PHENOMENOLOGICAL MODEL OF THE COGENERATION HEATING PLANT

MODEL FENOMENOLOGIC AL CENTRALELOR DE COGENERARE

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Abstract: *The use of mathematical models to investigate processes in energy systems and their functional components is a priority direction of research. The purpose of the paper is to develop and verify the mathematical model applied for the analysis of technical and economic indices of operation of cogeneration heating plants, which operate in the district heating systems. The investigation methodology is based on the concept of selecting the most significant factors influencing the technical-economic indicators of operation of generation sources. The fuel converted into energy (natural gas) was selected as a significant factor. By processing the technical-economic indices of operation of the sources, the functions of approximation of the production of electric and thermal energy, of the fuel utilization factor were determined, which are the main calculation relationships of the elaborated phenomenological model. The results of the parametric analysis of the evolution of the value added obtained in the transformation of fuel into energy for sets of values of energy supply tariffs and tariffs of the fuel, as well as the results of theoretical calculations and experimental data are presented. The proposed concept of elaborating the phenomenological model is also robust for other types of sources for transforming fuel into energy.*

Keywords: energy transformation, electrical and thermal power plants, global efficiency, fuel utilization factor, input-output block diagram, tariff, added value, technical and economic efficiency.

Rezumat: *Utilizarea modelelor matematice pentru investigarea proceselor din sistemele energetice și componentele lor funcționale este o direcție prioritară a cercetării. Scopul lucrării constă în dezvoltarea și verificarea modelului matematic, aplicat pentru analiza indicilor tehnico-economici de funcționare a centralelor termice de cogenerare (CET), care funcționează în sistemele de aprovizionare centralizată cu energie termică. Metodologia investigației se bazează pe conceptul de selectare a celor mai semnificativi factori care influențează indicatorii tehnico-economici de funcționare a surselor de generare. Ca factor semnificativ a fost selectat combustibilul (gaz natural) transformat în energie. Prin prelucrarea indicilor tehnico-economici de funcționare a surselor, s-au*

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determinat funcțiile de aproximare a producerii de energie electrică și termică, a factorului de utilizare a combustibilului, care sunt principalele relații de calcul ale modelului fenomenologic elaborat. Sunt prezentate rezultatele analizei parametrice a evoluției valorii adăugate obținute în procesul de transformare a combustibilului în energie pentru un set de valori ale tarifelor la energia de furnizată și tarifului la combustibil, precum și rezultatele calculelor teoretice și ale datelor experimentale. Conceptul de elaborare propus a modelului fenomenologic este robust și pentru alte tipuri de surse de transformare a combustibilului în energie.

Cuvinte cheie: transformarea energiei, producerea energiei electrice și termice, eficiența globală, factor de utilizare a combustibilului, diagrama bloc intrare-ieșire, tarif, valoare adăugată, eficiența tehnico-economică.

1. Introduction

The development and implementation of technologies for the combined production of electricity and heat is a priority direction for the development of modern energetics systems. Mostly, the implementation of these technologies is possible in localities with district heating systems (DHS). The main advantage of implementing simultaneous production technologies, at least of two types of energy delivered as goods on the market, is to increase the efficiency of conversion of primary fuel by transforming it into electricity and heat. A significant advantage of the combined production of electricity and heat consists in that this technology is the cheapest method of reducing carbon emissions and has one of the lowest carbon footprints in the category of power plants, which use fossil fuels [1]. The energy and economic efficiency of DHS is determined by several factors, including the performance of the technologies used to convert primary energy resources into energy.

The transformation of energy resources into energy is performed by district combined heating plants. As a result of the fact, that these plants produce two types of energy supplied to consumers at the same time, there are some difficulties in estimating the energy efficiency of these energy sources in the DHS and planning their use during the year.

To characterize the efficiency of DHS generation sources, several sets of indicators are used. For example, more than 20 methods and procedures are listed in the paper [2], which are applied to estimate the effectiveness of CHPs. A more widespread use are the equilibrium method (physical method) and the energetics method. These methods are ultimately reduced to the procedure for determining the specific parameters values, which characterize the fuel consumption per unit of energy produced. The equilibrium method (physical method) and the energetics method have the most frequent use.

In case a district heating system is analyzed, where the primary fuel combustion technology is used, the efficiency of the fuel transformation in energy is characterized by the fuel utilization factor (*FUF*) [3, 4]. The *FUF* indicator is used more frequently in Western European countries, and in Russia and the Eastern European countries is the used of the specific fuel consumption for the unit of electricity and heat produced [4]. It also uses of the indicator called "thermal efficiency", which characterizes which part of the heat obtained as a result of combustion of the fuel is transformed into electric and thermal energy [4]. It is applied for the performing comparative analyzes of the CHPs: ratios of the electric to the overall power and thermal energy to the overall power of the power plant [5], the global efficiency of the cogeneration process, indicator of the high efficiency cogeneration [6, 7].

The meaning of the problem regarding the estimation of the energy efficiency of cogeneration in district heating systems is also determined by the fact, that electricity and heat are traded on the market, thus transforming from a physical equivalent to a financial equivalent (in money). The value of this cash equivalent depends not only on energy tariffs for the end user, but also on the cost of energy resources and the process of transforming them into energy.

The technical, economic and regulatory (tariffs) aspect [8] is used to analyze the efficiency of the operation of DHS's generation sources. The variable costs of fuel have the highest share in operational expenditure. Forced redistribution of fuel consumption on the electricity component [8] also creates difficulties in comparing the efficiency of the operation of CHPs in DHSs. Depending on the equipment structure of the generation source, the ratio of the cost of electricity and heat produced in cogeneration has different values from one plant to another.From this observation it can be considered that this indicator cannot ensure with high credibility the correctness of the estimation of the economic efficiency of the operation of CHPs.

The existence of several methods for estimating the efficiency of CHP operation, the use of extensive sets of indicators to characterize the particularities of operation and the formulation of strategies for the distribution of operational costs, based on assigning a high quality index to electricity compared with thermal energy (exergy method) can lead to erroneous estimates of the performance of the variable load generation source of the plant [9]. Heat supply systems include several generation sources, which have the different generating capacities, different types of equipment used and load characteristics.

This paper examines the question of the determination of the technical and financial indices of the exploitation of the sources of electric and thermal energy generation from DHSs, including in cogeneration mode, taking into account the evolution of the costs of the primary energy resources used and the tariffs for the supply of electricity and heat produced, based on the phenomenological model of CHP.

2. The concept of the phenomenological model

A. Significant aspects of the analyzed concept

The variability of the thermal load, of the delivered energy tariffs, the costs of purchasing natural gas over time creates difficulties in estimating the technical-economic and financial indexes of the operation of the CHPs within the DHS. In this context, it is reasonable to address the problem of analyzing the efficiency of the operation of CHPs, as well as DHS by selecting the most significant and influencing factors for building the phenomenological model of the generation source based on available statistical data. This allows us to examine the source of energy production as a "black box", which is characterized by ***m*** inputs and ***n*** outputs. The ratios between inputs and outputs are established on the basis of operational statistical data, with the selection of the most significant influencing factors.

These parameters must be linked to the interests of the parties that supply and consume energy. The balance of interests and its maintenance is an important element in ensuring the stability and safety of the operation of power supply systems. Maintaining balance is possible by using the flexible reaction mechanism to changes outside and inside the power system. Monitoring and forecasting the consequences over time of the impact of different disturbances can ensure the formulation of decisions and reasoned reactions, which are based on the results of parametric analyzes obtained by mathematical simulation of operating scenarios of the respective object to various external and internal disturbances, which can affecting stability and efficiency of the CHP.

The main commodity supplied by DHS to the final consumer is thermal energy. This is the argument that the production of thermal energy is the main destination of CHPs, and electricity is positioned as a by-product. For these reasons, it is argued that, as an independent variable of the phenomenological model, the useful thermal power P_q of the CHP in the cogeneration regime should be defined. In this case the electric power P_{EE} will be a derived variable, which will be determined by the value of the independent variable P_q.

As informative parameters in the analysis of the energy and economic efficiency of the CHPs of the DHS can be examined: the cost of the fuel purchased for transformation into energy (market product), the delivery and supply energy tariffs, the loading quota of the CHPs and the efficiency in the given operating regime, the exchange rate, the approved methodology for setting tariffs for different consumers, the reporting duration of the production indicators, the average value of energy or generating power of the plant in the selected time interval, greenhouse gas emissions, the loading curve of the plant, the dependence of different parameters on the loading load, the cost of consumables necessary to ensure reliable operation, payroll expenses, the planned level of income, taxes paid, etc.

The weight of the listed factors (incomplete set) in the economic efficiency indices of the CHPs is different. The preliminary analysis of the impact of the influencing factors indicates that the fuel procurement expenses have the highest share in the delivery tarifs of the energy produced. For the CHPs within DHS Cisinau, the share of the cost of fuel converted into energy reaches approximately 80% of the operating costs of cogeneration sources [10, 11].

In the Figure 1*a* it is shows the simplified block diagram of the CHP from the DHS component in the input-output variant. As the output function in this case it is reasonable to define the energy obtained as a result of the primary fuel transformation process or its equivalent in the form of power. The energy obtained is delivered to consumers in the form of thermal (*Y1*) and electricity (*Y2*) energy. Part of the electricity and heat produced is used for the own consumption of the source.

In Figure 1*b* is shwos the modified variant of the block diagram, in which only the fuel procurement costs (*X1*) are considered as input parameter.The other input parameters *X2;X3;…;Xn==Fk* (see Figure 1*a*) are defined as external disturbing parameters in the examined block diagram. The cost of sales or tariffs for thermal (*Y1*) and electrical (*Y2*) energy delivered by CHP are considered as output parameters in the block diagrams in Figure 1.

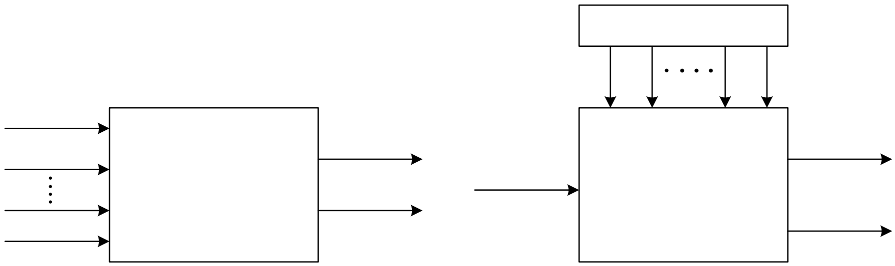

Figure 1. Simplified “input-output” block diagrams with many parametric input (a) and single input (b), when assigning to the other factors of the status of external disturbances in the process of energy transformations within the CHP

Since the purpose of economic activity consists in obtaining a benefit that would cover production costs, it is reasonable to select as a criterion the added value (plus the value) obtained as a result of the transformation of primary fuel into electricity and thermal energy sold to consumers. This "plus value" criterion is very useful for estimating and comparing the efficiency of different generation sources of the used in the DHS.

The use of this concept regarding the elaboration of the phenomenological model of the thermal and electric energy sources with different operating characteristics allows the estimation of the technological and economic efficiency of these sources at the thermal load variation at different periods of the year based on officially published of technical and economic indicators, taking into account tariffs approved by the energy regulatory organization.

B. Phenomenological model algorithm

In order to achieve the phenomenological model of the CHP, the following set of parameters was proposed:

$P_{e.n.}$ - electric power rating;

$P_{q.n.}$ - thermal power rating;

$P_{q.p.}$ - equivalent thermal power generation capacity for the time interval *t*;

$P_{e.p.}$ - equivalent electric power generation capacity for the time interval *t*;

$P_{e.oc.}$ - the value of electric power equivalent to the production of electricity in the time interval *t* used as own consumption;

$P_{q.oc.}$ - the value of the thermal power equivalent to the thermal energy in the time interval *t* used for own consumption;

P_q – independent variable (thermal power of the CHP for the load under consideration);

$E_{e.p.}$ - the amount of electricity produced in the time interval *t*, for example, quarter;

$E_{q.p.}$ - the amount of thermal energy produced in the time interval *t*;

$E_{e.del}$. - the amount of electricity delivered from the CHP bars;

$E_{q.del}$ - the amount of thermal energy delivered from the CHP collectors;

E_{PF} - the energy capacity of the primary fuel purchased and transformed by the CHP into energy for the selected period of time t.

η_{Gl} - the global efficiency of the source;

FUF - fuel utilization factor;

V_{PF} - the calculated total volume of fuel consumed by the source in the energy generation process;

V_{NG} - the volume of natural gas consumed by the source;

T_{EE} - electricity delivery tariff;

T_{ET} - the heat (thermal energy) delivery tariff;

T_{PF} - the tariff for the acquisition of primary energy resources by CET;

AV - added value;

C_{EGS} - gross cost of energy supplied;

$C_{PF} = C_{GN}$-gross cost of fuel (natural gases) used for energy production;

t - duration of the metering time of the energy produced $E_{e.p.}$ and $E_{e.p.}$

The phenomenological model as a tool for calculating the values of the parameters identified as informative values can be achieved in the following sequence:

Stage 1. Storing and processing information that characterizes the technical and economic indicators of operation: $P_{e.n.}$ - rated electrical power; $P_{q.n.}$- rated thermal power; $E_{e.p.}$- the amount of electrical energy produced in the selected time interval t, for example on the quarter; $E_{e.del.}$ - the amount of electricity delivered from the CHPs bars; $E_{q.del.}$ - the amount of thermal energy delivered from the CHPs collectors; η_{Gl} - overall efficiency of the source; V_{PF}- the amount of fuel consumed in processes of generating energy by the source; t - the duration of the metering time of the produced energy $E_{e.p.}$ and $E_{e.del}$. The amount of thermal energy produced and the amount of energy supplied from the collectors are basically the same, so $E_{q.p.} = E_{q.del}$.

Stage 2. Presentation of indices that characterize energy production and fuel consumption in the same unit of measurement. Transforming derived measurement units into SI: 1 MWh=1.163 Gcal; 1t.e.c.=7 Gcal=8.141 MWh; 1m^3 natural gases (NG)=8050 kcal (date of the SA Moldovagaz); 1Gcal=124.2 m^3 NG or 1MWh=106.8 m^3 NG.

Stage 3. Determining the equivalent values of the generation capacities, which can ensure the production in the time interval t of the respective volumes of thermal energy and electricity, which are calculated from the relations: $P_{q.p.} = \frac{E_{q.del.}}{t}$ and $P_{e.p.} = \frac{E_{e.p.}}{t}$, as well as the equivalent of the electricity generation capacity that ensures the coverage of the plant's own consumption: $P_{e.oc.} = \frac{E_{e.p.} - E_{e.del.}}{t}$. In the same way is determined of the generating capacity the CHP, which is necessary to cover its own heat consumption : $P_{q.oc.} = \frac{E_{q.p.} - E_{q.del.}}{t}$.

Stage 4. Determination of the approximation functions of the selected parameters, for example, the effective equivalent power of the electrical generating $P_{e.p.} = f\,(P_{q.p.})$ and the effective equivalent electrical power component to cover its own consumption $P_{e.oc.} = f\,(P_{q.p.})$ in the depending on the independent variable $P_{q.p.}$.

Stage 5. The determine of the function of approximating characteristic of the fuel utilization factor (*FUF*) depending on the thermal (heat) power of source $FUF = f\,(P_{q.p.})$. It is possible to present the *FUF* characteristic according to the total generating power of the source, so $FUF = f\,(P_{q.p.}+P_{e.p.})$.

Stage 6. Determination of the characteristics of the primary fuel consumption $V_{PF} = f\ (P_{q.p.})$. This characteristic describes the fuel consumption of the power plant necessary from ensure its thermal power defined by the parameter $P_{q.p.}$. The fuel requirement (equivalent to the thermal capacity $P_{q.p.}$ of the CHP) is determined from the relationship $E_{PF} = \dfrac{E_{q.p.} + E_{e.p.}}{FUF}$. The calculated values of the E_{PF} parameter allow to obtain the characteristic $V_{PF} = f\,(P_{q.p.})$.

Stage 7. The calculated E_{PF} value can be converted into units of measurement of the primary V_{PF} fuel required to produce the specified amount of energy. This can be done by using energy transfer coefficients in nominated units (see Stage 2 of this compartment).

Stage 8. We determine of price indices of the energy of source: the gross cost of the delivered energy C_{EGS} and the gross cost of the fuel used to produce the C_{PF} energy. For this it is necessary to know the tariffs for the delivery of the T_{EE} electricity and the thermal energy T_{ET}, as well as the energy quantities $E_{e.del.}$ and $E_{q.del.}$ delivered within the time period set. The gross cost C_{EGS} of the energy delivered by the source in the electrical and thermal networks is calculated with the relation $C_{EGS} = E_{e.del.} * T_{EE} + E_{q.del.} * T_{ET}$. On the basis of the T_{PF} tariff for the procurement of primary energy resources the gross cost of $C_{PF} = C_{NG}$ fuel is calculated as $C_{CHP} = V_{NG} * T_{PF}$ for the cogeneration source.

Stage 9. We determine the difference $\Delta C_{CHP} = AV = C_{EG} - C_{NG.\mathrm{CHP}}$, the cost of the energy delivered by the source and the cost of the fuel used to produce the energy supplied by the source. We will define this difference as the "added value" (AV) of primary fuel transformation in delivered energy, so $AV =. \Delta C_{CHP}$. From the point of view of the essence of a business, the parameter defined as " ***added value - AV***" has to cover all the costs of the generation source, including also a level of profitability of the enterprise. In this context, the AV parameter can be considered as the reasoned index for comparing the efficiency generation of the CHP in the DHS.

3. Phenomenological models of CHP

In order to elucidate of the application of algorithm for forming the phenomenological model of the cogeneration plant, we will use statistical data and indices of operation of district heating plants in the Republic of Moldova (two CHPs in Chisinau: SOURCE 1 (CHP-2) and SOURCE 2 (CHP-1)). These district heating power plants are equipped with aggregates of different rating power and the rate of production of electricity and heat is also different. Thus, it is possible to perform a comparative analysis of the operation of these generation sources in the composition of DHS.

The primary information on the technical and economic indicators of the SOURCE 1 (CHP-2) and SUORCE 2 (CHP-1) was selected from the website of SA TERMOELECTRICA [11]. As a result of the analysis of the production indicators of the power plants for the period 2012-2019 and their processing it are obtained the production characteristics of electric ($P_{e.p.}$) and thermal ($P_{q.p.}$) power of the plant, which are depending on the thermal demand requested by the consumer. These features can be presented by the functions: $P_{e.p.} = f\,(P_q)$ and $P_{e.del.} = f\,(P_q)$. In Figure 2 are presents of the characteristics of the power to generate electricity ($P_{e.p.}$) and of the power equivalent ($P_{e.del}$) to the energy delivered in the network of the electric power system as a result of processing the operation indices of SOURCE 1 and SOURCE 2 of SA TERMOELECTRICA during the years 2012-2020. These approximation functions present the evolution of the parameters $P_{e.p.}$ and $P_{e.del.}$ depending on the thermal power $P_{q.}$

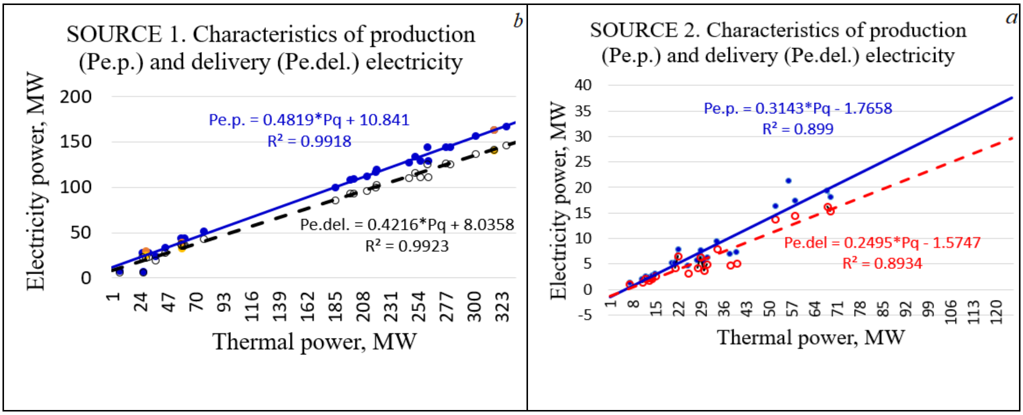

Figure 2. Electricity characteristics of production ($P_{e.p.}$) and delivery ($P_{e.del}$.) of SOURCE 1 (*a*) and SOURCE 2 (*b*)

The points on the graphs Figure 2 are the values calculated based on the energy production indices by SOURCE 1 and SOURCE 2. These values are calculated for the time interval of 2190 hours, which is the discrete interval of presentation of statistical information on the operation of generation sources. We notice that the values of the parameters $P_{e.p.}$ and $P_{e.del}$ calculated from experimental data and those based on the phenomenological model have a high degree of coincidence.

By processing the production indices of the power plants, the essential characteristics of the phenomenological model is obtained: the fuel utilization factor $FUF = f\,(P_q)$ as well as the characteristic of fuel requirement $P_{NG} = f\,(P_q)$ for producing the respective volume of electricity and thermal energy to the during of quarter. The value of the P_{NG} parameter was determined by approximating the fuel consumption characteristic and by recalculating the fuel requirement taking into account the non-linear character of the $FUF = f\,(P_q)$ characteristic. The nonlinear characteristic of the *FUF* parameter is useful to be approximate with linear functions for concrete evolution intervals of the P_q parameter (thermal generating power of the CHP). This simplifies the procedure for calculating the values of the operating parameters of the CHP at variable load, which is in fact a reality determined by the energy requirements of the consumer.

Analysis of the results of the approximation of the evolution of the operating values of the *FUF* parameter as a function of the thermal generating power P_q. indicated, that the appropriate function of approximation in the real evolution band of the parameter P_q can be considered the power function of the type: $y = Ax^k$. This function was adapted to the experimental values, including by introducing (if necessary) an additional term in the structure of this relationship.

An important step of the procedure for elaborating the phenomenological model consists in determining the characteristic $FUF = f\,(P_q)$. This characteristic is determined on the basis of quarterly operating data, which are published by the cogeneration company. When determining the function $FUF = f\,(P_q)$ for SOURCE 2, the particularity of the operation of this district heating plant in the period 2012-2020 was taken into account. Starting with 2017, SOURCE 2 operated mainly in the summer season (qr. II and qr. III) ensuring a higher value of the fuel use factor in these time intervals [10, 11]. As a result of the change in the operating mode of SOURCE 2, two approximation functions of the characteristic $FUF = f\,(P_q)$ were obtained (for the summer season and the winter season).

In order to reduce the error of the approximation of the real efficiency characteristic, it is useful to perform a statistical analysis of the primary data with the exclusion from the primary numerical series of the values, that can be considered as gross errors. This observation refers to the technical indicators of operation of SOURCE 2 (CHP-1) in qr. IV (2013) and qr.I (2014), whuch differs significantly from the efficiency parameters of the SOURCE 2 for the observating period. For example, the average value of the SOURCE 2 efficiency is 0.851, while for the indicated quarters of 2013 (qr.IV) and 2014 (qr.I), this parameter has the value of 0.727 for P_q = 22 MW and the value 0.746 for P_q = 55 MW, because are at the lower limit of the tolerance range to is determined on the Gaussian distribution of the values of the numerical series.

In Figure 3 are presents the approximation curves of the real data of the efficiency of SOURCE 1 and SOURCE 2 of DHS of Chisinau and their analytical presentation. These relations are a component part of the variants of the phenomenological models developed for SOURCE 1 and SOURCE 2.

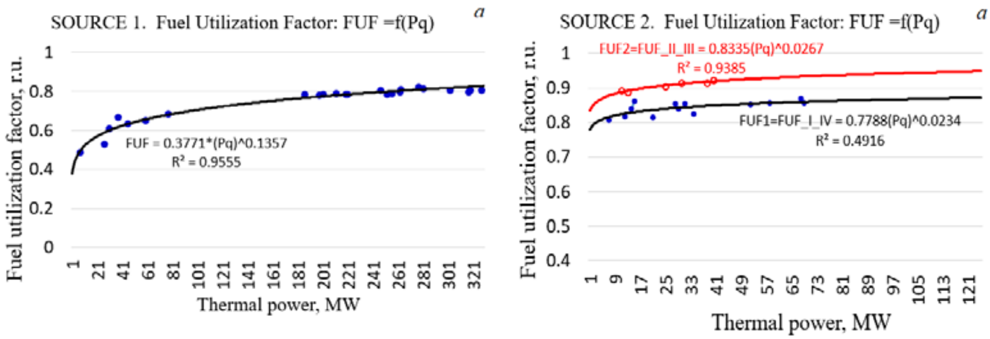

Figure 3. The efficiency characteristics of the SOURCE 1 (*a*) and SOURCE 2 (*b*) in dependentig of the equivalent thermal generating power during the quarter

The relationships of the phenomenological model of SOURCE 1 and SOURCE 2 of the DHS Chisinau are shown in Table 1.

Table 1 - *Calculation relations for the phenomenological model of SOURCE 1 and SOURCE 2*

N/o	Generation source	
	SOURCE -1 (CHP - 2)	SOURCE - 2 (CHP -1)
1	Equivalent electric power generation capacity, $P_{e.p.}$, [MW]	
	$P_{e.p.} = 0.4818*P_q + 10.841$ where P_q [MW].	$P_{e.p.} = 0.3143* P_q - 1.766$ where P_q [MW].
2	Equivalent electric power generation capacity (delivery), $P_{e.del.}$, [MW]	
	$P_{e.del.} = 0.4216*P_q + 8.036$	$P_{e.del.} = 0.2495*P_q - 1.5757$
3	Equivalent electric power generation capacity for own consumption, $P_{e.oc.}$, [MW]	
	$P_{e.oc.} = 0.0605*P_q + 2.755$	$P_{e.oc.} = 0.0453*P_q + 0.0142$ in the fourth quarter and first quarter; $P_{e.oc.} = 0.0555*P_q + 0.0136$ in the second quarter and third quarter
4	Coefficient use of fuel, FUF, [r.u.]	
	$FUF = 0.3775*(P_q)^{0.1357}-0.015$, where P_q [MW].	$FUF_{IV-I} = 0.7788*(P_q)^{0.0234}$ for quarter I and IV, where P_q [MW]. $FUF_{II-III} = 0.8335*(P_q)^{0.0267}$ for quarter II and III, where P_q [MW].
5	The equivalent power of the fuel for generation energy, P_{PF}, [MW]	

	$P_{PF} = \frac{P_{e.p.} + P_q}{FUF}$, where $FUF = f(P_q)$	$P_{PF} = \frac{P_{e.p.} + P_q}{FUF}$, where $FUF = f(P_q)$
6	Electricity produced, $E_{e.p.}$, [million kWh]	
	$E_{e.p}$ = ($P_{e.p.}$*2190)/1000.0	$E_{e.p.}$ = ($P_{e.p.}$, *2190)/1000.0
7	Electricity delivered, $E_{e.del.}$, [million kWh]	
	$E_{e.del.}$, = ($P_{e.del.}$, 2190)/1000.0	$E_{e.del.}$, = ($P_{e.del.}$, 2190)/1000.0
8	Thermal (heat) energy delivered, $E_{q.del.}$,[million kWh]	
	$E_{q.p.}$=$E_{q.del.}$=(P_q*2190)/1000.0	$E_{q.p.}$=$E_{q.del.}$=(P_q*2090)/1000.0
9	Heat (thermal energy) produced / delivered, [thousand Gcal]	
	$Eq.del.$ = (Pq*2.19)/1.163 where P_q [MW].	$Eq.del.$ = (Pq*2.19)/1.163 where P_q [MW].
10	Volume of natural gas used, V_{NG}, [million m^3]	
	V_{GN} = (P_{PF}*2.19)*0.10681 where P_{FP} [MW].	V_{GN} = (P_{PF}*2.19)*0.10681 where P_{PF} [MW].
11	The cost of electricity delivered to the network, $C_{e.del}$, [million MDL]	
	$C_{e.del.}$ = $E_{e.del.}$*T_{EE} where $P_{e.del}$ [mil kWh], T_{EE} [MDL/kWh].	$C_{e.del.}$ = $E_{e.del.}$*T_{EE} where $P_{e.del}$ [mil kWh], T_{EE} [MDL/kWh].
12	The cost of heat (thermal energy) delivered, $C_{q.del}$., [million MDL]	
	$C_{q.del.}$=$E_{q.del.}$*T_{ET}, where $E_{q.del}$ [Gcal], T_{ET} [MDL/Gcal]	$C_{q.del.}$=$E_{q.del.}$*T_{ET} , where $E_{q.del}$ [Gcal], T_{ET} [MDL/Gcal]
13	The cost of natural gass, C_{NG},[million MDL]	
	C_{GN} = V_{GN}*T_{PF}, where V_{GN} [mil. m^3]; T_{PF} [MDL/m^3]	C_{GN} = V_{GN}*T_{PF}, where V_{GN} [mil. m^3]; T_{PF} [MDL/m^3]
14	Added value, AV, [million MDL]	
	AV=$C_{e.del.}$ + $C_{q.del.}$ - C_{NG}	AV=$C_{e.del.}$ + $C_{q.del.}$ - C_{NG}

4. Case study

The relationships presented in Table 1 allow us to perform the parametric analysis of the operation of SOURCE 1 and SOURCE 2 in different operating modes. When performing the analysis, it is necessary to take into account the current status of the sources in the technological chain of energy production and supply. Two options are possible. The first - the sources have the status of independent economic agent, which make sales of energy products to electricity and heat distribution companies. In this case, each generation source will have its own tariffs for the supply of electricity and heat. This form of economic activity of the sources was valid until 2015. The second case, the sources are integrated in DHS as functional components of energy production, which is sold to the electricity distribution company or the final consumer in the case of thermal energy at tariffs. The tariffs are approved by the National Agency for Energy Regulation (NAER).

In the second case, it is necessary to take into account the energy losses in the thermal distribution networks of the DHS. According to NAER data from the Republic of Moldova, the losses from DHS Chisinau in 2018 amounted to about 19.64%. As a result of this particularity, it is necessary to consider that the useful volume of thermal energy supplied to the final consumer taken into account will be different from the thermal energy produced $E_{p.del}$ with the share of losses. In this case, the tariff approved by NAER for the final consumers will be used to calculate the cost of useful thermal energy. In the first case, we will work with the approved tariff for the thermal energy from CHP, sold to the distributor of this energy (cost at the entrance to the distribution networks or at the Source collectors).

In the context of the above, can be proposed of the indicators determining the production characteristics of electricity and heat for SOURCE 1 and SOURCE 2 for example costs of energy produced and supplied, as well as the cost of natural gas needed to produce of planed volumes of electricity and heat.

The primary information on the technical and economic indicators of SOURCE 1 (CHP - 2) and SOURCE 2 (CHP - 1) was selected from the website of S.A. TERMOELECTRICA [11]. As a result of the analysis of the production indicators of power plants for the period 2012-2019 and their processing, the production characteristics of electricity ($P_{e.p.}$) and thermal energy (P_q) are obtained. which depend on the thermal demand requested by the consumer. These functions can be represented by the functions: $P_{e.p.} = f\,(P_q)$ and $P_{e.del.} = f\,(P_q)$.

The calculations were performed for different values of natural gas purchase tariffs (5.237; 5.133; 6.028; 5.712; 5.0; 4.265; 4.018 MDL / m^3), tariffs of electricity 1.583 MDL / kWh (SOURCE 1), 1.6614 MDL / kWh (SOURCE 2) and tariffs of the thermal energy (heat) (987; 1068 and 1122 MDL / Gcal). Also, calculations were performed for the electricity tariff of the SOURCE 1 and SOURCE 2 equal to 1.16 MDL / kWh, recently proposed by ANRE (10.03.2020) with the determination of the added value obtained following the transformation of the primary fuel (natural gas supplied by GAZPROM) in energy. In generalized format, the results of these calculations are shown in Figures 4 -9.

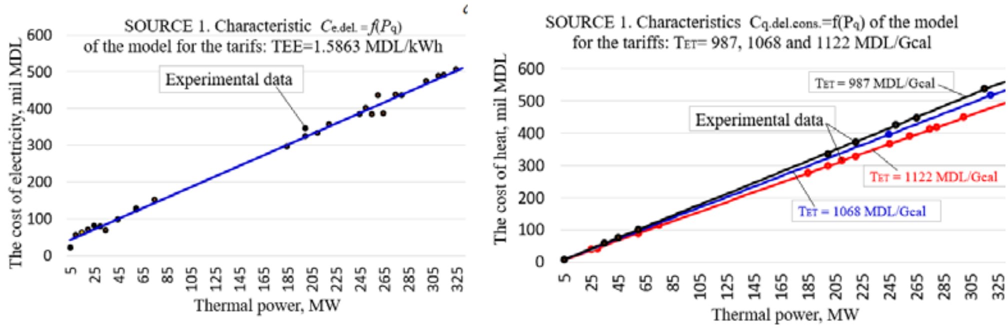

Figure 4. Characteristics of the phenomenological model for SOURCE 1 regarding the cost of electricity (*a*) supplied in the electricity network and thermal energy (*b*) supplied to the final consumer (for indicated tariffs) according to the thermal generating power P_q

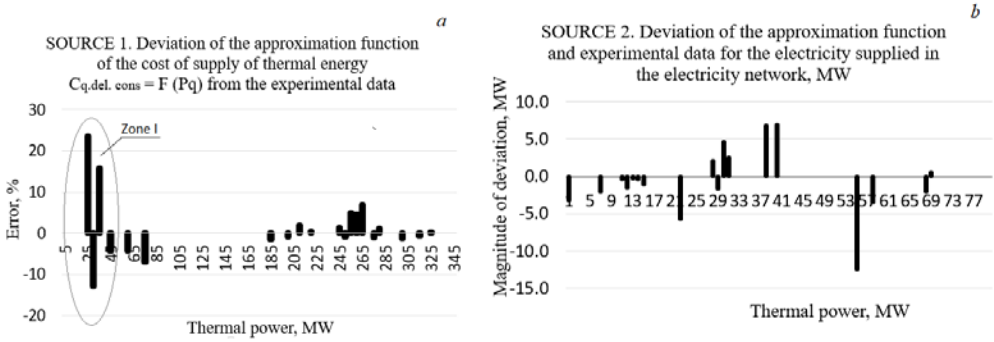

Figure 5. Deviation of the approximation function from the experimental values of electricity supplied in the electricity grid by SOURCE 1 (*a*) and SOURCE 2(*b*) as a function of thermal power P_q

Knowing the approximation functions of the equivalent power to generate electricity ($P_{e.p.}$) and the equivalent power ($P_{e.del.}$), which is determined by the volume of electricity provided by the CHP in the electricity network, allows the parametric analysis the cost of energy produced and supplied in different CHP operating regimes (Figure 4). Changing the heat tariff leads to a change in the cost of heat supplied to the final consumer (Figure 4*b*). At the same time, it is possible to mention the good coincidence of the calculated costs and the operating costs for the supplied electricity (Figure 4*a*) and for the heat supplied to the final consumer by SOURCE 1 (Figure 4*b*). Figure 5 shows the results of the analysis of the deviations of the experimental data from the theoretical function of the approximation of the thermal energy cost provided by SOURCE 1 (Figure 5*a*) and the magnitude of deviations (in the absolute units MW) from theoretical approximation (Figure 5*b*).

The most significant deviations of the experimental data from the approximation function are detected for the zone (Zone I) for small values of the thermal generating power P_q (Figure 5*a*).

The use of specific technical and economic indices is of interest for the comparative analysis of the transformation efficiency of primary fuel (natural gas). The specific parameters (kWh / m^3) and (MDL / m^3) are proposed as informative indicators. The first indicator (kWh / m^3) characterizes the technical efficiency of the transformation process and is determined by the technological performance of the generation source (Figure 6). The second indicator (MDL / m^3) is determined both by the performance of the plant technology and by the level of tariffs for energy supplied and the tariff for energy resources (natural gas) transformed into energy (Figure 7).

There is a good correlation between the calculated values of the specific indicators kWh / m^3 and MDL / m^3 and the experimental data for the period taken into account (2012-2019). Starting with 2016, there is an increase in the values of these performance indicators. We will mention that the calculation of the values of the specific indicators was made taking into account the evolution of the tariffs for thermal energy and natural gas in the period 2012-2019.

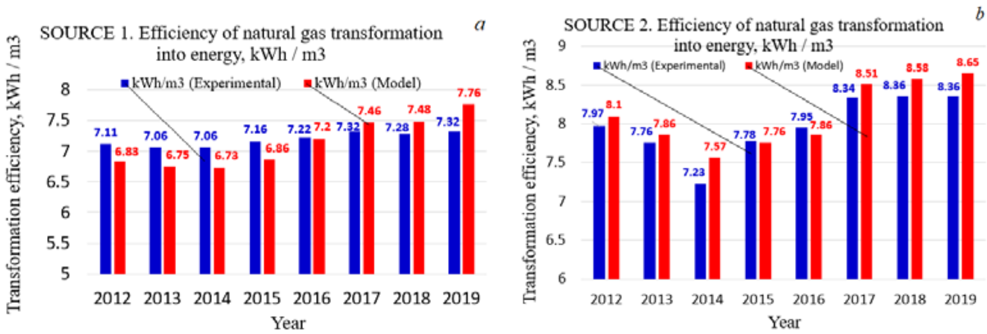

Figure 6. Indicators of the efficiency of the transformation of the energy potential of natural gas into energy by SOURCE 1 (*a*) and SOURCE 2 (*b*)

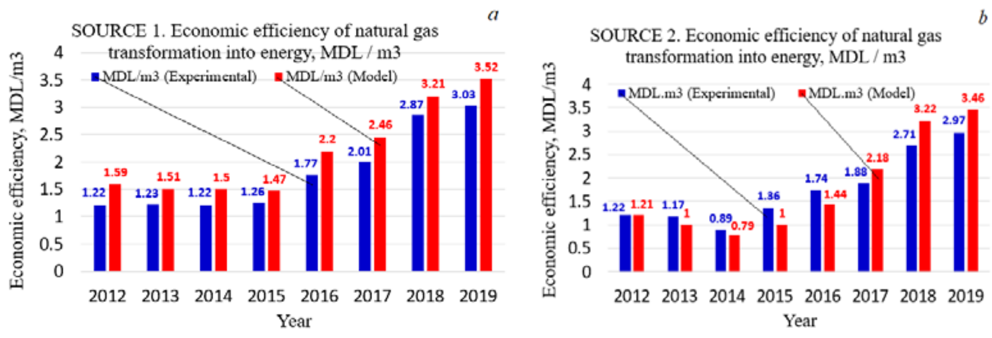

Figure 7. Indicators of the economic efficiency of the transformation of the energy potential of natural gas into energy by SOURCE 1 (*a*) and SOURCE 2 (*b*)

Figure 8 shows the diagrams on value added calculated for quarter II and quarter III of 2012-2019 based on experimental data. The second quarter includes the heating season for which an essential thermal load of the DHS is characteristic and as a result SOURCE 1 ensures the formation of a rather significant added value (Figure 8*a*). In the third quarter the thermal load of the SACET decreases and in these conditions SOURCE 1 the added value is negative or very close to zero (Figure 8*b*). The use in the third quarter to cover the thermal load in DHS of the SOURCE 2 leads to obvious economic benefits compared to the operating regime of SOURCE 1 (Figure 8*b*).

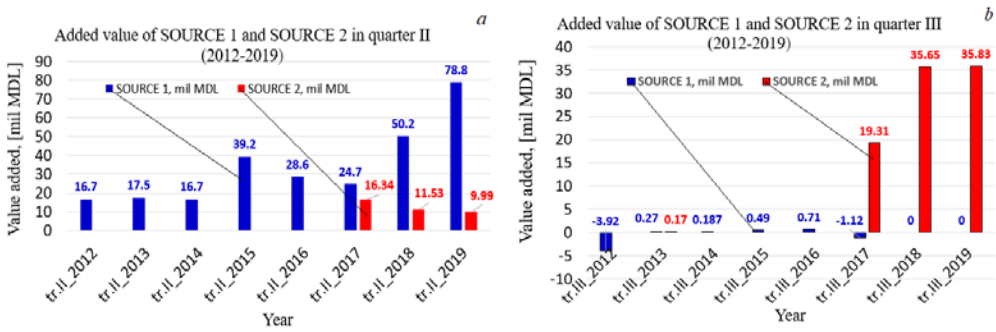

Figure 8. The value added formed by the transformation of natural gas into energy in qr.II (*a*) and qr. III (*b*) by SOURCE 1 and SOURCE 2 (2012-2019)

Figure 9 shows the results of the analysis of the impact of tariff of the electricity supplied on the variation of the added value formed by the transformation of natural gas into electricity and heat, which are provided in the electrical network and to the final consumer at existing of the tariffs. Balancing the electricity tariff leads to an increase in the economic efficiency of SOURCE 2 in the thermal load band of relative value (Figure 9b). When we applying of the electricity tariffs T_{EE} = 1.16 MDL / kWh in the evolution band of the thermal power P_q <175 MW for SOURCE 2 in the summer period, this decision will bring economic benefits to the company S.A. TERMOELECTRICA during the summer compared to using SOURCE 1. The best results will be obtain for heat load 40 <P_q <100 MW. The maximum benefit (gain at the level of about 9 mil MDL per quarter) can be obtained at the load P_q = (50-90) MW.

The use of the phenomenological model allows the selection of the charging regime of the generation sources in different periods of the year in order to obtain the highest economic benefit. This suggestion is confirmed by the results of the operation of SOURCE 2 in the period 2017-2019 (Figure 8). The application of this decision allowed the optimization of the operation of the generating sources of S.A. TERMOELECTRICA during the summer at low thermal loads.

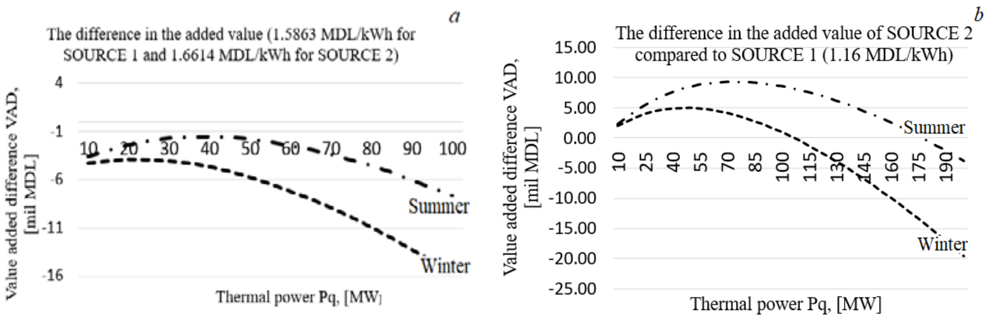

Figure 9. Evolution the difference of the added values of SOURCE 2 and SOURCE 1 for the electricity tariff T_{EE} = 1.5863 MDL / kWh (*a*) and the tariff T_{EE} = 1.16 MDL / kWh (*b*), where the thermal energy tariff constitutes T_{ET} = 1122 MDL / Gcal and for natural gas T_{GN}=4.018 MDL / m^3.

6. Conclusions

Based on the analysis of the satistical information on the technical-economic indicators of operation the CHP of the district heating systems, it was found that the fuel transformed into energy has the greatest weight on the economic efficiency of these enterprises. For S.A. THERMOELECTRICA (mun. Chisinau) the cost of fuel in operating expenses is (77 - 80)%. As a result, it was proposed to select as an indicator for estimating the technical-economic performance of CHP the added value obtained from the transformation of natural gas into energy compared to the costs of purchasing this fuel.

The phenomenological model of CHP has been proposed in which fuel is examined as input parameter and electricity and thermal energy produced as output parameters. The output parameters are used to calculate the derived (other) parameters: the energy costs supplied, technological efficiency indicators such as the efficiency of natural gas conversion into energy (kWh / m3), as well as the economic efficiency indicator such as the added value obtained as a result of primary fuel transformation in energy (MDL / m3).

The proposed phenomenological model allows the execution of the parametric analysis of the technical-economic indicators of CHP the district heating system, when changing the electricity and heat tariffs provided by CHP, the natural gas tariffs used, as well as the load regime of the CHP. These analyzes allow the argumentation of the optimal operating regimes of the CHP to ensure the maximum efficiency of the fuel transformation in energy, as well as the planning of the seasonal operation of the available DHS generation sources based on the criterion of economic efficiency.

The proposed methodology for bilding the phenomenological model is robust both for CHP and for boiler plants of the district heating systems.

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