LE engine;
- MAN E0836 E engine.

Table 5.10 compares the minimum, maximum and average global efficiencies for the 4 types of RICE-s with corresponding thermal and electrical capacities (nominal loads).

Table 5.10. Comparative table of minimum, maximum, average global efficiencies per engine

Engine	$q_{th,nom}$	$q_{el,nom}$	$\eta_{gl,oră}$ min.	$\eta_{gl,oră}$ max.	$\eta_{gl,oră}$ med.
	(kW)	(kW)	(%)	(%)	(%)
MAN E2676 E	86	145	52,50	72,20	61,81
MAN E3262 E	157	275	52,53	58,33	55,02
MAN E2676 LE	121	220	52,63	63,33	57,41
MAN E0836 E	37	56	52,65	85,24	78,10

Conclusions

It is observed that in the case of the load requested by the residential consumer, load strongly variable during the months of the year (months considered according to the hourly energy profiles of the average day of the month), the engine with the best efficiency is the one with the lowest thermal load. The explanation is that a small nominal thermal load more efficiently divides the range of required energy values, respectively the load is included several times in the required energy range. The effect is that the engines have several operating intervals at high partial loads, according to the mode of operation described (simultaneous). It can be deduced from the calculations that in the case of a trigeneration system with two engines, for a maximum hourly energy required to be produced of 120.8 kWh / h - in the case of the residential consumer, the optimum rated thermal load of an engine must be 30,2 kW, under the conditions of a cogeneration coefficient α = 0.5.

5.6 OPTIMIZING THE OPERATION OF THE TRIGENERATION SYSTEM FOR DIFFERENT TYPES OF CONSUMERS

CHOOSING THE OPTIMUM NOMINAL LOAD AND THE OPTIMUM NUMBER OF ENGINES FOR 4 TYPES OF CONSUMERS

The problem was to find the optimal number of engines and the optimal rated load, in accordance with the particularities of the energy profiles of each of the consumers. This was done with the Excel solver from Data Analysis for each type of consumer and for each of the two equations of variation developed, linear and exponential.

The calculation steps were as follows:

1. fixing the objective function;
2. establishing the dependent variables;
3. imposing boundary conditions;
4. choosing the calculation algorithm;
5. obtaining output data;
6. interpretation of results.

I. The linear equation method

1. Fixing the objective function

A common goal of optimizing the operation of the trigeneration system is to maximize the global efficiency of the system under conditions of variable thermal load to the consumer and under conditions of a predetermined maximum number of engines. The maximum number established for the engines (obviously of identical nominal capacity) is 10 pcs. engines. The objective function is to maximize the global efficiency values described by equation 3.2 in ch. 3.2.2 and resumed in 5.2:

$$f1 = max\{\eta_{gl} | Q_{MT} = 120{,}7\ kWh/h\} \qquad 5.1$$

$$\eta_{gl} = 0{,}4372 \cdot PL + 0{,}4152 \qquad 5.2$$

$$PL = \frac{Q_{MT}}{n \cdot q_{th,nom}} \qquad 5.3$$

2. Establishing the dependent variables

The dependent variables are:

- number of engines, n;
- nominal thermal load of the engine, $q_{th,nom}$;
- maximum required thermal load, Q_{MT}.

3. Imposing boundary conditions

The boundary conditions or system constraints are:

- the number of motors to be an integer, n∈Z;
- the number of engines is less than or equal to 10, n≤10;
- the number of motors multiplied by the rated thermal load to cover the maximum required thermal load, $n \cdot q_{th,nom} \geq Q_{MT}$;
- the partial operating load must be at least 50%,, PL≥0.5;
- the rated thermal load of an engine does not exceed the required maximum thermal load (the upper limit condition proved to be mandatory), $q_{th,nom} \leq Q_{MT}$;
- the maximum thermal load required to be a positive number, , $Q_{MT} \geq 0$;
- the maximum thermal load required to be at most equal to the maximum hourly thermal energy value determined in the profile of the energy produced in cogeneration regime, $Q_{MT} \leq Q_{MT} profil$.

4. Choosing the calculation algorithm

The Simplex LP (Simplex Linear Programming) algorithm is an algorithm for programming linearly dependent phenomena. Linear programming (also called linear optimization) is a method of obtaining the best result (such as maximum efficiency, minimum cost, etc.) in a mathematical model whose requirements are represented by linear equations. Linear programming is a special case of mathematical programming, also known as mathematical optimization.

The Simplex LP algorithm is a technique for optimizing a linear objective function, subject to linear equality and linear boundary conditions of inequality. The linear programming algorithm finds a point after several iterations in which the function has the lowest or the highest value, depending on the chosen objective, minimization or maximization.

5. Obtaining output data

After choosing the objective function, setting the decision variables, imposing the constraints and choosing the appropriate calculation algorithm, select the check box so that all decision variables without explicit lower limit have zero lower limit. The solver will solve the maximization of the linear equation and will display the results, **Fig. 5.7** for the residential consumer in this case.

6. Interpretation of results

If the correct calculation steps have not been followed, sufficient boundary conditions have not been imposed or a conflict occurs between the executed operations, the solver will display an error message announcing that it has encountered an incorrect value in the target cell or a constraint cell. If the procedure was completed correctly, the following will be displayed:

- optimal number of engines, n;
- the value of the optimal nominal thermal load of the motor, $q_{th,nom}$;
- the maximum optimal thermal load to be required, Q_{MT};
- the value of the optimal global efficiency, η_{gl}.

Termic MAXIM	Termic MINIM	$PL_{TRI}^{2E} = \frac{Q_{MT}}{n \cdot q_{th,nom}}$	$\eta_{global}^{2E} = 0,4372 \cdot PL_{COG} + 0,4152$		
120,706	0,294				
TERMIC REVISED Q_{MT}	"n" număr de motoare (MAXIM 10)	x=	5		
kWh/h	"$q_{th,nom}$" sarcina termica nominala (kW)	y=	29,133		
86,293	"Q_{MT}" sarcina th maximă ceruta, PUTERNIC VARIABILA	a=	145,667		
88,078	**obiectiv: maximizare randamentului trigenerarii "η^{nE}_{global}"**	obiectiv MAX	85,24%		
88,983	nr motoare să fie nr intreg	constraint 1	5	equals	integer
89,539	nr maxim de motoare să fie 10 (se poate schimba)	constraint 2	5	<=	10
90,571	nr MT x sarcina nominală să acopere maximul cerut	constraint 3	145,667	>=	120,706
92,744	Partial Load sa fie >= 50%	constraint 4	1	>=	0,5
109,281	sarcina nominala a unui motor să nu fie peste maximul th cerut din profilurile de consum construite-SUPRADIMENSIONARE	constraint 5	29,133	<=	120,706
118,146	sarcina th maxima cerută să fie între un MAX si un MIN	constraint 6	145,667	>=	0,294
112,007	determinate in profilurile de consum (de productie - STRIGEN)	constraint 7	145,667	<=	120,706

Fig. 5.7. Optimizing the operation of the system for the residential consumer, with the linear equation

<u>Residential</u>

Fig. 5.7 presents the optimization of the operation of the system for the residential consumer with linear equation. The value of the optimal global efficiency of the trigeneration system for the residential type consumer, respectively 85.24%, would be obtained for a value of the maximum hourly thermal energy required of 145.677 kWh / h (the real maximum is registered in July, 15, 120,706 kWh / h) with 5 thermal engines with nominal thermal load (capacity) 29,133 kW.

<u>II. The exponential equation method</u>

1. Fixing the objective function

The objective function is to maximize the overall yield values described in Equation 3.3 and repeated in 5.5:

$$f2 = max\{\eta_{gl} | Q_{MT} = 120,7\ kWh/h\} \quad 5.4$$

$$\eta_{gl} = 0,4926 \cdot e^{0,5498 \cdot PL} \quad 5.5$$

$$PL = \frac{Q_{MT}}{n \cdot q_{th,nom}} \tag{5.6}$$

The maximum number established for the engines (obviously of identical nominal capacity) is 10 pcs. engines. The variable thermal load required by the consumer imposes values of hourly thermal energy according to the profiles calculated in the previous chapters.

2. Establishing the dependent variables

The dependent variables are:

- number of engines, n;
- nominal thermal load of the engine, $q_{th,nom}$;
- maximum required thermal load, Q_{MT}.

3. Imposing boundary conditions

The boundary conditions or system constraints are:

- the number of motors to be an integer, n∈Z;
- the number of engines is less than or equal to 10, n≤10;
- the number of motors multiplied by the rated thermal load to cover the maximum required thermal load, $n \cdot q_{th,nom} \geq Q_{MT}$;
- the partial operating load must be at least 50%,, PL≥0.5;
- the rated thermal load of an engine does not exceed the required maximum thermal load (the upper limit condition proved to be mandatory), $q_{th,nom} \leq Q_{MT}$;
- the maximum thermal load required to be a positive number, , $Q_{MT} \geq 0$;
- the maximum thermal load required to be at most equal to the maximum hourly thermal energy value determined in the profile of the energy produced in cogeneration regime, $Q_{MT} \leq Q_{MT}profil$.

4. Choosing the calculation algorithm

The Nonlinear GRG algorithm means 'Generalized reduced gradient'. In its most basic form, this method of solving concerns the gradient or slope of the objective function as the input values (or decision variables) change and determines that an optimal solution has been reached when the partial derivatives are canceled.

5. Obtaining output data

After choosing the objective function, setting the decision variables, imposing the constraints and choosing the appropriate calculation algorithm, select the check box so that all decision variables without explicit lower limit have zero lower limit. The solver will solve the maximization and display the optimization results.

6. Interpretation of results

If the correct calculation steps have not been followed, sufficient boundary conditions have not been imposed or a conflict occurs between the executed operations, the solver will display an error message announcing that it has encountered an incorrect value in the target cell or a constraint cell. If the procedure was completed correctly, the following will be displayed:

- optimal number of engines, n;
- the value of the optimal nominal thermal load of the motor, $q_{th,nom}$;
- the maximum optimal thermal load to be required, Q_{MT};
- the value of the optimal global efficiency, η_{gl}.

Fig. 5.8 presents the optimization of the operation of the office building consumer with the exponential equation.

$f_{obj} = max\{\eta_{gl}|Q_{max,RICE} = 534.25\ kWh/h\}$ $\eta_{gl} = 0.4926 \cdot e^{0.5498 \cdot PL}$ $PL = \frac{Q_{RICE}}{n \cdot q_{th,rated}}$

	Input data	Variables	Constraints	
"n" - number of engines (maximum 10)	x=	8		
"$q_{th,rated}$" - rated thermal load (kW)	y=	66.782		
"Q_{RICE}" - heat load required	a=	534.254		
objective: maximize the global efficiency values "η^{nE}_{global}"	MAX=	85.36%		
number of engines is integer	constraint 1	8	equals	integer
number of engines is less than or equal to 10	constraint 2	8	<=	10
number of engines multiplied with rated thermal load to cover	constraint 3	534.254	>=	534.254
partial load is at least 50 %	constraint 4	1	>=	0.5
rated thermal load of a engine does not exceed the maximum heat load required	constraint 5	66.782	<=	534.254
maximum heat load required to be between a minimum and a maximum value	constraint 6	534.254	>=	0.000
	constraint 7	534.254	<=	534.254

Fig. 5.8. Optimizing of the rated load and of the number of engines for the office buiding consumer

<u>Office</u>

Fig. 5.8 presents the optimization of the operation of the the system for office consumer, with the exponential equation. The method used is the same as for the residential consumer: the objective function is the same - exponential equation 5.5, the decision variables are the same, the boundary conditions are the same with the values corresponding to the office hourly energy profile, GRG Nonlinear calculation algorithm.

The value of the optimal global efficiency of the trigeneration system for the office consumer, respectively 85,36%, would be obtained for a value of the maximum hourly thermal energy required of 534,254 kWh / h, a maximum that is also obtained in July, at 2 p.m. with 8 thermal engines with nominal thermal load (capacity) 66,782 kW.

Table 5.11 presents the results of optimizing the operation of the trigeneration system, for the 4 consumers, with linear equation and exponential equation.

Table 5.11. Comparative table of results of optimization, by consumers, with linear equation and with exponential equation

Consumator	Ecuația 1 liniară (ec. 3.12)				Ecuația 2 exponențială (ec. 3.13)			
	număr optim motoare	sarcina termică nominală optimă	energia termică solicitată optimă	randament global optim	număr optim motoare	sarcina termică nominală optimă	sarcină termică solicitată optimă	randament global optim
	n	$q_{th,nom}$	Q_{MT}	η_{gl}	n	$q_{th,nom}$	Q_{MT}	η_{gl}
	(-)	(kW)	(kWh/h)	(%)	(-)	(kW)	(kWh/h)	(%)
rezidențial	5	29,133	145,667	85,24	5	29,133	145,667	85,36
birouri	8	66,782	534,254	85,24	8	66,782	534,254	85,36
spital	8	29,178	233,422	85,24	7	33,346	233,422	85,36
comercial	10	51,803	518,031	85,24	10	51,803	518,031	85,36

6 CONCLUSIONS, PERSPECTIVES

Trigeneration technologies with reciprocating internal combustion engines as prime movers have the great advantage of operating at different loads without reducing significantly their efficiencies. Engines can modulate their operation through automation to operate at half rated capacity. A 50% decrease in operation, caused by the consumer's variable demand, causes a decrease in global efficiency of approx. 10%.

The maximum efficiency of a thermal equipment does not automatically equate to its operation at rated load (at 100%). It was observed during the research that in the case of internal combustion engines this is obtained at a partial load (PL) located around the range of 85% ÷ 91%. Another important observation is that for higher thermal capacity the range of the maximum thermal efficiency is widening.

The global efficiency obtained from the research and studies conducted, actually measured or deduced from elaborated calculations, were, in general, slightly lower than the specified values in the literature. This is a consequence of the age of the cogeneration system, 10 years in the studied case. However, an accurate comparison statistic cannot be presented because there are a multitude of influencing factors (particular operating conditions, calculation assumptions, imposed boundary conditions, measurement accuracy and device errors, etc.) and the analysis would be extremely broad and complex on this subject.

The obtained equations were statistically analyzed and conclusions were drawn on the meanings of terms and coefficients. These equations provide the method of fixing the calculated efficiency according to known formulas so that the final result is as accurate as possible to the real conditions obtained in practice in the operation.

In the experimental case, the modeling of the system operation and the linear equation elaborated in chap. 3.2.2 of the thesis led to differences in values between the modeled global efficiency and the global efficiency from the database (real global efficiency) between 5.96% and 9.58%.

The second constructed equation, of exponential type, chap. 3.2.3 of the thesis, improved the model for predicting the values of the modeled global efficiency according to the variation of the partial load of the trigeneration system.

The processing of information in the database and the equations developed for global efficiency values, followed by mathematical optimization have led to improved operation of trigeneration systems in terms of choosing optimal thermal loads for the base source of the consumer) and the choice of the precise number of engines to meet that requirement. The issue was resolved in the respective subchapters from a strictly mathematical point of view, in practice the obvious nominal tasks existing on the market will obviously be chosen.

A good adaptability of the trigeneration technology with RICE-s for each type of consumer was observed. This advantage also derives from the wide range of nominal powers on the market, from the smallest, 50 kW, to the largest, 12 MW. Wärtsilä 31SG, a 20-cylinder Otto cycle engine, powered by pure gas, of medium speed produces a power of 12 MW. The rated powers of the heat engines for cogeneration given in the manufacturers' declarations are rated electric powers (according to ISO 3046-1 / 2002).

Another conclusion resulting from the studies and research during the thesis, in arguing a slight adaptability, is that in the case of strong variation of the consumption characteristic is preferable a sizing and a choice of more fragmented nominal capacities, ie more load motors. lower nominal loads to cover the required load (at a cogeneration index minimum $\alpha = 0.5$ and minimum 4500 operating hours). This multiplies the simultaneous operating intervals at partial loads around PL = 88%, when the yields reach the maximum.

PERSONAL CONTRIBUTIONS

The main personal contributions made through this doctoral thesis are:

- analysis of the operating modes of internal combustion engines within a cogeneration system and realization of a mathematical model for simulating the operation;

- carrying out the case study on the real cogeneration plant in Buzău, having thermal engines as a basic source;

- obtaining, based on the information in the database, the equations of variation of thermal, electrical and global efficiencies with the partial operating load of the motors;

- obtaining an exponential equation for the variation of the overall efficiency of the cogeneration system with partial operating load;

- construction of hourly energy profiles for all types of utilities consumed by 4 categories of consumers: residential, office, hospital and commercial;

- construction of an optimal method of selection of the number of RICE-s and the optimal nominal thermal load of the engine to satisfy the highly variable demand of the hourly consumption, of the average day of each month, for 4 different categories of consumer.

PRACTICAL APPLICABILITY

The global efficiencies values from the experimental study, lower by approx. 5 percent than the values in the data sheets and than the values presented in theoretical studies in the literature, are the values most indicated to be considered in practice, at the time of the decision to implement a co / trigeneration system.

The mathematical model built to simulate the operation of the engines and the prediction values of the efficiencies offered by the regression models represent a preferable method instead of using approximate values or estimated values.

The analysis of the efficiencies of co / trigeneration systems and the assessments in this paper provide sufficient arguments to state that technologies with reciprocating internal combustion engines as prime movers have a high adaptability to highly variable loads.

The energy profiles built in the thesis can be successfully applied and can be harmonized, from the consumer's perspective, on similar buildings, with results very faithful to the reality on the ground. Consequently, the results obtained in the end in the sphere of produced energies in cogeneration, following the procedure indicated in the thesis, will draw an almost exact image of the way in which the desired system for implementation must be configured.

PERSPECTIVES

In the perspective of the research will be considered:

- analysis of the operation of trigeneration systems with thermal engines on different climatic zones;

- the study of the operation of the new generation engines, with the latest reference levels in terms of efficiency and reduction of greenhouse gas emissions;

- analysis of the influence of the coupling of heat engines with two- or three-stage absorption refrigeration installations, with EER values of 1, respectively 1.4 ÷ 1.6, according to the scientific literature.

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