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ECONOMIC ASPECTS AT SIZING OF THE URBAN COGENERATION PLANTS WITH GAS AND STEAM COMBINED CYCLE IN ROMANIA

BY

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Abstract. The paper shows the optimal sizing manner of the urban cogeneration plants with gas and steam combined cycle by optimizing the solution with the economic analysis criterion (NPV). It also presents the calculation and application of the main economic analysis criteria commonly used in these types of calculations. There were presented areas of economic efficiency of the cogeneration solutions in the sensitivity analysis. It was achieved an effective tool for determining the discounted payback period achieved for these types of cogeneration plants based on the brute payback period for different values of the discount rate.

Key words: urban cogeneration; gas and steam turbines combined cycle; economic efficiency; optimal cogeneration nominal coefficient; sensibility analysis; breakeven point.

1. Introduction

The paper was realized to show the calculation manner and application of the main economic analysis criteria for the sizing calculations of the urban cogeneration plants with gas and steam combined cycle.

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In the sizing purpose of these cogeneration plants it is designed a technical-economic calculation program which took into account all the necessary conditions for implementing these types of cogeneration plants in Romania. The program calculation took into account the uncertainties and risks of the future.

The paper was realized to show the calculation manner and application of the main economic analysis criteria in the sizing calculation of the urban cogeneration plants with gas and steam (GT/ST) combined cycle.

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2. The Calculation and Application Manner of the Main Economic Analysis Criteria

2.1. Brute Payback Period (BPP)

The brute payback period (BPP) it is considered the simplest indicator of economic efficiency. Its calculation involves estimating of the net present value, according to relation

$$\sum_{i=1}^{n}\left(V_i - C_i\right) - I_P = 0. \quad (1)$$

a) *The annual energy productions of the cogeneration plant are considered constant in time* (*or less variable*)

The following relations are using:

$$\mathrm{BPP} = \frac{I_P}{V_B}, \text{ [years]}, \quad (2)$$

$$V_{B,i} = V_i - C_i, \text{ [€/years]}, \quad (3)$$

$$V_B = \sum_{i=1}^{n}\left(V_i - C_i\right), \text{ [€]}, \quad (4)$$

where: V_i, C_i, [€/years] represent, respectively, annual incomes and costs; $V_{B,i}$, [€/years] – brute annual incomes; V_B, [€] – brute incomes for the whole study period; I_P, [€] – investment from own funds.

b) *The annual energy productions of the cogeneration plant are considered variable in time*

In this case relation

$$\mathrm{BPP} = \frac{I_P}{V_B^{\mathrm{opt}}}, \text{ [years]}, \tag{5}$$

is proposed. V_B^{opt} can be determined when

$$\sum_{i=1}^{n}(V_i - C_i) - I_P = 0, \tag{6}$$

where V_B^{opt}, [€], represents the optimal value of the brute incomes obtained for the whole study period.

It is preferable a project which ensures a swift recovery of the cogeneration plat costs and the acceptability criterion for a project which uses as reference: BPP, must have a payback period less or at most equal with the real standardized recovery term, *Tm*, whose values are shown in the Fig. 1 (Athanasovici *et al*., 2010; Hoară *et al*., 2011; Berceanu *et al*., 2010).

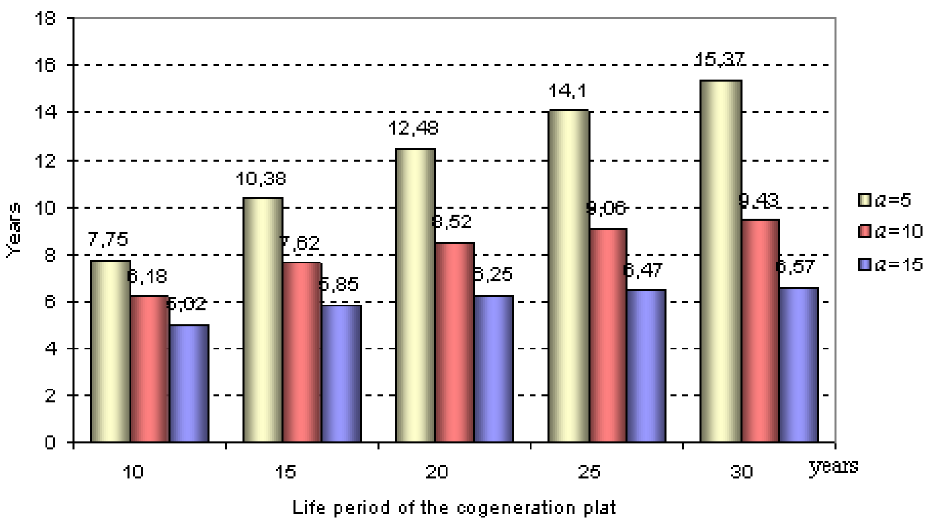

Fig. 1 – The real values of the standardized term, *Tm*, depending by life period of the cogeneration plant and by discount rate, *a*.

2.2. Net Present Value (NPV)

The net present value (NPV) is the algebraic sum of the annual discounted net incomes. It is the basic criterion, the other criteria are derived from it (valid in some simplifying assumptions) and represents the most conclusive criterion. It can be used to compare multiple variants of a project investment, and in some cases, to be conclusive this comparison, it is necessary the equivalence of the variants from the point of view of the useful effects and of the life period. The information provided by this criterion are presented in absolute values by quantitative nature, so it is complemented by other criteria: discounted payback period, internal rate of return, profitability index – which provides qualitative information. The calculation relation for the net present value estimation is

$$\mathrm{NPV} = \sum_{i=1}^{n} \frac{V_i - C_i}{(1+a)^i} - I_P \text{ , [€],} \tag{7}$$

where: I_P , [€] represents the investment covered from own funds, a, [%] – discount rate, n, [years] – study period for which the calculations shall be made (Athanasovici *et al*., 2010; Hoară *et al*., 2011)

2.3. Total Net Present Value (TNPV)

The calculation relation for the total net present value is

$$\mathrm{TNPV} = \sum_{i=1}^{n} \frac{V_i}{(1+a)^i} - I_P \text{, [€],} \tag{8}$$

(Athanasovici *et al*., 2010; Hoară *et al*., 2011; Berceanu *et al*., 2010)

2.4. Total Discounted Costs (TDC)

The total discounted costs is a simplified form of NPV criterion corresponding to the situation where all the analysed variants are considered equivalent from the point of view of the useful effects or will be brought to the equivalence trough equivalence calculations. This criterion is simple, and requires no determination of the annual incomes. It allows only a comparative analysis of the selected variants efficiency, without giving information about the effective economic efficiency of the chosen variants. Therefore, after a sorting of variants by TDC criterion, the retained variants are analysed from point of view of the effective economic efficiency, by other criteria (NPV, IRR, payback period, etc.). The calculation relation for the total discounted costs criterion is

$$\mathrm{TDC} = \sum_{i=1}^{n_e} \frac{I_P}{(1+a)^i} + \sum_{i=n_e+1}^{n} \frac{C_i}{(1+a)^i} \text{, [€],} \tag{9}$$

where: I_P , [€], is the investment covered from own funds for years: i = 1,…,n_e; C_i , [€/years] – annual costs for years: $i = n_e +1$, $n_e +2,...,n$; n_e , [years] – execution period (Athanasovici *et al*., 2010; Hoară *et al*., 2011; Berceanu *et al*., 2010).

2.5. Internal Rate of Return (IRR)

The internal rate of return (IRR) represents the discount rate for which the net present value criterion is equal with zero (NPV = 0). In other words, this is the minimum acceptable internal rate of return for a CHP solution, a lower rate indicating that the revenues will not cover the costs of CHP plant,

$$\text{NPV} = \sum_{i=1}^{n} \frac{V_i - C_i}{(1+a)^i} - I_P = 0. \tag{10}$$

The solution of this eq. results from an iterative process or it can be determined from the graphical representation NPV *vs*. IRR. Investment can be promoted if IRR is greater than the minimum discount rate (threshold).

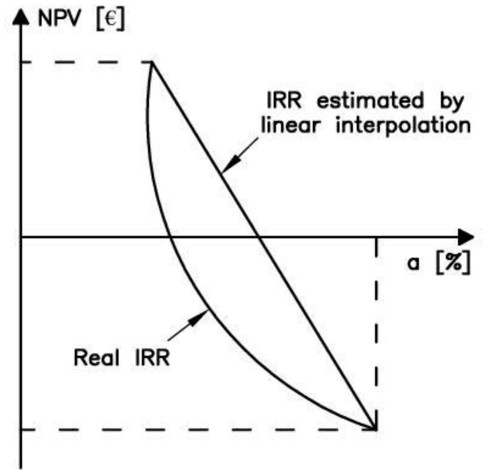

Fig. 2 – The net present value variation *vs.* the discount rate (Athanasovici *et al.*, 2010; Hoară *et al.*, 2011; Berceanu *et al.*, 2010).

2.6. Profitability Index (PI)

The profitability index is an indicator represented in relative values which illustrates the qualitative aspects related to the economic efficiency of an investment project allowing comparison of solutions which not necessarily have to be equivalent from the point of view of their effects.

The optimal variant corresponds to maximum profitability index (PI). The calculation of this indicator is based on the relation

$$\text{PI} = 1 + \frac{\text{NPV}}{I_P}, \tag{11}$$

(Athanasovici *et al*., 2010; Hoară *et al*., 2011; Berceanu *et al*., 2010).

2.7. Benefit–Cost ratio (B/C)

The cost–benefit ratio is a complementary indicator of NPV, comparing the net present value of the revenues with the net present value of the costs, including the amount of investment throughout the whole study. The relation for determining the cost–benefit ratio is

$$\frac{B}{C}=\frac{\sum_{i=1}^{n}V_i}{\sum_{i=1}^{n}C_i+I_P}, \tag{12}$$

(Athanasovici *et al*., 2010; Hoară *et al*., 2011; Berceanu *et al*., 2010).

2.8. Discounted Payback Period (DPP)

The discounted payback period can be defined as the time needed to recover the investment cost based on the discounted cash flows. Defining the payback of the capital requires the establishing of an origin time. Usually, the accepted convention is to calculate the duration from the time of commissioning

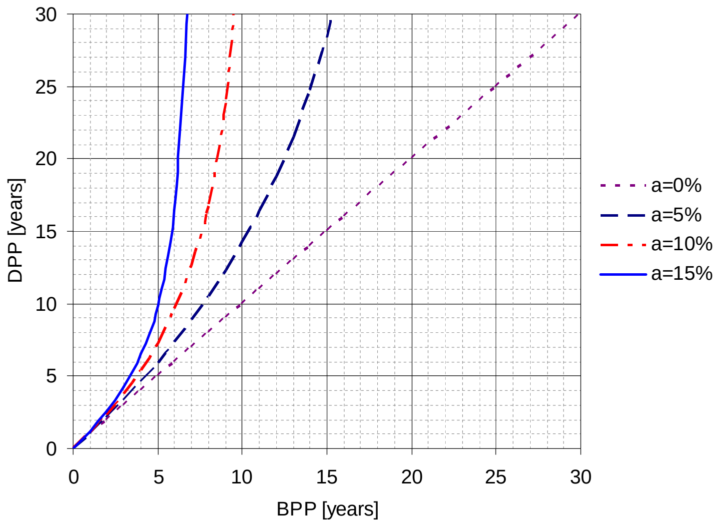

Fig. 3 – The discounted payback period *vs*. brute payback period, taking into account the discount rate, *a* (Athanasovici *et al*., 2010; Hoară *et al*., 2011; Berceanu *et al*., 2010).

of the objective. The discounted payback period (DPP) is the life of the pursued objective, after which it can cover the initial investment and it can achieve an additional income corresponding to the considered discount rate. The calculation of DPP may be performed as follows:

$$\mathrm{DPP}=\frac{\ln\left(\frac{1}{1-a\mathrm{BPP}}\right)}{\ln(1+a)},\ \text{[years]}. \tag{13}$$

For determination of DPP, it must determine the brute payback period (BPP).

In the case in which the BPP is known, the discounted payback period can also be determined on the graphical way, as in Fig. 3.

3. Determining of the Economically Optimal Cogeneration Solution

The optimal sizing of CHPP is done by finding the optimal delivery heat capacity of ICG reported at the nominal thermal capacity of CHPP, representing the optimal cogeneration nominal coefficient, $\left(\alpha_{cg}^{n}\right)_{\text{opt}} = q_{icg}^{n} / q_{\text{CCG}}^{n}$. The cogeneration nominal coefficient is influenced by the energy performance of the cogeneration plant and the related investments achieving it. Therefore, it is determined in the optimization calculations, which must take into account all the effects of its adoption over the technical and economic performance of the cogeneration plant. Optimization criterion adopted is the net present value (NPV). Determining of the optimal solution is theoretically accomplished by writing the mathematical form of the eq. of NPV, obtained by expressing of all the components that make up NPV according to the cogeneration nominal coefficient. Thus, the optimal cogeneration nominal coefficient shall be determined from the following eq.:

$$\frac{\partial \text{NPV}}{\partial \alpha_{cg}^{n}} = 0, \tag{14}$$

with respecting the condition:

$$\frac{\partial^{2} \text{NPV}}{\partial \left(\alpha_{cg}^{n}\right)^{2}} > 0, \tag{15}$$

(Athanasovici *et al*., 2010; Hoară *et al*., 2011; Berceanu *et al*., 2010).

4. Theoretical Aspects Regarding the Sensibility Analysis Used for the Correctly Estimation of the Cogeneration Solution

All the models which analyse the economic efficiency are deterministic models. They start from a set of premises which represent input data for the computer program. To consider a large field of the possibilities, these assumptions can be modified by enlarging the areas where each parameter can take values. In this way, the valuation model takes into account future uncertainties and risks. The sensitivity analysis provides the enlargement of the domain of definition of each of the parameter situated on the study assumptions list. It can be done in two ways namely:

a) setting the domain in which take values such a parameter and calculate the output values for the entire range;

b) determining by calculation, usually iterative, of a limit value of the respectively parameter, beginning from the cogeneration solution which becomes profitable or economically interesting.

The CHP solutions undergo economic analysis usually heave very high lifetime, the proposed case in this paper having a lifetime of 18 years. In this time period, the input data for the economic analysis model will certainly change.

Therefore, for a correct estimation of the economic efficiency of a cogeneration solution it is necessary to assess the effect over the efficiency criterion that changes the input values in the model: NPV, TNPV, TDC, IRR, DPP, PI, *B*/*C*. This it can be performed in the sensitivity analysis.

The sensitivity analysis is done for the following reasons:

a) the economic analysis is based on hypotheses regarding uncertain future events;

b) the fuel price and electric energy tariffs traded through regulated or bilateral contracts, the heat sales price, etc., are variable and may change dramatically during the analysis of the project (18 years);

c) the risk elements should be considered whenever there is likelihood that a cogeneration solution to generate different results comparative with those prognosed.

Trough the sensitivity analysis it aims

a) the sensitivity of the cogeneration solution's indicators at the parameters variations;

b) determining of the project breakeven point, under the conditions of parameters variations;

c) determining of the appearance probabilities of a favourable or adverse event and the correlations between variables;

d) determining of the external risks of the cogeneration solution;

e) identification of the critical variables which significantly influence the results of the project;

f) the effects of the selected elements variation (costs and benefits) over the economic analysis criteria;

g) establishing of the project’s weaknesses and identify of the risk areas.

In the sensitivity analysis it can be determined the breakeven point of the cogeneration project, *i.e.* identifying of a parameter for which NPV is zero, IRR is equal with the discount rate and DPP is equal with the lifetime.

Breakeven point is expressed as

a) the absolute value of the parameter for which NPV = 0, IRR = a and DPP = lifetime;

b) the percentage change of a parameter in order to lead NPV = 0, IRR = = a and DPP = lifetime (Athanasovici *et al*., 2010; Hoară *et al*., 2011; Berceanu *et al*., 2010).

5. Economic Effects at Sizing of the Urban Cogeneration Plants with Gas and Steam Combined Cycle. The Sensitivity Analysis

In this section it used a calculation program for dimensioning of combined cycle cogeneration plants (GT/ST) for small and medium power, presenting the economic effects by applying of the main economic analysis criteria most often used in investment projects. The calculations were made for the gas and stem combined cycle cogeneration plant, with a rated thermal input of 31.5 MWt, which sells electric energy in SEN trough regulated contracts and is sized by the heat demand shown in Fig. 4 (for a study period of 18 years). In this case CHPP has no restrictions in terms of electric power values produced in the CHPP, all of the electric energy produced in cogeneration mode being delivered in SEN, as shown in Fig. 5.

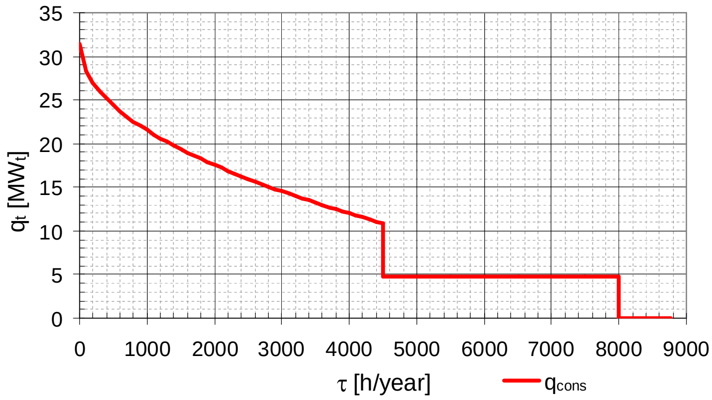

Fig. 4 – The annual duration curve of the urban heat demand.

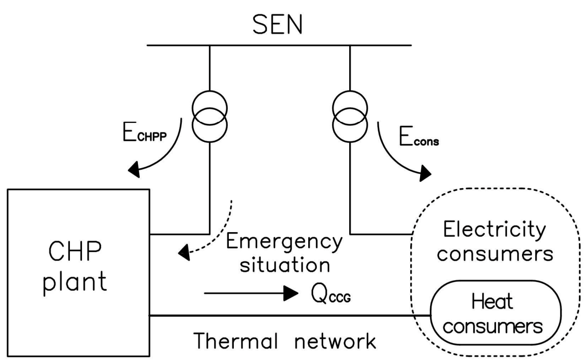

Fig. 5 – Urban CHP plant sized to meet the heat demand with selling electricity through the regulated contracts.

In the Table 1 are presented follow prices for the whole study period: p_{cb} is the purchase price of fuel; $p_{\mathrm{el}.cg}^{\mathrm{SEN}}$ – the selling price of electric energy in SEN, in cogeneration mode; $p_{\mathrm{el}}^{\mathrm{DAM}}$ – the selling price of electric energy on the Day Ahead Market; Vb_{cg}^{el} – the bonus amount given for electricity sold in CHP mode; p_t – the sale price of the thermal energy (Hoară *et al.*, 2011, ANRE, OPCOM).

Table 1
The Prices of the Fuel, Electrical and Thermal Energy, Respectively the Bonus for Cogeneration

Year	p_{cb} €/MW$_{cb}$h	$p_{\mathrm{el}.cg}^{\mathrm{SEN}}$ €/MW$_{\mathrm{el}}$h	$p_{\mathrm{el}}^{\mathrm{DAM}}$ €/MW$_{\mathrm{el}}$h	Vb_{cg}^{el} €/MW$_{\mathrm{el}}$h	p_t €/MW$_t$h
1	20.0	47.4	52.7	39.6	30.6
2	20.6	48.9	54.4	38.3	31.4
3	21.2	50.3	55.9	37.0	32.0
4	21.7	51.5	57.3	35.7	32.7
5	22.2	52.7	58.6	34.4	33.3
6	22.8	53.9	59.9	33.2	33.9
7	23.3	55.2	61.3	31.9	34.5
8	23.8	56.5	62.7	30.6	35.1
9	24.4	57.8	64.2	29.3	35.8
10	24.9	59.1	65.6	28.0	36.4
11	25.5	60.4	67.2	26.8	37.1
12	26.1	61.8	68.7	0.0	37.8
13	26.7	63.2	70.3	0.0	38.5
14	27.3	64.7	71.9	0.0	39.3
15	27.9	66.2	73.5	0.0	40.0
16	28.6	67.7	75.2	0.0	40.8
17	29.2	69.3	77.0	0.0	41.5
18	29.9	70.9	78.7	0.0	42.3

After calculations it resulted the economic optimal solution by optimizing the solution on the base of NPV. In the optimal solution there were determined the economic analysis criteria values, presented in Table 2.

Table 2
The Economic Analysis Criteria Values, Corresponding to the Nominal Optimal Coefficient Cogeneration

$(\alpha_{cg}^{n})_{\mathrm{opt}}$	NPV$^{\max}$ €	IRR %	PI	B/C	TNPV €	BPP years	DPP years
0.56	3,388,707	11.7	1.10	1.03	68,535,807	7.4	14.0

For the cogeneration optimal solution, there were presented the results of the total undiscounted incomes and costs of the cogeneration plant (Fig. 6). The CHPP incomes include those realized from the electric energy and heat sold by the CHPP, from the bonus for the cogeneration, from the residual value of the CHPP and from the measures realized to promote and support of the cogeneration solution.

The CHPP costs are the sum of variable and fixed costs with the fuel, the operation and maintenance, the costs considered by introducing different environmental taxes, the cost of returning the loan (if the loan was used to carry out a bank loan) and the costs with the fees and taxes for the specific legislation area where can be implemented the cogeneration solution (Fig. 7).

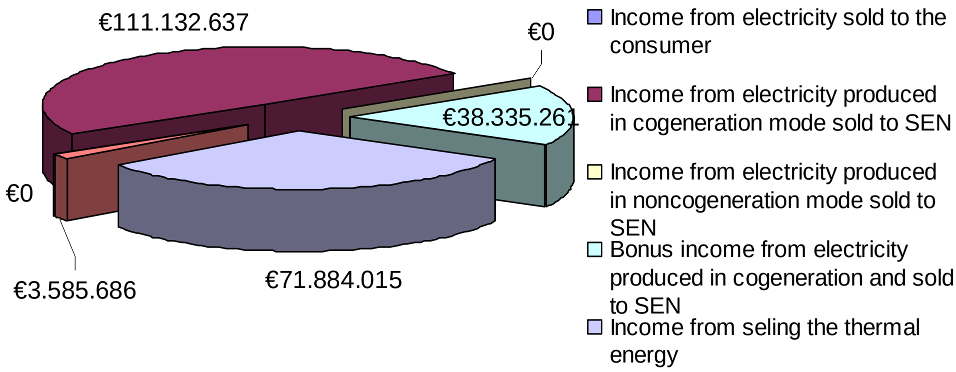

Fig. 6 – The undiscounted total incomes structure of CHPP and its percentage from the undiscounted total income of CHPP.

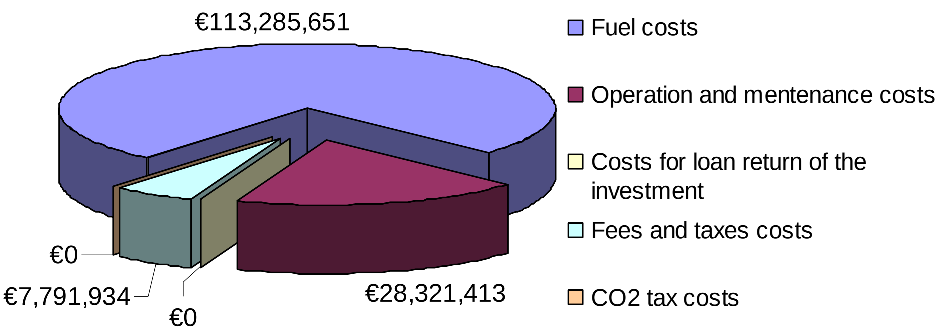

Fig. 7 – The undiscounted total costs structure of CHPP and its percentage from the undiscounted total cost of CHPP.

There were presented the economic analysis criteria values of NPV, PI, B/C and reports TNPV/$C_{i,a}$, VB, a/I_p, under the graphical form in the Figs.

8,…,15 for the discount rate variation. The economic optimal cogeneration solution has been determined for a discount rate of a = 10 %. It is found that for a value of the discount rate equal to IRR, determined in Fig. 8, for the criteria of economic analysis and ratios mentioned, there is a limit below which their values lead to inefficiency of the investment project. Also in the Figs. 13 and 14, by variation of TDC and V_i, as well as TNPV and $C_{i,a}$, it is seen that the values of the discount rate is greater than the internal rate of return determined, TDC become bigger than $V_{i,a}$, and TNPV become smaller than $C_{i,a}$, leading to inefficiency of the investment project. According to sensitivity analysis, the breakeven point is when NPV = 0, the internal rate of return determined is equal with the discount rate, IRR = a and DDP = lifetime. In the Figs. 9,…,14 it is shown this breakeven point, the cogeneration solution values being above the breakeven point. Fig. 15 shows DPP variation *vs*. the discount rate and it is found that for a value of the discount rate equal with determined IRR, DPP is equal with lifetime of the cogeneration plant, DPP = 18 years. Also, it can be

Fig. 8 – Graphical determination of the internal rate of return, IRR.

seen that as the payback discounted duration value of the cogeneration solution is less, the investment can be recovered quickly, rejection the cogeneration solution being gave by increasing the duration of payback over a certain threshold required by the customer, which usually can not be greater than a value of DPP which takes into account by the standardized payback period presented in the Fig. 1.

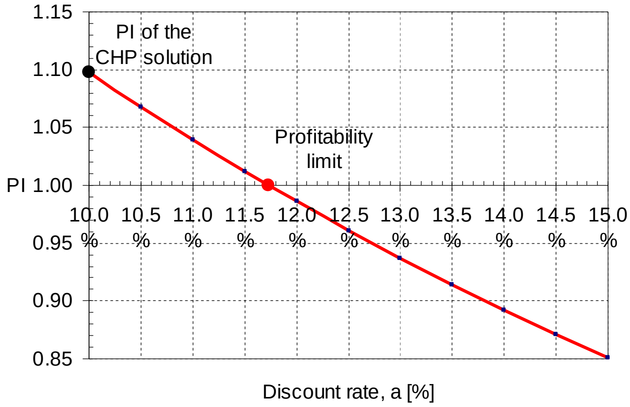

Fig. 9 – Variation of the profitability index variation *vs*. the discounted rate, PI=$f(a)$.

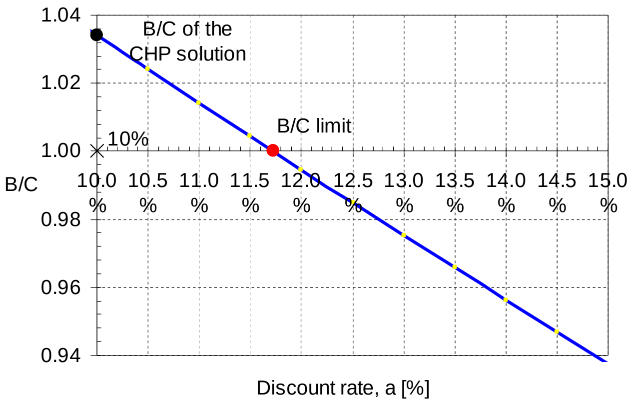

Fig. 10 – Variation of the Cost–Benefit ratio variation *vs*. the discounted rate, $B/C=f(a)$.

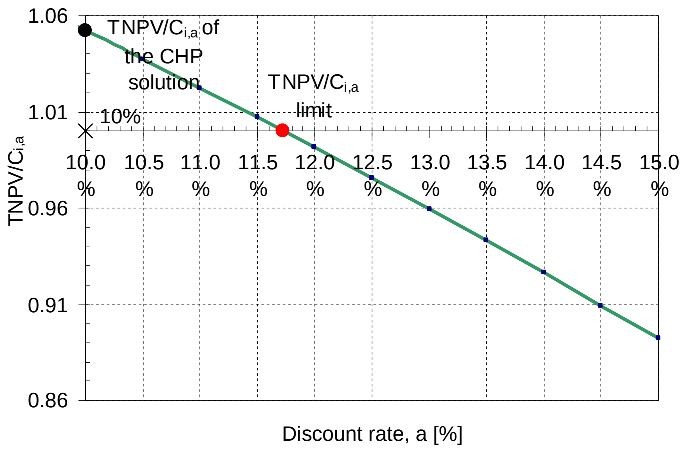

Fig. 11 – Variation of the TNPV-discounted costs ratio variation *vs*. the discounted rate, TNPV/$C_{i,a}=f(a)$.

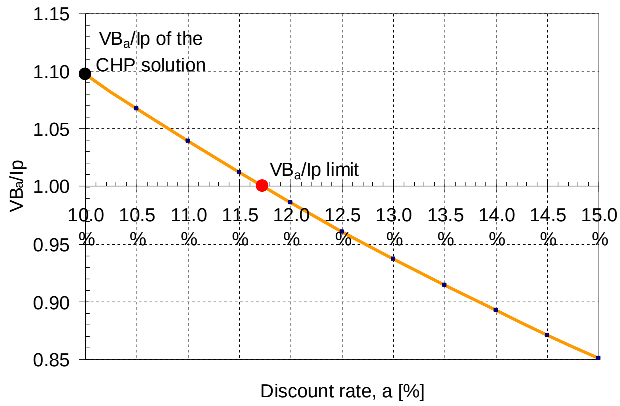

Fig. 12 – Variation of the discounted brute incomes-investments from own founds ratio *vs*. the discounted rate, VB,$a/I_p=f(a)$.

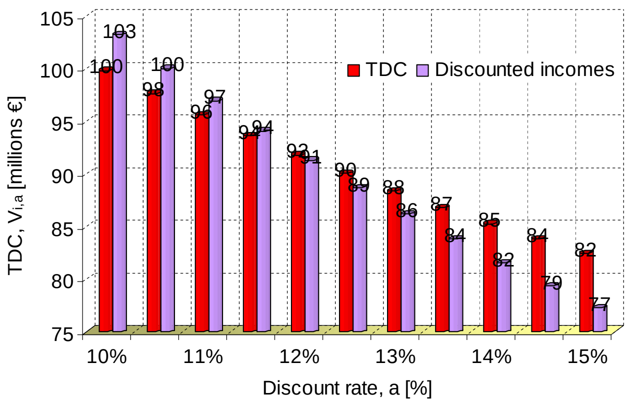

Fig. 13 – Variation of the TDC and discounted incomes variation *vs*. the discounted rate.

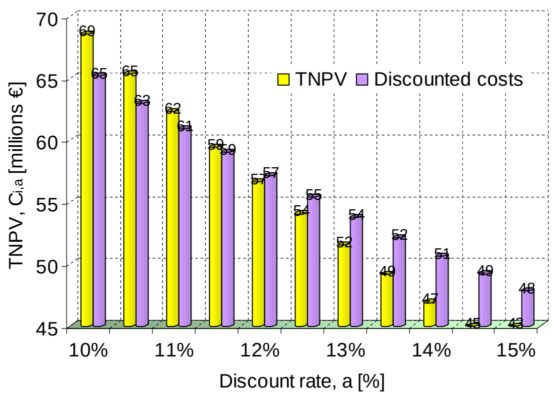

Fig. 14 – Variation of the TNPV and discounted costs variation *vs*. the discounted rate.

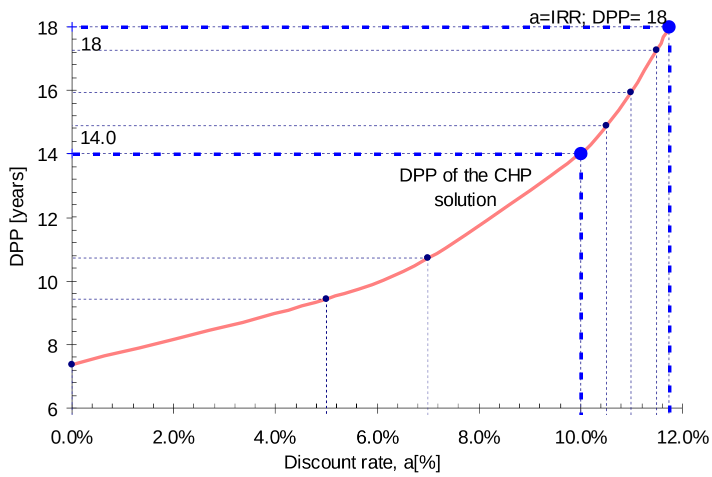

Fig. 15 – DPP variation *vs.* the discounted rate, DPP=*f*(*a*).

In the Tables 3 and 4 are presented the values of the economic analysis criteria, the present values of revenues, costs, gross income and the investment value from own founds, determined in the case in which CHPP is at the breakeven point when, NPV = 0 (Structural Funds *et al.*, 2008; Hoară *et al.*, 2011).

Table 3

The Economics Analysis Criteria Values of CHPP at the Breakeven Point

a = IRR %	NPV €	DPP years	TNPV €	TDC €	PI	*B*/*C*
11.7	0	18	58,155,292	92,786,236	1.0	1.0

Table 4

The Discounted Values of the Incomes, Costs, Brute Incomes and the Value of the Investment Realized from Own Founds of CHPP at the Breakeven Point

$V_{i,a}$ €	$C_{i,a}$ €	$V_{B,a}$ €	I_p €
92,786,236	58,155,292	34,630,944	34,630,944

6. Conclusions

In this paper there were presented the calculation manner of the economic analysis criteria most commonly used for the sizing calculations of the urban cogeneration plants with gas and steam combined cycle. Also there were presented an effective tool for determining the discounted payback period (DPP) depending on the brute payback period (BPP) for different values of the discount rate (*a*).

Following the application of these economic analysis criteria in the sizing calculations of a gas and steam combined cycle cogeneration plants with an installed capacity of 31.5 MWt, it resulted the economically optimal solution by optimizing solution based on net present value, where NPV^{max} = € 3,388,707 corresponding to an optimal nominal cogeneration coefficient $\left(\alpha_{cg}^{n}\right)_{\text{opt}}$ = 0.56. At the optimal solution there were determined the economic analysis criteria values: IRR, PI, *B*/*C*, TNPV, BPP, DPP.

In the sensitivity analysis there were determined efficiency domains of the cogeneration solution at the considered parameter variation (discount rate, *a*). The CHP solution begins to be profitable or economically interesting for the values of the discount rate lower than the value determined for the case where NPV = 0, *i.e.* *a* = IRR = 11.73%. The breakeven point from where the cogeneration solution begins to be economically attractive was presented graphically for each criterion of economic analysis. Considering the efficiency domain shown in these figures it resulted that the urban cogeneration plant with gas and steam combined cycle brings profit for

Economic Analysis Criteria	Conditions for the CHPP profitability	
NPV	>	0 €
TNPV	>	58,155,292 €
TDC	<	92,786,236 €
IRR	>	11.7 %
BPP	<	7.4 years
DPP	<	18 years
PI	>	1
B/*C*	>	1
TNPV/$C_{i,a}$	>	1
VB,*a*/IP	>	1
$V_{i,a}$/TDC	>	1

List of Notations:

Notation	Description	MU
$C_{i,a}$	Annual discounted costs of the cogeneration plant	€
CHPP	Cogeneration plant	–
E_{CHPP}	The electric energy produced by the cogeneration plant and commercialized through the regulated contracts	MW_{el}
E_{cons}	The electric energy demand of the consumer	MW_{el}
ICG	Cogeneration installation	-
Q_{CHPP}	Thermal power delivered by CHPP	MW_t
q_{ICG}	The delivery capacity of the heat from ICG	MW_t
q^{n}_{ICG}	Nominal thermal capacity of CHPP	MW_t
SEN	National power system	–
GT/ST	Gas turbine/steam turbine	–
τ	Annual duration of CHPP operation	h/year
$V_{i,a}$	Discounted incomes of CHPP	€
$V_{B,a}$	Discounted brute incomes of CHPP	€

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ASPECTE ECONOMICE LA DIMENSIONAREA CENTRALELOR DE COGENERARE URBANE CU CICLU MIXT GAZE–ABUR, ÎN ROMÂNIA

(Rezumat)

Se prezintă modul de dimensionare optimă a centralelor de cogenerare urbane cu ciclu mixt gaze–abur prin optimizarea soluției cu ajutorul criteriului de analiză economică venitul net actualizat (VNA). De asemenea se prezintă modul de calcul şi aplicare a principalelor criterii de analiză economică utilizate frecvent în cadrul acestor tipuri de calcule. S-au identificat domenii de eficiență economică a soluțiilor de cogenerare în cadrul analizei de sensibilitate. S-a realizat un instrument eficient de determinare a termenului actualizat de recuperare a investiției realizată pentru aceste tipuri de centrale de cogenerare pe baza termenului de recuperare brut pentru diferite valori ale ratei de actualizare.