

**SIMULATION OF COGENERATION PLANTS OPERATION  
EQUIPPED WITH GAS AND STEAM COMBINED CYCLE  
TECHNOLOGIES FOR SMALL AND MEDIUM POWERS.  
COMPARATIVE EFFECT ON THE ECONOMIC  
EFFICIENCY OF THE COGENERATION PLANTS  
DEPENDING ON THEIR MODE OPERATION**

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*This paper presents the sizing methods of gas and steam combined cycle cogeneration plants for small and medium powers, in the case of using the current prices on the Romanian market. So, it has made sizing of these cogeneration plants to meet heat demand and also electricity demand and it determined the economic efficiency of these cogeneration plants for the sizing modes presented. In this paper, a very well contoured aspect is the sale of the electric power for the different types of contracts. Finally it has been taken into account different comparisons between economic efficiencies of these cogeneration plants, taking into account all the aspects considered.*

**Keywords:** combined cycle, gas-steam, cogeneration plant, small and medium powers, economic efficiency

**List of abbreviations:**

Notation	Description	UM
$\alpha_{cg}^n$	Nominal cogeneration coefficient	-
$(\alpha_{cg}^n)_{opt}$	Optimal value of economic point of view of nominal cogeneration coefficient	-
$E_{CCG}$	Electrical energy produced by cogeneration plant	$kW_{el}h$
$E_{cons}$	Electrical energy produced by the cogeneration plant and delivered to the consumer	$kW_{el}h$
ICG	Cogeneration facility	-
ITV	Peak thermal facility	-
$P_{cons}$	Electrical power demanded by the eligible consumer	$kW_{el}$
$P_{CCG}$	Momentary electric power of the cogeneration plant	$kW_{el}$
$P_{cg}^n$	Nominal electrical power produced in cogeneration mode	$kW_{el}$
$p_{el}$	Price of electricity sold through bilateral contracts	$\text{€}/MW_{el}h$

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$p_{el,cg}^{SEN}$	Price of electricity sold through regulated contracts	€/MW <sub>el</sub> h
$P_{ICG}$	Momentary electric power of the cogeneration facility	kW <sub>el</sub>
$P_{ICG}^n$	Nominal electric power of the cogeneration facility	kW <sub>el</sub>
$P_{SEN}$	Momentary electric power of the cogeneration plant that can be sold through regulated contracts	kW <sub>el</sub>
$Q_{CCG}$	Heat production of the cogeneration plant	kW <sub>h</sub>
$q_{CCGn}$	Nominal thermal capacity of the cogeneration plant	kW <sub>t</sub>
$q_{cg}^n$	Nominal thermal power delivered in cogeneration mode	kW <sub>t</sub>
$q_{cons}$	Momentary thermal power demand	kW <sub>t</sub>
$q_{dissipated}$	Thermal power disposed into the atmosphere	kW <sub>t</sub>
$q_{ICG}$	Momentary thermal power of the cogeneration facility	kW <sub>t</sub>
$q_{iv}^n$	Nominal thermal power of peak thermal facility	kW <sub>t</sub>
$q_{max}$	Maximum thermal power demanded by the consumer	kW <sub>t</sub>
SEN	National electricity system	-
NPV	Net present value	€
$y_{cg}^n$	Nominal cogeneration index	kW <sub>el</sub> /kW <sub>t</sub>

## 1. Introduction

Simulation of cogeneration plants operation equipped with gas and steam combined cycle technologies for small and medium power and its economic efficiency analysis involved the development of technical and economical efficiency calculations aimed to establish the technical and economic efficiency of alternative technical solutions. For this purpose, have been taken into account:

- optimal size in terms of installed capacity to produce heat and electricity;
- ranking from the point of view of economic efficiency of cogeneration solutions analyzed, identifying the optimal solution (with the highlight optimal solution);
- calculation of energy performance and the main economic indicators, which characterizes each cogeneration solution analyzed;
- determination the sensitivity of economic efficiency of optimal cogeneration solution resulting from calculation.

Technical and economic efficiency calculations were made for cogeneration solutions, taking into account the duration of the study and the development therein of the investment production capacity, and annual energy delivered-sold. This meant that all technical and economic efficiency calculations had to be made by applying economic criteria based on the method of discounting, net present value, and taking into account the financial arrangement adopted for the investment related to the aim in view.

## 2. Calculation methods for the load type of cogeneration plants with gas-steam combined cycle for small and medium power

Taking into account the operating mode, sizing of cogeneration plants with gas-steam combined cycle of small and medium power can be achieved in two ways, depending on the considered energy demand: to meet heat demand and to meet electricity demand. Next, it shows how the sizing modes of cogeneration plants with gas-steam combined cycle for small and medium power for these two operating types.

### 2.1 Sizing the cogeneration plants to meet heat demand

Sizing the cogeneration plants to meet heat demand, where electricity produced will be a result of its insurance, implies that once made it, depending strictly by heat demand ( $q_{CCG}$ ) and by ( $\alpha_t$ ), electrical power of cogeneration facilities, ( $P_{ICG}$ ), will always be produced strictly on realize of ( $q_{ICG}$ ), meaning will be produced strictly in cogeneration mode ( $P_{ICG} = P_{cg}$ ). (6.1.)

Such an operation involves the following steps:

- for an maximum necessary of heat requested a cogeneration plant, ( $q_{CCG}^n$ ), it is established which is the share of this value to be delivered in cogeneration mode, ( $q_{cg}^n$ ), determined by the choice of the nominal cogeneration

$$\text{coefficient, } \alpha_{cg}^n = \frac{q_{cg}^n}{q_{CCG}^n} \quad (6.2.)$$

- for cogeneration technology, chosen on the basis of thermal load value, ( $q_{cg}^n$ ), results:

$$P_{cg}^n \cdot y_{cg}^n = \frac{P_{cg}^n}{q_{cg}^n} \quad (6.3.)$$

$$\text{so: } P_{cg}^n = q_{cg}^n \cdot y_{cg}^n \quad (6.4.)$$

In short, the nominal value of the cogeneration coefficient, ( $\alpha_{cg}^n$ ), and the nominal value of cogeneration index, ( $y_{cg}^n$ ), determined the nominal electric power produced in cogeneration mode ( $P_{cg}^n$ ).

For an operation after the heat demand, the cogeneration plant can deliver the electrical energy thus produced in two ways:

## I. The cogeneration plant delivers electricity to the national energy system, by regulated contracts

In this case, it is assumed that the cogeneration plant does not have restrictions for the production of electricity, the whole amount of electrical power produced, being purchased by the national energy system, as shown in figure 2.1.

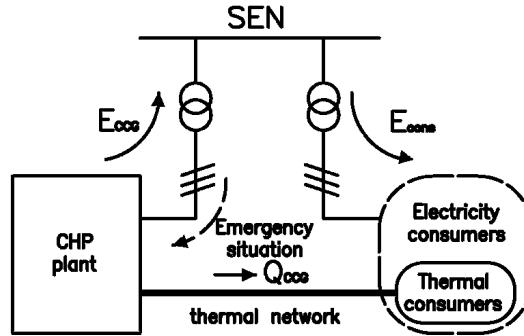


Fig. 2.1 Sizing of the cogeneration plants to meet heat demand, with the sale of the electricity by regulated contracts

## II. If the cogeneration plant delivers electricity also to consumers by bilateral contracts, cogeneration plant can be found in one of the following situations:

(a)  $P_{cg}^n < P_c$  ( $P_c$  is the electrical power needed for the eligible consumer) situation in which the cogeneration plant will have to appeal in a supplementary source of electricity (most of the times the national electricity system, but may also be another individual producer with a reverse situation) to cover need for electricity of consumer;

(b)  $P_{cg}^n = P_c$  which means that the cogeneration plant fully covers the electricity demand of the consumer, with which has concluded bilateral contract, based on the nominal power installed. In this case, cogeneration plant is not in a position to buy or sell electricity from an additional source of electricity;

(a)  $P_{cg}^n > P_c$  in this case, the cogeneration plant fully meet electricity demand of the consumer, with which has concluded bilateral contract, while the remaining electricity ( $P_{cg}^n - P_c$ ) is delivered to the national electricity system, by the regulated contracts.

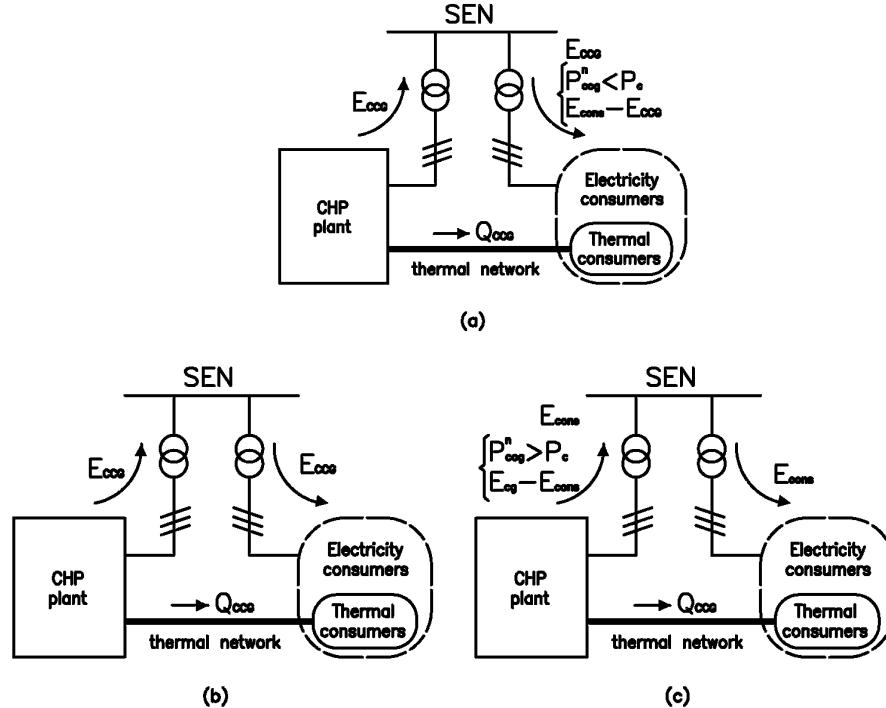


Fig. 2.2 Sizing of cogeneration plants to meet heat demand, with the sale of electricity by bilateral contracts

## 2.2 Sizing the cogeneration plants to meet electricity demand, with operation in cogeneration mode

Sizing the cogeneration plants to meet electricity demand admits that the heat momentary demand will be fully ensured. Its covering repartition between ICG and ITV will be a consequence of electricity demand, and assumes that at all times, regardless of the value of heat demand, ( $q_{CCG}$ ), will be produced strictly the required electrical power, ( $P_{CCG}$ ), by cogeneration facilities (ICG) of cogeneration plant.

Starting from a certain value of the nominal electric power installed in the cogeneration facilities, will result the heat momentary production in accordance with the next calculation relationship:

$$q_{cg}^n = \frac{P_{cg}^n}{y^n} \quad (6.5.)$$

According to the value obtained, it is compared with the maximum heat demand,  $(q_{\max})$ , settling the capacity of the peak sources,  $(q_{iv}^n)$ . So, will result also the nominal value of the cogeneration coefficient:

$$\alpha_{cg}^n = \frac{q_{cg}^n}{q_{CCG}^n} \quad (6.6.)$$

From the point of view of heat produced, taking into account that the cogeneration facilities operates following the electrical power required, may occur following situations:

(a) the momentary production of heat, so made, exceeds the momentary demand of heat:  $q_{cg} > q_c$ , the excess of heat:  $q_{dissipated} = q_{cg} - q_c$  (6.7.), can be discharged into the atmosphere (valid for facilities with gas turbines and heat engines);

(b) the momentary heat output which was achieved, taking into account the electrical load, is smaller than the heat demand,  $q_{cg} < q_c$ . If the difference does not exceed the installed capacity in the peak source, then this lack of heat will be produced from the peak source. If the difference exceeds the nominal load of the peak source, this regime can not be accepted;

From the point of view of electrical power,  $(P_{cg}^n)$ , resulting in the first phase of sizing to meet heat demand, by the initial choice of  $(\alpha_t^c)$  as against the total power,  $P_{cg}^* \equiv P_{CCG}^*$ , to sizing the cogeneration plants to meet electricity demand,  $P_{cg}^{c*}$  is equal with  $P_{cg}^n$  ( $P_{cg}^{c*} = P_{cg}^n$ ), in this case the operation of cogeneration plants being only in cogeneration mode.

### 3. Simulation of the cogeneration plants operation to meet heat demand. The economic efficiency analysis

Sizing the cogeneration plant to meet heat demand, it can deliver electricity to national electricity system, with which it can conclude regulated contracts, or to an electricity consumer, with which it can conclude bilateral contract, as was set out in subsection 2.1. From this point of view, was performed simulation of cogeneration plant operation in the following variants:

#### A. The entire quantity of electricity produced by cogeneration plant is sold through regulated contracts

To be able to watch how is influenced the economic efficiency of cogeneration plant at changing the nominal value of the cogeneration coefficient, it was simulate its operation according to the description given in sub-section §2.1

paragraph I. To this end, it were calculated the net present values for different values of the nominal cogeneration coefficient (between 0 and 1), establishing the maximum net present value. After determining the maximum net present value, it was determined the optimal value of the nominal cogeneration coefficient. In figure 3.1 are presented the results of this calculation.

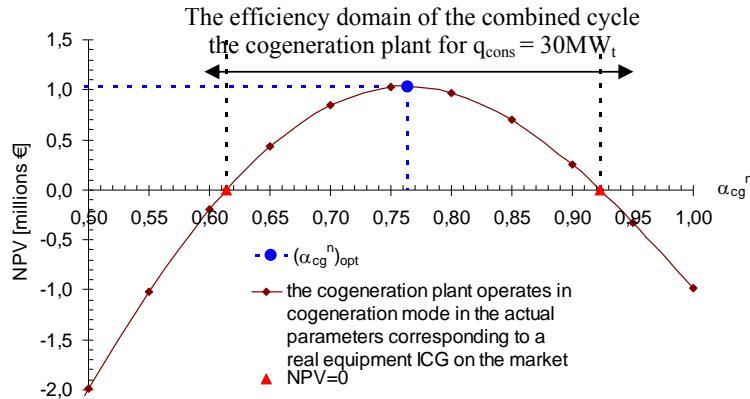


Fig. 3.1 NPV variation depending on the nominal value of the cogeneration coefficient, in accordance with the conditions in which cogeneration plant sells electricity only through regulated contracts

Having regard to that simulation of cogeneration plant operation has been carried out in real conditions of prices, it is found that for a heat demand of 30 MW<sub>t</sub>, as shown in Figure 3.1, implementation of a combined cycle cogeneration plant for small and medium power is cost-effective only for a range of the nominal cogeneration coefficient between 0,61 and 0,92. For values of the nominal cogeneration coefficient of 0,61 and 0,92, cogeneration plant is at the breakeven point where NPV = 0. For nominal cogeneration coefficient values lower than 0,61 or higher than 0,92, the investment made in combined cycle cogeneration plant can no longer amortize, this recording losses becoming higher. It is inferred that the investment made in a combined cycle cogeneration plant of small and medium power can not be amortized at the majority operation with peak heating systems. The optimal value of nominal cogeneration coefficient corresponds to the value  $(\alpha_{cg}^n)_{opt} = 0,76$ , where the net present value records a maximum value,  $NPV^{\max} = 1 \text{ mil. €}$ .

#### B. The entire quantity of electricity produced by cogeneration plant is sold through bilateral contracts

Taking into account the fact that the cogeneration plant has the possibility to conclude bilateral contracts to sell the electrical energy produced, in this

chapter, the cogeneration plant is sized according to the description given in subsection §2.1 paragraph II., where it got the situation in which cogeneration plant fully delivers the electric energy produced, to a consumer with which conclude bilateral contract, a situation described at the point (b) of the same section.

In this case, cogeneration plant sells electricity only through bilateral contracts, whose price is much higher than the price of electricity sold through regulated contracts. Because of this, the economic efficiency of cogeneration plant is higher. Whereas the price of electricity delivered to the consumer with which has concluded bilateral contract, is lower than the electricity price that the electric consumer would pay from an energy operator, both the cogeneration plant and the electrical consumer are having a joint interest from the economic point of view.

Starting from the hypothesis presented in the section §2.1 paragraph II. (B), where cogeneration plant is in the situation to deliver electrical energy only to the consumer with which conclude bilateral contract, was analyzed a comparison, from the point of view of net present value, with a situation where cogeneration plant would deliver electrical energy only to the national electricity system with which the conclude regulated contracts. The results of this calculation are shown in Figure 3.2.

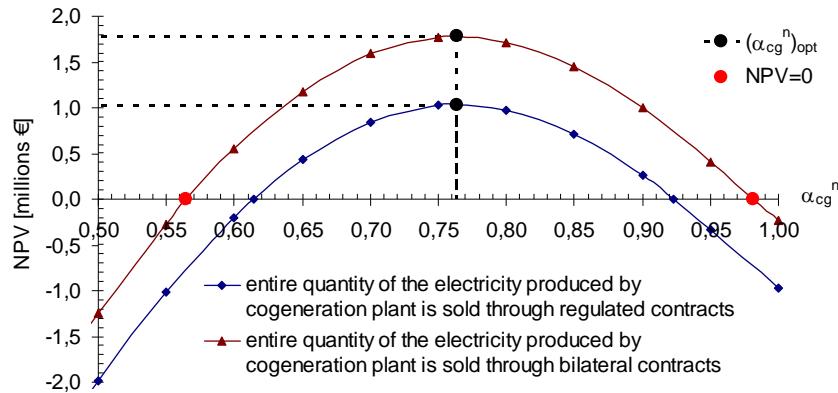


Fig. 3.2 The comparative variation of the net present value depending on the nominal value of cogeneration coefficient for the two cases – cogeneration plant sells electrical energy either through regulated contracts or through bilateral contracts

From Figure 3.2, it follows that, in the event of the cogeneration plant sells electrical energy through bilateral contracts, NPV values are higher than those obtained in the case where cogeneration plant sells electrical energy through regulated contracts, registering for the two cases studied a difference between the maximum NPV values:  $NPV_{cons}^{max} = 1,8$  mil. € versus  $NPV_{SEN}^{max} = 1$  mil. €. Optimal value of the nominal cogeneration coefficient, corresponding for the NPV

maximum value, decreases slightly when the cogeneration plant sells electricity through the bilateral contracts compared with the case where CIP plant sells electricity through the regulated contracts. From the Figure 3.2 result also that, from one case to another, the domain of economic efficiency is different. So, in the case where cogeneration plant sells electrical energy through bilateral contracts, it is efficiency for  $0,57 < \alpha_{cg}^n < 0,98$ , while, in the case where cogeneration plant sells electrical energy through regulated contracts, it is efficiency only for  $0,61 < \alpha_{cg}^n < 0,92$ .

In conclusion, it can be said that when it implements a combined cycle cogeneration plant with gas and steam turbine for small and medium power, must be taken into account if there is a possibility to conclude bilateral contracts for sale of electricity produced, because of the advantages it offers compared with the case in which cogeneration plant sells electrical energy through regulated contracts:

- higher economic efficiency;
- wider domain of economic efficiency.

### **C. One part of the electrical energy produced by cogeneration plant is traded through regulated contracts and another part through bilateral contracts**

In the case where, the electrical power production of cogeneration plant exceeds the electrical power demanded by the consumer with which it concluded bilateral contract, the difference ( $E_{CCG} - E_{cons}$ ) is sold through regulated contracts. In this case, cogeneration plant was sized in accordance with sub-section §2.1 paragraph II. (C). Increasing consumer demand of electricity determines to an increase of NPV, and can be reached in a situation in which there are no more differences between the electrical power production of the cogeneration plant and electricity demand of the consumer, so:  $E_{CCG} = E_{cons}$ . In this case, the situation becomes similar to that shown in sub-section §2.1 paragraph II. (B), where the NPV values are equal to those obtained in sub-section § 3/B. When the electricity needs of the consumer is greater than the amount of electricity produced by cogeneration plant, the situation is similar to that described in sub-section §2.1 in paragraph II (a), and the difference required by the consumer should be taken from the national electricity system, through a direct agreement between the cogeneration plant and the national electricity system. Figure 3.3 shows the variation mode of maximum NPV determined for the cogeneration plant depending by the electricity needs of the consumer.

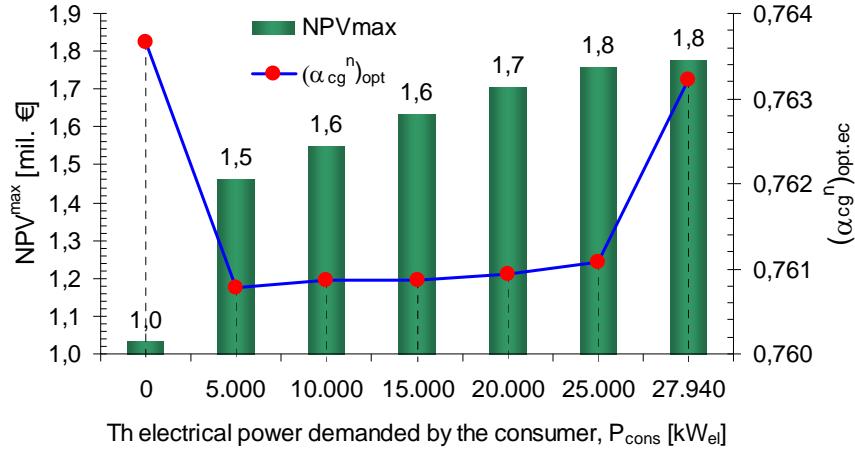


Fig. 3.3 NPV<sup>max</sup> and  $(\alpha_{\text{cg}}^n)_{\text{opt}}$  variation depending on the electrical power, demanded by the consumer with which cogeneration plant has concluded a bilateral contract

From Figure 3.3, it result that with the increase of electrical power required by consumer with which cogeneration plant has concluded a bilateral contract, the optimal values of the nominal cogeneration coefficient increase, simultaneously with maximum values of NPV; with the observation that when cogeneration plant delivers (to consumer) electrical powers in the range 0÷5MW<sub>el</sub>, the optimal values of the nominal cogeneration coefficient increase.

Upward trend of the economic efficiency that cogeneration plant registers to the increase of electrical power delivered to the consumer, with which cogeneration plant concluded bilateral contract, are due to higher price of electricity sold to it compared to the electricity price sold through regulated contracts,  $(p_{\text{el}}^{\text{cons}} > p_{\text{el,cg}}^{\text{SEN}})$ .

In the figure 3.4 shows the electrical power dependence (delivered by cogeneration plant to the national electricity system) by the electrical power required by the consumer, with which the cogeneration concluded bilateral contract; it is found that it decreases with the increase in electrical power required by the consumer  $(p_{\text{el}}^{\text{cons}} > p_{\text{el,cg}}^{\text{SEN}})$ .

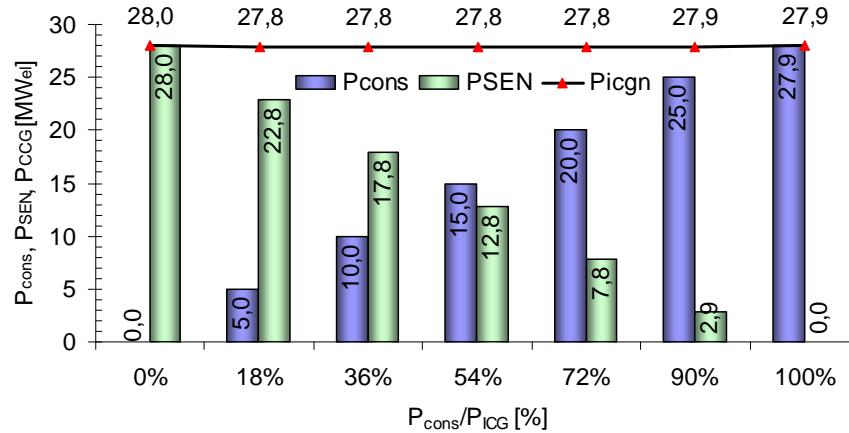


Fig. 3.4 Variation of electrical power sold through regulated contracts depending on the electrical power needed of the consumer, with which the cogeneration plant conclude bilateral contract

In conclusion, in the event that is aimed to increase the economic efficiency of cogeneration plant, it is recommended that the amount of electricity sold under bilateral contracts to be as high as possible to the quantity of electricity sold by the regulated contracts.

**4. Simulation of the cogeneration plants operation to meet electricity demand, with electrical energy production only in cogeneration mode. Determination of the economic optimal electrical power delivered directly to the consumer**

Whereas, in the case joint cycle gas-steam, dissipation of heat in the atmosphere is not cost-effective (as of §2.2 (a)), sizing GCC after the date of application for electricity has been carried out in accordance with §2.2 point of (b), as a result, GCC is in a position to deliver thermal energy a consumer on the basis of the production of electrical power, and the difference required heat consumer is given by the installation of thermal peak. In this case, GCC has been scaled after the regime electric, with operation in scheme of co-generation, for more of the values in the application of electrical power, with a request for heat power time stamp (momentary) 30 MW<sub>t</sub>. So, it has been determined optimum choice from an economic point of view, taking account of the variation of heat power supplied ICG and ITV. This has been done in the example of calculation of which the results are shown in figure 4.1.

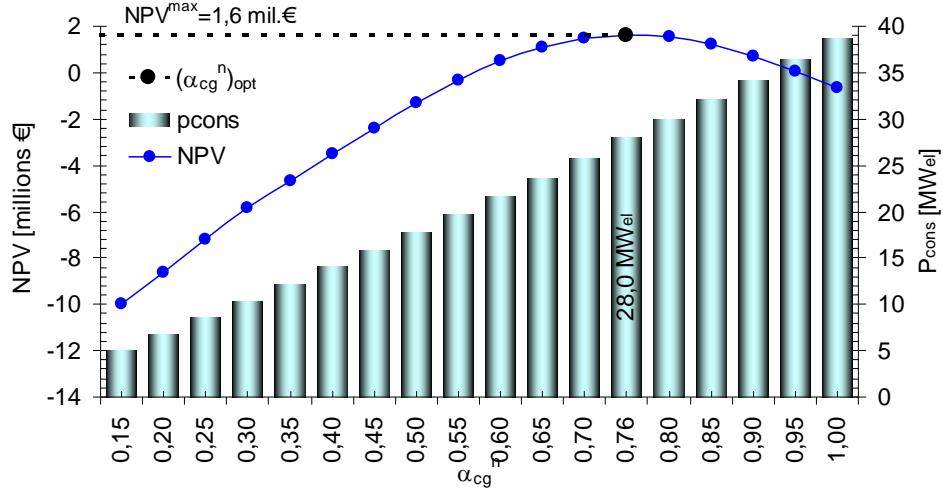


Fig. 4.1 NPV variation depending on the electrical power required by the consumer, in conditions where cogeneration has a consumer with necessary heat of 30 MW<sub>t</sub>

Due to the constant momentary heat power required by the consumer ( $q_{\text{cons}} = 30 \text{ MW}_t$ ), variation of electrical power demanded by the consumer modifies the NPV values of cogeneration plant as well as the quantities of heat delivered from ICG and ITV, the ratio of heat production between  $q_{\text{ICG}}$  and  $q_{\text{CCG}}$ , being increase with increasing demand for electricity. In this case it obtain an optimal value NPV of 1,6 million € at a nominal coefficient of 0,76 for a value of electric power demand of 28 MW<sub>el</sub>. It has been determined, the case where the cogeneration plant is at the critical threshold of profitability, where  $\text{NPV}^{\text{max}}=0$ , for an electricity demand of 20,5 MW<sub>el</sub>.

In conclusion, it can be said that the size of gas and steam combined cycle cogeneration plant for small and medium power with electricity production only in cogeneration mode, with a heat demand of 30 MW<sub>t</sub>, it can successfully implement for of electrical power demands over 20,5 MW<sub>el</sub>, having the economic optimum for an electricity demand of de 28 MW<sub>el</sub>, as shown in Figure 4.1.

## 5. Conclusions

Analyzing the effects on the economic efficiency of gas and steam combined cycle cogeneration plant for small and medium power, to simulate its functioning to meet heat demand and electricity demand, it is found: in both cases it was considered a consumer with a heat request of 30 MW<sub>t</sub>, in accordance with the conditions in which cogeneration plant sells the electrical power only through

bilateral contracts, it is found that it is effective from an economic point of view in the event of:

- the cogeneration plant operates to meet heat demand, for nominal cogeneration coefficient values between  $0,57 < \alpha_{cg}^n < 0,98$ . These nominal values of the cogeneration coefficient are points where cogeneration plant is at the breakeven point where  $NPV = 0$ . The maximum value attainable by optimizing the nominal cogeneration coefficient, is  $NPV^{max} = 1,8$  mil. €, at  $(\alpha_{cg}^n)_{cons}^{opt} = 0,76$ ; the electrical power delivered to the consumer at the optimum nominal cogeneration coefficient is  $P_{cons} = 27.490$  kW<sub>el</sub>.
- the cogeneration plant operates to meet electricity demand, for nominal cogeneration coefficient values,  $\alpha_{cg}^n > 0,57$ . At this value of  $\alpha_{cg}^n$ , cogeneration plant is at critical threshold of profitability where  $NPV = 0$ . The maximum value of  $NPV$  determined at  $(\alpha_{cg}^n)_{cons}^{opt} = 0,76$  is:  $NPV^{max} = 1,6$  mil. €. In this case, the electrical power delivered to the consumer at the optimum nominal cogeneration coefficient is:  $p_{cons} = 28.033$  kW<sub>el</sub>.

By comparing the two versions (with two operating modes of cogeneration plant), it is found that, from the point of view of the maximum value of  $NPV$ , in the case where cogeneration plant is sized to meet heat demand, this value is higher with  $NPV_{grafic. termic}^{max} - NPV_{grafic. electric}^{max} = 146.286$  €, for an electrical power delivered to the consumer smaller with  $P_{cons}^{grafic. termic} - P_{cons}^{grafic. electric} = -93$  kW<sub>el</sub>, the efficiency domain of variance where cogeneration plant has been dimensioned to meet heat demand is higher when compared with that of variance where cogeneration plant has been dimensioned to meet electricity demand.

When comparing the case where cogeneration plant is sized to meet electricity demand and sells electric power only through of bilateral contracts with the case where cogeneration plant is sized to meet heat demand, but sells electrical energy wholly or partly through regulated contracts, it is found that the economic efficiency is higher in the first case comparative with the second case only for the cases where cogeneration plant, sized to meet heat demand, sells electrical energy through bilateral contracts at electrical powers which do not exceed  $P_{cons} = 14.648$  kW<sub>el</sub>, the rest of electrical energy produced by the cogeneration plant being sold through regulated contracts at a power of  $P_{SEN} = 13.199$  kW<sub>el</sub>. In this case, the maximum net present value determined is equal to one determined in the case where cogeneration plant is sized to meet electricity demand, but sells electrical energy only through bilateral contracts,  $NPV_{heat demand}^{max} = NPV_{electricity demand}^{max} = 1.628.527$  €. For the case where cogeneration plant, sized to meet heat demand, sells electrical energy through bilateral contracts, at electrical

power higher than  $P_{\text{cons}}=14.648 \text{ kW}_{\text{el}}$ , the maximum net present value, determined in these cases, is higher than that calculated where cogeneration plant is sized to meet electricity demand and sells electrical energy only through the bilateral contracts,  $\text{NPV}_{\text{heat demand}}^{\max}$  increasing in the interval: (1.628.527€; 1.775.812€].

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