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High Efficiency Cogeneration: Electricity from cogeneration in CHP Plants

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Abstract

In 2004, the European Parliament and the Council of the European Union adopted the Directive 2004/8 EC whose purpose is to increase energy efficiency and develop high efficiency cogeneration of heat and power. Italy brought into force this law by means of the Legislative Decree February 8, 2007, n. 20 and two ministerial decrees (the ministerial decree of Environment Ministry (August 4, 2011), that integrates the Decree n.20, and the ministerial decree of Ministry of Economic Development (September 5, 2011), that lays down the conditions and procedures for access to the support system of cogeneration).
From January 1, 2011, the legislative and incentive cogeneration context is radically changed and, consequently, new boundary conditions must be taken into account in order to evaluate performance of cogeneration plants. Therefore, in this paper authors have analysed the different types of plants in operation in Italy and have calculated the percentage of electricity from cogeneration of each type of plant, taking into account the typical operating parameters. The result of this paper may therefore be a valuable tool for the operators of the cogeneration sector in order to identify the suitability of an investment in this sector.

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Keywords: high efficiency cogeneration; electricity from cogeneration; primary energy saving

1. Introduction

The sector of cogeneration plants in Italy has undergone significant changes in terms of direct and indirect benefits after that the European Directive 2004/8 EC was entered into force. The previous legislation (AEEG 42/02),

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in fact, established that if cogeneration parameters (primary energy saving and thermal limit) were greater than the minimum thresholds in a year of operation, the total production of electricity was recognized as electricity from cogeneration. The new Directive (High Efficiency Cogeneration), instead, recognizes as electricity from cogeneration only the electricity which, together with useful heat, is generally produced by a portion of the cogeneration plant where the overall efficiency is 80% (or 75%, it depends on the typology of the cogeneration plant). Such electricity from cogeneration, together with useful heat, is then used as a parameter for the determination of the incentives (and/or reductions of charges) which the plant can receive. In this paper, therefore, taking into account the actual production (electricity and useful heat) of Italian cogeneration plants from the entry into force of Directive 2004/8 EC, we have analysed the different types of plants in operation in Italy and we have calculated the percentage of electricity from cogeneration of each type of plant, taking into account the typical operating parameters of these power plants. This analysis is not related to specific power plants and therefore it allows to obtain important information about the quantity of electricity from cogeneration in the different power plants. The result of this paper may therefore be a valuable tool for the operators of the cogeneration sector because they can help to identify the suitability of an investment in this sector, taking into account the new legislative context.

Nomenclature

CHP Eη	electrical efficiency of the cogeneration production
CHP Hη	heat efficiency of the cogeneration production
E_{CHP}	electricity from cogeneration
$E_{non\text{-}CHP}$	non-CHP electrical/mechanical energy
F_{CHP}	fuel input used to produce the sum of useful heat output and electricity from cogeneration
$F_{non\text{-}CHP,E}$	fuel energy for non-CHP electrical/mechanical energy
$F_{non\text{-}CHP,H}$	fuel energy for non-combined generation of useful heat energy
H_{CHP}	useful heat from cogeneration
$H_{non\text{-}CHP}$	non-combined useful heat energy
Ref Eη	efficiency reference value for separate electricity production
Ref Hη	efficiency reference value for separate heat production

2. High efficiency cogeneration : European directives and Italian transposition

In 2004, the European Union adopted the Directive 2004/8 EC [1] whose purpose is to develop *high efficiency cogeneration* of heat and power based on useful heat demand and primary energy savings.

The Annex II of the Directive introduces the concept of “*Electricity from Cogeneration*” (E_{CHP}) :

$$E_{CHP} = C * H_{CHP} \tag{1}$$

where:

- E_{CHP} is the electricity from cogeneration
- C is the “*power to heat ratio*”
- H_{CHP} is the useful heat from cogeneration (calculated for this purpose as total heat production minus any heat produced in separate boilers or by live steam extraction from the steam generator before the turbine and so on).

The Annex III of the Directive defines the “High Efficiency Cogeneration” as the cogeneration production from cogeneration units that provides *primary energy savings* (PES, see below) at least 10% compared with the references for separate production of heat and electricity (small scale cogeneration units, installed capacity below 1 MWe, and micro cogeneration units, installed capacity below 50 kWe, must provide *primary energy savings*, that is PES>0).

The *primary energy savings*, in accordance with Annex II, shall be calculated using the following formula:

$$PES = 1 - \frac{1}{\frac{CHP\ H\eta}{REF\ H\eta} + \frac{CHP\ E\eta}{REF\ E\eta}} \quad (2)$$

where:
- CHP Hη is the heat efficiency of the cogeneration production defined as annual useful heat output (H_{CHP}) divided by the fuel input (F_{CHP}) used to produce the sum of useful heat output and electricity from cogeneration;
- Ref Hη is the efficiency reference value for separate heat production;
- CHP Eη is the electrical efficiency of the cogeneration production defined as annual electricity from cogeneration (E_{CHP}) divided by the fuel input (F_{CHP}) used to produce the sum of useful heat output and electricity from cogeneration;
- Ref Eη is the efficiency reference value for separate electricity production.

The efficiency reference values must be calculated according to the following main principles: (i) the comparison with separate electricity production shall be based on the principle that the same fuel categories are compared; (ii) each cogeneration unit shall be compared with the best available and economically justifiable technology for separate production of heat and electricity on the market in the year of construction of the cogeneration unit. These reference values were first published in 2006 [2] and they are differentiated by year of construction and types of fuel. Then, these values were reviewed in 2011 [3].

The methodology for determining the *Electricity from Cogeneration* and the others parameters involved in PES calculation was postponed to successive Decisions. After the publication of the Directive 2004/8 EC, the Decision of November 19, 2008 (2008/952/EC) [4], establishing detailed guidelines for the implementation and application of Annex II to Directive 2004/8/EC, stated that a cogeneration unit, operating with maximum technically possible heat recovery from the cogeneration unit itself, is said to be operating in *full cogeneration mode* and all electricity is considered combined heat and power (CHP) electricity (Fig. 1). For cases in which the plant does not operate in full cogeneration mode, it is necessary to identify the electricity and heat not produced under cogeneration mode, and to distinguish it from the CHP production. The energy input and output of the heat-only-boilers, which in many cases are part of the on-site technical installations, are to be excluded.

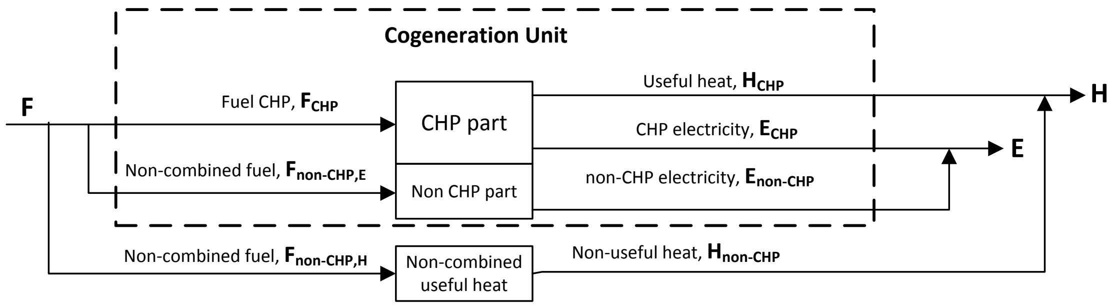

Fig. 1. Cogeneration unit

Italy brought into force these laws by means of the following decrees: Legislative Decree February 8, 2007, n. 20, ministerial decree of Environment Ministry (August 4, 2011) and ministerial decree of Ministry of Economic Development (September 5, 2011) [5, 6, 7]. In February 2012 the Italian Ministry of Economic Development published detailed guidelines entitled “Guidelines for the implementation of ministerial decree of Ministry of Economic Development (September 5, 2011)” [8]. First of all, the guidelines give rules to calculate overall efficiency. To determine the overall efficiency (η_g) of a CHP plant in a reporting period, the following parameters must be known (fig.1):
- total useful heat energy (H)
- total electrical/mechanical energy (E)
- total fuel energy (F)

- non-combined useful heat energy ($H_{non-CHP}$)
- non-combined fuel energy for non-combined generation of useful heat energy ($F_{non-CHP,H}$)

CHP useful heat energy must be determined as follows:

$$H_{CHP} = H - H_{non-CHP,H} \tag{3}$$

The overall efficiency is:

$$\eta_g = \frac{E + H_{CHP}}{F - F_{non-CHP,H}} \tag{4}$$

If the overall efficiency (η_g) achieves or exceeds the values in Annex II of the CHP-Directive (η_{CHP}=0,80 for combined cycle gas turbines with heat recovery and steam condensing extraction turbines-based plants or η_{CHP}=0,75 for the other types of cogeneration units, i.e. steam backpressure turbine, gas turbine with heat recovery, internal combustion engine, microturbines, stirling engines, fuel cells), the CHP plant does not generate non-CHP electrical/mechanical energy ($E_{non-CHP}$) and then:

$$\begin{aligned} H_{CHP} &= H - H_{non-CHP,H} \\ E_{CHP} &= E \\ F_{CHP} &= F - F_{non-CHP,H} \end{aligned} \tag{5}$$

Otherwise the non-CHP electrical/mechanical energy ($E_{non-CHP}$) and the referring fuel energy ($F_{non-CHP,E}$) have to be determined (Fig. 1). To determine the non-CHP electrical/mechanical energy ($E_{non-CHP}$) and the referring fuel energy ($F_{non-CHP,E}$) of a CHP plant and to isolate the CHP part, the following steps have to be done:

1) determination of power loss coefficient (β). This parameter must be calculated for steam condensing extraction turbine-based plants. It gives the electricity loss due to steam extraction for heat production and so it is:

$$\beta = \frac{h_{estr} - h_{cond}}{h_{estr} - h_{ref}} \cdot K_p \tag{6}$$

where:
- h_{estr} is the enthalpy of the steam extraction;
- h_{cond} is the steam enthalpy at the condenser inlet;
- h_{ref} is reference enthalpy (evaluated as the water enthalpy at 15°C e 1 bar abs)
- K_p is given by the Guidelines where there is a matrix of values differentiated by power of the steam turbine; this parameter takes into account mechanical and electric losses.

The value of h_{estr} is calculated by using pressure and temperature of the steam extraction. The value of h_{cond} is calculated by using the procedure illustrated in the guidelines: briefly, it consists of an energy balance of the steam turbine, known the power of the steam turbine and the mass flow-rate and the enthalpy of all extractions and all inlets in the turbine. If the steam turbines has more than one extraction, the parameter β is calculated as a weighted average of the different extractions.
For all the other types of cogeneration units, it is β=0.

2) determination of the efficiency of non-combined electrical/mechanical energy generation:

$$\eta_{non-CHP,E} = \frac{E + \beta \cdot H_{CHP}}{F - F_{non-CHP,H}} \quad (7)$$

It important to underline that the efficiency of non-combined electrical/mechanical energy generation represents a conventional efficiency of the power plant in "full electrical load".

3) determination of the power-to-heat ratio (named C_{eff} in Italian legislation. This parameter is the C_{actual} of the European legislation):

$$C_{eff} = \frac{\eta_{non-CHP,E} - \beta \cdot \eta_{CHP}}{\eta_{CHP} - \eta_{non-CHP,E}} \quad (8)$$

where η_{CHP} is equal to 0.8 for combined cycle gas turbines with heat recovery and steam condensing extraction turbines-based plants and 0.75 for the other types of cogeneration units.

4) determination of CHP electricity/mechanical energy:

$$E_{CHP} = C_{eff} * H_{CHP} \quad (9)$$

5) determination of non-CHP electricity/mechanical energy:

$$E_{non-CHP} = E - E_{CHP} \quad (10)$$

6) determination of fuel energy for non-CHP electricity/mechanical energy generation:

$$F_{non-CHP,E} = \frac{E_{non-CHP}}{\eta_{non-CHP,E}} \quad (11)$$

7) determination of fuel energy for CHP electricity/mechanical energy generation:

$$F_{CHP} = F - F_{non-CHP,H} - F_{non-CHP,E} \quad (12)$$

Using such a procedure, the CPH part of a cogeneration plant will achieve an overall efficiency exactly equal to the overall efficiency (η_{CHP}=0.8 or η_{CHP}=0.75) established in Annex II of the CHP-Directive.

3. Cogeneration sector in Italy: analysis of energy production

In this section, data of the production of electricity and heat from cogeneration plants in Italy in the years 2011-2013 are shown. The results are drawn from the data provided by Terna [9-11], assuming that all the useful heat may be regarded as CHP useful heat. The technologies here analysed are:

- steam condensing extraction turbine-based plants (SC)
- steam back-pressure turbine-based plants (SBP)
- combined cycle power plants with heat recovery (CC)
- gas turbines with heat recovery (GT)
- internal combustion engines with heat recovery (ICE)

The Fig. 2 shows the production of CHP useful heat from cogeneration plants in the years 2011-2013. This figure shows that in Italy about 50% of the CHP useful heat is produced by combined cycle power plants with heat recovery (CC). The remainder useful heat is produced by the other types of power plants in a similar quantity, excluding steam condensing extraction turbine-based plants (SC) which, in 2011, produced almost 25% of total useful heat production.

In terms of electricity produced (Fig. 3), the combined cycle power plants with heat recovery (CC) attain the top spot with a share of about 80% of the total electricity production while steam back-pressure turbine-based plants (SBP) are placed in last place with a share of about 2% of the total production. Finally, Figure 4 shows the different efficiencies of the cogeneration plants in the year 2013: in blue the overall efficiency of cogeneration plants is shown, in red the electrical efficiency (gross electricity production / heat input) and in green the thermal efficiency (heat / heat input). Looking at the overall efficiency, it can be noted that no type of plant reaches the limit threshold except steam back-pressure turbine-based plants (SBP). This means that all the other types of cogeneration plants will be divided, in agreement with the Directive 2004/8 EC, in a CHP part and in another no-CHP part.

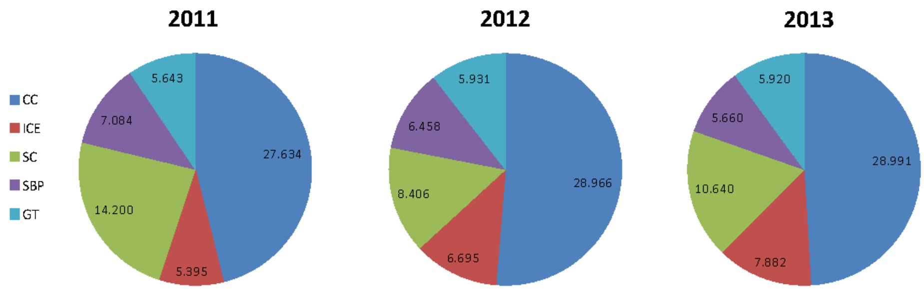

Fig. 2. Heat production in Italy by cogeneration plants (GWh)

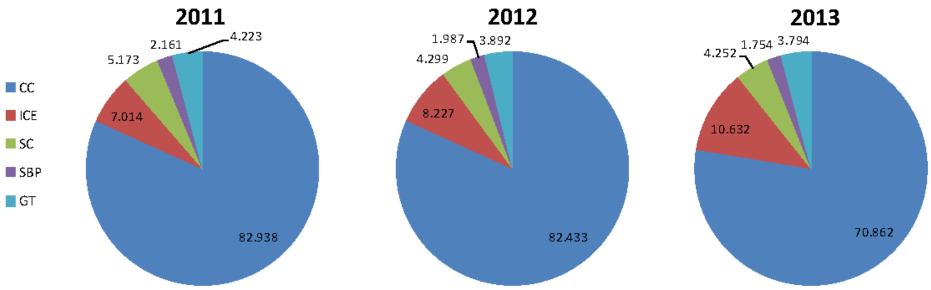

Fig. 3. Gross Electricity production in Italy by cogeneration plants (GWh)

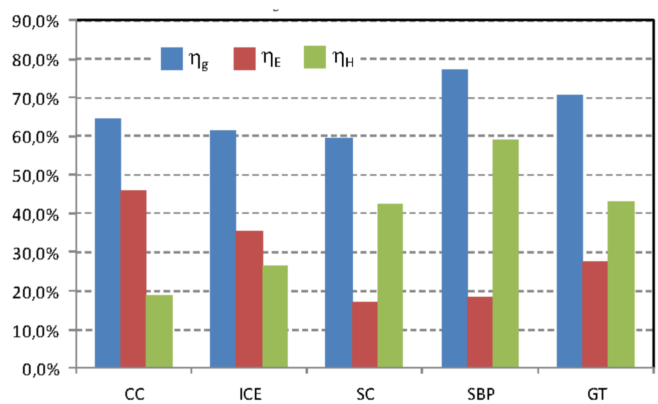

Fig. 4. Efficiency in Italian cogeneration plants (2013)

3.1. Energy performance of CHP plants without power loss coefficient

The types of cogeneration plants without power loss coefficient are the steam back-pressure turbine-based plants (SBP), the gas turbines with heat recovery (GT) and the internal combustion engines with heat recovery (ICE). As SBP plants have an overall efficiency greater than threshold, these power plants do not have to be divided in a CHP part and in a no-CHP part.

For the other two types of cogeneration plants (ICE and GT), instead, the subdivision is very simply because the power loss coefficient is equal to zero ($\beta = 0$). Thus exploiting the relations introduced in par. 2, and assuming $\beta = 0$, it is possible to evaluate the input energies and the output energies of the total power plants and of the CHP parts.

Fig 5 shows the production of electricity and useful heat, together with the heat input, for the overall system and for the CHP part. Assuming that all heat is CHP useful heat, there is no difference between the total heat in the total plant and the heat in the CHP part. With regard to electricity instead, the electricity from cogeneration (that is the electricity produced in the CHP part) is lower than the total electricity production. More in details, for the gas turbines with heat recovery (GT) the electricity from cogeneration is very high (about 91%), while for the internal combustion engines with heat recovery (ICE) it is lower (about 66%).

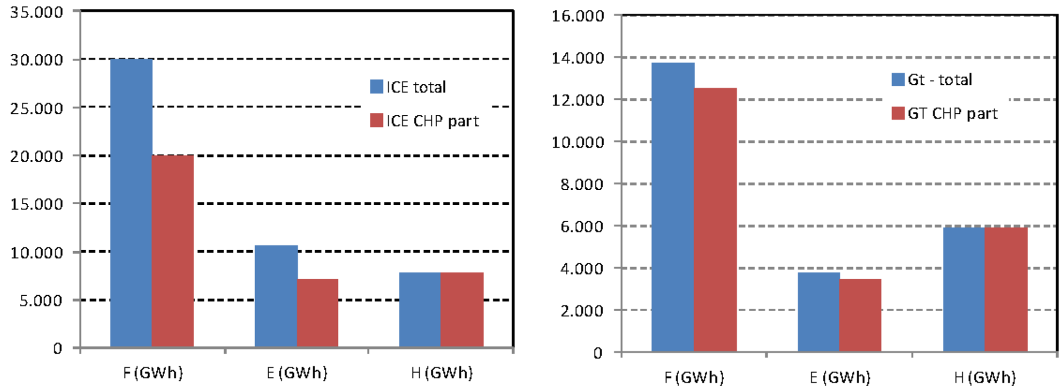

Fig. 5. Energy input and output in Italian cogeneration plants (2013)

3.2. Energy performance of CHP plants with power loss coefficient

The types of cogeneration plants with power loss coefficient are the steam condensing extraction turbine-based plants (SC) and the combined cycle power plants with heat recovery (CC). In order to calculate the power loss coefficient, it is necessary to define the bleeding that will feed the thermal user. Because the aim of this paper is to provide a general overview of the different types of cogeneration units in the new legislative context, we have chosen generic schemes, able to represent a great number of installations. In addition, input parameters of these power plants were chosen as average values, representative of actual operating technologies. More in details, for steam turbine-based plants live steam pressure and temperature are respectively 90 bars and 490°C, deaerator pressure is 5 bar, extraction pressure is variable from 1 bar (district heating application) to 60 bar (very high quality heat for industrial applications) and the condenser pressure is 0.05 bar for the steam condensing extraction turbine-based plants. For combined cycle power plants, the gas turbine has a net efficiency of 36% and the temperature of exhaust gases at the heat recovery steam generator (HRSG) inlet is 520°C; the HRSG has two pressure levels (90 bar and 5 bar) and the steam turbine is a condensing extraction turbine where the extraction pressure is variable from 1 bar to 60 bar (as in the previous case) and the condenser pressure is 0.05 bar.

A parametric analysis was performed in order to assess, as function of the extraction pressure, the value of the power loss coefficient and therefore the value of the power-to-heat ratio (Ceff). The results are shown in Fig 6 for the steam condensing extraction turbine-based plants (SC). In the Fig. 6a the trend of the power loss coefficient as function of the extraction pressure is shown as a continuous line; we have used two different values of the isentropic efficiency during steam expansion (in red we have reported the results obtained when the isentropic efficiency is equal to 0,75 and in blue when it is equal to 0,85). The dotted line shows the trend of power-to-heat ratio (Ceff). Obviously, the power loss coefficient increases when the extraction pressure increases, while the power-to-heat ratio decreases when the extraction pressure increases. In our parametric analysis, the value of power-to-heat ratio is 2,5, which corresponds to the same ratio of overall steam condensing extraction turbine-based plants (SC) in Italy in the year 2013. In the Fig 6b the efficiency of non-combined electrical energy generation is shown; obviously this parameter is almost constant even if the extraction pressure varies. The same graph shows the trend of the electrical efficiency as a function of extraction pressure: obviously, it decreases with increasing extraction pressure.

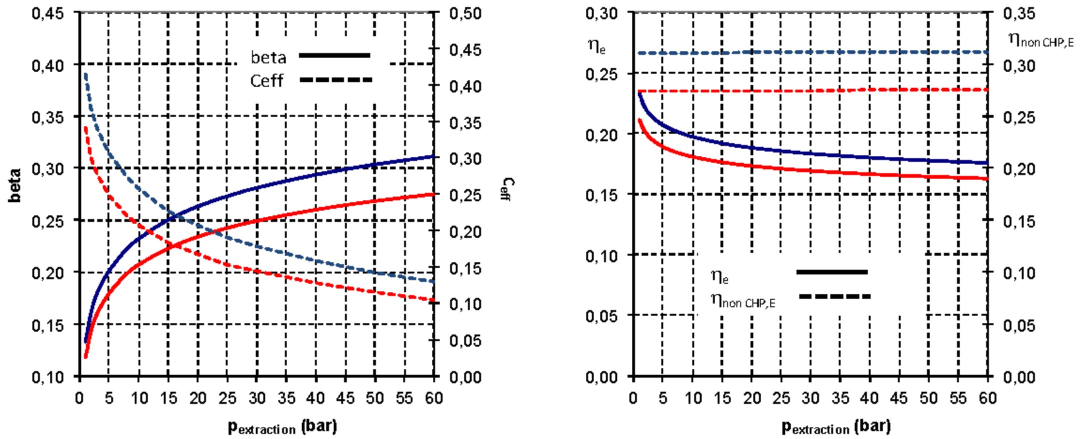

Fig. 6a High efficiency cogeneration parameters (SC) Fig. 6b

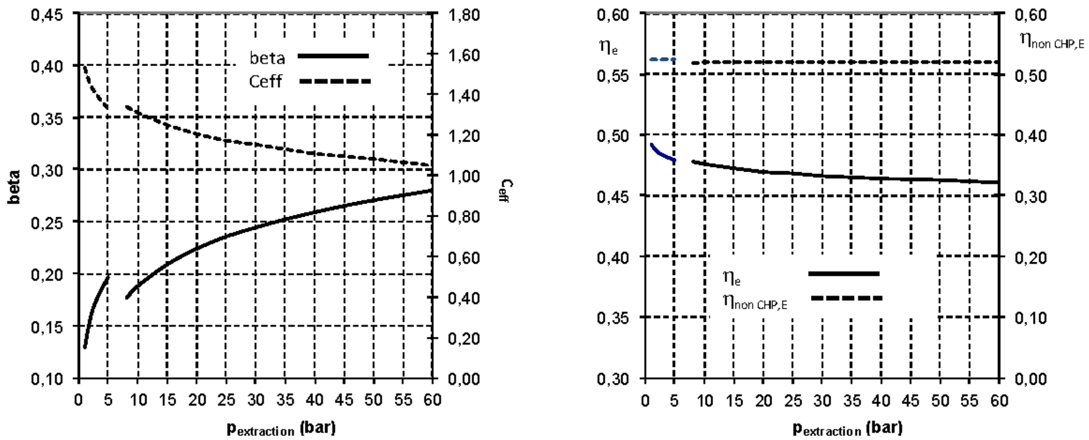

Fig. 7a High efficiency cogeneration parameters (CC) Fig. 7b

Similar considerations can be drawn for the combined cycle power plants with heat recovery (CC) (Fig. 7). The discontinuities in the graphs depend on the extraction pressure: in fact there are discontinuities when the extractions are made upstream or downstream of the mixing of the steam flow rate exhausted from the first turbine and the steam flow rate produced by heat recovery steam generator at low pressure. In this parametric analysis, the value of power-to-heat ratio is 0,4, which corresponds to the same ratio of overall combined cycle power plants with heat recovery in Italy in the year 2013.

Finally, in Fig 8 the CHP electricity-to-electricity ratio is shown as a function of the extraction pressure. It can be seen that (Fig. 8a) this ratio is very high for the steam condensing extraction turbine-based plants (SC) when the extraction pressure is very low, while it is low (about 28-32%) when the extraction pressure is very high (60 bar). For the combined cycle power plants with heat recovery (CC), instead, (Fig. 8b), this ratio never reaches the unitary value; high values of this ratio (greater than 60%) can be reached only with very low extraction pressure, while this ratio less than 45% when the extraction pressure is high.

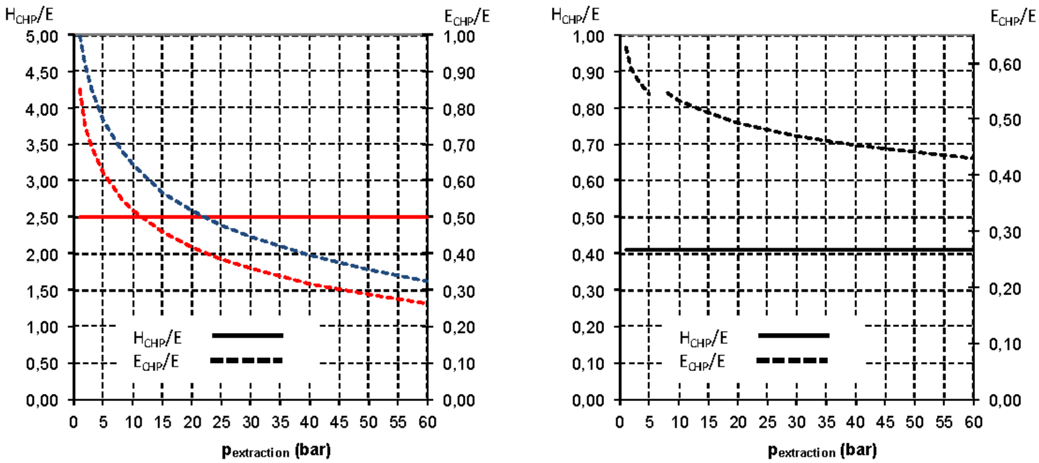

Fig. 8a CHP electricity-to-electricity ratio Fig. 8b

3.3. Electricity from cogeneration in CHP plants

On the basis of the evaluations carried out here, it is therefore possible to provide an indication of the value of the ratio E_{CHP}/E for each type of cogeneration plants. For cogeneration plants with power loss coefficient, it is possible to choose a proper range of variability of the extraction pressure (in the range 5-30 bar the electric efficiencies of the CC and SC cogeneration plants here calculated are very similar to those obtained in 2013) . In this range, the minimum and the maximum value of of the ratio E_{CHP}/E is equal to 0,4-0,7 for the steam condensing extraction turbine-based plants (SC) and 0,45-0,55 for the combined cycle power plants with heat recovery (CC).
These values are shown in Fig. 9, where the main results are:

- for all power plants, electricity from cogeneration is lower than total electricity produced, except for steam backpressure turbine-based plants;
- for combined cycle power plants with heat recovery (CC), the ratio E_{CHP}/E is the lowest;
- also for steam condensing extraction turbine-based plants (SC), this ratio is low, but it can reaches the same value of the internal combustion engines with heat recovery (ICE) when optimistic assumptions are considered;
- gas turbines with heat recovery (GT) have excellent performance: about 90% of the electricity produced is electricity from cogeneration
- in terms of electricity from cogeneration, steam backpressure turbine-based plants are the best solution because all electricity produced is electricity from cogeneration (PES must be verified).

These considerations can become very useful for operators of the cogeneration sector because they can help to identify the suitability of an investment in this sector, taking into account the new legislative context. It is important to remember that these analyses were carried out using the energy production data given by Terna; a parametric analysis as function of useful heat produced was performed by authors in another paper [12].

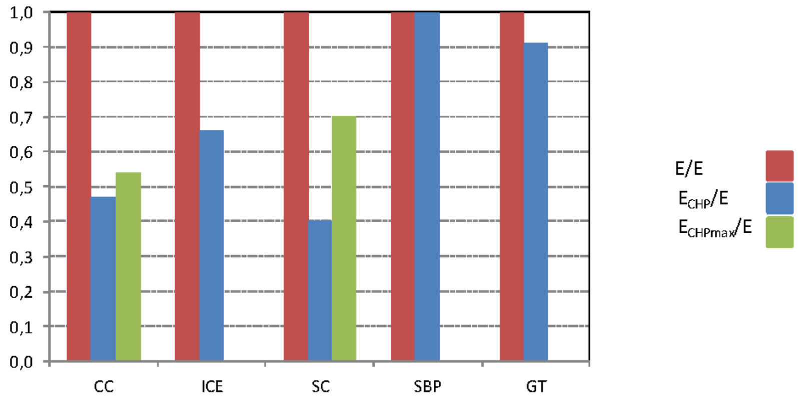

Fig. 9 Ratio E_{CHP}/E for each type of cogeneration plants

4. Conclusions

In this paper, performance assessment of Italian industrial cogeneration plants, operating in 2013 in the new legislative context, was carried out. First of all, the salient features of high efficiency cogeneration legislation were illustrated. Then, the procedure for the calculation of high efficiency cogeneration parameters was presented and finally five different cogeneration technologies were analysed (using data available by Terna) and their high efficiency cogeneration performance was calculated and compared. The main results are:

- for CHP plants without power loss coefficient, the gas turbines with heat recovery (GT) have a very high ratio E_{CHP}/E (about 0,91; the internal combustion engines with heat recovery (ICE) have a lower ratio E_{CHP}/E (0,66). The steam backpressure turbine-based plants do not have to be divided in a CHP part and in a no-CHP part: for them the ratio ECHP/E is equal to 1;
- for CHP plants with power loss coefficient, steam condensing extraction turbine-based plants (SC) have very high ratio E_{CHP}/E (about 0,7-1) when the extraction pressure is low, while the ratio E_{CHP}/E is low (about 0,28-0,32) when the extraction pressure is very high (60 bar). Combined cycle power plants with heat recovery (CC), instead, have a quite low ratio E_{CHP}/E (about 0,45-0,55 when the extraction pressure is10-60 bar) and this ratio never reaches the unitary value.

These considerations can become very useful for operators of the cogeneration sector because they can help to identify the suitability of an investment in this sector, taking into account the new legislative context.

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