CASE STUDY REGARDING THE ENERGY EFFICIENCY OF COGENERATION COMPARED TO SEPARATE HEAT AND POWER SUPPLY OF A RESIDENTIAL AREA

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Articolul prezintă o analiză de caz a eficienţei energetic a cogenerării comparativ cu soluţia separată de alimentare cu căldură şi energie electrică a unei zone rezidenţiale. Au fost analizate două soluţii: centrală termică cu cazane de apă fierbinte (energia electrică se cumpără din sistemul energetic naţional) şi centrală de cogenerare cu turbine cu gaze. Au fost efectuate analiza energetică şi economică pentru ambele soluţii. Concluziile acestui studiu de caz conduc la aceea că soluţia de cogenerare conduce la o eficienţă energetic mai mare iar indicatorii economici au valori mai mari, astfel că soluţia este optimă pentru acest studio de caz.

The paper presents a case study regarding the energy efficiency of cogeneration compared to separate heat and power supply of a residential area. There have been analysed two solutions of heat supply: thermal plant with heat only boilers (electricity is purchased from the national power grid) and cogeneration plant with gas turbines. There have been performed an energy and economic analysis of both solutions. The conclusions of this case study are that cogeneration leads to better energy efficiency and higher economic criteria. Thus, this solution has been chosen as being the optimal one for this case study.

Keywords: cogeneration, energy efficiency, gas turbine

1. Introduction

The EU Council has adopted the energy strategy for the period until 2020 “Europe 2020 for an intelligent, sustainable and favourable for inclusion growth” [1]. The strategy sets the following goals:

- Reduction with 20 % of green house gasses emissions.
- Increasing with 20 % the share of energy production from renewable energy sources.
- Increasing with 20 % the energy efficiency.

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For reaching these goals in the field of energy generation and utilisation the main ways are to use "clean" technologies, which lead to a higher efficiency and lower environmental impact, [2 and 3].

In this context, cogeneration, as a technology for combined production of power and heat, through its energy, economic and environmental advantages, can be defined as a "clean" technology for energy generation that corresponds both to increasing energy efficiency and reduction of environmental pollution.

The new cogeneration technologies, based on small scale gas turbine and internal combustion engine technologies, are penetrating the market due to their high energy, economic and environmental performances, [4, 5 and 6].

The economic evaluation based on the fuel savings of the combined power and heat production compared to separate energy generation shows the advantages of cogeneration technology. Fuel savings also lead to decreasing the environmental pollution through diminishing the green house gasses emissions, but also have an indirect positive impact on the environment.

Increasing the energy efficiency and decreasing the environmental pollution through use of cogeneration for a given costumer lead to increasing the economic efficiency.

The paper will present a case study for comparison of cogeneration and separate energy production for a residential area.

2. Presentation of the analysed costumer and different alternative energy supply solutions

The analysed customer is represented by a residential area with houses, placed at an altitude of about 750 m above sea level. Table 1 presents the main characteristics of the analysed customers.

Table 1

Main characteristics of the analysed customers

Costumer	**Number of apartments**	**Surface**		**Distance to the heat source [m]**
		Apartment [m2]	**House [m2]**	
House 1	9	30	270	550
House 2	5	35	175	450
House 3	7	30	210	930
House 4	6	40	240	900
House 5	6	40	240	950
House 6	6	35	370	1130
	2	80		
House 7	10	40	560	250
	2	80		
House 8	15	35	875	550
	5	70		
House 9	6	30	420	1280

Costumer	**Number of apartments**	**Surface**		**Distance to the heat source [m]**
		Apartment [m2]	**House [m2]**	
	2	120		
House 10	6	40	1420	1430
House 11	20	35	720	600
	9	80		
Restaurant 12	-	300		850
House 13	5	45	225	750
Restaurant 14	-	400		600
Restaurant 15	-	500		500
Shop 17	-	90		750
Sauna 18	-	20		400
Fitness 18	-	40		

There will be analysed two solutions for centralised heat supply:

a) Thermal plant equipped with hot water boilers (HOB) that supplies heat and electricity is supplied from the national power grid.

b) Cogeneration plant with gas turbines, which supplies customers with power and heat.

For both solutions there should be supplied the following forms of energy:

- Heat for space heating.
- Heat for domestic warm water preparation.
- Electricity.

3. Initial data and hypotheses for the case study

A. Initial data for the geographic area

- Average annual temperature: $t_{med,an} = 5\,°C$.
- External temperature for calculus: t_e^c = -21 °C.
- Wind zone: IV.
- Number of degree-days: N_z = 4270 degree-days.
- Duration of the heating period: τ_{iz} = 243 days.

B. Initial economic data

- Actualisation rate: a = 0.1.
- Fuel price: P_b = 24.47 €/MWh.
- Heat selling price: P_Q = 39 €/MWh.
- Electricity selling price: P_e^v = 50 €/MWh.
- Boiler's efficiency: $\square_{cz}$ = 0.89.
- Minimal equipment load: d = 0.4.
- Electricity buying price: P_E^c = 80 €/MWh.

It is has been considered that all consumers shall be connected to the centralised heat sources through 4 connection points as follows:

- Consumers 7, 18, 8 and 11 are connected to connection point 1.
- Consumers 17, 19, 13, 12 and 5 are connected to connection point 2.
- Consumers 2, 15, 1 and 14 are connected to connection point 3.
- Consumers 4, 3, 6, 9 and 10 are connected to connection point 4.

There have been considered the following hypotheses for the analysis:

- The temperature of the cold water is 5 °C.
- Heat losses of the district heating network have been assumed of 12 %.
- For the cogeneration plant the peak heat load is ensured by hot water boilers.
- Energy and economic evaluation of the solutions has been performed for 20 years, which is the life span of the equipment.
- The economic comparative analysis has been performed based on actualized values and using the Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (PBP).

4. Energy analysis of the solutions for energy supply

Estimation of the average heat demand for heating

$$q_i^{md} = q_i^c \cdot \frac{t_i^c - t_e^{md}}{t_i^c - t_e^c} \tag{1}$$

Where:

$$t_e^{md} = 20 - \frac{N_z}{\tau_{iz}} = 20 - \frac{4270}{243} \Rightarrow t_e^{md} = 2.428 \text{ °C} \tag{2}$$

t_e^{md} - average outside temperature for the heating period.

$$q_i^{md} = 962.1 \cdot \frac{20 - 2.428}{20 - (-21)} \Rightarrow q_i^{md} = 412.3\ MW \tag{3}$$

Estimation of the minimum heat demand for heating

t_e^* - outside temperature for starting the district heating $t_e^* = 12$ °C

$$q_i^{min} = q_i^c \cdot \frac{t_i^c - t_e^*}{t_i^c - t_e^c} = 962.08 \cdot \frac{20 - 12}{20 - (-21)} \Rightarrow q_i^{min} = 187.7 \text{ MW} \tag{4}$$

Estimation of the nominal heat demand for heating

S_e – equivalent heat transfer are; S_e = 14.644 m^2
N_{ap} – number of conventional apartments; N_{ap} = 140 apartments

$$q_{sp}^c = 469 \left[\frac{W}{m^2}\right]$$

$$q_c^i = N_{ap} \cdot S_e \cdot q_{sp}^c = 140 \cdot 14.644 \cdot 469 = 962.1[\frac{MW}{m^2}] \quad (5)$$

Estimation of heat demand for domestic warm water preparation

$$q_{ac}^{md} = G_{ac}^{md} \cdot c_{pa} \cdot (t_{ac} - t_{ar}) \quad (6)$$

Where: q_{ac}^{md} - heat demand for domestic warm water preparation
t_{ac} – domestic warm water temperature; t_{ac} = 60 °C
t_{ar} – temperature of cold water; t_{ar} = 5 °C
c_{pa} – specific heat value for water; c_{pa} = 4.2 kJ/(kg °C)
The average flow of domestic warm water is calculated as follows:

$$G_{ac}^{md} = N_{ap} \cdot n_p \cdot G_{ac}^z \quad (7)$$

Where: n_p = 2.5 and $G_{ac}^z = 110\, l/zi$

$$G_{ac}^z = 110[\text{l/zi}] = \frac{110}{86400}[\text{l/s}] = \frac{110 \cdot 10^{-3}}{86400}[\text{m}^3/\text{s}] = \frac{110 \cdot 10^{-3}}{86400} \cdot 10^3[\text{kg/s}] = 1.273 \cdot 10^{-3}[\text{kg/s}]$$

$$G_{ac}^{md} = N_{ap} \cdot n_p \cdot G_{ac}^z = 140 \cdot 2.5 \cdot 1.273 \cdot 10^{-3} \Rightarrow G_{ac}^{md} = 0.446\,[kg/s] \quad (8)$$

$$q_{ac}^{md} = G_{ac}^{md} \cdot c_{pa} \cdot (t_{ac} - t_{ar}) = 0.446 \cdot 4.20 \cdot (60-5) \Rightarrow q_{ac}^{md} = 102.9\,[MW] \quad (9)$$

Estimation of heat demand for the entire residential area

The heat demand for the entire residential area can be estimated using the following formula.

$$q_u^c = q_i^c + q_{ac}^{md} + q_{i\ \text{terț}}^c + q_{ac\ \text{terț}}^{md} = 1.2 \cdot (q_i^c + q_{ac}^{md}) \quad (10)$$

Where: q_i^c - heat demand for heating;

q_{ac}^{md} - heat demand for domestic warm water preparation.

Due to the fact that heat losses in the district heating network have been considered as being about 10-12 % there can be written:

$$q_u^c = 1 \cdot 1.12 \cdot (q_i^c + q_{ac}^{md}) = 1 \cdot 1.12 \cdot (962.1 + 102.9) \Rightarrow q_u^c = 1278\ MW \quad (11)$$

Table 2 shows the main data for heat demand for the analysed residential area.

Table 2

Main data for heat demand

Nominal heat demand for heating, q_i^c, MW	**Average heat demand for heating, q_i^{md}, MW**	**Minimal heat demand for heating, q_i^{min}, MW**	**Heat demand for domestic warm water preparation, q_{ac}^{md}, MW**	**Total heat demand, q_u^c, MW**
962.077	412.333	187.722	102.9	1278

A. Heat supply solution: Thermal plant with HOB

The sizing of the thermal plant has been performed using the following formula:

$$n_{cz} \cdot q_{cz}^c \geq q_u^{c,total} \quad (12)$$

Where: n_{cz} – represents the number of boilers;

q_{cz}^c - is chosen as function of the type of boiler.

Table 3 shows the installed capacities for different HOB.

Table 3

Installed capacities for different HOB, MW

Installed capacities for HOB						
1.16	3.5	5.8	10.6	29	58	116

Taking into consideration heat demand value for the residential area, there have been chosen to install 13 HOB with an installed capacity of 116 MW.

B. Heat supply solution: Cogeneration plant equipped with gas turbines

Fig. 1 shows the simplified scheme of the cogeneration plant with gas turbine.

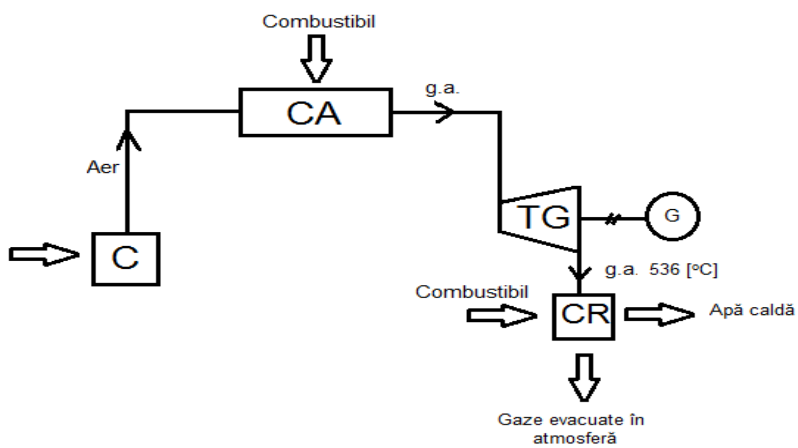

Fig. 1. Simplified scheme of the cogeneration plant with gas turbine.

The sizing of the cogeneration plant is performed based on the formula:

$$q_u^{c,total} \le q_b^c + q_v^c \tag{13}$$

Where: q_b^c - heat generated by the cogeneration equipment;

q_v^c - heat generated by peak equipment.

The sizing of the gas turbine is performed using the cogeneration index:

$$n_{TG} \cdot P_{TG}^c = q_b^c \cdot Y_{TG}^c \tag{14}$$

Where: n_{TG} - number of gas turbines; $n_{TG} = 2$;

P_{TG}^c - installed power of the gas turbine;

Y_{TG}^c - cogeneration index; $Y_{TG}^c = 0.6$

$$P_{TG}^c = \frac{q_b^c \cdot Y_{TG}^c}{n_{TG}} \tag{15}$$

Where: q_b^c shall be determined using the heat demand curve; $q_b^c = 128.5$ MW

$$P_{TG}^c = \frac{128.5 \cdot 0.6}{1} \Rightarrow P_{TG}^c = 77.077 \text{ MW} \tag{16}$$

Table 4 shows the main characteristics of the chosen gas turbine.

Table 4

Main characteristics of the gas turbine

Manufacturer	Model	Installed capacity, PTG, MW	Electric efficiency, □e	Temperature of flue gasses, tga, °C
GE Energy Heavy Duty	PG7121(EA)	85.1	0.33	536

Using the main characteristics of the gas turbine there have been calculated the real values of the cogeneration index and heat production of gas turbines.

$$Y_{TG}^{c^*} = \frac{1}{\frac{1}{\eta_e} - 1.06} \cdot \frac{1}{X_R} \tag{17}$$

Where: X_R - represents heat recovery index, and can be calculated as follows:

$$X_R = \frac{t_{ga} - t_{ga}^r}{t_{ga} - t_{ma}} \tag{18}$$

Where: t_{ga}^r - represents the temperature of evacuation into atmosphere of flue gasses; t_{ga}^r = 120 °C;

t_{ma} - represents the temperature of the environment; t_{ma} = 10 °C.

$$X_R = \frac{t_{ga} - 120}{t_{ga} - 10} \Rightarrow X_R = \frac{536 - 120}{536 - 10} \Rightarrow X_R = 0.791 \tag{19}$$

$$Y_{TG}^{c^*} = \frac{1}{\frac{1}{\eta_e} - 1.06} \cdot \frac{1}{X_R} \Rightarrow Y_{TG}^{c^*} = \frac{1}{\frac{1}{0.33} - 1.06} \cdot \frac{1}{0.791} \Rightarrow Y_{TG}^{c^*} = 0.642 \tag{20}$$

$$q_b^{c^*} = \frac{n_{TG} \cdot P_{TG}^{c^*}}{Y_{TG}^{c^*}} \Rightarrow q_b^{c^*} = \frac{1 \cdot 85.1}{0.642} \Rightarrow q_b^{c^*} = 132.608 \text{ MW} \tag{21}$$

Analysing the above equations results:

$$q_b^{c^*} \geq q_b^c \tag{22}$$

The quantity of heat generated in peak equipment has been estimated as follows:

$$q_v^c = q_{as}^c + n_{cz} \cdot q_{cz}^c \tag{23}$$

Where: q_v^c - represents the quantity of heat generated in peak equipment;

q_{as}^{c} - represents the quantity of heat generated by post-combustion;

q_{cz}^{c} - represents the quantity of heat generated in HOB.

$$q_{as}^{c} = 2.8 \cdot q_{b}^{c*} \Rightarrow q_{as}^{c} = 2.8 \cdot 132.6 \Rightarrow q_{as}^{c} = 371.303 \text{ MW} \tag{24}$$

$$q_{v}^{c} = 413.162 \text{ MW} \tag{25}$$

$$n_{cz} \cdot q_{cz}^{c} = q_{v}^{c} - q_{as}^{c} \Rightarrow n_{cz} \cdot q_{cz}^{c} = 413.162 - 371.303 \Rightarrow n_{cz} \cdot q_{cz}^{c} = 41.859 \text{ MW} \tag{26}$$

The calculations led to choosing 4 boilers with an installed capacity of 10.6 MW.

Estimation of annual fuel consumption

Estimation of annual fuel consumption has been performed based on the annual energy production for both solutions of heat supply.

A. Thermal plant

Annual fuel consumption has been calculated using the following formula:

$$B = \frac{Q_{cz}^{an}}{\eta_{cz}} \tag{27}$$

Where: $\eta_{cz} = 0.89$

$$B = \frac{Q_{cz}^{an}}{\eta_{cz}} \Rightarrow B = \frac{3263663}{0.89} \Rightarrow B = 3.667.038 \text{ MWh} \tag{28}$$

It has been considered that electricity (equivalent with the quantity generated in the cogeneration plant) will be purchased from the national power grid, where it is generated with an efficiency of 0.34. So, annual fuel consumption for electricity generation is 20759000 MWh/year.

Thus, the total annual fuel consumption for solution A is

B(solution A) = 57422938 MWh/year.

B. Cogeneration plant with gas turbines

$$B = \frac{E_p^{an}}{\eta_{TG}} + \frac{Q_{as}^{an}}{\eta_{as}} + \frac{Q_{cz}^{an}}{\eta_{cz}} \Rightarrow B = \frac{705806}{0.33} + \frac{521957}{0.98} + \frac{1270665}{0.89} \Rightarrow B = 4099000 \text{ MWh/year} \quad (29)$$

5. Economic analysis of solutions

A. Thermal plant

Table 5

Economic analysis of solution with thermal plant, Euro

Year	Investment	Expenses	Revenues	Brut revenues	Net revenues	Net present value	Cumulated net present value
0	77952393	112025078	126281060	14255982	-63696411	-63696411	-63696411
1	0	112025078	126281060	14255982	14255982	12959984	-50736427
2	0	112025078	126281060	14255982	14255982	11781803	-38954624
3	0	112025078	126281060	14255982	14255982	10710730	-28243894
4	0	112025078	126281060	14255982	14255982	9737028	-18506866
5	0	112025078	126281060	14255982	14255982	8851843	-9655023
6	0	112025078	126281060	14255982	14255982	8047130	-1607893
7	0	112025078	126281060	14255982	14255982	7315573	5707680
8	0	112025078	126281060	14255982	14255982	6650521	12358201
9	0	112025078	126281060	14255982	14255982	6045928	18404129
10	0	112025078	126281060	14255982	14255982	5496298	23900427
11	0	112025078	126281060	14255982	14255982	4996635	28897062
12	0	112025078	126281060	14255982	14255982	4542395	33439457
13	0	112025078	126281060	14255982	14255982	4129450	37568908
14	0	112025078	126281060	14255982	14255982	3754046	41322953
15	0	112025078	126281060	14255982	14255982	3412769	44735722
16	0	112025078	126281060	14255982	14255982	3102517	47838239
17	0	112025078	126281060	14255982	14255982	2820470	50658709
18	0	112025078	126281060	14255982	14255982	2564064	53222773
19	0	112025078	126281060	14255982	14255982	2330967	55553740
20	0	112025078	126281060	14255982	14255982	2119061	57672801

Simple Payback Period, TRB:

$$TRB = \frac{Investment}{Revenues - Expenses} = \frac{77952393}{126281060 - 112025078} = 5.47\, years \quad (30)$$

Internal Rate of Return (IRR) = 18 %
Cumulated Net Present Value (NPV) = Euro 58 mil.

B. Cogeneration plant with gas turbines

Table 6

Economic analysis of solution with cogeneration plant, Euro

Year	Investment	Expenses	Revenues	Brut revenues	Net revenues	Net present value	Cumulated net present value
0	73792541	119387937	143356182	23968245	-49824296	-49824296	-49824296
1	0	119387937	143356182	23968245	23968245	21789313	-28034983
2	0	119387937	143356182	23968245	23968245	19808467	-8226516
3	0	119387937	143356182	23968245	23968245	18007697	9781181
4	0	119387937	143356182	23968245	23968245	16370634	26151814
5	0	119387937	143356182	23968245	23968245	14882394	41034208
6	0	119387937	143356182	23968245	23968245	13529449	54563658
7	0	119387937	143356182	23968245	23968245	12299499	66863157
8	0	119387937	143356182	23968245	23968245	11181363	78044520
9	0	119387937	143356182	23968245	23968245	10164875	88209396
10	0	119387937	143356182	23968245	23968245	9240796	97450192
11	0	119387937	143356182	23968245	23968245	8400724	105850915
12	0	119387937	143356182	23968245	23968245	7637021	113487937
13	0	119387937	143356182	23968245	23968245	6942747	120430683
14	0	119387937	143356182	23968245	23968245	6311588	126742271
15	0	119387937	143356182	23968245	23968245	5737807	132480078
16	0	119387937	143356182	23968245	23968245	5216188	137696267
17	0	119387937	143356182	23968245	23968245	4741989	142438256
18	0	119387937	143356182	23968245	23968245	4310899	146749156
19	0	119387937	143356182	23968245	23968245	3919000	150668155
20	0	119387937	143356182	23968245	23968245	3562727	154230882

Simple Payback Period, TRB:

$$TRB = \frac{Investment}{Revenues - Expenses} = \frac{73792541}{143356182 - 119387937} = 3.08\,years \tag{31}$$

Internal Rate of Return (IRR) = 32 %
Cumulated Net Present Value (NPV) = Euro 151 mil.

6. Conclusions

The comparative energy analysis of two solutions of energy supply of a residential area has revealed the energy efficiency advantages of cogeneration through an annual fuel savings of 1643938 MWh/year. This value corresponds to a fuel consumption reduction compared to solution with thermal plant, generating heat and electricity purchased from the national power grid, with about 29 %.

This fact has also environmental consequences, leading to reduction of fossil fuels consumption, which is also good due to diminishing the environmental impact through reducing the emissions of green house gasses with an equivalent of reduction of fuel consumption. Thus, it can be said that cogeneration leads significantly to reducing the green house effect overall.

The final decision regarding the optimal solution for energy supply of a residential area is taken based on the economic criteria. Thus, the results of the economic analysis of both solutions, based on different economic criteria (TRB, IRR and NPV) led to choosing the cogeneration plant with gas turbines as being the optimal one.

The economic analysis of each solution led to the following conclusions:

- $NPV_A > 0$ and $NPV_B > 0$, which leads to conclusion that both solutions are economically efficient, but $NPV_A < NPV_B$. Based on this result it can be said the optimal solution from the point of view of maximal NPV is solution B – cogeneration plant with gas turbines.
- The analysis of IRR leads to same conclusion as before, cogeneration plant with gas turbines is the optimal solution, since $RIR_A > a$ and $RIR_B > a$, but $RIR_A < RIR_B$.
- The Simple Payback Period is lower for the cogeneration plant with gas turbines than for thermal plant with heat only boilers. Both values are lower than seven years. Thus, it can be said that from this point of view the cogeneration plant with gas turbines is the optimal solution for heat supply of a residential area analysed in this case study.

Table 7 presents the economic criteria for both solutions.

Table 7

Economic criteria for both solutions

	Solution	
	Thermal plant	**Cogeneration plant with gas turbines**
TRB, years	5.47	3.08
IRR, %	18 %	32 %
NPV, Euro	57672801	150668155

R E F E R E N C E S

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