ENERGY, ECONOMIC AND ECOLOGICAL ANALYSIS OF COGENERATION

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ABSTRACT

The paper analyzes the energy, economic and environmental factors that influence the production of heat and electricity in cogeneration, process which involves the existence of a thermal machine (steam turbine, gas turbine, heat engine) that (co)generates the two directly usable energy flows: thermal and electrical. The thermal car works based on a direct thermodynamic cycle (engine), taking a high-temperature heat flow from the "hot source" and eliminating a lower temperature heat flow to the "cold source".

KEYWORDS: cogeneration, heat, power, efficiency, economic, energy, environment

1. INTRODUCTION

Cogeneration is the combined and simultaneous production of mechanical work and heat from a single primary energy source.

The process involves the existence of a thermal machine (steam turbine, gas turbine, heat engine) that (co)generates the two directly usable energy flows: thermal and electrical. The thermal car works based on a direct thermodynamic cycle (engine), taking a high-temperature heat flow from the "hot source" and eliminating a lower temperature heat flow to the "cold source".

Cogeneration consists of using at least part of the heat extracted from the cycle and using it in this form to supply some consumers, which partially or totally take over the role of cold source of the motor thermodynamic cycle [1].

By its nature, the process of combined and simultaneous production of the two forms of energy achieves an effective saving of primary energy (fuel) compared to the separate production of mechanical work (in a thermoelectric power plant) and heat (in a thermal power plant). This fuel saving is reflected from an economic point of view, in the reduction of fuel costs of the production plant and from an ecological point of view, in the reduction of environmental pollution.

Thus, cogeneration is one of the most economical technologies for reducing greenhouse gas emissions, a role officially recognized by the European Union, along with the use of renewable energies.

By its nature, the combined and simultaneous production process achieves an effective saving of primary fuel compared to the separate production of mechanical work (in a thermoelectric power plant) and heat (in a thermal power plant). This saving translates firstly into a reduction in the fuel costs of the manufacturing facility and secondly into a reduction in environmental pollution.

2. ENERGY ANALYSIS

The problem of estimating the nominal thermal capacities of the various equipment arises in the case of cogeneration plants, when the total thermal capacity q^C must be broken down between the basic installations q^C_B and the peak thermal installations which can be additional combustion $q^C_{V,AS}$ (only in the case of cogeneration with gas turbines) and/or peak boilers $q^C_{V,C}$.

The nominal thermal capacity of the cogeneration plants themselves is:

$$q^C_B = \alpha^C \cdot q^C \qquad (1)$$

where α^C is the nominal coefficient of cogeneration, and q^C is the total thermal capacity of the source.

In the case of cogeneration plants, regardless of the nature of the basic energy equipment – gas turbines or heat engines, the cogeneration plant is sized for:

$$q^C = q_i^C + q_{ac}^{mdC}$$

This way of sizing is justified by:

- the maximum consumption of domestic hot water is not simultaneous in time, which flattens the daily consumption curve;
- the transmission and distribution system and the heat consumers for heating have a natural capacity to accumulate heat high enough to take over the daily variations in domestic hot water consumption.

The nominal coefficient of cogeneration α^C is an indicator characteristic of the design of a cogeneration plant. The value of this indicator is determined differently according to the relation of the cogeneration plant with the energy system.

In the case of cogeneration plants that do not change power with the energy system (even if it is interconnected for safety reasons), the nominal cogeneration coefficient α^C is determined from the balance of electrical powers, respectively from the equation:

$$P^C = \alpha^C \cdot y_T^C \cdot q^C \qquad (2)$$

where y_T^C is the cogeneration index (a characteristic of the cogeneration equipment used, and PC - the electrical power required by the electricity consumers supplied by the cogeneration plant.

In the case of some cogeneration plants that exchange power with the energy system, the value of this coefficient is determined following the optimization of the capacity structure of the equipment in the cogeneration plant.

A cogeneration plant with gas turbines can cover by recovery (in cogeneration itself) a quantity of heat q_B^C and by additional combustion in the recovery boiler, an amount of heat $q_{V,AS}^C$. As a result, the gas turbine cogeneration plant covers the total amount of heat q_{TG}^C:

$$q_{TG}^C = q_B^C + q_{V,AS}^C \qquad (3)$$

and the special peak boilers the amount of heat $q_{V,C}^C$:

$$q_{V,C}^C = q^C - q_{TG}^C \qquad (4)$$

The heat capacity to be produced by additional combustion $q_{V,AS}^C$ is determined as follows:

- if $\alpha^C \le \alpha_{\lim}^C = 1 - \frac{q_{V,AS}^{Max}}{q^C}$, then

$$q_{V,AS}^C = q_{V,AS}^{Max} \qquad (5)$$

For gas turbine installations of current configuration, in the event of the use for additional combustion in the recovery boiler of the same fuel as the one burned in the combustion chamber of the gas turbine installation, the simplified equation can be written:

$$q_{V,AS}^{Max} \simeq (2 \div 4) \cdot q_B^C \qquad (6)$$

With the above value, the value can be estimated:

$$\alpha_{\lim}^C \simeq 0{,}2 \div 0{,}33 \qquad (7)$$

if $\alpha^C \ge \alpha_{\lim}^C = 1 - \frac{q_{V,AS}^{Max}}{q^C}$, then:

$$q_{V,AS}^C = (1 \quad \alpha^C) \cdot q^C \qquad (8)$$

and $q_{V,C}^C$=0.

Once the value of the nominal coefficient of cogeneration has been determined, the number and nominal capacity of the equipment used is determined with the relations:

$$n \cdot q_{B,0}^C \ge q_B^C \qquad (9)$$

$$n_c \cdot q_{V,0}^C \ge q_{V,C}^C \qquad (10)$$

where n is the number of cogeneration energy groups; NC - the number of peak hot water boilers to be installed $q_{B,0}^C$- the nominal thermal capacity of a cogeneration group (excluding additional combustion, if any); q_0^C- the nominal capacity of a peak boiler; q_B^C and $q_{V,C}^C$ the thermal load produced only in the basic (cogeneration) plants and respectively in the peak boilers.

The number of energy equipment and peak boilers in the cogeneration plant shall be chosen as follows: $1 \le n_c \le 3...4$ and $1 \le n_c \le 3...4$. The reasons for this choice are the same as those envisaged in the case of thermal power plants.

2.1. Estimation of annual heat productions

The annual heat productions were established, similar to the installed thermal capacities, based on the annual heat consumption covered and the heat losses during transport.

If several energy installations (recovery boilers, additional combustion – if applicable – and peak boilers) participate in covering the annual heat production, the participations of each installation were established based on the modeling of the annual thermal load curve, considering their installed capacities.

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$$Q^a = Q_i^a + Q_{ac}^a \quad (11)$$

where:

$$Q_i^a = q_i^C \cdot \frac{20-t_e^{mdi}}{20-t_e^C} \cdot \tau_i \quad (12)$$

in which:

$$t_e^{mdi} = 20 - \frac{24 \cdot N_Z}{\tau_i} \quad (13)$$

and:

$$Q_{ac}^a = q_{ac}^C \cdot \delta_{ac} \cdot \tau_{ac} \quad (14)$$

where q_i^C and q_{ac}^C are the nominal heat consumption for heating and for the preparation of domestic hot water provided by each source; t_e^C and $t_e^{mdi}$the conventional minimum outdoor temperatures (according to the regulations) and averages during the winter period; N_Z numarul de grade zile (conform normativ); τ_i si τ_{ac} the duration of the heating period (according to the regulations) and the hot water supply period; and δ_{ac} the degree of flattening of the daily curve gives domestic hot water consumption ($\delta_{ac} \simeq 0{,}5$) [2].

In the case of cogeneration plants, it is necessary to know how the cogeneration plants and peak plants participate in covering the annual heat production of the source considered:

Taking into account the basic cogeneration plants and the peak thermal ones, the following relation can be written:

$$\alpha^a = \frac{Q_B^a}{Q^a} \quad (15)$$

where α^a is the annual coefficient of heating (cogeneration) achieved, and Q_B^a the participation of the cogeneration plants to cover the annual heat production.

In case of cogeneration plants with gas turbines based on the nominal heatig coefficient installed α^C and participation ($\alpha_{TG}^C = \frac{q_{TG}^C}{q^C}$) of the gas turbine working in nominal regim (including additional combustion- $q_{TG}^C = q_B^C + q_{V,AS}^C$) When covering the heat delivered by the source, the annual shares of the recovery (heat delivered in base mode) α^a from the flue gases and of the gas turbine installation α_{TG}^a(including additional combustion) to cover the annual heat production $Q^a$are determined. So, the following relations can be written:

$$Q_B^a = \alpha^a \cdot Q^a \quad (16)$$

$$Q_{TG}^a = \alpha_{TG}^a \cdot Q^a \quad (17)$$

$$Q_{V,AS}^a = Q_{TG}^a - Q_B^a \quad (18)$$

$$Q_{V,C}^a = Q^a - Q_{TG}^a \quad (19)$$

2.2. Estimation of annual electricity productions

The annual electricity productions are established, similar to the installed electrical capacities, differentiated according to the dependence of the cogeneration plant with the energy system:

- in the case of cogeneration plants that do not exchange power with the energy system, the annual electricity productions are established on the basis of the annual electricity consumption to be covered, the electricity consumption for pumping hot water and the own energy consumption of the cogeneration groups;

- in the case of cogeneration plants that exchange electricity with the energy system, they are estimated based on the annual heat productions of the basic installations Q_B^a and the specific electricity productions of the cogeneration installations on account of the recovered heat (produced in the basic installations).

The specific electricity production of a cogeneration plant, or its cogeneration index, characterizes the plant from the point of view of the quality of the conversion processes. The method of determination and the values of this cogeneration index depend on the type of cogeneration plant and can be estimated with the equation:

-for gas turbine cogeneration plants:

$$y_T \simeq \frac{1}{\frac{1}{\eta_{TG}} - 1.05} \cdot \frac{1}{x_R} \quad (20)$$

$$x_R \simeq \frac{t_g^{ev} - t_g^{CR}}{t_g^{ev} - t_0} \quad (21)$$

where η_{TG} is the electrical efficiency of the gas turbine (given by the literature); x_R the degree of recovery of the heat discharged from the turbine with the flue gases; t_g^{ev} the temperature of the flue gases discharged from the turbine (given by the literature, correlated with the efficiency); t_g^{CR} the temperature of the flue gases discharged from the recovery boiler (depends on the fuel used by the gas turbine installation: for natural gas t_g^{CR} it is about 120 °C, and for liquid fuel t_g^{CR} it is about 150 °C); t_0 ambient temperature.

Regardless of the type of cogeneration plant, the electricity produced annually in cogeneration will be calculated with the equation:

$$E_T^a = y_T \cdot Q_B^a \quad (22)$$

However, a cogeneration group can also produce electricity without it being obtained in cogeneration, so the annual production of electricity must meet the condition:

$$E_p^a \geq (E_T^a = y_T \cdot Q_B^a) \quad (23)$$

The amount of electricity delivered annually E^a will be:

$$E^a = E_p^a - E_{SI}^a \quad (24)$$

where E_{SI}^a represents the annual consumption of the internal services of the cogeneration plant (the consumption of the installations annexed to the cogeneration groups plus the consumption for pumping the heat transport agent).

2.3. Estimation of annual fuel consumption

In the case **of cogeneration plants,** the estimation of annual fuel consumption is based on the knowledge of the annual heat and electricity productions.

For cogeneration plants **with gas turbines**, the annual fuel consumption (expressed in energy units) is:

$$B_{TG} = \frac{E_p^a}{\eta_{TG}} + \frac{Q_{V,AS}^a}{\eta_{AS}} + \frac{Q_{V,C}^a}{\eta_C} \quad (25)$$

Where E_p^a is the electricity produced annually; $Q_{V,AS}^a$ heat produced in the recovery boiler based on additional combustion (heat produced in peak mode); $Q_{V,C}^a$ the heat produced annually in the special peak boiler (if applicable); and η_{TG}, η_{AS} η_C also the yields of electricity production by the gas turbine, additional combustion and the special peak boiler.

3. ECONOMIC ANALYSIS

Estimation of investments

For an easy use of investment data, analytical equation established by regression based on data from the literature were used in the calculation programs. They refer to the reference equipment for each type of basic installation (boiler, turbine, engine) for cogeneration plants:

- with gas turbines (including the recovery boiler):

$$I_{TG,0} = 7.5 \cdot 10^6 \cdot \left(\frac{P_0^C}{10}\right)^{0,75} [€] \quad (26)$$

- with gas turbines with recovery boilers with afterburners, the additional cost due to additional combustion is added to the above values:

$$I_{AS} \simeq 10 \cdot q_{AS}^C \; [€] \quad (27)$$

The equation refers to a single piece of equipment, the unit thermal and q_0^C unit electrical powers P_0^C are introduced into the MW.

If peak boilers are also installed in the cogeneration plant, the investments in them calculated with the corresponding relation were also considered [3].

The total investments will be for the case of a cogeneration plant with gas turbines (with n_{TG} gas turbines with the related recovery boilers and with additional combustion and *with nine* special peak boilers):

$$I_{CET,TG} \simeq n_{TG} \cdot I_{TG,0} + 10 \cdot q_{V,AS}^C + n_c \cdot I_{CT,0} \; [€] \quad (28)$$

Estimate of annual receipts

The annual revenues from the sale of heat and electricity were estimated based on the annual quantities of heat and electricity delivered:

$$\text{In} = Q^a \cdot p_Q + E^a \cdot p_E \quad (29)$$

where *Qa* and *Ea* are the annual quantities of heat and electricity (if the source is the cogeneration plant) sold annually; and p_Q also p_E the selling prices of heat and electricity. In the case of boilers, the equation is particularized by imposing *Ea=0.*

Estimation of annual production costs

The annual production costs can be estimated:

$$C = C_B + C_{E+I} \quad (30)$$

where *CB* are the annual expenses for the purchase of fuel; *CE+I* annual operating, maintenance and repair expenses.

The annual expenses for the purchase of fuel are:

$$C_B = B \cdot p_B \quad (31)$$

where B is the annual fuel consumption, and p_B is the unit price of the fuel used.

The annual expenses for operation, maintenance and repairs are determined based on data from the specialized literature as follows:

-for cogeneration plants with gas turbines:

$$C_{E+I} \simeq 8,77 \cdot 10^3 \cdot P_{TG}^c + 2,1 \cdot E_p^a + 2\% \cdot I_{V,C} \quad [€/an] \quad (32)$$

where, apart from the notations defined above, $P_{TG}^c P_{TA}^c$ the total electrical power installed in the cogeneration power plant, in MW, was also noted; and with E_p^a the electricity produced annually by the cogeneration power plant (with gas turbines or thermal engines), in MWh/year; and with $I_{V,C}$ the investment in peak boilers.

According to the methodology used in calculations of this kind in Romania or in those agreed by foreign banks or companies, the updated net income criterion was used for the technical-economic comparison.

The discounted net income criterion uses the discounting technique that allows the expression of the amounts spent and/or collected at different times in monetary values brought at the same reference time.

Depreciation is not included in the annual expenses. Their inclusion would lead to the consideration of investments twice, once directly and once indirectly through depreciation [4].

4. ECOLOGICAL ANALSIS

The determination of the ecological and economic effects were made for cogeneration - gas turbines (TG).

The objective of carrying out the environmental impact analysis is to provide the necessary elements for the environmental impact assessment of the possible technical solution for supplying heat and electricity to an urban area.

The following steps were completed:

- establishing the hypotheses of the application of the method;
- compilation of a database with specific emissions by type of equipment;
- determining the emissions related to the production of heat and electricity;
- establishing and calculating impact indicators;
- analysis of the determined impact indicators;
- interpretation and comparison of the impact indicators resulting from the ecological analysis carried out, with the existing norms and regulations;
- economic quantification of environmental effects, in the cost of heat and electricity produced, within the different production chains (in cogeneration and/or separate).-

The environmental impact of heat and electricity production is based on:

- the type of energy source;
- the type of fuel used in the energy source;
- the stages of the life cycle considered.

The environmental impact analysis was done taking into account the energy conversion stage within the source.

A particularly important stage is the establishment of the hypotheses for carrying out the analysis. These are:

- for all cogeneration sectors, the same type of fuel with the same characteristics is considered;
- the environmental impact aspects of the manufacture of energy production facilities within cogeneration plants are neglected, because the impact of the component materials of these plants is much lower than the impact of their operation;
- the efficiencies of turbomachinery, electric generators, recovery boilers are considered included in the overall efficiency of cogeneration systems.

Based on the established hypotheses, the following were determined:

- the values of pollutant emissions into the atmosphere released as a result of combustion processes, expressed in mg/Nm3 flue gases (within the CCG).

In order to determine the emissions, it was necessary to know:

- the type of fuel used (lower calorific value, Hi);
- fuel consumption;
- the values of specific emissions into the atmosphere;
- the characteristic technical aspects, by overall efficiency, ηg;
- energy production (electrical, thermal);
- indicators specific to the cogeneration solution.

The emissions related to the energy production chains analyzed were calculated, for a specific case, the heat supply of an urban area.

When determining the emissions, the mode of production (conversion yields) of the two forms of energy was taken into account:

electricity and thermal (in cogeneration, in peak installations).

They were determined for average combustion plant yields, for the same type of fuel and having approximately the same extraction, processing and transport yields.

The greenhouse effect

It represents the warming of the atmosphere caused by the capture of infrared radiation reflected by the earth's surface.

This index compares the instantaneous emission of a kilogram of gas with the emission of a kilogram of carbon dioxide considered as a reference (its global warming potential is considered unitary).

The overall greenhouse effect potential of a gas is determined by summing the elementary effect potentials corresponding to each component gas of cogeneration emissions:

$S(ki)=\Sigma S_{ij}=\Sigma m_{ij}.sj$[kg/functional unit] (33)

Where: S(ki) represents the greenhouse effect potential of gaseous effluent 'k' emitted by subsystem 'i'; Sij - the potential greenhouse effect of the element "j" emitted by the subsystem "i"; MIJ – the amount of element that produces the greenhouse effect "j" emitted by the subsystem "i", in kg/functional unit; sj – GWP (20 years) of one kilogram of element "j".

The main gases that directly participate in the creation of the greenhouse effect are: carbon dioxide (sCO2 = 1) and methane (sCH4 = 35).

Oxidizing photo emissions

The contribution of gaseous substances of type "j" emitted by subsystem "i", to the destruction of the stratospheric ozone layer, related to cogeneration, is characterized by an indicator described by the equation:

$$I_i = \Sigma m^i_j \cdot ODPj \quad (34)$$

where: Ii is an indicator of the subsystem 'i' which represents the contribution to the destruction of the stratospheric ozone layer; MIJ – mass of greenhouse gaseous substance 'j' emitted by subsystem 'i';

ODPj – the degradation power of the ozone layer of one kilogram of gas in relation to the same amount of CFC11.

Acidification

It represents the disturbance of the acid-base balance of the atmosphere due to the gaseous emissions of an acidic nature resulting (from the processes related to cogeneration). They can cause significant disturbances of all elements of the environment (air, water, soil), inducing an increase in pH.

The most widely used acidification indicator is the equivalent acidity (in relation to SO2).

$$I^i = \Sigma j\ AP_j \cdot m^i_j \quad (35)$$

where: Ii is the contribution to acidification of subsystem 'i', in kilogram of SO2 equivalent; APj – acidification potential of substance 'j'

Where:

$AP = \Sigma x\ (q_x \cdot APx)$ [kg echivalent SO_2] (36)

and q_x is the mass of substance 'x' emitted into the air, in kg; APx – acidification potential of substance "x"; PA – the potential for acidification of the effluents of a system, in kg of SO2 equivalent.

5. CONCLUSIONS

The paper analyzes the energy, economic and environmental factors that influence the production of heat and electricity in cogeneration.

Thus, the number of energy equipment and peak boilers in the cogeneration plant are chosen as follows: $1 \leq n_G \leq 3...4$ and $1 \leq n_c \leq 3...4$. The reasons for this choice are the same as those considered in the case of thermal power plants. Also, the criterion of the net discounted income uses the updating technique that allows the expression of the amounts spent and/or collected at different times in monetary values brought at the same reference time, and the analysis of the environmental impact was made taking into account the stage of energy conversion within the source.

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